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Abstract

This study examined the behavior of AE sensor couplants for through-transmission of acoustic signals or out-of-plane motion. In order to provide controlled conditions, face-to-face transmitter-receiver arrangement was utilized. All liquid and gel couplants are found to give satisfactory service with careful installation, producing the minimum couplant thickness of 5 to 8 \( \mu m \). Their performance is nearly identical to 1.2 MHz. With normal installation procedures, however, the loss can be 3 to 5 dB with viscous resins and gels, as couplant thickness can become 10 to 15 \( \mu m \) and high frequency components are lost more than the peak amplitude reduction. Honey turns out to be an excellent couplant because of its higher acoustic impedance, while commonly used silicone grease can be a poor choice at higher frequencies. Higher frequency transmission loss increases with thickness as predicted by theory of through-gap transmission with approximately linear dependence on frequency.

Keywords: Sensors, Couplants, Through-transmission, Attenuation, Frequency effects

Introduction

In all acoustic emission (AE) tests, a sensor must be mounted on a test object unless a more expensive non-contact sensor is used. Sensor couplants have been discussed in several articles over the years [1-6]. These were preceded by discussion of ultrasonic couplants for contact testing [7-10]. ASTM E650 provides comprehensive guidelines for AE sensor mounting [11]. In selecting a specific type of AE sensor couplant, Theobald [12] provided the best available guidelines at present and summarized the features of various couplants. His group also showed some spectral transmission characteristics of couplants [5].

We have recently evaluated sensor characteristics and assessed couplant behavior as a part of the sensor studies [13]. Here, our studies are limited to the conditions for through transmission of acoustic signals or out-of-plane motion, using face-to-face transmitter-receiver arrangements. Quite often, AE applications detect in-plane motion of guided waves. The present results ignore such AE signals since their detection critically relies on the sensor size, signal frequency spectra as well as the vibration modes. The use of controlled condition also precludes effects of surface roughness and curvatures, which often add to coupling loss. While most liquid couplants provide satisfactory results with careful usage, conventional mounting practices can lead to loss of sensitivities, especially at higher frequencies above 1 MHz. Results are given below.

Experimental

Couplants are characterized using face-to-face sensor arrangements. Both wideband and resonant sensors are utilized. Most sensors have an almina face plate (except Dunegan S140B and AET AC175L with epoxy facing) and were used in cleaned state without any special surface
preparation. Transmitter is excited using short (<2 µs duration) high-voltage pulses. Received signals are digitized at 2 ns interval and analyzed using FFT with using the data length of 262,144, providing 1.9 kHz resolution. The signal length was mostly 10 µs (5,000 points) for broadband sensor pairs and up to 100 µs (50,000 points) with a resonant sensor. The FFT routine of Noesis (Enviroacoustics, ver. 5.8) was used with the pre-set parameters and Hamming window. All tests were conducted at 21±1°C.

Following couplants are examined. Water, motor oil (SAE 5-30 grade), honey, Vaseline, High vacuum (HV) silicone grease (Dow Corning), Stopcock silicone grease (Dow Corning), Nonaq stopcock grease (S-530, Fisher Sci.), Couplant resin (SC-6, AET), epoxy resin (quick-setting, HFT or Harbor Freight Tools), ultrasonic shear gel (54-T04, Sonotech) and a plastic film as dry couplant (Saran wrap). Of these, Nonaq and AET resin are no longer available commercially.

Results and Discussion

1. Best practice

When the viscosity of couplants is high, it takes time to establish ideal couplant thickness. During mounting with such couplants, a sensor must be pressed using 20-50 N force and be rotated to squeeze out excess couplant. With Vaseline and honey, it takes 5 to 10 min, while more viscous (like SC-6) and stiffer (HV grease) couplants require 20 to 30 min. In contrast, water and motor oil provide the maximum transmission from start, though these thinner couplants require some pressure (several N force) to maintain good contact.

![Fig. 1 FFT magnitude spectra of received signals through couplant, or t vs. frequency, f. Vaseline: dark blue curve, motor oil: red, Nonaq: blue, High vacuum grease: purple, Stopcock grease: brown, SC-6 resin: green. V103 transmitter and FC500 receiver.](image)

Using a 1-MHz transducer (13-mm diameter, Olympus V103) as a transmitter and a wideband sensor (FC500, AET) as a receiver in a face-to-face sensor arrangement, the output frequency spectra are shown in Fig. 1. These also represent transmission spectra, t. Six couplants are used and best contact was achieved for each. Data spread is less than 1 dB to 1.2 MHz, but three curves...
start to deviate lower. Differences between the spectra or $\Delta t$ are plotted in Fig. 2, where Vaseline data is used as reference. Two curves for oil (red) and Nonaq (blue) deviate positively $>1.2$ MHz, while three become lower. Of the three, the purple curve for HV silicone grease is the lowest, being $\sim 2$ dB lower than Vaseline $>1.5$ MHz. This is surprising as this is a commonly used couplant and the peak values differ only 0.5 dB (Vaseline result is higher than HV silicone). Another silicone grease is comparable to viscous resin couplant (SC-6) with both $\sim 1$ dB lower than Vaseline.

Fig. 2 Differences in transmission spectra, $\Delta t$, of received signals through couplant using Vaseline spectrum as reference. Motor oil: red, Nonaq: blue, High vacuum grease: purple, Stopcock grease: brown, SC-6 resin: green. V103 transmitter and FC500 receiver.

Fig. 3 Differences in transmission spectra, $\Delta t$, of received signals through couplant using Vaseline spectrum as reference up to 4 MHz. Motor oil: red, Nonaq: blue, High vacuum grease: purple, Stopcock grease: brown. NDT Systems C16 transmitter and FC500 receiver.
Another set of best-effort coupling used a 2.25-MHz transducer (13-mm diameter, NDT Systems C16) as a transmitter and a wideband sensor (FC500, AET) as a receiver. In terms of peak voltage of the waveform, HV grease was 1.8 dB lower and stockcock grease was 1 dB lower (despite waiting >30 min under 15 N force and 50 N during measurement). Figure 3 shows the differences in the spectra, again using the Vaseline result as reference. High frequency loss for the silicone grease cases was even higher than in the previous tests, reaching 3 to 4 dB >2.5 MHz. Both oil and Nonaq had better coupling than Vaseline above 2.5 MHz (these used 50 N force). It is unclear why better coupling could not be made for the silicone grease cases, but at least these showed lower peak voltages, indicating poorer performance.

In the best coupling conditions, all the couplants tested performed equally to 1.2 MHz, while some have 1 to 2 dB (or 3–4 dB) higher transmission loss >1.5 MHz (or >2.5 MHz).

![Fig. 4 Differences in transmission spectra of received signals, $\Delta t$, through couplant using Vaseline spectrum as reference. Non-optimum sensor installation for viscous couplants. Motor oil: red, Nonaq: blue, Shear gel: dark blue, High vacuum grease: purple, Stopcock grease: brown, SC-6 resin: green, plastic film: black. V103 transmitter and FC500 receiver.](image)

2. Normal coupling

In normal AE testing, we typically mount a sensor within a short time, spending no more than 30 sec. Adequate couplant is applied, squeezed with force in compression and in shear, then fix the sensor with a spring and/or a holder, or by winding tape over the sensor. With such a method, viscous couplants typically produce a thicker layer with higher transmission loss. In the next series of tests, eight couplants were used. With the best Vaseline coupling as reference, spectral differences are plotted in Fig. 4. Nonaq (blue), water (red dash) and shear gel (dark blue) achieved essentially same peak amplitude (−0.1 to −0.6 dB) and the spectra differed less than 1 dB to 2 MHz (except water had a slightly larger loss at 200–600 kHz). Silicone grease (brown and purple curves) and SC-6 (green) suffered higher losses. In the case of HV grease, the loss reached 10 dB at >1.7 MHz. These three had lower peak amplitude: HV grease showing −6.3 dB, stopcock grease, −3.6 dB and SC-6, −2 dB, respectively. Another one is a plastic film, used as dry couplant. As
expected, this performed poorly: −7 dB in peak signal amplitude and larger transmission loss than most liquid/gel couplants except HV grease >1.2 MHz.

Thus, we need to be selective in choosing a couplant when high frequency response is sought. In particular, the use of high viscosity couplants should be avoided unless one can spend adequate time to properly achieve good coupling. One remedy is to raise the couplant temperature during installation, thus lowering their viscosity. Another point of interest is that the shear gel did not provide any special advantages even though it is expensive. Note also that Nonaq is no longer marketed commercially. Our bottle is ~50 years old as we rarely used it.

3. Couplant vs. solid bonding

For mechanical stability, solid bonds are superior to liquid couplants. Bonding with glue is also needed for better shear wave detection. It is assumed intuitively that solid bonds should provide better wave transmission as the wave velocity increases with curing of thermosetting polymers, such as epoxy. We examined the wave transmission of epoxy resin during curing. A quick-setting 2-part epoxy (Harbor Freight Tools) was used. Three sets of curing tests were conducted; two were face-to-face tests using resonant sensors (R15, S140B and AC175) and one used 38-mm thick Al plate buffer between FC500 and 1-MHz UT transducer (Automation Ind., 13-mm diameter). In all cases, the pairs were excited with high voltage pulse and the output waveforms recorded and analyzed.

![Graph of Transmission spectra, t, of received signals through couplant. Vaseline reference: blue curve, epoxy resin (as mixed): green, epoxy resin (cured for 30 min): red. FC500 transmitter and Automation Ind. 1 MHz-1/2”](image)

The peak amplitude of the received signals remained constant from the time of coupling with mixed epoxy resin to complete curing at 30 min. Some spectral changes can be seen in Fig. 5, but overall spectra remain essentially constant. This data is for the higher frequency transducer pair, but similar results are found for the pairs of resonant sensors. It is concluded that coupling behavior is unaffected by epoxy curing, changing liquid resin into solid bond.
The solid epoxy bond was stripped from the Al plate after test and its thickness was 13 µm. The epoxy resins, both before and after mixing, had consistency of honey. From some epoxy literature, quick setting types have viscosity of about 10 Pa·s (or 10,000 centipoise). Honey is listed as 7 to 10 Pa·s at 20°C. Thus, we can assume the thickness of moderately viscous liquid couplant layers to be similar to the hardened epoxy bond, or 13 µm. Note that water has the viscosity of 1 mPa·s and grade-30 motor oil 250 mPa·s. Their couplant layer thickness should be less.

4. Couplant thickness

Next, we examined effects of couplant thickness. In comparing various couplants (cf. Fig. 4), we used Vaseline as reference. Upon the initial application of this couplant, the thickness is much higher than the minimum we can obtain after applying forces for 5 to 10 min. The received amplitude is also lower. In the same series of tests for Fig. 4, Vaseline gives only 1.89 V, which eventually increases to 2.91 V; i.e., the initial value is 3.7 dB lower. For these two tests, the received signal spectra and their difference are plotted against frequency in Fig. 6. The difference linearly increases with frequency, reaching 6.2 dB at 2 MHz. Thus, the loss in peak amplitude is due mainly to the high frequency components above 500 kHz.

![Fig. 6 Transmission spectra, t, of received signals through Vaseline couplant. Vaseline reference: red curve, Vaseline couplant after normal mounting: blue. Spectral difference, ∆t, between normal and reference installation is plotted in purple curve, which follows linear frequency dependence in black dash line. ∆t (dB) = 3.10 f (MHz). FC500 transmitter and Olympus V104 receiver.](image)

Using plastic shims with a 13-mm diameter hole, we examined the thickness effect directly using honey, water, Vaseline and stopcock grease. Peak output voltage is plotted against the couplant thickness (in mm) in Fig. 7. From the top curve for honey (purple), water (red), Vaseline (blue) and stopcock grease data are shown. The lower three data follow straight lines in log-log plotting, indicating the power law behavior. The bottom two lines are nearly identical. The honey data can be represented by a second-order polynomial. The data show that the peak amplitude decreases with thickness, but the thickness dependence is not unique. Since honey shows the highest output below 0.2 mm, the viscosity is not the only factor for the transmission loss. A
possible cause of honey’s higher response is its higher acoustic impedance, Z. It is at 2.89 E+6 kg/s m² and is about twice that of water. The sound velocity for Vaseline and stopcock grease were not found in the literature, so approximate measurements were made. With their published density of 0.9 and 1.0, their acoustic impedances are found to be 1.72 and 1.87E+6 kg/s m², which are 15 and 25% higher than that of water. With similar Z values, more steep decrease of signal amplitude in Vaseline and silicone grease appears to come from their higher viscosity. In fact, it is more appropriate to call them gels.

![Fig. 7 Thickness dependence of output voltage of received signals through honey (dark blue), water (green), Vaseline (blue), stopcock grease (red). FC500 transmitter and Olympus V104 receiver.](image)

In Fig. 7, the left-most point for each curve corresponds to the highest output signal level and the couplant thickness was extrapolated from the best fit curve. For water, this thickness was 5 µm, while the thickness for the other three was 6 µm. These represent effective minimum couplant thickness.

From the power law fit for Vaseline, the couplant thickness for the lower amplitude case in Fig. 6 is estimated to be 14.6 µm. This is comparable to the case of epoxy discussed earlier. Thus, gels like Vaseline and silicone grease can easily develop couplant layers two to three times that of their best condition with attendant several dB of transmission loss. The situation also applies to viscous liquids like resins and honey except honey has much better transmission even near 100 µm thickness.

While the data in Fig. 7 indicates overall transmission loss, frequency plays a major role in determining the loss. Figure 8 shows the frequency dependence for two couplants, water and honey. In both cases, the loss increases with frequency, roughly linear with frequency, but usually with non-zero intercept. For water with the thickness of 0.04 and 0.13 mm, it reaches 4 and 12 dB at 1 MHz. For honey with 0.05 and 0.28 mm, the corresponding values are 2 and 10 dB at 1 MHz. That is, water has approximately twice attenuation over honey and the same thickness or similar attenuation at half the thickness. This effect is more pronounced at lower frequencies.
Transmission coefficient, $T$, through a gap filled with liquid (or gas) has been treated since the early days of ultrasonic testing since this has direct bearing on the success of ultrasonic flaw detection [7]. For the case of identical materials (of the acoustic impedance $Z$) on both sides of the gap and the gap distance, $d$, being much less than $V/2\pi f$ ($V$ is the wave speed), or $d \ll V/2\pi f$, we have an approximate expression for $T$ from Krautkramer [7] as

$$T = [1 + (\pi f Z / Z_g V)^2]^{-0.5}$$

where $f$ is the frequency, $Z_g$ are the acoustic impedance of the gap medium with $Z_g \ll Z$. This expression was derived by considering the interferences of waves repeatedly reflected at the two interfaces of the gap. That is, it is appropriate for continuous waves.
Values of transmission coefficient, $T$, for a gap filled with water and honey are calculated and given as Fig. 9a and 9b. Frequencies chosen are 1, 0.5, 0.2, 0.1 and 0.05 MHz and $d$ values are in the range of 0.003 to 10 mm. The transducer face materials are typically alumina and $Z = 38\times10^6$ kg/s m$^2$ is used. Results show that $T$ starts to decrease at 3 µm to 0.15 mm depending on frequency and $Z_g$. The value of $T$ reaches −20 dB ($T = 0.1$) as $d$ reaches 3 to 10 mm at 50 kHz. At 1 MHz, $T$ drops 20 dB at 0.2 mm for water and 0.5 mm for honey.
The reduction in transmission coefficient, \( \Delta T \), is higher at higher frequencies. Figure 10 gives the frequency dependence of \( \Delta T \) for the thicknesses examined in Fig. 8; i.e., 0.04 and 0.13 mm for water and 0.05 and 0.28 mm for honey. Effects of frequency are not linear, but these curves can be approximated by straight lines, implying the presence of similar trends found for the data in Fig. 8. The calculated \( \Delta T \) values are 3 to 5 dB higher than the observed values of transmission loss for water at 1 MHz: \( \Delta T \)'s are 7 and 17 dB (4 and 12 dB observed). For honey \( \Delta T \)'s are 2 and 9 dB (in comparison to 2 and 10 dB observed), so these are in agreement. Differences found for water cases cannot be attributed to inaccuracies in the gap size as it is hard to make the gap thinner than the shim thickness. The cause is unknown presently.

The classical calculation is thus applicable in the present case probably because pulse transit time through a 0.3-mm gap is 0.15~0.2 \( \mu \)s and the pulse duration is ~2 \( \mu \)s. Although not visible in most waveforms examined, reverberation should be possible. When the gap reaches a certain range, oscillations do occur, but at narrower or wider gap sizes, the waveforms revert to those similar to the narrow gap cases.

**Summary**

This study examined the behavior of AE sensor couplants for through transmission of acoustic signals or out-of-plane motion, using face-to-face transmitter-receiver arrangement. Results follow:

1. All liquid and gel couplants can achieve a minimum transmission loss by careful installation producing the minimum couplant thickness of 5 to 6 \( \mu \)m. At the optimum condition, the loss is within 0.8 dB of the best couplants (motor oil, Nonaq and water).
2. With normal installation procedures, the loss can be 3 to 5 dB over that of the best case. With viscous resins and gels, couplant thickness can be 10 to 15 \( \mu \)m and high frequency attenuation is higher than the peak amplitude reduction.
3 Honey turns out to be an excellent couplant because of its higher acoustic impedance. In contrast, oft-used silicone grease needs special attention to reduce its thickness as high frequency loss is substantially higher than others.

4 Higher frequency transmission loss increases with thickness as predicted by theory of through-gap transmission with approximately linear dependence with frequency.

5 Coupling behavior is unaffected by epoxy curing, changing liquid resin into solid bond, albeit the solid bond is always preferable for the stability of coupling.

A follow-up study for the detection of guided waves will be beneficial for most practical AE applications. However, careful consideration is needed to arrange appropriate experimental conditions as noted in the Introduction.

References

10. Y.H. Kim, S.-J. Song, S.-S. Lee and J.-K. Lee, A study on the couplant effects in contact ultrasonic testing, Proc. 10th APCNDT, AINDT, 17-21 September 2001, Brisbane, Australia, ndt.net: Note that some of their equations are missing square-root signs in denominator.
An Experimental Study of Acoustic Emission Waveguides

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Abstract

This study reports the characteristics of acoustic emission (AE) waveguides using displacement pulse of about 1-µs duration from an ultrasonic transducer, driven by a short impulse. By using one of broadband sensors as a receiver, improved characterization of waveguides is possible over 50 to 2000 kHz. Here, we obtained responses of circular rod waveguides of different diameters from 1.6 to 12.7 mm with lengths varying from 60 to 900 mm. It is found that the low-frequency part of L(0,1)-mode rod waves is dominant in thin rod waveguides. This mode is increasingly suppressed above 6-mm diameter. This mode is also responsible for stretching a short-duration (~1 µs) source into a long pulse of more than 100 µs as its velocity is reduced at higher frequencies. At larger diameters, slower L(0,3)-mode becomes the dominant one, and its peak is found at its highest velocity over a narrow range of frequency. To keep the pulse duration short, it is necessary to keep the waveguide diameter below 3 mm, preferably at 1.6 mm or less so that the relatively non-dispersive L(0,1)-mode prevails over the frequency range of interest. Diameter reduction, however, leads to reduced sensitivity unless small aperture sensors are used. Tube waveguides are found to offer a significant advantage of spectral smoothness. In tubes, L(0,2) mode plays an important role of providing nearly constant velocity and spectral flatness. Effects of threading are also evaluated. Three practical waveguide designs are suggested. More extensive exploration of tubular waveguides is highly recommended.

Keywords: Waveguides, Rod waves, Tube waves, Threaded rods, Dispersion, Reverberation

Introduction

Waveguides have important roles in practical acoustic emission (AE) monitoring since the earliest days. They are widely used in various industries, including petrochemical, electric power generation, gas and oil transport, among others. Anderson et al. [1] reported their uses for fast breeder reactors at the first conference on AE in 1971. Rods, tubes and wire bundles were already used in this work. Typical commercial waveguides are of stainless steel rod of 6 to 13 mm in diameter and 300 mm in length, with or without a sensor mounting conical endpiece. They may be welded to a structure to be monitored or with a pointed end for pressed contact. They are also valuable in laboratory for conducting high or low temperature AE testing. For example, platinum wire waveguide was used to detect oxide cracking and spallation at 1000°C [2]. Various references on rod wave propagation and mechanical waveguides can be found in literature [1, 3-7]. While the basic theory of rod waves was established over a century ago, more waveguide related works are continuing [8, 9].

Our previous study evaluated waveguide characteristics of rods and tubes of different size and length and concluded that commonly used 6-mm waveguide to be a good compromise in terms of attenuation and signal broadening [3]. It was also suggested to keep the diameter small and stay in the low frequency range to utilize the L(0,1)-rod-wave mode. Sikorska and Pan [10, 11] conducted extensive evaluation of short waveguides of several different materials relying on
wavelet analysis as the main tool and compared their results with rod wave calculations. They also examined traditional AE features. Perhaps most striking is the dominance of longitudinal resonance due to the length values ranging from 18 to 177 mm. Hamstad [12] examined thin waveguides of 1.6 mm in diameter using a high-fidelity NIST sensor and reported good reproduction of pencil-lead-break (PLB) induced plate waves through such waveguides, but with 11-13 dB attenuation. A thicker (3.2 mm) waveguide produced less attenuation (~5 dB), but also with less fidelity in waveform; i.e., more attenuation at higher frequencies. He evaluated plate waves, dominated by low frequency $A_0$-mode and the observed non-dispersive waves are apparently due to the dominance of $L(0,1)$-rod-wave mode, noted earlier [3]. A more recent study of Zelenyak et al. [13] introduced the finite element modeling (FEM) to the thin waveguide evaluation, extending the Hamstad study and reproducing the essential features [12]. They showed that FEM can be used in lieu of experiment allowing parametric study of waveguide behavior. Their results show that a wave entering a waveguide exits with basically similar features. Attenuation was low below 100 kHz, but tended to increase to about 10 dB at 1 MHz. It is noted, however, that the frequency dependence of the simulated plate-wave signal of PLB is 40 dB/decade (from 0.1 to 1 MHz) after 100-mm propagation. This is twice that of the expected step-function source used to simulate the PLB (with the rise time of 1 µs). As is well known, the calculated Fourier transform of a step function has the inverse-frequency dependence ($F = 2/j2\pi f$). Accompanying experimental result showed an even higher value of 50 dB/decade, which is 15 dB/decade higher than that reported by Hamstad [12] in his comparable experiment. It is unclear why such discrepancy arises from seemingly sound FEM methodology and essentially identical experimental set-up, albeit different sensors. Because of the strong $A_0$-mode plate waves, these PLB-based studies inadvertently focus on the low frequency segment. It is hoped that future FEM work can reveal the frequency dependence of amplitude attenuation in waveguides quantitatively.

In order to clarify the waveguide behavior under well-defined conditions, qualitative wave propagation experiments were conducted using waveguides of three different materials, as well as various diameter and length combinations. Three types of rods are included; solid round rods, threaded rods and tubes. Previously, the facial displacement of an ultrasonic transducer was characterized under pulse input [14]. That work used a step-down pulse, but this time the pulse-generator output was shunted with 50-ohm load, achieving a shorter impulse output of ~1 µs duration. The displacement waveform was measured using a laser interferometer. This displacement pulse is sent through a waveguide under test and the displacement on the other end is detected using a broadband sensor. The received signal is then analyzed using an FFT routine and Choi-Williams transform to evaluate the waveguide characteristics. This study first reports the time-frequency distribution of received signal intensity, and identifies the wave mode when it can be established by a comparison to theoretical dispersion curves of rod and tube waves. It is aimed to provide general view of wave propagation behavior in the size range for practical AE waveguide applications. Next, the insertion loss (or attenuation) and reverberation (or multiple reflections) effects are evaluated since these two have to be balanced to obtain workable waveguides. That is, a low-loss waveguide has extended reverberation, limiting it to applications with low AE event rates. Some practical approaches are suggested.

Experimental

The source of displacement pulse utilized an ultrasonic transducer (AET FC500), which is identified as 19-mm diameter element at 2.25 MHz center frequency. This was driven by an impulse shown in Fig. 1 a) with the rise time of 50 ns, peak voltage of 225 V, decay time of
3 μs. We used a laser interferometer (Thales Laser S.A. SH-140) at Aoyama Gakuin University (AGU). It has dc-20 MHz bandwidth as noted previously [14]. The displacement normal to the front face is shown in Fig. 1 b), with the peak at 7.6 nm, returning to zero within 1.5 μs, followed by low level oscillations to 30 μs. The rise time of the displacement pulse is 0.26 μs (or 0.16 μs if 10%-90% value is used). The FFT result for the entire waveform of 30 μs length is given in Fig. 1 c, showing adequate spectral intensity extending to 1.2 MHz and beyond at reduced intensity. This FFT used Noesis (ver. 5.8) with 64-k points at 100 MHz sampling and the result is given as FFT magnitude spectrum in dB. The original signal was recorded at 500 MHz. Most other FFT used 256-k points at 500 MHz. Note that when a step pulse is used to drive the FC500, the initial pulse waveform was identical, but a tail extended for 10 μs (see Fig. 2 c) in [14]). This produces unwelcome low frequency components in the present experiment. Also used as the source of displacement pulse were Olympus V103, 1 MHz, 12.7-mm diameter transducer and KRN BB-PCP conical sensor.

Fig. 1 a) Excitation pulse. b) Displacement output from FC500.
The displacement sensor utilized one of two broadband transducers. The primary receiver was KRN (BB-PC), which is based on NIST-originated conical element sensor with compact backing. This is a small aperture sensor of about 1 mm in diameter. Olympus V103 (or NDT Systems C16. 2.25 MHz) with 12.7-mm element was also used to represent the displacement of the entire end surface. When the KRN sensor is in contact with the source transducer (FC500), or the face-to-face arrangement, the output of KRN receiver is shown in Fig. 2. This closely follows the input waveform of Fig. 1 b) with the main pulse width of 1 µs. There is a low-level tail to 25 µs, however. The Choi-Williams transform (CWT) was applied on the KRN sensor output and the result in a frequency-time-intensity plot or CWT spectrogram is given in Fig. 3. AGU-Vallen Wavelet software was used for this operation. Peak intensity is found at 0.85 µs and covers the range of 300 to 650 kHz, but signal intensity is present from 50 to 1800 kHz. In the following, however, the discussion is mostly limited to 1500 kHz as the higher frequency range is usually not of interest in waveguide applications.
The FFT of the received signal is given in Fig. 4 as KRN sensor response, showing ±6 dB flatness over 50 to 1200 kHz. When the FC500 spectrum is subtracted from the KRN response, we get KRN sensor response, shown by a green curve in Fig. 4. This part was discussed in a separate report [15], and showed a broadband response over 50 to 1800 kHz (±6 dB). Note that the V103 sensor has a similar response as this KRN sensor [15].

For the characterization of a waveguide, it is placed between the transmitter (FC500) and the receiver (KRN-PC) except as noted. Vaseline petroleum gel was used as couplant. In the following, we present the Choi-Williams transform applied on the KRN sensor output for each waveguide examined. Such time-frequency spectrograms are compared with the rod wave dispersion curves, obtained using Disperse software. One example is given here for an aluminum rod of 6.4-mm diameter in Fig. 5. It shows the group velocities of ten longitudinal L(0,x) and flexural F(1,x) modes with x of 1 to 5. This leads to the identification of the wave modes present. When different values of rod diameter are used, the horizontal scale needs modification. For double the diameter, the frequency should read half the value shown here. For example, L(0,2) peak (green curve) will be at 400 kHz for 12.8-mm diameter Al rod, instead of 800 kHz shown in Fig. 5. Attenuation can be estimated by comparing the observed spectrum with Fig. 4, although this part is skipped, since the main aim is to find the general propagation behavior of waveguides. For the evaluation of attenuation and signal broadening, it is best to use narrow-band signals as in Ref. [8].
Fig. 4 FFT magnitude of the received signal or KRN sensor output (V) in purple, FC500 displacement output (nm) in red, and KRN sensor response (V/nm) in green vs. frequency.

Another set of dispersion curves are calculated for tube waveguides. Figure 6 shows two of them; Fig. 6 a) is for Al ($V_p = 6.32$ mm/µs, $V_s = 3.13$ mm/µs) with outer diameter/thickness (D/t) ratio of 8.0, showing three L-mode velocities. Here, thickness is meant as the wall thickness. Figure 6 b) is for Fe ($V_p = 5.95$ mm/µs, $V_s = 3.26$ mm/µs) with D/t = 4.0. In both cases, L(0,1) velocity dips sharply near the cut-off frequency for L(0,2) mode. For Al, these values are 0.23 and 0.25 MHz·mm and, for Fe, 0.57 and 0.61 MHz·mm. Initially, L(0,1) velocity is near the rod velocity, then L(0,2) mode has comparable velocity over a wider range of frequency-thickness (f·t) product. For Fe, tube wave velocity exceeds 5 mm/µs at f·t < 0.26 MHz·mm and for 0.92 < f·t < 1.42 MHz·mm.

Waveguides of aluminum, copper alloys and steels were used. Material composition of most rods is unknown as cut rod samples typically come without identification or chemical analysis. Most aluminum rods are believed to be Al 1100, except for 6.4 or 12.7 mm diameter rods of Al 2024. Four brass rods are expected to be C260, but two copper brazing alloys are of unknown composition. From their densities, the alloy is presumed to be CP-3 (90Cu-2Ag-7P). Thinner steel rods are of 1080 steel, while some are HSLA and stainless steels of unknown composition. The longitudinal wave velocity can be obtained from the fastest arrival time along with the rod wave velocity and mass density from sample weight. Thus, the elastic properties can be estimated when needed. Table 1 lists the materials and dimensions of waveguides used. The diameter ranges from 1.6 mm to 12.7 mm, while the length varied from 59 mm to 913 mm. Tubes of the same materials were also included in the study. Many of them were from our previous work [3]. The ends of these waveguides were polished down to 600-grit sandpaper using a jig.
Fig. 5 The dispersion curves of group velocity of rod waves in Al rod of 6.4-mm diameter.

Fig. 6 The dispersion curves for tube waveguides of Al and steel with diameter-to-thickness ratio of 8.0 or 4.0, respectively.
Table 1 Waveguide materials and shape

<table>
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<th>Material</th>
<th>Shape</th>
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<th>Length</th>
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<td>1.6 mm ø</td>
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</tr>
<tr>
<td></td>
<td>rod</td>
<td>2.36 mm ø</td>
<td>305 mm</td>
</tr>
<tr>
<td></td>
<td>rod</td>
<td>3.0 mm ø</td>
<td>305 mm</td>
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<td></td>
<td>rod</td>
<td>3.2 mm ø</td>
<td>305 mm</td>
</tr>
<tr>
<td></td>
<td>rod</td>
<td>4.8 mm ø</td>
<td>303 mm</td>
</tr>
<tr>
<td></td>
<td>rod</td>
<td>5.0 mm ø</td>
<td>299 mm</td>
</tr>
<tr>
<td></td>
<td>rod</td>
<td>6.0 mm ø</td>
<td>299 mm</td>
</tr>
<tr>
<td></td>
<td>rod</td>
<td>6.4 mm ø</td>
<td>305 mm</td>
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<tr>
<td></td>
<td>rod</td>
<td>8.0 mm ø</td>
<td>301 mm</td>
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<tr>
<td></td>
<td>rod</td>
<td>9.6 mm ø</td>
<td>60, 151, 304 mm</td>
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<td>rod</td>
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<td>302 mm</td>
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<td>rod</td>
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<td>9.7 mm/1.3 mm with thread of 0.91 mm pitch, 543 mm</td>
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<td>tube</td>
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<td>88, 375 mm</td>
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<td>tube</td>
<td>6.4 mm/0.76 mm</td>
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<td>rod</td>
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<td>305 mm</td>
</tr>
<tr>
<td></td>
<td>rod</td>
<td>4.8 mm ø</td>
<td>(235*) mm</td>
</tr>
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<tr>
<td></td>
<td>rod</td>
<td>5.3 mm ø</td>
<td>200 mm</td>
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<td>tube</td>
<td>5.6 mm/0.4 mm</td>
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<td></td>
<td>tube</td>
<td>6.4 mm/0.4 mm</td>
<td>305 mm</td>
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<td>Cu brazing</td>
<td>rod</td>
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<td>200 mm</td>
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<tr>
<td></td>
<td>rod</td>
<td>2.36 mm ø</td>
<td>51, 149, 298 and 913 mm</td>
</tr>
</tbody>
</table>

Tube: Outer diameter/wall thickness
*: pointed end
a*: angled end face
Results and Discussion

1. Aluminum waveguides

Received waveforms from six waveguides (9.6 to 1.6 mm) are shown in Fig. 7. These are nominally 305 mm long. The time scale was chosen to start before the first arrival (50 µs) and to end at 170 µs before the first reflection at about 180 µs. The initial peak corresponds to L(0,1)-mode arrival. It had the maximum height for rods of 4.8 mm or less arriving after traveling at ~5 mm/µs and decreased as the diameter increased, as shown in Fig. 8 a). At larger diameters, the maximum height was found corresponding to L(0,3)-mode arrival with ~3 mm/µs velocity. The peak height of the L(0,3)-arrival increased with diameter (see Fig. 8 a). The relative intensity ratio of these two modes was calculated by summing the rms-voltages over 50-70 µs and 85-110 µs as follows:

\[
\frac{\text{L}(0,3) \text{ intensity}}{\text{L}(0,1) \text{ intensity}} = \frac{\sum_{85}^{110}(\sqrt{V_T^2})}{\sum_{50}^{70}(\sqrt{V_T^2})}.
\]

This ratio increased with the rod diameter, as shown in Fig. 8 b). Changes are large, going from ½ to 2 as the diameter increased from 1.6 mm to 9.6 mm.

The signals are extended to longer than 100 µs duration in a sharp contrast to the 1-µs main peak duration of the face-to-face condition. The trailing parts beyond the L(0,1)-arrival also have higher frequency contents. Corresponding Choi-Williams spectrograms are shown in Fig. 9 for the diameters of 3.2 and 1.6 mm. The time scale is shifted 50 µs and both show the arrival of L(0,1)-rod-wave mode at ~8 µs. Wave velocity scale is given below the time scale. For the 3.2-mm waveguide, high intensity part extends from 50 to 500 kHz and the wave velocity decreases to 2.5 mm/µs at 850 kHz. For the 1.6-mm waveguide, this goes from 80 to 650 kHz and the velocity is nearly unchanged. For these two waveguides, the diameter ratio is two, so the same velocity of 3.75 mm/µs is found at 700 and 1400 kHz, respectively. The high intensity part thus has low dispersion. This partly explains why the frequency of the peak intensity shifted down from the face-to-face condition (the peak appears at 450 kHz in Fig. 3). For the 4.8-mm waveguide (Fig. 10), strong L(0,1) zone shrinks to below 300 kHz, while the trailing part has low level indications to 1000 kHz at velocities slower than 3.2 mm/µs. This part is barely visible here as well as in Fig. 9 a), and propagation modes are obscure.

The above observations show that the thin waveguides give good transmission of L(0,1) mode with low dispersion at lower frequencies. When the diameter is reduced, the low dispersion zone extends to higher frequencies. Thus, very thin rods provide wide-band transmission, while moderately thin rods give band-limited transmission with low dispersion.
Fig. 7 a-c) Received waveforms from thin waveguides of 9.6 to 4.8 mm diameter (305 mm length). KRN transmitter and receiver.
Fig. 7 d-e) Received waveforms from thin waveguides of 3.2 to 1.6 mm diameter (305 mm length). KRN transmitter and receiver.
Fig. 8  a) Peak height of the initial arriving L(0,1)-mode signal (blue curve) and that of late arriving L(0,3)-mode signal (red curve). b) Ratio of L(0,3) and L(0,1) intensity vs. diameter.
Fig. 9 CWT spectrograms for Al waveguides of a) 3.2- and b) 1.6-mm diameter. Time scale is shifted 50 µs. Group velocity values are given by vertical marks.
When the rod diameter reaches or exceeds 6.4 mm, higher rod-wave modes become visible, as shown in Fig. 11. Here, the dispersion curves are shown on the left with the same frequency scale, but the horizontal scales are different. L(0,1) mode is visible at low frequencies as shown above and through its velocity minimum at 2.1 mm/µs. A new feature is a strong L(0,3) peak appearing at 3.1 mm/µs in the frequency range of 800 to 1100 kHz. Also visible are weak indications of L(0,2) and L(0,4). These identifications owe to a comparison to the rotated dispersion curves shown on the left. These features are retained as the diameter is enlarged to 12.7 mm, while keeping the length at nominally 305 mm (figure omitted). When the length is doubled, as shown in Fig. 12, L(0,4) mode becomes stronger and L(0,5) is clearly noticeable. For the 6.4-mm rod, shorter waveguides down to 66 mm showed the same features. However, in 9.6-mm or 12.7-mm diameter rods, waveguides shorter than 150 mm produce much weaker L(0,1)-mode zone, as shown in Fig. 13. Here, Fig. 13 a) is for 12.7-mm diameter rod of 152 mm and the main peak is L(0,3) mode at 400-600 kHz. For the 9.6-mm rod (Fig. 13 b), L(0,3) position was at 550-850 kHz, proportionately higher. The weakening of L(0,1) is understandable as the wavelength at 100 kHz is 50 mm and the rod length is only three times the wavelength. Rod waves are constructed by multiple interactions with the rod surfaces and a minimum length does exist at larger diameters. Figure 14 indicates corresponding signal waveform of Fig. 13 b) and the peak amplitude occurs at the time of L(0,3) peak. The waveform was omitted in Fig. 10, but the same trend was observed. The presence of multiple wave modes contributes to the lengthening of the transmitted signal as the maximum peak corresponds to the time of L(0,3) arrival. The waveform of 305-mm long waveguide of the same 9.6-mm diameter was shown earlier in Fig. 7 a). While L(0,1) peak height remained nearly the same, L(0,3) peak was about double at the half length.
Fig. 11 Dispersion curves for 6.4-mm waveguide (left) and observed CWT spectrogram (right). Time scale is unshifted and group velocity values are given by vertical marks, covering 5 to 2 mm/μs.

Fig. 12 Observed CWT spectrogram for 12.7-mm Al waveguide (611 mm length). Time scale was shifted by 98 μs for CWT. Original time scale and group velocity values are given by vertical marks, covering 5 to 2 mm/μs.

Thicker waveguides develop higher rod-wave modes, L(0,3) in particular. This mode requires less propagation distance to fully develop than the low-frequency L(0,1) mode, which needs more than three-times the wavelength for rods of 9.6 mm or larger diameter. The transmission of L(0,3) mode can be utilized as a narrow-band mechanical filter and may be combined with a resonating sensor design. For the range of diameter used here (6.4 – 12.7 mm), the
frequency range of 400 to 1100 kHz can be achieved. For 150-mm long rods, these ranges are: 6.4 mm, 800-1100 kHz; 9.6 mm, 500-750 kHz; 12.7 mm, 400-600 kHz.

Fig. 13 Observed spectrograms for 150-mm long Al waveguides of a) 12.7 and b) 9.6-mm diameter. Group velocity values are given by vertical marks, covering 6 to 2 mm/μs.

Fig. 14 Signal waveform of 9.6-mm waveguide, 152-mm length (Fig. 13 b) The peak amplitude corresponds to L(0,3) peak.

When hollow cylinders or tubes are used as waveguides, the transmission characteristics become different from those of solid rods, as expected from the dispersion curves shown earlier (Fig. 6). Figure 15 shows an example with an Al tube (9.5 mm OD, 7.5 mm ID, 290 mm length: D/t = 9.5). The dispersion curves for D/t = 8 is shown as Fig. 15 a) for L(0,1) and L(0,2) modes. (The cut-off frequency for L(0,3) mode is above 1.5 MHz). Results given in Fig. 15 b) match with the dispersion curves well, with the peak L(0,2) activity at 350-800 kHz and the strongest L(0,1) peak occurring at <100 kHz. The latter frequency is lower than the calculated values of 120-150 kHz. Extra peaks are also present between the two modes at 200 kHz with 4.3 to 4.8
mm/µs velocity. However, this frequency is at the minimum velocity for L(0,1) mode, where FFT magnitude also shows a dip as will be discussed later. Thus, these peaks appear to be spurious although their origin is unknown. Wave intensity is reduced for slow moving waves: by 17 dB at >3 mm/µs. That is, signal lengthening is limited to <50 µs, a factor of 2 to 3 shorter than rod waveguides of similar diameters.

In comparison to rod waveguide behavior (see for example, Figs. 11 and 12), the slow L(0,3)-rod wave is gone. Instead, L(0,2)-tube wave behaves like the L(0,1)-wave for thin rods with low dispersion. These are also beneficial for waveguide applications.

![Dispersion curves](image1.png)

**Fig. 15** a) The dispersion curves of tube waves for D/t = 8 with t = 1.18 mm. b) Observed CWT spectrogram for Al tube (9.5 mm OD, 7.5 mm ID, 290 mm length: D/t = 9.5).

Although ten other tubes of various sizes were examined from a previous work [3], no clear patterns emerged. L(0,1)-mode was always present and strongest, while L(0,2)-mode was absent in some conditions. Even when 12.7-mm diameter tubes are used, we did see L(0,1) at low frequency in contrast to solid rod cases where only L(0,3)-rod waves were found. When a low frequency waveguide of large diameter is needed, a tube provides a solution. When L(0,2) is absent, effects of the spurious peaks are significant and further study is needed to clarify their origin.

2. **Steel Waveguides**

The rod wave velocities of steel and aluminum are comparable: 5.06 vs. 5.18 mm/µs [5, p. 78]. However, Poisson’s ratio is smaller for iron and steel (0.29) than in aluminum (0.34) and lateral stiffness is higher in steel. This is expected to affect how rod waves develop in steel, specifically, in the transition from the L(0,1)-dominated thin-rod behavior to multi-mode thick-rod behavior. Dispersion curves for steel of 2.7-mm diameter are given in Figure 16 [15]. Figure 17 gives the CWT spectrogram for 6.4-mm diameter steel rod of 383-mm length, showing the thin-rod behavior with mostly L(0,1) mode and weak L(0,3). This L(0,3) essentially disappeared at 496-mm length. In an aluminum waveguide of the same diameter, the L(0,3) mode was already well developed, as was shown in Fig. 11.
It is interesting to note that this diameter - length combination is commonly found in industrial applications. Two commercially available waveguides from PAC and AECI share these dimensions – ¼” x 12” in the traditional US unit. From the present results, these waveguides work best in the range up to 250 kHz, making them suitable for the often used frequency of 150 kHz. In the previous study [3], we did conclude that this diameter is appropriate for industrial waveguide applications, although we only evaluated aluminum.

When a higher frequency detection is required, thinner waveguides offer the solution. At 4.8-mm diameter, one obtains L(0,1) response to 400 kHz and to 550 kHz using 3.2-mm diameter (similar to Fig. 9 a) for 3.2-mm Al). Using 1.6-mm steel rod, the response is comparable to Al case of the same diameter (Fig. 9 b), except the signal strength drops off slightly faster than in Al. In this case, low dispersion response to 600 kHz is possible.

When the length was halved to 150 mm for the 6.4-mm rod, the L(0,1) mode failed to develop fully at frequency below 200 kHz (Fig. 18). This is a significant drawback in practical application since oft-used 150-kHz AE sensor’s peak sensitivity is missed. The limitation posed by the use of a certain length needs to be explored when the diameter approaches the transition to multi-mode behavior.

When one examines these two spectrograms (Figs. 17 and 18), it is obvious that L(0,1) mode in the short waveguide extends to higher frequency (600 kHz compared to 400 kHz) at slow speed limits observed. This appears to indicate that the calculated dispersion curves, such as the one shown in Fig. 5, are not applicable to short length rods. This is a reflection of inadequate developments of various wave modes. This part requires verification through future FEM calculations.
Steel waveguides exhibit another behavior during the transition. Multi-mode behavior is found once the diameter reaches ~8 mm. For 7.8-mm diameter, $L(0,3)$ mode is dominant from a short rod (59 mm) to a long one (648 mm). At 59 mm length, modes are not as clearly separated, but showing both $L(0,1)$ and $L(0,3)$ as well as possibly $L(0,2)$ spots (Fig. 19). Figure 20 shows the nearly single $L(0,3)$-mode behavior that evolved in longer waveguides. This observation points to the needs of considering the waveguide design from both the diameter, which is of course the main parameter, and also the length. Since the partition of energy transmission into various modes cannot be theoretically predicted at present, we need to evaluate individual waveguide design to ascertain its performance.
Fig. 19 Observed waveform and CWT spectrogram for a short steel waveguide of 7.8-mm diameter (59 mm length). The reflected waves appear starting at 34 µs.

Fig. 20 Observed waveform and CWT spectrogram for a long steel waveguide of 7.8-mm diameter (648 mm length).
Fig. 21 a) The dispersion curves of tube waves for D/t = 4 with t = 1.6 mm. b) Observed CWT spectrogram for a steel tube (6.4 mm OD, 3.3 mm ID, 394 mm length: D/t = 3.7). Group velocity values are given by vertical marks, covering 5 to 3.7 mm/µs.

In testing tube waveguides of steel, four tube sizes were available with the outer diameter of 4.8 and 6.4 mm and D/t ratio of 3.7 to 8. These are of austenitic stainless steel, presumably of 304 type. Main response was L(0,1)-and L(0,3), similar to the case for Al tube (Fig. 15). For a long heavy wall 6.4-mm tube (D/t = 3.7; 394 mm length), Fig. 21 shows the CWT spectrogram together with the calculated dispersion curves. L(0,2) velocity agrees well with the calculated values, while L(0,1)-mode shows lower frequency at a given velocity. The highest received intensity corresponds to L(0,2) mode here with D/t = 4, while it was L(0,1) mode in the case of Al with D/t = 8 (cf. Fig. 15). Note that spurious peaks are again seen at 300-500 kHz over 8-10 µs in this shifted time scale.

When the tube diameter is reduced to 4.8 mm with D/t = 6.6, the dispersion of L(0,2) mode is reduced as shown in Fig. 22 a). The position of L(0,1) peak is similar to Fig. 21, but its intensity is stronger. The middle spectrogram (Fig. 22 b) is for the same diameter of 6.4 mm, but with a thinner wall or D/t = 8 and at less than a half-length. Here, L(0,1) is absent and only the L(0,2) mode is found from 400 to 1100 kHz. This is a beneficial effect of a shorter length, which is below the minimum length needed for developing the L(0,1) mode. In Fig. 22 c), a similar result is exhibited with another short waveguide of 6.4 mm: D/t = 3.7 (the same tube for Fig. 21) and the length of 90 mm. This effect was also observed in Al cases.
Fig. 22 Observed CWT spectrograms for steel tubes. a) tube diameter = 4.8 mm; D/t = 6.6 (377 mm length). b) tube diameter = 6.4 mm; D/t = 8 (168 mm length). c) short (90 mm) waveguide of 6.4 mm: D/t = 3.7. Time shift is marked in the figure.

From these cases, we find that tube waveguides are advantageous over rods of smaller diameter in rejecting low frequency components. It appears that a large D/t ratio enhances L(0,2)-mode, as was found in Al tube waveguides. The same high-pass filtering effect can be obtained by using a shorter waveguide as L(0,1) mode requires a certain minimum length to develop. This length appears to be about 5-times the wavelength.

3. Copper Alloys

For this group, copper rods (of three different lengths), two copper tubes, brass rods (of five different diameters), brass tubes (of four different diameters) and two copper brazing alloy rods were used. All the rods are thin, the maximum diameter being 5.3 mm and their wave propagation behavior mostly resembled those of thin Al rods. Poisson’s ratios of aluminum, copper, and brass (30Zn-70Cu) are in the range of 0.32 to 0.36 and the lateral stiffness is comparable to each other. The thin-rod behavior is observed for 305-mm length up to 4 mm in diameter and for 5-mm-diameter brass rod of 200-mm length, but the multi-mode behavior is found for 5-mm brass rod of 300-mm length.

The copper brazing alloy rods tested were identified by their mass density as CP-3 alloy with 90Cu-2Ag-7P composition. Diameters are 1.6 and 2.4 mm. Thinner 1.6-mm rod is of 200-mm length, while thicker 2.4-mm rod samples have lengths of 51, 149, 298 and 913 mm. All of them showed the thin rod behavior of single L(0,1) mode. Two examples are given in Fig. 23.

Of the two, the top graph approximates the condition used by Hamstad and Zelenyak [12, 13], who used 1.6-mm diameter Cu wire. The observed CWT spectrogram shows that L(0,1) mode has a nearly constant velocity to 450 kHz, the primary frequency range of their A₀-mode plate wave. For this range, this wire size gives good reproduction of input waveforms. At higher frequencies, the wave velocity and transmitted amplitude decrease, as was observed in Hamstad’s experiment. For 2.4-mm wire case, the flat response zone is reduced to less than 250 kHz and
waveform fidelity is reduced substantially. The high frequency velocity slow down and attenuation also occur, commencing at 200 kHz.

Fig. 23 Observed CWT spectrograms for wires of a copper brazing alloy (type CP-3). a) 1.6 mm diameter. 200 mm length. b) 2.36 mm diameter. 913 mm length. Group velocity values are given by vertical marks, covering 4 to 2 mm/µs.

In copper tube testing, common 6.4-mm diameter copper refrigeration tubes were evaluated as waveguides. The tube is available in wall thickness of 0.5 or 0.76 mm, giving D/t of 12.5 or 8.35. Basic features are identical to those of Al and steel, but Fig. 24 a) shows an example with a large length (627 mm). This tube’s D/t was 8.35. Because of the length, both modes developed fully. However, the spurious peaks showed up, centering at 250 kHz, corresponding to a dip in FFT magnitude over 170-270 kHz. This large length does decrease the peak in waveform by 10 dB in comparison to shorter waveguides of 80 to 150 mm length.
A set of brass tubes are also examined. These tubes have the diameter of 4.8 to 6.4 mm and the wall thickness of 0.4 mm, with D/t of 12 to 16. A representative CWT spectrogram is given in Fig. 24 b). At higher D/t ratios, L(0,1) is reduced compared to the common 6.4-mm Cu tube. Due to high D/t, this 4.8-mm tube is useful for 500-1300 kHz range with low dispersion. With a larger diameter, the frequency range moves lower; to 400 to 1100 kHz for 6.4 mm diameter (D/t = 16). Thus, we again observe with a tube waveguide the low dispersion L(0,2)-propagation mode and the suppression of low frequency L(0,1) mode, giving a high-pass filtering effect.

Fig. 24 CWT spectrograms of copper and brass tube waveguides. a) copper, 6.4 mm diameter, D/t = 8.35, 626 mm length. Time shift = 150 µs. b) brass, 4.8 mm diameter, D/t = 12, 305 mm length. Time shift = 75 µs.

4. Threaded waveguides

Next series of tests are included in order to evaluate effects of surface condition on the propagation of rod waves. Readily available surface modification is the use of threaded rods. The first example is shown in Fig. 25. This is an Al rod with ¼"-20 thread (6.2 mm diameter-1.27 mm pitch thread) of 305 mm length. Corresponding smooth rod CWT spectrogram is given in Fig. 11 (right graph), showing multi-mode transmission with strong L(0,1) and L(0,3) intensity. In contrast, Fig. 25 shows strong L(0,1) mode and much weaker L(0,3) mode in the threaded rod. Thus, this waveguide behaves like a non-threaded rod of smaller diameter. In addition, the velocity of the observed L(0,1) mode is approximately 10% slower than that of non-threaded rod: 4.77 mm/µs vs. 5.28 mm/µs. A much slower (~2.5 mm/µs) peak is present at the intersection of L(0,1), F(1,2) and F(1,3). This was also found in Fig. 11, but their origin is unclear.

In contrast, Fig. 25 shows strong L(0,1) mode and much weaker L(0,3) mode in the threaded rod. Thus, this waveguide behaves like a non-threaded rod of smaller diameter. In addition, the velocity of the observed L(0,1) mode is approximately 10% slower than that of non-threaded rod: 4.77 mm/µs vs. 5.28 mm/µs. A much slower (~2.5 mm/µs) peak is present at the intersection of L(0,1), F(1,2) and F(1,3). This was also found in Fig. 11, but their origin is unclear.
Figures 26 and 27 show a comparable pair of stainless steel. Diameter is again 6.35 mm for smooth rod and the thread is $\frac{1}{4}”$-20 with the length of 301 mm (6.2-mm diameter). Fig. 26 shows the result of the non-threaded rod, indicating the presence of both L(0,1) and L(0,3) modes. Figure 26 is the threaded counterpart. L(0,3) mode was not observed as was the case for Al (cf. Fig. 25). Again, threading of rod suppressed the higher rod-wave mode.

When the rod diameter is increased to 12.7 mm using steel rod (length = 306 mm), the threading effect was different from the 6.35-mm examples of Figs. 25 and 27. Figure 28 shows the non-threaded case while Fig. 29 plots the threaded one. Thread is $\frac{1}{2}”$-13 (12.7-mm nominal diameter with 1.96 mm pitch). Figure 28 shows a strong L(0,3) mode, but weak L(0,1) and L(0,4) are also present. With threading, L(0,3) remains the strongest, but L(0,1) becomes stronger second mode. That is, weakened L(0,3) and higher modes contributed to make L(0,1) more prominent.

A similar trend is found in five other sets of threaded and non-threaded rods, indicating that threaded rods enhance L(0,1) mode at the expense of higher L-modes. In most cases, threading reduced the L(0,1) mode velocity by about 10%. In one case of brass, the velocity was nearly unchanged. It is possible that compositions of the alloys are not identical because many brass compositions are used in commercial applications, and the samples came from different sources.

These observations imply that the primary benefit of threaded rods as waveguides is to promote the lowest L mode while depressing higher modes. This may arise from reduced surface reflectivity, but is also due to smaller effective diameter of the threaded rods.

![CWT spectrogram of a $\frac{1}{4}”$-20 threaded Al waveguide of 6.2 mm diameter, 305 mm length.](image)

Fig. 25. CWT spectrogram of a $\frac{1}{4}”$-20 threaded Al waveguide of 6.2 mm diameter, 305 mm length. See Fig. 11 for the corresponding rod waveguide of 6.4 mm diameter.
Fig. 26. CWT spectrogram of a 6.4-mm diameter stainless steel waveguide, 305 mm length. Compare to Fig. 27.

Fig. 27. CWT spectrogram of a ¼”-20 threaded stainless steel waveguide of 6.2 mm diameter, 305 mm length. See Fig. 26 for the corresponding rod waveguide.

Fig. 28. CWT spectrogram of a 12.7-mm diameter steel waveguide, 306 mm length. Compare to Fig. 29.
Fig. 29 CWT spectrogram of a ½”-13 threaded steel waveguide, 306 mm length. See Fig. 28 for the corresponding rod waveguide.

5. Insertion loss

Three effects reduce the net sensitivity using a waveguide. One is an extra boundary introduced. When best coupling is achieved, the loss is expected to be 1 dB or less below 500 kHz, but the loss can easily be several dB higher [17]. Another effect comes from the mismatch of acoustic impedance among test piece, waveguide and sensor face. When materials of the waveguide and tested structure are similar, the insertion loss can be ignored. But when an Al waveguide is used between steel structure and a sensor with alumina face plate, it is ~2 dB. Thus, these two loss sources present no major issue when proper sensor mounting practice is used.

The third factor is the diameter of waveguides. From past experience and present results, it is clear that thinner waveguides are conducive to less dispersive transmission of L(0,1)-rod wave. However, the reduction of waveguide diameter also decreases the wave energy transmitted and received. On the source side, the reduction of waveguide size can be useful in preventing waveform averaging effects that cancel parts of non-uniform surface vibration [18]. However, the reduced sensing area on the receiving sensor proportionally decreases its sensitivity relative to the sensitivity from the total sensing area [15]. For example, when a 1.6-mm diameter waveguide is used with a 12.7-mm diameter sensor, the effective sensor sensitivity is reduced by 18 dB (or $(12.7/1.6)^2 = 67$ times) compared to the case of the same sensor receiving plane-wave input on its entire sensing area.

The size effect is best examined through the use of FFT magnitude spectra of signals that propagated through a waveguide. The received signals are cut off before the first reflection reaches the sensor. Thus, signal length was different depending on the waveguide length. These spectra are naturally reduced from the face-to-face spectrum of the same transducer pair used. An example of such comparison is given in Fig. 30. Here, Al rods of 10, 8, 6.4 and 3.2 mm diameter, nominally 305 mm length, are used as waveguides. The face-to-face response is the top curve (purple: V103 to NDT). The next curve (blue dash) is the face-to-face response minus 4.1 dB, corresponding to area reduction to 10-mm diameter. This agrees to the blue curve of the 10-mm waveguide (blue curve) below 200 kHz, but the waveguide response is 3 to 6 dB lower (more at many dip points). For the three other curves, the area corrections needed are 8.0, 11.9 and 23.9 dB. As the diameter becomes smaller, alignment becomes more difficult and the difference between the value based on the face-to-face spectrum and correction factor and the observed increased. Still, the differences were 6-8 dB even for the thinnest, 3.2-mm waveguide below 800
kHz. The main source of the insertion loss (excluding the area correction) is the lack of good coupling due to poor alignment.

Another prominent feature of these waveguide spectra is the presence of many dips, especially above the frequency corresponding to the velocity minimum of L(0,1)-mode wave. For these four curves, the values are 330, 490, 600 and 1200 kHz. These rod spectra are relatively smooth below the L(0,1) dip. Other large dips correspond to velocity minima of higher propagation modes. However, many other dips have no clear origins.

Fig. 30 FFT magnitude spectra of signals propagated through Al waveguide of 10 (blue), 8 (red), 6.4 (green) and 3.2 (light blue) mm diameter, 305 mm length. Face-to-face response of V103-NDT transducer pair is given by purple curve (top). Its area corrected response (minus 4.1 dB) is shown by blue dashed curve.

The second example is a comparison between rod and tube waveguides, shown in Fig. 31. Material is Al, with the same diameter of 8 mm. The red curve (same as the red one in Fig. 30) is for a rod (8 mm ø x 305 mm), while the blue curve is for a tube (7.9-mm OD x 6 mm ID x 290 mm length). The red and blue dash curves are area-corrected ideal spectra from the face-to-face data (purple curve). As before, 3 – 6 dB differences are found for the rod, while the tube data differ more above 200 kHz. A large dip exists centering at 240 kHz. This corresponds to the dip in velocity for L(0,1) and the cut-off frequency of L(0,2) mode. Above this dip, the tube data is much more smooth to 2 MHz. The flat spectrum zone from 300 to 900 kHz for the tube corresponds to L(0,2) mode, but modes at higher frequencies are unknown at present. Still, this tube spectrum is smoother than the rod spectrum at the same frequency.

The third example is 3.2-mm steel waveguides of differing length, 71, 165 and 238 mm. The face-to-face and area corrected spectra are in purple in Fig. 32, while steel data are in blue (short), red (medium) and green (long). The rod data are flat to 1 MHz, but differences are 10-20 dB. Length effects are not obvious as coupling is more critical. This frequency range corresponds to L(0,1) mode.
Fig. 31 FFT magnitude spectra of signals propagated through Al waveguide of 8 mm diameter, 305 mm length (red) and a tube of 7.9-mm OD, 6-mm ID, 290 mm length (blue). Face-to-face response of V103-NDT transducer pair is given by purpl curve (top). Its area corrected responses (minus 8.0 and 11.9 dB) are shown by red and blue dashed curves.

Fig. 32 Output spectra from 3.2-mm steel waveguides of length, 71 (blue), 165 (red) and 238 (green) mm. Face-to-face response of V103-NDT transducer pair is given by purple curve (top). Its area corrected response (minus 19.5 dB) is shown by purple dashed curve.
Fig. 33 FFT magnitude spectra of signals propagated through steel waveguide of 6.4 mm diameter, 382 mm length (red) and a tube of 6.4-mm OD, 3.5-mm ID, 393 mm length (blue). Face-to-face response of V103-NDT transducer pair is given by purple curve (top). Its area corrected responses (minus 11.9 and 14.4 dB) are shown by red dash and blue dash curves.

The last example is a comparison between steel rod and tube of 6.4 mm diameter. Figure 33 shows the face-to-face and area-corrected spectra as top three curves. The rod (6.4 mm ø x 383 mm) is in blue, showing a dip due to the L(0,1) velocity cusp at 0.5 MHz. This is 5 to 8 dB below the blue dash curve of the predicted spectrum. The dotted red curve is for the predicted spectrum for 6.4-mm tube (3.5 mm ID x 393 mm). The observed spectrum is shown in red. These two match well below 300 kHz before reaching a dip due to L(0,1) dip/L(0,2) cut-off frequency over 286-404 kHz. Beyond the dip, a differences of 3-6 dB are observed to 2 MHz. This zone has a smooth spectrum.

These observations are also found in several other sets of rods, tubes, and their mix of different length. Results are comparable over all. However, a few pairs of transducers produced more attenuation in rods or tubes. The reason for this discrepancy is unknown at present.

6. Reverberation

Reverberation (or multiple reflections) is another important feature of waveguides that has to be considered in their design. This effect has been recognized from the beginning of their usage. Earlier waveguide studies [2, 10, 11] observed unwanted signal stretching, sometimes exceeding 10 ms. Sikorska and Pan [10, 11] examined angled face up to 60°, but only 5 to 8 dB attenuation was achieved. Ono and Cho [3] evaluated a pointed-end waveguide and found improved pulse definition, but the suppression of multiple reflections was not addressed.

The first usual step one takes to suppress unwanted reflections is applying damping medium on such waveguides. Examples are shown in Fig. 34 (using V103 transmitter, NDT receiver). The top figure (Fig. 34 a) is the output signal from a brass rod (5.3 mm ø x 200 mm length),
lasting 0.5 ms to 20 dB down. Figure 34 b) shows the same rod, but its 60-mm length in the middle covered with clay (plumber’s putty, a mixture of natural clay and linseed oil). The signal length is halved to 0.15 ms, while the peak amplitude decreased 2 dB. In both cases, reflections are buried in the slow-moving signals. The third graph is for a Cu tube waveguide (6.4-mm diameter, 0.76 mm wall thickness, 224 mm length), giving signal length of 0.12 ms. With clay applied in the middle, Fig. 34 d) results, with the same signal length but amplitude reduced beyond 0.04 ms. For these tube waveguides, the initial decay is large and reflections can be easily seen. Again, clay damped slow-moving waves more than the initial pulse, which only decreased by 1 dB.

These signals can be represented by an exponential decay equation of

\[ V = V_0 \exp[-\alpha(t - t_0)], \]

where \( V_0 \) is the initial peak, a decay constant and \( t_0 \) signal arrival time. For these four signals, we obtain decay constant \( \alpha \) of 3.2, 7.6, 5.9 and 7.3 in the unit of ms\(^{-1}\). These show that tube is more effective in reducing higher mode waves, and obtain better damping effects from surface absorber like clay. As noted before, L(0,3)-rod wave is strong in Fig. 34 a) while L(0,1)-tube wave is dominant in Fig. 34 c).

The increased decay constants resulted from the reduction in slow moving L(0,1) and L(0,3) modes. The CWT spectrogram of the rod (Fig. 34 a) is similar to Figs. 17 and 26 for 6.35-mm steel rods, while the rod with clay damper resembles threaded steel rod (Fig. 27). The spectrograms for tubes with or without clay are similar to Fig. 24 a), except the velocity slow-down at high-frequencies is absent. Their signal spectra are given in Fig. 35, with the red curves showing the effects of clay damping. The top curves (Fig. 35 a) are for the rod cases, indicating essentially no amplitude loss from clay below 200 kHz but the loss increasing above 300 kHz. The higher frequency parts are barely present in the CWT spectrograms as they are spread over time. Figure 35 b) is for the tube cases. Here, amplitude loss appears only above 1 MHz, reflecting a small reduction in the peak amplitude (see Fig. 34 c and d). Slower segment of L(0,1) mode is reduced by clay damper, but this is not shown in the FFT spectra. Again, CWT spectrograms show the high frequency parts only at the first arrival. Thus, in these two cases, the decay constants are the best indicator of damping effects.

Twelve more cases were tested using the same set-up. Table 2 summarizes the values of decay constants, \( \alpha \). The third column lists the results from tests that used two conical transducers (KRN PCP).
Fig. 34 Effects of damping. a) Signal waveform for 5.3-mm diameter brass rod (200-mm long), b) Same as a) but with clay covering over 60 mm. c) Signal waveform for 6.4-mm diameter Cu tube (0.76-mm wall thickness, 224-mm long), d) Same as c) but with same clay covering. V103-NDT transducer pair used.
Fig. 35  
a) FFT magnitude spectra of signals propagated through brass waveguide of 5.3 mm diameter, 200 mm length: blue, no damping, red, with clay damping.  
b) Same for Cu tube waveguide, 6.4 mm diameter, D/t = 8.4, 224 mm length: blue, no damping, red, with clay damping.  
V103-NDT transducer pair used.

Table 2 Decay constants (unit = ms\(^{-1}\))

<table>
<thead>
<tr>
<th>Material</th>
<th>Sizes</th>
<th>V103-NDT</th>
<th>KRN-KRN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al rod</td>
<td>1.6 mm (\phi) x 305 mm</td>
<td>6.1</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>3.2 mm (\phi) x 305 mm</td>
<td>5.7</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>6.4 mm (\phi) x 305 mm</td>
<td>5.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Steel</td>
<td>2.38 mm (\phi) x 305 mm</td>
<td>5.3</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>4.0 mm (\phi) x 305 mm</td>
<td>4.0</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>6.4 mm (\phi) x 305 mm</td>
<td>2.9</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>4-40 thread (\times) 305 mm</td>
<td>6.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>6-32 thread (\times) 307 mm</td>
<td>5.3</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>(\frac{1}{4})&quot;-20 thread (\times) 383 mm</td>
<td>2.2</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>tube 4.8 x 0.73 mm, 377 mm</td>
<td>4.0</td>
<td>--</td>
</tr>
<tr>
<td>Brass</td>
<td>3.2 mm (\phi) x 305 mm</td>
<td>3.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Cu</td>
<td>tube 6.4 x 0.5 mm, 375 mm</td>
<td>2.3</td>
<td>--</td>
</tr>
</tbody>
</table>

The above results show the following trends. Decay constants increase:  
a) By increasing rod diameter,  
b) Using threaded rod over smooth rod of the same diameter,  
c) Using V103-NDT transducer set over KRN transducer set.
For trend a), slow-moving wave modes become more dominant with increased rod diameter. For trend b), threaded rods provide less efficient surface reflections, producing dragging effects on rod wave propagation. For trend c), the conical transducers have small contact area and less energy transfer occurs into them, thus reducing damping effects.

Effects of non-parallel end faces were examined using rods and tubes. With the face angles of 15 to 30°, 4 to 6 dB reduction of reflection was obtained, confirming the findings of Sikorska and Pan [11].

Another variation of waveguide design is the use of a pointed end. One of the steel rods tested (3.2-mm diameter, 238-mm length) was converted to a pointed end, reducing the diameter by 12.5 times (or −22 dB). Results were opposite of anticipated; i.e., the decay constant was reduced from 8.0 for a straight rod to 2.6 for the rod with a pointed end of 0.9-mm diameter. Signal duration was also lengthened by 2.5 times in the pointed end waveguide. By reducing the contact area, the energy loss was decreased, increasing reverberation of the rod with a pointed end. The initial idea was to suppress the reflections by reducing the area normal to the wave propagation. However, the size of local shape change is small relative to the wavelength and desired damping of reflections was not realized. Thus, the benefit of a pointed tip waveguide comes from increased contact stress, while the reduced contact area decreases the signal intensity and stretches out the signal duration. Its use should be evaluated carefully.

7. Summary and practical suggestions

The spectral characteristics of rod and tube waveguides are summarized below.

1) In small diameter rods, L(0,1) mode extends to relatively high frequency with low dispersion. This gives good waveform reproduction, but thin rods lack bending stiffness and reduce the signal intensity proportionately.

2) With increasing diameter, L(0,1) mode becomes limited to low frequency region and higher rod-wave modes, especially L(0,3) mode, become dominant. This contributes to undesirable signal stretching.

3) Tube waveguides possess a low dispersion behavior due to L(0,2) mode, along with low frequency L(0,1) mode. Larger diameter-to-thickness ratio is preferred.

4) Threaded rods promote lower rod modes, delaying a shift to multi-mode behavior as diameter increases.

5) Low frequency (large wavelength) modes need a minimum distance for their development, being absent in shorter waveguides.

6) Major effect of sensitivity reduction comes from the waveguide cross-sectional area. In comparison to the face-to-face spectrum of the sensor pair used, the spectra of waveguides are generally lower than the predicted spectra obtained with cross-sectional area correction. Except at dips, the decrease is typically 3–8 dB, expected from poor coupling. The latter can be reduced by better mechanical design/finish.

7) For the rod spectra, many dips are present, starting with the dip corresponding to the L(0,1) velocity minimum. Major dips also originate from higher mode velocity minima or at their cut-off frequencies.

8) For the tube spectra, the first dip is at the L(0,1) velocity minimum/L(0,2) cut-off frequency. Spectrum on either side of the dip is smooth unlike the rod spectra.

9) Effects of waveguide length appear in the peak value of received signals, but length effect is small in terms of FFT spectra.
10) Application of damping materials like clay reduces high frequency components, often of higher wave modes.

It is notable that the tube spectra are smoother than the rod spectra. When we need to use spectral features in received signals, this behavior is significant. In terms of amplitude, no advantage was found in an earlier study [3], but this spectral smoothness provides a major impetus for exploring tube waveguides from now on. Also notable is the emergence of low dispersion L(0,2) mode in thinner, higher D/t waveguides as discovered in the present study. Reduced transmission of low frequency L(0,1) mode with shorter tubes gives rise to a high-pass filtering effect, which can be exploited for selective detection of AE signals from fast mechanical events over frictional sources, for example.

![CWT spectrogram for #4-40 threaded rod of stainless steel, 305 mm length. V103-NDT transducer pair used.](image)

Fig. 36 CWT spectrogram for #4-40 threaded rod of stainless steel, 305 mm length. V103-NDT transducer pair used.

From the present study, three improved waveguides are proposed for practical uses. The first is the use of thin threaded rods, such as #4-40 or #6-32 thread stainless steel rods. These or corresponding metric M2.6 or M3 threaded rods are commonly available to 0.9-1 m length. The advantages are the relative ease in designing connecting jigs and their moderate bending stiffness. For #4-40 threaded rod, CWT spectrogram is given as Fig. 36. A wide frequency range of transmission is achieved from 50 to 1000 kHz. Over 50 to 500 kHz, the wave velocity is within 5%, giving a low dispersion. This can be easily interfaced to a sensor like PAC HD50, which has a stud of the same thread size. Only L(0,1) mode is present.
The second design is a modification of commonly used steel-rod waveguide of 6.4-mm diameter. The change suggested is to use a threaded rod (of \( \frac{1}{4}''\)-20 thread) in lieu of smooth rod. A CWT spectrogram for a basic threaded rod was given in Fig. 27. Here, clay damper is applied over 8 cm section and its thickness is 2-3 mm. This removes slow moving wave modes and increases the decay constant from 2.2 to 4.2. An improved CWT spectrogram is given as Fig. 37.
As can be seen, this gives good transmission from 50 to 450 kHz, the most common AE inspection frequencies.

The third waveguide design combines the threading and tubular elements that we have examined. This design is built on the availability of threaded tubing; two sizes are most commonly available in the US, known as 1/8” and ¼” iron pipe size. Under the ISO system, these are defined in BS EN ISO 228-1: 2003, based on the British and Japanese standards, as G 1/8 or G ¼. In the US, these are commonly used for electrical lamps. The tube used has 9.73 mm in (major) diameter, pitch of 0.907 mm, inner diameter of 7.10 mm, 543 mm length, which is the 1/8” size. The most prominent feature is the mechanical rigidity of this tube design due to its diameter and wall thickness. In addition, a good transmission behavior is obtained. Figure 38 shows two CWT spectrograms; a) on the left is without clay damping and b) on the right is with 12 cm segment in the middle covered with clay. The clay covering reduced the wave amplitude by 12 dB. With no clay, the decay constant was 1.9. This value increased to 2.9 with clay damping added. CWT spectrograms clearly show the shortening of the received signals from 80 µs down to 30 µs. The wave modes are the same, but, in the damped case, signal strength is absent above 600 kHz. The FFT magnitude spectra are shown in Fig. 39. These again show the intensity dips around 200 kHz. In Fig. 38, this corresponds to the zone between L(0,1) and L(0,2) at 8 – 30 µs, which is apparently spurious indications of unknown origin. The FFT spectra show that this waveguide can be used for the popular inspection frequency of 150 kHz without damping applied. The L(0,2) mode can also add a useful range of 300-700 kHz. Even with damping that reduces the higher frequency transmission, it is useful in low frequency applications below 120 kHz without signal stretching. With the decay constant of 2.9, reverberation is in the manageable range.

Fig. 39 FFT magnitude spectra of received signals for the threaded tube (cf. Fig. 38). Red curve is without damping, blue curve is with clay damping.
Conclusions

AE waveguides are characterized using a pair of broadband ultrasonic transducers. This allows improved characterization of waveguides over 50 to 2000 kHz. Here, we examined responses of circular rod waveguides of different diameters from 1.6 to 12.7 mm with length varying from 60 to 900 mm. These are of solid, hollow or threaded rods made of Al, Fe and Cu alloys. In thinner solid rods, the low-frequency part of L(0,1)-mode rod wave is dominant and provides good transmission behavior with low dispersion. This mode is increasingly reduced above 6-mm diameter. At larger diameters, slower L(0,3)-mode becomes dominant. In tube waveguides, L(0,2) mode plays an important role of providing nearly constant velocity and spectral flatness, while threaded rods favor a lower L-mode. In tube waveguides with large D/t ratios, low frequency L(0,1) mode is suppressed and high-pass filtered broadband conditions are achieved, especially with a short length waveguide. Three practical waveguide designs are suggested, but many more can provide improved signal detection under difficult test conditions. Further exploration of various waveguide geometry is recommended to improve AE detection capability in noisy and harsh environments.

Acknowledgment

The author is grateful to Dr. Hideo Cho of Aoyama Gakuin University, Sagamihara, Japan, for calculating the dispersion curves of rod and tube waves and to the reviewers, who provided most meticulous critiques and helped to improve the submitted manuscript.

Appendix

Figure A1 illustrates a set-up of wave propagation experiment. This set-up used two KRN transducers, which were screwed into threaded holes in the mounting jigs. In this case, contact pressure was adjusted by rotating one of the transducers. For larger diameter rods, vertical arrangements were used. For tubes, small metallic discs were used with the KRN transducers.

The pulser used in this study was built in-house and the core part of its circuit diagram is given in Fig. A2. This design was a modified version of a pulser developed by Suzuki for his doctoral work at Aoyama Gakuin University, Sagamihara, Japan. It uses a high-voltage MOSFET (2SK1758) and usually operates at a repetition frequency of 3 Hz. A more recent MOSFET (STFH10N60M2) has a higher peak current of 30 A and performance was slightly improved. While the peak pulse voltage was essentially unchanged, the rise time (10% to 90%) was reduced by a factor of two (from 83 ns to 39 ns) with an FC500 connected. An attempt to reduce the rise time by adding an FET driver produced a desired decrease to under 20 ns, but unwanted oscillations occurred when a transducer is connected. Further work is needed to eliminate these spurious oscillations.
Fig. A1. Experimental set-up with two KRN transducers. Receiver is terminated with 10 k-ohms. A pair of FC500 transducers are in front of the pulser used.

Fig. A2. The circuit diagram of a high-voltage pulser used in this study. Normally, H-setting for the largest capacitor was used. The high-voltage supply can be switched to 380 V for low-frequency transducers, but this was unneeded in this work.
References


Clustering of Fiber-Break Related Events in Carbon Fiber Reinforced Polymer Composites Using Acoustic Emission

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Abstract

The objective of this paper is to develop a technique capable to providing timely warning of the onset of critical damage events that precede the catastrophic failure of composite specimens. The sequential failure of numerous adjacent fibers is known to trigger the final fracture of composite structural elements. In this paper, the detection of the formation of such critical clusters of fiber breaks among the millions of damage events that include matrix cracks, delamination, and individual fiber breaks, is shown to be feasible through cross-correlation of acoustic emission waveforms. Acoustic emissions released during static loading of \([0/90]_S\) cross-ply and \([\pm45/90/-45/0]_S\) quasi-isotropic specimens were examined in detail for a large number of specimens.

Keywords: Fiber composites, clustering, critical damage events, cross-correlation

Introduction

Damage initiation and progression in carbon fiber reinforced composites have been well studied and is known to occur in stages and involves several failure mechanisms (e.g., matrix cracking, fiber breakage, delamination) [1 – 6]. The presence of certain mechanisms may give an indication on where along the failure process the material currently is. Each mechanism has a unique physical process in terms of duration and energy release rate which should produce distinct AE signals. The subtle differences in AE signals have been a focus for distinguishing the failure modes. Liu et al. [7] and Mechraoui et al. [8] studied the various failure mechanisms using primarily AE amplitude with each mechanism occupying a distinct amplitude range but noted that amplitude values will depend on the material system as well as the source to sensor distance. Yu et al. [9] looked at specific frequency values to monitor failure in carbon reinforced composite specimens. Bussiba et al. [10] showed that not only do the different failure modes generate unique frequencies but they also have noticeably different durations. Fiber breaks are very short duration events and are known to give rise to relatively high frequency content [11]. However, examining a given parameter may not provide sufficient information regarding the source [12] since the failure modes may occupy common parameter regimes.

The various failure modes have different effects on the integrity of the structure and can potentially be classified as either critical or non-critical damage. This ultimately depends on the make-up of the composite which dictates the failure process. Damage initiation and progression in fiber reinforced composites have been well studied in the past with several techniques utilizing micromechanics based models to predict the behavior of the material under certain load conditions. Ogi et al. [13] developed a probabilistic model to predict transverse matrix crack in cross-ply panel and compared it to experimental results. Wharmby et al. [14] related the transverse crack density to changes of the elastic modulus which is more drastic in the absence of 0°plies. It was noticed that the majority of the stiffness reduction occurred within the first 10% of
the normalized life. Acoustic energy can also be a useful parameter to study damage progression. High energy events signify large crack growth which can be captured and characterized using acoustic emission techniques. Using cumulative AE energy was shown to agree well with C-scanning and microscopic analysis when monitoring damage accumulation [15]. Such methods have been shown to sufficiently capture the material behavior as long as the stress state information can be determined. However, there has not been a technique that focuses on identifying the onset of critical damage in real time. Even AE techniques, which attempt to distinguish between the different failure modes in real time, do not differentiate between non-critical and critical damage growth. For this study, critical damage is defined as that which indicates significant damage or directly precedes final failure.

Filtering out inconsequential signals not only allows for greater emphasis to be placed on important events but also addresses the data management issue associated with AE in unidirectional composite materials. Unidirectional composites are profuse emitter of acoustic emissions and can produce tens of thousands of signals during a simple coupon test. This can be counteracted by raising the trigger threshold to decrease the AE hit rate. Consequently, lower amplitude signals will be missed as a result. Under the assumption that critical damage signals start with low energy, ignoring lower amplitude signals may limit the ability to detect the early onset of critical damage growth. Without a filter, all relevant signals across the entire amplitude spectrum can be analyzed and also stored for later processing if necessary. The volume of AE data generated during testing may restrict the acquisition parameters used or the test duration. Ultimately, this process is a balance between determining the minimum amplitude/energy of relevant signals and staying below the maximum number of signals capable of being analyzed by post-processing software.

This work utilizes a cross-correlation technique as a filter to discriminate between non-critical and critical damage in carbon fiber-reinforced polymer (CFRP) panels while accounting for relevant low energy signals. Cross-ply and quasi-isotropic specimens were cut from laminates developed at NASA Armstrong Flight Research Center. The layups of the laminates were designed to resemble those of carbon fiber composites used in current aerospace structures. Damage evolution as it transitions from insignificant crack growth to meaningful damage was investigated using AE techniques.

**Experimental**

Each panel was made by stacking unidirectional tape to achieve a desired layup. Two layups were manufactured: quasi-isotropic [45/0/-45/90]_{2S} and cross-ply [0/90]_{3S}. After each lamina were positioned and vacuumed bagged, they were heated 1.1°C/min to 121°C, held at that temperature for one hour then cooled at room temperature. ASTM tension test standard D3039 was used to determine the dimensions of each rectangular specimen which was 25 mm x 275 mm x 3 mm. The sensor to sensor length was approximately 108 mm and piezo-electric wafer sensors (10 mm wide, 20 mm long, 0.5 mm thick) were bonded adhesively on both ends of the gage section while damped ultrasonic transducers of 6 mm diameter were attached outside the gage to function as guard sensors (12 mm from PZT sensors). The frequency range for the PZT sensors and ultrasonic transducers was 100 to 700 kHz and 100 to 400 kHz, respectively, and no appreciable resonances were seen. Also, even though the guard sensors were more sensitive to the out-of-plane mode, their overall sensitivity was good enough to eliminate signals outside the gage. This was confirmed using lead breaks. The polarization direction for the wafer sensors was
along the width direction, which increased sensitivity to signals propagation axially in the specimen. Wideband PAC 2/4/6 preamplifiers were used and the 40 dB setting was typically used for both static and fatigue tests. All AE data was recorded on a 4-channel PCI-2 AE system and a 35 dB_{AE} threshold was used. A sampling rate of 5 MHz was used to measure waveforms of 2048 data points with a pre-trigger of 256 µs. Hit definition and hit lockout time were 100 µs and 400 µs, respectively. Five specimen from each layup were tested.

The specimens were loaded in tension using a hydraulic testing machine. Quasi-static tension tests were done at a rate of 14 MPa/min to ensure a sufficient number of AE events would be captured to characterize the separate failure regions. With the tensile strengths for the cross-ply and quasi-isotropic specimens were 965 MPa and 717 MPa respectively, each tensile test was roughly one hour. Initially, lead breaks were done to ensure each sensor had similar frequency responses and sensitivity. Also, the time of flight of signal from one sensor to the next can be measured and used to calculate the speed of sound (velocity) of the signal, which is useful in determining source location. A schematic of an instrumented specimen is shown below in Fig. 1.

![Fig. 1. Tensile specimen dimensions (left) showing dimensions of the length and sensor to sensor distance, specimen during testing.](image)

**Methodology**

Each static test is capable of generating tens of thousands of signals depending on parameters such as threshold value, sensor sensitivity, and failure process of the material. This study utilized a cross-correlation technique to extract important signals based on the density of signals generated in a particular area over a set period of time. This approach relates an area where a high density of similar AE signals is being generated to critical localized damage growth. Localized damage growth is considered to be where a given source mechanism continuously grows or happens within a relatively small area or volume. In such case, that mechanism should produce repetitive signals as long as there has not been a drastic change in the medium. A focus
is placed on critical localized damage, such as fiber breaks, that significantly reduces the strength of the component. It is known that a fiber breakage causes stress redistribution into neighboring fibers which may fail if their ultimate strength is exceeded [16]. These neighboring fibers simultaneously fail in groups, or i-plets, at high load [1, 3, 6]. This behavior has been captured in great detail using computed tomography [4]. Capturing the failure of these i-plets in terms of AE clusters can provide great insight on the damage state of the material in real-time. Also, given that composites may initially exhibit random cracking, such a technique may be able to distinguish between separate localized damage areas.

The correlation process relies on raw waveform data captured by the individual sensors to determine location and various AE parameters (duration, frequency, energy, etc.). Typical AE software calculates such information but analyzing waveform data using MATLAB was found to be more effective. The cross-correlation technique \textit{xcorr} in MATLAB used to compare separate data sets is shown below in Eqs. (1–3), (MATLAB R2013a, MathWorks Inc., Natick, MA, 2013).

If there are two continuous functions representing waveform data, \( x \) and \( y \), there will be an expected value, \( E \), resulting from comparing the two functions. The variable \( m \) is the lag or shift, the output is the correlation array, \( c \), and \( N \) is the number of data point in the waveform. Each correlation value corresponds to a lag value and the degree of how similar two waveforms are can be found by finding the maximum value of \( c \). A visual representation of how this technique works is shown in Fig. 2. The first signal detected by each sensor serves as the initial reference signal and the following signals that fall within a specified window, 50 for the data presented later, are correlated to the reference. For the test data shown here, a window size of 50 yielded consistently good results. However, the necessary size will vary depending on the rate of the load applied and sensor sensitivity. This standard window length was used which cut out most of the regions of inactivity. Some events were clearly shorter or longer than this window but nearly all useful data was capture in either case. Utilizing lead breaks, a 90% correlation factor was seen to be sufficient in discriminating surface signals 2 mm apart. In the figure on the left, using waveform 1 as the reference, two red signals that follow in the window indicate they correlate at a high percentage with 1 and form a cluster of 3, including the reference. Next, signal 1 and it’s two matching waveforms are removed and process repeats using waveform 2 as the reference, which forms a cluster of 4 of the following waveforms. When clustered signals are removed from the data set, the remaining signals are shifted to fill the empty spaces and the next iteration of the process begins. Each cluster is independent of one another and is sensitive to localized damage. This “on-the-fly” technique uses real time data to monitor critical damage growth and has potential to be used \textit{in-situ}. 
When attempting to distinguish between the various source mechanisms, there are expected parameter regimes each mechanism should occupy. However, these parameter values vary with propagation distance. Using correlation, the effects of the attenuation, dispersion, and other aspects of wave propagation on the measured waveform can be taken into account. Such as, signals of the same source type and from the same location should be nearly equally affected by the aforementioned processes. During the early onset of damage, signals that are captured within a relatively short time that correlate at a high percentage may indicate localized damage growth and as the damage becomes more pronounced, individual signals travel approximately the same path within the medium. For a finite time, the medium is assumed to not change due to damage and the signals that occur within this window that correlate at or above a predetermined percentage are, therefore, grouped into clusters. Whereas most models require intrinsic knowledge about the state of the material to predict failure, here, the rate of cluster formation as well as cluster size was seen to be an indicator of critical damage for quasi-static tests.

**Results**

*AE Parameters Analysis*

The AE data generated during static loading for both the cross-ply and quasi-isotropic material can be seen below. Cumulative AE events vs stress plots can be seen in Fig. 3 and highlight the separate regions where matrix cracking, delamination, and fiber breaks occur at a high rate. Initially, a sudden increase in the number of events at low stress is seen due to failure of the matrix which generates a high rate of acoustic emissions. This behavior typically happens around 20-40% of the ultimate stress and saturate shortly after. Matrix cracks saturation is followed by an intermediate period characterized by minimal AE signal generation. At this point, the fibers are completely responsible for carrying load and the drastic increase of AE activity seen before failure is primarily associated with fiber breakage and delamination.
The above cumulative AE plots follow the expected multi-stage failure process [17] but do not show much difference between the two materials. Since the first and last regions contain extensive matrix cracking and fiber breaks, respectively, examining the AE parameters may provide information on the individual failure mechanisms. Splitting of the matrix occurs over a certain area and happens over a particular period of time whereas carbon fibers have a relatively smaller cross-sectional area and break almost instantaneously. Ideally, this difference in source duration and energy release of the failure modes should generate unique signals in terms of the traditional AE parameters.
Below, the average frequency and duration plots of the individual AE events, shown as blue dots in Fig. 4. The average frequency was calculated by estimating the number of cycles within a waveform in a given time window. Ideally, matrix cracking and fiber breaks should generate very distinct signals but there is only a minimal difference in the frequency characteristics seen for the two regions. This is seen in both cross-ply and quasi-isotropic material. However, the later region for the cross-ply seems to have a slightly higher average frequency than the quasi-isotropic material. Duration plots for both material as well as any other parameter plots provided very limited information on the damage development due to signals being affected by attenuation, dispersion, and scattering. The effects of attenuation and dispersion as a function of material properties and geometry have been well documented. However, the effects of attenuation and dispersion as a function of damage is not well understood because they depend on the amount of damage a signal encounters on its path to a sensor rather than the amount of overall damage.

**Correlation of AE signals**

Clustering of AE signals usually involves extracting parameters and forming groups or classes based on waveform characteristics. Some methods utilize un-supervised approaches that make use of amplitude or weighted metrics as classification metrics [18-21]. The accuracy of such techniques depends on accurate measurement of distinguishing features while accounting for effects of wave propagation, which is heavily dependent on distance.

The proposed correlation technique took the same data that generated limited insight from a traditional AE parameter standpoint and extracted meaningful information in terms of critical damage growth. To account for the change in the propagating medium due to damage, a window was used to only analyze successive signals to find clusters. This window, 50 successive events, assumes that the material microstructure of a given signal path stays constant or exhibits insignificant change for a finite period of time or stress. The clusters plots using a 90% correlation value are shown in Fig. 5 and detail how various cluster sizes grow as a function of stress. Each line represents an individual cluster size.

![Cumulative cluster growth for cross-ply specimen: sensors 1 (left) and 2 (right). Cluster sizes of 6 to 10 were plotted. This behavior was seen for quasi-specimens as well (not shown).](image)

Fig. 5. Cumulative cluster growth for cross-ply specimen: sensors 1 (left) and 2 (right). Cluster sizes of 6 to 10 were plotted. This behavior was seen for quasi-specimens as well (not shown).

The most accurate and non-trivial way to accurately capture the fiber break phenomenon is to physically count the breaks using high resolution microscopy. Reifsnider and Jamison [1] manually observed fiber breakage in each ply of a cross-ply and unidirectional specimens using scanning electron microscopy (SEM). A specimen was loaded to a certain percentage of the
ultimate stress, then unloaded and dissected, and the number of fiber breaks for given area (mm²) was determined. This was done at multiple ultimate stress percentages. Figure 6 shows a comparison between these findings and the results of this work. The AE data is a cumulative plot of AE clusters that have a size of 10 or greater. After sifting through the data, it was determined that 10 was a consistent metric for a minimal cluster size.

Fig. 6. Comparison of AE clusters seen in cross-ply to fiber break measurements using SEM [1].

From the above plot, the trend of the AE data falls between the SEM data as expected since the lay-up of the AE specimen falls between the layup of the other two. Having such physical evidence can provide calibration and fine tuning of the AE data analysis, which will allow this behavior to be characterized without any labor intensive or computationally heavy processes. With that being said, the ultimate comparison would involve the same specimen for AE measurement and SEM imaging.

The waveforms that make up the clusters were also examined and the AE features were studied. AE parameter analysis of clustered waveforms may provide information not noticeable when all AE data is analyzed. The frequency content of the reference waveform of each cluster was plotted with respect to stress, Fig. 7.

Fig 7. Average frequency of cluster signals (red) and all AE data measured in cross-ply specimen: data from sensor near failure (left), away from failure (right).
In the above average frequency plots, the reference signals (red) are superimposed over all the AE data. Since the clusters are associated with localized damage growth resulting from fiber breakage, it is expected that the signals contain relatively higher frequency content. Theoretically, fiber breaks should generate much higher frequencies than what is shown in Fig. 7 but the PZT wafer sensors had an upper frequency limit around 700 kHz. Sensors having a broader frequency response can be used but the influence of attenuation on the signals seems to play a more significant role in the measurement of higher frequencies. Hence, the reference signals from a given sensor tend to occupy the upper frequency domain when failure occurs near or at that sensor.

Location of clusters

The process of identifying clusters started with understanding localized damage growth. In this section, the origin of AE signals is studied and determined. Location of AE events itself is a well-understood process and has been studied extensively. In the case of transient waves, individual sensors may be triggered by different parts of the same waveform. A detailed waveform analysis was done to mitigate this problem and help enhance source location of AE clusters. Such as, when an event is captured by the two sensors, both waveforms are analyzed to ensure that each sensor was triggered by the leading peaks. This provided a safeguard against measuring incorrect time of arrival which affects the ability to accurately locate the events.

Since clusters are composed of multiple signals, source location only applies to the reference waveform and the subsequent signals are assumed to have originated from the same location. To verify that the clusters originated from the same location, random waveforms from various clusters were chosen and located. The transient nature of the signals makes it difficult to get precise time of arrival measurements. The extensional mode, given its faster velocity and non-dispersive nature over the frequency*thickness range of interest, was used to determine the velocity of the wave, which was found to be approximately 5000 m/s. However, as in the case of an aluminum plate, the in-plane surface displacement of the extensional mode is usually inversely proportional to its frequency, with most of the energy of the in-plane component being contained near the mid-plane of the material; the opposite effect is seen for the out-of-plane component of the extensional mode [22]. The PZT wafer sensors used are designed to be much more sensitive to the in-plane component but there is only a small percentage of in-plane energy available for measurement. The internal structure of composite materials is quite different from isotropic media but this phenomenon may have also influenced AE measurements in this study.

Figure 8 shows the location of raw AE data and the corresponding signal density plots relative to sensor placement. While it is possible to notice some areas of higher AE activity, the copious nature of polymer matrix composites can mask useful information due to the sheer number of events. The density plot highlights regions of high localized activity that is not clearly visible in the raw data. The density scale is based on the number of AE clusters per square mm, with dark areas corresponding to regions of high AE activity. These clustered signals are the targets of the correlation technique and can be indicators of critical damage growth. In addition, having location information gives the ability to see where the specimen will fail in real time.
Fig. 8. Raw AE location data for unclustered data (left) and signal density of the unclustered data (right) plots for cross-ply specimen. S1 and S2 refer to sensors 1 & 2, which were 75 mm apart. Events are the individual dots. The black area in right plot is due to dense AE activity.

The above plot shows the raw location of AE events as the specimen was loaded to failure. Tens of thousands of signals were measured but the events were seemingly distributed randomly along the gage section. Using only location, there was not a relative clustering of signals near the failure region which would be noticeable in the density plot on the right. However, there was useful information extracted from the above data using correlation and it was plotted in the form of clusters, seen below.

Fig. 9. Raw AE cluster location for clusters of 10 (left) seen in cross-ply specimen. Right figure shows the cluster location data transformed into a cluster density plot to highlight the location of clusters.

Figure 9 shows the results of applying the correlation technique to raw AE data. Whereas the raw data and the AE parameter data gave very limited insight, the cluster based approach provided indication of critical damage growth as well as location information. Failure of the specimen occurred slightly above sensor 2 which corresponds well with the dense region of AE clusters. On the color spectrum, black indicates an area of high cluster density. The two dense clusters align well with the failure area but slightly less dense clusters appear near sensor 1 right before failure. Ideally, the location of the clusters should indicate where the material will fail. However, the uncertainty associated with the material in terms of its internal structure, Lamb
wave behavior, and even the speed of sound right before sudden failure is not well understood and requires more investigation.

Conclusions

Quasi-static tension tests were performed on cross-ply and quasi-isotropic CFRP specimens. The traditional acoustic emission parameters, such as frequency and duration, were examined for information pertaining to the different types of damage growth during testing. While slight differences were noticed in the average frequency and duration plots of the matrix crack saturation region and the fiber break region for the cross-ply material, there was too much scatter in the data to quantify anything useful. The AE parameter analysis for the quasi-isotropic data was unable to highlight the different failure regions as well.

A correlation technique was developed to extract localized damage growth information associated with critical damage growth. Using the same AE data that yielded minimal information from traditional parameter analyses, the correlation process was able to extract localized clusters which are assumed to be related to fiber failure. The results were consistent and repeatable for both layups and verified on multiple specimens. This technique was able to monitor the development and growth of various clusters sizes and found that the occurrence of large clusters directly precedes sudden failure.

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References


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The Japanese Society for Non-Destructive Inspection (JSNDI) & International Institute of Innovative Acoustic Emission (IIIAE)
Review of Acoustic Emission Source Mechanisms on Large Movable Structures

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ABSTRACT: This paper reviews and compares three case studies involving acoustic emission (AE) monitoring of anomalous noises on large movement structures. In particular, probable source mechanisms for the various audible noises observed on the structure and investigated by AE and other measurements are identified and discussed. The three case studies include a movable stadium roof and two movable bridges, one bascule-type and one swing-type. The stadium roof and bascule bridge both showed AE correlated with similar stick-slip behaviors, albeit on two very different mechanisms. The swing bridge showed two distinct noise sources, each associated with different aspects of bridge motion.

15.1 INTRODUCTION

In the course of operation, movable structures such as stadium roofs, movable bridges, and industrial gantries sometimes emit audible noises loud enough to be disturbing the structure owner and the public. This paper will review three cases studies in which such loud noises, termed anomalous audible events (AAEs), were observed during commissioning of movable structures, with particular consideration of probable underlying noise source mechanisms. In each case, the structure owner needed to know whether the noises were benign or indicative of some mechanical (i.e. with the lift machinery) or structural problem. Identification of AAE source locations on large steel structures is challenging due to sound propagation and re-radiation through structural members, giving the impression to the human ear that the sound is coming from all around. It has been shown [e.g. 1,2] that acoustic emission (AE) monitoring with judicious sensor placement on the structural steel can provide unambiguous AAE source location results. Consideration of source location results along with structural/mechanical measurements such as strain, displacement, and rotation can provide insight into the underlying source mechanism, which in turn informs decision-making by the structure owner.

1.1.1 Overview of Case Studies

Three case studies are considered herein. All of these structures are located in the northern tier of the United States, in climates with hot summers and cold winters. Deicing salts are used on both bridges. The structures are:

1) Movable roof on a baseball stadium
2) Rolling bascule bridge carrying a town street over a freshwater commercial waterway
3) Swing bridge carrying a city arterial street over a marine commercial waterway

1.1.2 Considerations for Movable Structures

Movable structures present a variety of engineering challenge not found in static structures. Considerable wear occurs on bearing surfaces, and members are often subject to large cyclic loads, up to complete stress reversals [3]. In this sense, movable bridges and stadium roofs behave more like large machines than structures. For example, the primary girders on a bascule-type movable bridge change conceptually from a simple span when the bridge is closed and locked, to a cantilever span when the bridge first opens, to something like a beam-column with both bending and axial loads when the bridge is fully open (i.e., the leaf is nearly vertical). Access to structural and mechanical elements of interest also presents challenges. For example, bearings or raceways in a swing-type structure may be located in a confined space, as in the swing bridge case study. In addition, the size of the structure and the relative motion between various structural elements complicates sensor installation and cable connections to the AE measurement equipment – it is typically necessary to adopt a piecewise approach to
instrumentation. Finally, a considerable amount of spurious noise (i.e. other than AAEs) is generated during normal operation from benign processes such as sliding movements on bearings, crushing of oxides and debris on rolling surfaces, and so forth. These noises must be filtered away to concentrate on AAEs.

15.2 CASE STUDY: STADIUM ROOF

AE monitoring was used to identify AAE sources on the radial retractable roof at the Miller Park baseball stadium in Milwaukee, Wisconsin, USA shortly after the structure opened to the public. The radial roof opens and closes like a handheld folding fan, as shown in Figure 1. This roof system is both a signature aesthetic feature of the structure and an essential operating mechanism – unlike most domed stadiums, Miller Park includes a grass (rather than artificial turf) field requiring regular doses of sunlight through the opened roof.

![Figure 1: Stadium roof closing sequence showing roof panels pivoting on bearings above home plate (Milwaukee Journal-Sentinel illustration)](image)

Each of the five movable roof panels is supported by a bearing on a tree-like structure behind home plate. The tree structure and a typical bearing are shown in annotated photographs in Figure 2. Each panel weighs between 1,590 and 2,270 metric tons (3.5-5.0 million pounds), with approximately 40% of the load supported by the pivot bearings [4]. The remainder of the load is supported by motorized bogies on the outfield wall, which also provide the tractive effort to move the panels along a railroad-style track. The movable roof panels span approximately 180 m (600 ft) from the pivot bearings to the track [5].

![Figure 2: (a) Annotated photograph showing one side of tree-like structure supporting the five roof panel pivot bearings; (b) close-up of typical roof panel bearing showing location of AE transducer](image)

Instrumentation and monitoring of the roof panels was described by Prine [2]. Each of the five pivot bearings was instrumented in turn and tested by moving the corresponding roof panel. A non-contact laser displacement sensor measured the position of the roof panel truss as the truss pivoted about the bearing. The laser displacement sensor had micrometer sensitivity but limited range - approximately 6 mm. Thus, displacement data were
available for only the first 6 mm of travel. Nevertheless, plots of acoustic emission peak amplitude and roof truss rotation revealed correlation between AAEs and changes in the time rate of displacement, as shown in Figure 3.

![Figure 3: Time history of AE amplitude (green dots) and roof panel truss displacement (red line) showing correlation between AE and changes in displacement rate. Dashed lines indicate times of AE events, for comparison to displacement data.](image)

It is clear from Figure 3 that acoustic emission hits are correlated with momentary pauses in change in displacement followed by resumption of movement – that is, stick-slip behavior. Due to the long span of the roof panel trusses, very small displacements/rotations at the bearing correspond to large movements at the drive bogies along the outfield wall. When the home plate bearing sticks, considerable strain energy may accumulate in the roof truss until the bearing slips. This undesirable behavior indicated that the selected bearing design was not suitable to the application. When the bearings were replaced with thrust bearings designed to accommodate the downward load associated with the weight of the roof panels, the AAEs ceased [5]. The stadium roof remains in service and is operated frequently during baseball season.

### 15.3 CASE STUDY: ROLLING BASCULE BRIDGE

AE monitoring was used to characterize audible noises generated during opening and closing of a Scherzer-type rolling bascule bridge over a busy waterway. Rolling bascule bridges open by rocking along a toothed track plate at the heel of the bascule girder, as shown in elevation view sketch and photograph in Figure 4. During operation, as well as when the bridge is locked in the closed position, the entire weight of the movable leaf (approximately 450 metric tons) is supported by a relatively small contact area on the lower track plate. This contact area moves along the upper and lower track plates during bridge movement.

![Figure 4: Sketch of bascule bridge leaf and photograph of bascule girder heel showing moving contact areas](image)
Instrumentation and data reduction (including development of post-processing filters) for the rolling bascule bridge is described in a previous paper [2]. After the drive machinery had been ruled out by first-hit analysis, linear and planar location analyses were employed to determine whether AAEs corresponded to particular contact locations during lift cycles. Linear location analysis along the top and bottom track plates showed that AE events associated with AAEs followed the rolling contact point between those plates. Planar analysis, in which an array of AE transducers was deployed to cover a wide area of the heel of the bascule girder, yielded unambiguous results indicating that AE events associated with AAEs occurred exclusively along the bottom edge of the bascule girder heel, as shown in Figure 5.

![Figure 5: Planar location results showing events along bottom flange of bascule girder heel. AE transducer locations are indicated by the numbered red dots, and located AE events by green dots.](image)

While the source location of the AAEs was evident from the planar location results, the specific source mechanism remained unclear. A toothed track plate is bolted to the bottom flange of the bascule girder. This curved upper track plate mates with the flat lower track plate as the bridge moves. The bolted connections consist of groups of bolts on the bottom flange (on either side of the bascule girder web; each group of bolts was separated from the groups on either side by a radial stiffener. These long and short radial stiffeners are visible in the drawing in Figure 5.

After the bolts themselves were eliminated as potential AE sources by a close-up transducer array, it was hypothesized that the AAEs may originate elsewhere along the bascule girder-upper track plate interface. An orthogonal pair of eddy-current type non-contact displacement sensors was deployed to measure any displacement or deformation along or perpendicular to the interface – in other words, quasi-shear or normal deformation. A nearby tilt sensor nearby measured the angle of the bridge, from which the track plate contact position could be calculated. These sensor locations and orientations are shown in Figure 6.

The measured displacements – particularly the quasi-shear displacements – presented a distinct stepwise pattern during portions of the bridge lift cycle. Timestamps of acoustic emission events associated with AAEs are superimposed on the quasi-shear displacement time histories in Figure 7. While the total change in displacement during the lift cycle is quite small (64 mm or 0.025 inch), it is evident, particularly in Figure 7b, that AAEs are correlated almost one-to-one with stepwise jumps in displacement.

Because the apparent stick-slip movements were very small and occurred away from the bolts, the bridge designer judged the AAEs and the underlying stick-slip mechanism to be benign. Anecdotal reports indicated that the AAEs subsided during the first year of regular operation of the bridge. These reports suggest that the stick-slip action on the bascule girder-track plate interface was related to “break-in” initial wear on the interface. The bridge remains in regular operation, opening tens of times daily during the summer months.
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Because the apparent stick-slip movements were very small and occurred away from the bolts, the bridge designer judged the AAEs and the underlying stick-slip mechanism to be benign. Anecdotal reports indicated that the AAEs subsided during the first year of regular operation of the bridge. These reports suggest that the stick-slip action on the bascule girder-track plate interface was related to “break-in” initial wear on the interface. The bridge remains in regular operation, opening tens of times daily during the summer months.

![Figure 6: Photograph and sketch showing displacement sensor (a) location and (b) orientation (exaggerated scale) on bascule girder - upper track plate interface](image)

![Figure 7: Correlation of AAEs with displacement along the interface between the bascule girder bottom flange and the curved upper track plate during bridge closing, showing (a) entire closing and (b) close-up of 10 second period of greatest movement](image)

15.4 CASE STUDY: SWING BRIDGE

Anomalous audible events of two distinct types – one described as “clicking”, the other as “popping” or “booming” – were reported during operation of a swing bridge carrying a city arterial street across a busy marine waterway. AE monitoring was employed to characterize the two types of AAEs. The bridge owner was particularly curious whether AAEs were associated with any particular bridge position or rotational speed.

Instrumentation and data reduction (including development of post-processing filters) for the swing bridge is described in a previous paper [2]. Following preliminary tests to rule out other areas of the bridge, the center pivot and outer drive pinion areas were identified as likely noise sources. Locations on the center pivot area of the bridge are described using the clock face system shown in Figure 8a. In this scheme, the 9 o’clock-3 o’clock axis represents the longitudinal axis of the bridge when closed, and the 12 o’clock-6 o’clock axis represents the bridge’s fully open position. A rotary encoder on the center gear recorded bridge position.
Testing revealed that clicking-type AAEs occurred only while the bridge was in motion. When the bridge was moving at approximately constant speed, AAEs occurred at regular five second intervals and were not generally associated with bridge starts or stops. It was hypothesized that a particular “hot spot” along the rotation arc might be the source of the periodic clicking AAEs. Planar location analysis was conducted on the plate at the top of the pivot bearing (AE channels 1-4 in Figure 8b) to test the hot spot hypothesis. The results, shown in Figure 9, were consistent with an AAE hot spot at the 5 o’clock position.

Specifically, when locatable events are distributed into bins based upon the time within the bridge movement at which they occurred, it is evident that earlier AAEs tend to occur toward the 5 o’clock position, and the subsequent AAEs generally tend to occur clockwise of that position, subtending an arc from 5 o’clock to 8 o’clock. This distribution is generally consistent with the motion of the bridge as it moves from fully closed to fully open; thus it may be reasonably concluded that a single source at the 5 o’clock position on the pivot base could cause the clicking-type AAEs.
The “popping” or “booming”-type AAEs on the swing bridge were found to be fundamentally different than the clicking type. While the clicks were strongly periodic and associated with steady motion, the booms occurred almost exclusively during stops and starts, as shown in the distribution of AAEs by bridge angle in Figure 10.

Figure 10: Stacked histogram of AAEs (n = 257) with bridge angle for selected clockwise (red) and counterclockwise (blue) bridge movements, showing clusters of AAEs at starts and stops, including a pause at +52 degrees during clockwise motion. Figure courtesy of Daniel Marron (unpublished data).

Linear and planar location analyses showed that the booms originated along the box girders supporting the drive pinions. The drive pinions (with drive shafts oriented vertically) engage a rack on a large-diameter ring about the center pivot point. Locatable events were concentrated near the groups of bolts that tie the pinion bearings (supporting the vertical pinion shafts) to the box girder, as illustrated by the annotated histogram in Figure 11.

Figure 11: Distribution of AAE source locations along pinion girder. Pinion bearing/box girder through-bolt groups are highlighted in yellow. Figure courtesy of Daniel Marron (unpublished data).
15.5 DISCUSSION AND CONCLUSIONS

The three case studies demonstrate that AE may be successfully applied to localization and characterization of anomalous acoustic events on large movable structures, and that the AE method can identify events with various underlying acoustic source mechanisms. AAEs may be produced by movable structures in several ways. Despite differences in structure purpose and geometry, similar micro-level source mechanisms are present. In the case of the swing bridge, two distinct source mechanisms were identified, each with particular relationships to bridge motion (i.e. constant speed vs start/stop).

1.1.3 Stick-Slip Behavior

The baseball stadium roof and the rolling bascule bridge present clear examples of stick-slip behavior leading to AAEs. Displacement during the slip was quite small, on the order of micrometers; however, the slip occurred nearly instantaneously, resulting in a sudden energy release. Typically, processes producing audible sounds (e.g. AAEs) emit acoustic energy over very broad frequency spectrum [6,7]; thus it is expected that the AAEs would be readily detectable by both the human ear (sensitive from roughly 20 Hz to 20 kHz) and commercially-available AE transducers (sensitive from roughly 150 kHz to 675 kHz).

Both structures emitted AAEs throughout movement cycles, as opposed to emission during start/stop acceleration only. In both cases, stick-slip behavior is almost certainly related to the high normal forces on the surface. On the stadium roof, approximately half the weight of the roof panel acted normally to the bearing surfaces; on the bascule bridge, it is believed that the vertical stiffeners played a role in “focusing” loads to particular areas.

1.1.4 Localized Movement Around Bolts

The “popping” AAEs observed on the swing bridge appear to be related to localized movement around the bolts in the pinion girder. However, similar tests to monitor bolted connections between the track plate and bascule girder on the rolling bascule bridge yielded no significant acoustic emissions. The difference between these two observations is likely related to the stiffness of the thick bascule girder flange versus the relatively thin walls of the swing bridge pinion box girder. Close-in displacement measurements showed that the pinion box girder does deflect during starts and stops, indicating a possible “oil can” deflection mode at moments of high stress from the pinion torque during movement starts and stops. Thus it seems that in areas of relatively lower stiffness, localized movement around bolts can be a source of AAEs.

1.1.5 “Hot Spots”

Both bridges showed “hot spots”, areas of concentrated AE activity associated with AAEs. On the bascule bridge, planar location analysis showed that most AE events occurred along a line (i.e., the interface between the bascule girder heel and the curved upper track plate). On the swing bridge, the “clicking” AAEs were shown to originate from the center pivot area; planar location vs. time analysis suggests that the AAEs may be associated with a particular point on the center pivot bearing. It is by no means surprising that acoustic emission phenomena would be concentrated in particular high-stress regions.

1.1.6 Limitations and Opportunities

Uniqueness of large civil structures, as opposed to manufactured systems, presents some challenges for scientific analysis of acoustic emission behavior associated with AAEs. Each structure in the case studies was designed for and constructed at a specific location. Even if similar structures were available for comparison testing, site-specific design elements, site conditions, construction details, and operating practices affect the boundary conditions for the structure itself as well as the dynamic processes associated with movements. This uniqueness of constructed facilities stands in contrast to the repeatability found in manufactured systems, which are built in large volumes under controlled conditions. Furthermore, the scope of investigations for movable structures is limited by access methods and time available for testing. Since structures are typically closed to the public during testing, structure owners are motivated to conclude testing as soon as actionable information is obtained, rather than conduct additional work to fully characterize the problem. Thus, opportunities for detailed in-situ investigation of the mechanics underlying AAE phenomena are limited. It is hoped that building a library...
of case studies in the literature will provide sufficient information to inform faithful simulations and laboratory investigations. In addition, guidance from movable structure case studies may help forge additional connections laboratory-scale phenomena in the existing AE literature and the experiences of full-scale field observations.

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REFERENCES


On Acoustic Emission Sensor Characterization

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ABSTRACT: We examined calibration methods for acoustic emission (AE) sensors. In spite of the self-evident needs of reliable calibration, the current state is deplorable globally. The only primary standard at NIST (US) is non-operational, yet no other standard has emerged. Widely practiced face-to-face calibration methods have no validated foundation. Reciprocity calibration methods are invalid for the lack of reciprocity and sensor dependent reciprocity parameters. This work provides three workable solutions based on laser-based displacement measurement, which leads to “direct” method using the face-to-face arrangement. This leads to the second “indirect” method of mutually consistent determination of transmitting and receiving sensitivities of sensors/transducers. For all ultrasonic and AE sensors examined, their receiving and transmitting sensitivities are found to be always different and non-reciprocal. Displacement vs. velocity calibration terminology is clarified, correlating the “V/μbar” reference to laser-based calibration. We demonstrate the validity of the direct and indirect methods and the third one based on Hill-Adams equation, called Tri-Transducer method. This uses three transducers as in reciprocity method, but incorporates experimentally determined reference sensor sensitivities ratio without a transfer block and can get both transmitting and receiving sensitivities. These three methods provide consistent calibration results for over 30 AE sensors.

1. INTRODUCTION

In acoustic emission (AE) testing, sensors are essential components of a nondestructive test system. Their characterization attracted much interest over the years. Notable reviews on AE sensor calibration appeared in the 1980s [1-3], but only established standards are two ASTM standards for the primary and secondary calibration of AE sensors [4, 5]. These are based on seismic pulse on a large transfer block, developed at NIST [6] and are for the calibration of the surface wave sensitivity. Currently, they are dormant. Burks and Hamstad [7, 8] reexamined the NIST procedures and suggested revisions. One of them is to use measured displacement, rather than analytical calculation since the capillary-break source is elliptical, rather than a point. No ASTM standard exists for AE sensor calibration for normal incidence waves.

AE sensor manufacturers typically provide a sensitivity curve based on face-to-face calibration. This calibration procedure has been treated as proprietary information and described only inadequately [9]. Calibration curves are usually in reference to the reference level of 1 V/μbar, but this reference remains undefined. ASTM E976 standard guide [10] is often cited as the basis, but E976 specifically excludes the face-to-face procedure. This widely practiced face-to-face calibration methods presently have no validated foundation. It does benefit from the ease of set-up, reasonably good repeatability and the ability to handle long-duration signals of high-sensitivity (undamped or minimally damped) AE sensors. Commonly used AE sensors reverberate beyond 1 ms when free and often over 200 μs even coupled to a metal block, enlarging the needed size of a transfer block to inconvenient sizes of over 1 m. Thus, it is desirable to give it physics-based validation.

Reciprocity calibration methods have been well established for acoustic transducers and hydrophones. In ultrasonic transducer calibration, more advanced methods have appeared and the frequency range extended to 20 MHz routinely [11] and to 100 MHz in laboratory [12-16]. These include uses of direct measurement of particle velocity in water, time-delay spectroscopic methods, an optical multilayer hydrophone as reference and pulse-echo with a reflector. This is in sharp contrast to the unsatisfactory state of AE sensor calibration. In general cases of differing transmitting and receiving sensitivities, Hill and Adams [17] showed that the reciprocity calibration method requires the independently determined ratio of transmitting and receiving sensitivities of an auxiliary transducer. This condition of non-reciprocity prevails in all the piezoelectric transducers examined [18]. We also showed [18] that reciprocity parameters are sensor-pair dependent. Reciprocity calibration methods for AE sensors [19-23] are thus invalid for the lack of reciprocity for AE and UT transducers when used in contact with solid medium.

In well-damped transducers, laser techniques provided satisfactory results for surface displacement/velocity measurement as discussed extensively by [24]. In the present study, we will utilize laser interferometry as the basis for sensor/transducer characterization [25] and consider three sensor calibration methods.
Let us denote the transmission output of the i-th transducer due to an electrical pulse as $T_i = t_i \cdot V_i$, where $t_i$ is the transmit transfer function and $V_i$ is the FFT spectrum of the pulse input. Here, the transducer output is measured in displacement. Using a laser interferometer, we can experimentally determine $T_i$ or $t_i$. Next, $R_j$ is the receiving displacement sensitivity spectrum of the j-th transducer. That is, voltage output for a given displacement input on the face of the receiver. When transducer i is coupled face-to-face with transducer j, this constitutes a transmission-reception (T-R) test. We get its output $E_{ij}$ with the above notation (without separating the input spectrum) as

$$E_{ij} = T_i \cdot R_j = t_i \cdot V_i \cdot R_j$$

(1)

Knowing $T_i$ from laser interferometry, $R_j$ can be obtained. Actual calculation relies on the spectral division procedure using FFT magnitude spectra of $E_{ij}$, $T_i$ and $R_j$. This is designated as “Direct” method. Using the direct method, we can obtain the $R_j$ spectra for any sensors (which need not be transmitting) and transducers (capable of transmitting as well). This method also applies to sensors with integrated preamplifiers.

Using transducers as transmitters in combination with sensors of known $R_j$, we can also determine their transmitting sensitivities, $T_i$ via the same equation (1). Combining a transducer needing $T_i$ with the sensors $R_j$, we determine multiple spectra of $E_{ij}$ with T-R tests. By spectral division with known $R_j$, $T_i$ is determined. To minimize the scatter expected, it is normal to obtain several spectra for a particular transducer’s transmitting sensitivity and average them. This is “Indirect” method. This method can also utilize the transmitting sensitivity thus obtained for getting receiving sensitivity spectra of still other sensors. Again, multiple spectra are averaged to minimize the scatter. Consistency of the present calibration procedures can be verified through the reconstruction of T-R tests comparing $T_i$ and $R_j$ thus obtained with experimentally measured $E_{ij}$. Good consistency was found. Results of the indirect method are also compared with those of direct method. As shown later, two methods produced good agreement as well.

Since AE sensors are always used in contact with solid medium, it is desirable to evaluate them using a transfer block. With the above notation (without separating the input pulse spectrum) plus the transfer function of the transfer medium $X_{ij}$, a T-R test for transducers i and j leads to

$$E_{ij} = T_i \cdot X_{ij} \cdot R_j = E_{ij} \cdot X_{ij}$$

(1a)

The transfer function $X_{ij}$ can be obtained from equations (1) and (1a); Face-to-face T-R experiment provides $E_{ij}$, while $E_{ij}$ in (1a) comes from a T-R test through a transfer block. This $X_{ij}$ function is dependent on a particular pairing of transmitter and receiver, requiring subscripts. Generally, T-R tests are not reversible; $E_{ij} \neq E_{ji}$.

Hill and Adams [3, 17] analyzed generalized cases of reciprocity calibration, in which $T_i$ and $R_i$ of transducers differ and the law of reciprocity is no longer satisfied. Three-transducer set-up is used as in classic reciprocity calibration methods. One of the three (auxiliary transducer) is used as a reference needing both $T_i$ and $R_i$ functions, while another acts as a transmitter. The third is the target of calibration and can be receiving only. Here, transducer pairs of 1 and 2, 1 and 3, and 2 and 3 are selected and transducer 3 is the auxiliary transducer while 2 is the target transducer of calibration. We have

$$E_{12} = T_1 \cdot X_{12} \cdot R_2, \quad E_{13} = T_1 \cdot X_{13} \cdot R_3, \quad \text{and} \quad E_{32} = T_3 \cdot X_{32} \cdot R_2.$$  

(2)

Taking ratio of the first two equations, $E_{12}/E_{13} = (X_{12} \cdot R_2)/(X_{13} \cdot R_3)$, we get $R_2 = (E_{12} \cdot X_{13} \cdot R_3)/(E_{13} \cdot X_{12})$, and the third one yields: $R_2 = E_{32}/(X_{32} \cdot T_3)$. Combining, we have for pairs coupled through the transfer block

$$R_2 = [(X_{13} \cdot E_{12} \cdot E_{32} / (X_{12} \cdot X_{32} \cdot E_{13}) \cdot (R_3 / T_3)]^{1/2}.$$  

(3)

There are six unknowns of $T$ and $R$ for transducers 1 to 3, but $T_2$ was unused and $T_1$ cancels out in getting equation (3). We can thus obtain $R_2$ by getting from experiment six $E_{ij}$ values that provide three $X_{ij}$ and the ratio $R_3/T_3$, determined separately from these six T-R experiments. Notice that no transducer reciprocity is required in the above derivation.

We deviate here from [17] by using the transmission parameters $X_{ij}$. In Hill-Adams analysis, $X$ was defined as a unique function of the transfer medium, because $X$ is based on the Green’s function for point to point transmission. Because of diffraction effects, each transducer pair of finite sizes has a unique $X_{ij}$. Also the size of the transfer block
is a factor, as well as the receiver size. For some pairs, $X_{13}/X_{12}$ can be treated as unity over a limited frequency range and only $X_{32}$ is needed. When $X_{13}/X_{12}$ is unity, equation (3) reduces to Hill-Adams equation [17], given as

$$R_2 = \left[ \frac{E_{12} \cdot E_{32}/X_{13}}{(R_3/T_3)} \right]^{1/2}. \quad (3a)$$

Reciprocity calibration cannot provide the ratio of $T_i$ and $R_i$ of the reference transducer, required in equation (3) or (3a) expressing the receiving sensitivity, $R_2$. This problem can be overcome when $T_i$ sensitivities are obtained using the laser interferometry, which in turn provide $R_i$ sensitivities using the direct and indirect methods discussed above.

It is noticed that $E_{ij} = E^*_{ij} \cdot X_{ij}$ from equation (1a). Upon substitution into equation (3), we obtain

$$R_2 = \left[ \frac{(E^*_{12} \cdot E^*_{32}/E^*_{13})}{(R_3/T_3)} \right]^{1/2}. \quad (3b)$$

This means that $X_{ij}$ and the use of transfer block are not required. Face-to-face arrangement can replace calibration procedures with a transfer block. We designate this approach without a transfer block based on equation (3b) as Tri-Transducer (TT) method.

We examine here the inadequacy of sensitivity calibration methods for AE sensors available today and provide three workable solutions based on physically measurable quantities. Other related issues are also discussed including front-loading effects and $\mu$bar reference.

2. TRANSDUCER SENSITIVITY CALIBRATION – TRANSMISSION AND RECEPTION

The use of laser interferometry for transducer calibration is straightforward [24, 25]. Commercial interferometers of various design are now available, although their uses have been limited due to high cost. Two works [21, 22] made significant advances using laser interferometry to verify the displacement of surface pulse and obtained the sensitivity for surface-wave reception of PAC $\mu$-80 and UT1000 sensors. This approach is a good supplement to the NIST method.

In our studies that have focused on normal incident waves, we have used a displacement-sensitive laser interferometer (Thales, LH140, 20 MHz bandwidth with the sensitivity of 0.1 V/nm at Aoyama Gakuin University, Sagamihara, Japan; Dr. H. Cho graciously conducted measurement). Three typical transmission curves with a fast initial rise and slower decay with several oscillations are shown for broadband ultrasonic transducers (Olympus V101, V103 and V104) in Fig. 1a with their corresponding FFT magnitude in dB scale (Fig. 1b). The peak displacement values are 10 - 12 nm. These are shifted in time and level as noted. The raw FFT spectral data contained noise and it was reduced by using 25-point smoothing Savitzky-Golay algorithm [26]. The observed displacement waveforms are basically of mono-polar shape with trailing oscillations. This feature results from the forward radiation at the front face and the presence of absorber behind piezoelectric element, as predicted by theory [27, 28]. The peak displacement value is approximately 50 pm/V, which is expected from a typical lead-metaniobate piezoelectric element. The other half of piezoelectric displacement is radiated backward into the absorber and mostly damped.

The FFT magnitude transmitting spectrum is relatively smooth for V104 (Fig. 1b). The spectra of V101 and V103 shows many peaks and dips, showing strong fluctuation. Some of them are extraneous vibrations as the transducer front face is free, only facing air. With face-to-face arrangements, these apparently disappear as these transducers produced smooth spectral curves in T-R tests. Front-face loading effectively suppressed extraneous vibrations. It appears that the low frequency oscillations coming from radial resonance are not suppressed adequately. Comparing six $T_i$ spectral curves, we selected to use V104 as the reference transducer and use the remaining five for confirmation by avoiding the range where irregular changes are observed.

The transmission characteristics of V104 are shown in Fig. 2 up to 5 MHz, though higher range is less important in AE. The HV pulse spectrum is curve 1. The displacement transmitting spectra of V104 are curves 2 and 4 (unit = nm). The latter is corrected by subtracting the HV FFT spectrum, indicating much less frequency dependence of V104 transmission and showing a broad peak at 2.6 MHz. By multiplying the angular frequency, $2\pi f$, these curves are converted to show the velocity response of V104 transmission, curves 3 and 5 (unit = m/s), with or without the HV electrical pulse spectrum.
Once $T_{V104}$ of the reference transducer is obtained, we determine $R_i$ of other transducers by conducting T-R test in a face-to-face arrangement of the reference against a sensor under test (SUT) using equation (1). This provides $E$ for the transducer-sensor pair. The $R_{SUT}$ is then determined by $R_{SUT} = E - T_{V104}$. The 0 dB reference for the $R_{SUT}$ is 1 V/nm with frequency in kHz.

Using $V104$ transmitter, we first examine the response of a conical PZT sensor, home-made using the Proctor design [29]. The conical FFT spectrum minus $T_{V104}$ spectrum has broad distribution, reaching the maximum at -15 dB, in good agreement with the value of -14 dB Proctor reported for his conical sensors [29]. Next, using the direct method and five UT transducers, all well damped, we obtain the $R_{SUT}$ curves (Fig. 3). Three 2.25 MHz transducers show similar smoothly varying sensitivities except V101 and V103 have major dips at 1.1 and 2.3 MHz. These all show the peak of -2 to +5 dB sensitivity and large fluctuations at low frequencies.

The direct method used for broadband UT transducers applies to general-use AE sensors as well. These are typically of higher sensitivity and most have more than a single resonance. Three receiving spectra are shown in Fig. 4. PAC R15a is most sensitive here, showing a peak displacement sensitivity of 13 dB at 162 kHz. PAC R15 shows a similar spectral shape, but shows a little lower sensitivity. PAC R6a is a newer sensor, but this is designed for low frequency (60 kHz) surface-wave detection: here the peak is near 300 kHz. All of these general-use AE sensors have the peak sensitivity of 0 to 13 dB or about 1 to 4.5 V/nm.

Next, we used nine UT transducers as transmitters and receivers. By using multiple $T_i$ and $R_i$ sensitivity spectra thus obtained, the $T_i$ and $R_i$ sensitivity spectra of any transducer can be determined. This is the “Indirect” method. In order to get $T_i$ of transducer A, couple it to transducers B, C, D, etc. with known $R_i$ spectra. Since results vary
slightly, they are averaged to finalize the $T_\lambda$ sensitivity of transducer A. Even though the laser-based $T_i$ sensitivities showed some irregular peaks and dips, the averaged spectra are generally smooth, indicating the front-face loaded $T_i$ sensitivities have smooth spectra. An example of the $T_i$ sensitivity of NDT thus obtained is shown in Fig. 5 and compared to that due to laser interferometry. These two curves differ by 0.7 dB on average over 22-1400 kHz. For the indirect spectra, the absence of two large dips at 1.5-2 MHz indicates that the front-face loading removed extraneous vibration through the coupling of a receiving sensor. In the present case, both front face materials are alumina plates with matching acoustic impedance. The indirect method can be applied in reverse to determine the $R_i$ spectra of a transducer. Three such examples are shown in Fig. 6. These have the peak sensitivity of about 1 V/nm. Results of the two methods, direct and indirect, generally agree better than 0.5 dB on average to 2 MHz. Maximum difference reaches 5 dB at low frequencies.

Finding both $T_i$ and $R_i$ spectra of a transducer, we can verify these calibration results. This is done by constructing the combined $T_i$ and $R_i$ ($i \neq j$) spectrum for any combination of transducers and comparing it with the corresponding T-R experiment. An example is given in Fig. 7, where V189 and V195 were paired. $T_{V195}$ spectrum was obtained from other transducers’ $R_i$ spectra and is marked V195 $T$ (red). $R_{V189}$ is the bottom curve. The sum of these two is plotted as $T + R$ in purple and is compared to face-to-face output, marked $T \ R$ (exp) in green curve. These two agree well over 150-1200 kHz and 1.3-1.7 MHz, but poorer near the dip of $R_{V189}$ and above 1.7 MHz. For twelve cases examined in detail, spectral comparison yielded better than this example. The average discrepancy was typically about 1 dB except below 200 kHz or above 2 MHz, where discrepancy is slightly higher. For validation purpose, we can also utilize laser-based transmitting sensitivity (but avoiding the frequency range that shows irregular peaks and dips: >250 kHz for V101, >650 kHz for V103, >1400 kHz for NDT C16). These were set aside in preference of using V104, but they do provide a back-up. Here, agreement was moderate.

In the above comparative procedure of the combined $T_i$ and $R_i$ sensitivity versus directly measured $T+R$ sensitivity, it is necessary to account for the area of a receiving sensor when it is larger than the transmitter it is paired with. Assuming that the receiving sensitivity is uniform over the entire area, one adds 4.99, 7.04 and 12.04 dB for the diameter ratio of 1.333, 1.5 and 2, respectively. The present results of good matching of the experimental combined spectrum and one deduced from the calibration of $T_i$ and $R_i$ spectra indicate the uniformity assumption is valid. We can thus determine mutually consistent transmitting and receiving sensitivities of transducers and sensors.

The ratios of the $R_i$ sensitivity and $t_i$ sensitivity (excluding the HV pulse spectrum) were obtained for 17 transducers including both broadband and resonance types. Surprisingly, the general spectral shapes of $R_i/t_i$ spectra were similar except for shift in values. Four examples are shown in Fig. 8. Below about 600 kHz, the spectral difference exhibits the dependence is $f^{1.8}$ for V101, and $f^{1.33}$ for the rest. All show a peak around 800 kHz and start decreasing at higher frequencies. It is also strange that the middle two curves for V103 and V104 are essentially identical despite their non-matching sensitivity spectra. All other curves are between the top and bottom (except V195). This observation on $R_i/t_i$-ratios can be related to the spectral difference between a half-sine mono-polar
displacement pulse and a full-cycle sinewave pulse (approximating a Gaussian pulse and its derivative). The difference of their FFT spectra is also plotted in Fig. 8 as a blue (dash-dot) curve. The lower frequency part is linear with frequency until it approaches the peak at 900 kHz. The transmission pulse shapes from damped transducers are usually mono-polar, just like a half-cycle sinewave (see Fig. 1a). In contrast, the received signals tend to have an oscillatory, bi-polar shape. The differing transmission and reception behaviors originate from the mechanisms of pulse generation of a piezoelectric element [27] and produce the observed spectral ratio.

This section demonstrates that 1) the direct method of calibration is successfully used with the face-to-face arrangement, providing receiving sensitivity of various sensors/transducers, 2) the indirect method is used to determine both transmitting sensitivity and receiving sensitivity, 3) the indirect method suppressed extraneous oscillations of transmitters that may occur in free space, 4) calibration results of the two methods agree well, 5) mutual consistency of transmitting and receiving sensitivities is verified and 6) the receiving and transmitting sensitivities of a transducer always differ while their ratio shows similarity among various transducers.

3. VELOCITY RESPONSE OF A TRANSDUCER

We have shown that piezoelectric sensors generate output voltages responding to displacement input. It can still be described in terms of the time-derivative of displacement input, namely, particle velocity. The standard approach started with ASTM E1106 [4], which treats a sensor output to be proportional to the displacement function with a typical unit of V/nm. However, its FFT magnitude can be converted to express the sensitivity in reference to the input velocity function. This is accomplished by the multiplication of $2\pi f$ factor to the input function according to an identity in Fourier transform theory. When one divides the sensor output function by the velocity input function, the velocity sensitivity spectrum is obtained with a typical unit of V/m/s or Vs/m. The $T_1$ spectra in terms of displacement can be treated in this manner, as shown in Fig. 5, curve 3. Here, the unit was changed from nm to m, corresponding to 180 dB subtraction in dB-scale. A note of caution: one cannot multiply $2\pi f$ to a receiving displacement sensitivity spectrum in an attempt to get the velocity response. Instead, you need an opposite operation: Divide by $2\pi f$ and add a factor of $10^{19}$.

In the AE field, it is common to find the use of $\mu$bar in place of m/s as the unit of velocity. This originated from Dunegan’s use in 1968 of hydrophone calibration scheme in characterizing a reference transducer [30]. In 1968, Dunegan obtained calibration limit up to 400 kHz. Today, the frequency limit for miniature ultrasonic hydrophone calibration is extended to 20 MHz [11]. The physical meaning of 1 $\mu$bar reference pressure has not been articulated in any AE standard documents. When an AE sensor receives the pressure wave, most of the wave is reflected back into water as the acoustic impedance of the sensor facing or sensing element is usually much higher than that of water. The transmitted pressure wave generates particle velocity in the sensor facing or the sensing element. However, this pressure cannot be measured. Thus, it is impractical to use it as the basis for calibration. In a recent study, Burks and Hamstad [9] concluded that the conversion procedure of sensor response to V/$\mu$bar reference is illogical and arbitrary unless one measures “the transient output pressure as a function of frequency from the driving transducer”.

The most logical interpretation of V/$\mu$bar reference is that of pressure in water, as practiced in the underwater acoustics field for the hydrophone calibration [31]. In the immersion tank where a hydrophone is calibrated, the acoustic pressure field is known as a function of frequency. The acoustic pressure in water is defined as the product of the acoustic impedance of water (1.48 MPa/(m/s)) and particle velocity. Thus, the pressure of 1 $\mu$bar (= 0.1 Pa) in water corresponds to 67.6 nm/s. By placing a reference transducer at the position of known acoustic pressure, it can be calibrated as a function of frequency. This can then be combined with a broadband transmitter in face-to-face arrangement, from which the transmitter output can be calibrated in reference to equivalent acoustic pressure with the unit of $\mu$bar. Subsequently, a sensor under test is substituted for the reference transducer and calibrated in terms of V/$\mu$bar reference. With this interpretation, the commonly used reference of AE sensors, 1 V/$\mu$bar, can be related to physically based reference of 1 V s/m. That is, 0 dB (ref. 1 V/$\mu$bar) is 143.4 dB in reference to 0 dB at 1 V s/m. Alternately, xx dB in ref. to 1 V s/m = xx − 143.4 dB in ref. to 1 V/$\mu$bar.
Some $R_i$ sensitivity curves for common AE sensors are shown in Fig. 4. These have the peak sensitivity of around 0–15 dB in reference to 0 dB at 1 V/nm. After converting their response to volts per unit velocity of 1 m/s, we have the velocity response curves for one of them ($R_{15a}$) shown in Fig. 9. Curves plotted on the lower side are further converted in reference to the scale of 0 dB at 1 V/μm. For PAC $R_{15a}$, the calibration provided by the manufacturer is plotted as green curve, just above the lower velocity spectrum. Their values are typically 10-20 dB above our calibration for >0.1 MHz and the shape of this curve matches better with the displacement calibration. This discrepancy exists for almost all other sensors examined, not just from this manufacturer, implying a possible existence of industry-wide systematic error. An interim solution is to add 72-74 dB to manufacturer’s calibration, thereby obtaining the displacement calibration in reference to 0 dB at 1 V/nm.

![Fig. 9 Velocity calibration curves of R15a sensor.](image)

It is worthwhile to consider direct differentiation of displacement waveforms from transmitters to velocity waveforms. This procedure uses the Savitzky-Golay algorithm [26] and offers physical insight to velocity output. The waveform changes from monopolar to bipolar and the rise time was halved. As expected, the FFT spectra are comparable with the 2,response curves. The above discussion shows that it is unproductive to classify a sensor to displacement-response or velocity-response without specifying the frequency range or the flatness of response. NIST-type conical sensors with a large mass backing clearly have a broad range of flat displacement response, while typical accelerometers are designed to produce nearly flat wideband response in acceleration below the resonance frequency. Common AE sensors have been designed for resonance-based peak sensitivity, while newer designs start to broaden the peak sensitivity ranges.

This section leads to the clarification of pressure calibration references in terms of 1 V/(m/s) and 1 V/μbar and demonstration of equivalence of two conversion methods to velocity.

4. RECIPROCITY AND TRI-TRANSUCER CALIBRATION METHODS

Our laser-based calibration method has demonstrated that the $T_i$ and $R_i$ sensitivities of UT and AE transducers differ. Hill and Adams [17] analyzed the classic reciprocity methods for the cases appropriate for contact piezoelectric transducers. In their analysis of reciprocity calibration methods, $T_i$ and $R_i$ sensitivities are not required to be identical; that is, non-reciprocal. This exactly fits the experimental reality we have established. Their analysis led to the receiving sensitivity of sensor 2, $R_2$, to be given by Hill-Adams equation (3a) for pairs coupled through the transfer block, where $X$ is the point-wise transfer function of the propagating medium. This result leads to the demise of reciprocity calibration methods for piezoelectric contact transducers since there are six unknowns and only three equations. You cannot also express $T_i$ sensitivity from $E_i$ and $X$. Thus, without transducer reciprocity, current reciprocity calibration methods lack the foundation [19-23].

We have obtained $T_i$, $R_i$ and $R_i/T_i$ spectra for over 25 transducers. The ratio, $R_i/T_i$, needed in Hill and Adams equation, is frequency dependent, increasing with frequency, as shown in Fig. 10. Some are similar, but usually the spectra match poorly. Another parameter needed in Hill and Adams equation is $X$, which corresponds to the attenuation of longitudinal wave as it passes the transfer block. Experimentally, we find this to be dependent on a particular pair of transducers. A few examples are shown in Fig. 11. In our testing, a transfer block was of Al 7075 alloy (300 x 300 x 156 mm) with waves traveling normal to the broad faces. While $X_{ij}$ between two UT transducers is relatively smooth, those including a resonant sensor (R15) have large fluctuations. Diffraction effects and sensor resonances contribute to the prominent features. Overall trend is consistent, however. Deriving $X_{ij}$ functions from point-wise transfer function is a complex task, especially when one must also include resonance effects. Now, this is a moot point as $X_{ij}$ parameters have canceled out in equation (3b) and are no longer required in the Tri-Transducer (TT) method.

Before realizing that equation (3) reduces to (3b), eliminating the need of $X_{ij}$ parameters, we evaluated $R_i$ for 20 combinations using the extended Hill-Adams equation (3). These results are identical to those using equation (3b), or TT method. Fig. 12 shows the case for 1) 1 MHz UT, 2) FC500-2 and 3) FC500-1. The spectra for three $E_i$ (top group), $R_i$ (FC500-2) and the same from laser method (middle), and $R_i/T_i$ for FC500-1 (bottom curve) are plotted.
The values of $R_2$ by the TT and direct methods agree quite well below 1.5 MHz with the average difference of 0.34 dB. The dip in the two $E_{ij}$ curves are from #1, but it has no effect on the outcome. Even when two resonant sensors are in the group of 3 (not shown), the values of $R_2$ for R15a by the two methods are close, with the average difference of 1 dB below 600 kHz. Considering many peaks and dips in the spectra, this is a good match. These two cases show that the choice of transducer 1 is non-critical: just needed to transmit in the frequency range of interest. However, size correction is needed when receiver (SUT) is larger than the other two or reference transducer 3 is larger than the transmit-only transducer 1. Two more results of the TT method are given in Fig. 6. Two transducers, V103 and V104, show good to excellent agreement with the direct and indirect methods. With V103, average differences between the three methods to 2 MHz were 0.06, 0.25 and 0.19 dB. V104 results gave slightly higher average differences of 0.32, 1.36 and 1.04 dB. These values are for a set of experiment. By averaging, multiple set testing should further improve the performance. It is also necessary to explore the sources of errors.

This Tri-Transducer method developed from Hill-Adams analysis is beneficial for its reliance on the sensitivity ratio and avoiding direct use of displacement transmission reference alone. Reception from another transmitter is included so we can avoid potential problems that may arise from a particular combination of transducers. Still, this approach does require the determination of $R_3/T_3$ ratio of reference transducer 3 by laser interferometry. The TT-method has been used for over 20 combinations of three-transducers. Average difference (over 22 kHz to 2 MHz) with the result of direct method is typically less than 0.5 dB, although a few cases show values of 1 to 2 dB.

The TT method can be used to obtain the transmitting sensitivity, $T_1$, similarly to the indirect method. We have

$$T_1 = \left[ (E_{12}^*E_{13}/E_{32}^*) (T_3/R_3) \right]^{1/2}. \quad (4)$$

An example is plotted in Fig. 13. Three transducers used are V104, NDT and V103. Each of $E_{ij}$ curves peaks at 0.5-1 MHz. The transmitting spectra for V104 are obtained using the TT method with equation (4) (red) and compared to the result of the direct method (green). Except for oscillations below 200 kHz or above 2.3 MHz, excellent agreement is seen. The average difference in $T_{V104}$ was 0.12 dB over 22 kHz to 2 MHz. Three additional TT tests (including PAC Pico and S9220) produced comparable $T_{V104}$. The averaged $T_{V104}$ spectrum with the TT method differed from the direct method by 0.42 dB in the frequency range to 2 MHz. In addition, three $T_{V103}$ spectra with the TT method agreed better than 0.2 dB with that from the indirect method. With this method for getting $T_1$, the use of some resonant sensors as a receiver produced poor results and should be avoided. This approach provides a new means of verifying the laser interferometry and the front loading effects.
Conclusions from this section are:

1) With demonstrated differences in the transmitting and receiving sensitivities of UT and AE transducers, current reciprocity calibration methods for AE sensors is invalid. Experimentally obtained longitudinal wave reciprocity parameter X varies depending on transducer pair used and not invariant as the reciprocity theory requires.

2) Equation (3) derived by extending Hill and Adams equation reduces to equation (3b). Needs for X parameter vanished, but physically measured ratio of R3/T3 is still required for Tri-Transducer method.

3) Tri-Transducer method is tested for over 20 combinations and shows good to excellent agreement with those from direct or indirect methods. This provides both transmitting and receiving sensitivities.

5. CONCLUSIONS

We examined outstanding issues of sensitivity calibration methods for ultrasonic and acoustic emission transducers. Determining spectral sensing properties is of utmost importance, especially in AE sensors, but recent research activities in this area have been low. In addition, today’s emphasis in this field has been to model the sensor behavior using lumped parameter approach so that it can be integrated into systems modeling. On the other hand, physics-based analysis of piezoelectric sensing has been limited until recently. With new tools available today, laser interferometers and advance modeling methods, we are closer to the goal of finding a suitable and workable approach to transducer calibration and clarifying underlying sensing mechanisms.

Laser-based displacement measurement leads to the determination of transmitting sensitivities of transducers. This is Direct method. While simple in concept, some transducers generate extraneous vibrations on the front surface when it is free from solid contact. This issue was overcome by a suitable selection of a transmitter and by using an indirect method through the use of receiving sensitivities of other transducers. It was then possible to obtain mutually consistent transmitting and receiving sensitivities. This is Indirect method. The results also establish the foundation for face-to-face calibration methods, which were beset by the uncertainty of input parameters without access to the transmitter face. Good to excellent agreement has been observed between results of the direct and indirect methods using 30 sensors. Further, it is discovered that the receiving and transmitting sensitivities of over 20 transducers are always different, while their ratios exhibit unexpected similarity. The latter characteristics is traced to mono-polar pulse generation of damped piezoelectric transducers as a transmitter and, as a receiver, bi-polar received signals due to the reflection on the back face. This occurs even in transducers with good backing, likely from electrical impedance mismatch and charge transfer during elastic wave motion.

The observed difference in the receiving and transmitting sensitivities of a transducer leads to the invalidation of reciprocity calibration methods for piezoelectric contact transducers. The issue was raised in 1979 [17], but users of reciprocity calibration have ignored the fact that a separate measurement of ratio of the transmitting and receiving sensitivities is required. We have also measured the reciprocity parameters X in the case of through-transmission and found this to be dependent on transducer pairings, sizes, frequency, etc. in direct conflict with its definition in the reciprocity calibration methods. These are also not reversible in cases of different sized pairs.

After following Hill-Adams derivation, we found that parameters Xs cancel out, simplifying the expression for the receiving sensitivity, i.e., equation (3b). This is the basis for Tri-Transducer method, which has been tested for over 20 combinations. Results show good to excellent agreement with those from direct or indirect methods. The TT method can also provide the transmitting sensitivities of transducers, allowing a check of the laser method.

Displacement vs. velocity calibration terminology is examined, in view of ill-defined “V/µbar” reference used in commercial reporting of sensor property. Returning to the origin of its introduction by Dunegan [30], definition from hydrophone calibration standards clarified the reference. Procedure is given for converting between the velocity sensitivities in reference to unit velocity of 1 m/s and to acoustic pressure of 1 µbar.

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REFERENCES


Classification of acoustic emission signals using wavelets and Random Forests: application to localized corrosion

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ABSTRACT: This work aims at proposing a novel approach to classify acoustic emission (AE) signals deriving from corrosion damage, even if embedded into a noisy environment. Tests involving noise and crevice corrosion are conducted, by preprocessing the waveforms including wavelet denoising and extracting a rich set of features as input of the Random Forest algorithm. To this end, a software called RF-CAM has been developed. Results show this approach is very efficient on ground truth data and is also very promising on real data, especially for its reliability, performance and speed, which are serious criteria for the chemical industry.

1 GENERAL SPECIFICATIONS

Considering the crevice corrosion process, emitted gas (i.e. bubbles) coming from chemical reactions generate AE activity, which can be recorded by sensors located on the surface of the specimen. Since AE signals associated to crevice corrosion are characterized by low energy content, it is very difficult to separate those signals from the environmental noise [1, 2]. Thus, an in-depth work has been realized to preprocess the corresponding waveforms and a major motivation was to find the most relevant set of features. Chosen classification algorithm must be fast, reliable and not very sensitive to a mislabeled learning database (due to real-time and reliability industrial constraints). Moreover, it is preferable to provide a confidence level for the final decision. A whole approach combining the waveform preprocessing and Random Forest supervised classification has been implemented. To validate this new methodology, synthetic data were first used throughout an in-depth analysis, comparing Random Forests (RF) to the k-Nearest Neighbor (k-NN) algorithm, in terms of accuracy and speed processing. Then, tests on real cases involving noise and crevice corrosion were conducted. In order to build up various data sets, pH, temperature, NaCl concentration and H₂O₂ addition were controlled to obtain controlled crevice corrosion for some experiments and no corrosion for the others. The purpose of the classification is to isolate AE signals from corrosion to noise.

2 WAVEFORM PROCESSING

This important preliminary step is performed on waveforms directly acquired from sensors. The motivation here is to normalize those AE signals for consistent comparison. It is possible to discard useless information, numerically store the waveforms for further analysis and denoise them. The waveform preprocessing consists in the three following steps: Pre-trigger removing, tail cutting, Shape Preserving Interpolation (SPI) resampling. Tail cutting resides in dynamically cutting the end of the waveform according to an energy criterion. For each point in the waveform, the cumulative energy computed from the beginning is compared to the energy contained in a 10 μs length window following that point. If this energy is less than a certain threshold T (in %) of the cumulative energy, then the corresponding point represents the end of the signal. Wavelet denoising [3] can also be performed and uses the wden function from the Matlab Wavelet Toolbox. Specific parameters have been set: the universal threshold of Donoho [4] is used to select the wavelet coefficients in combination with a soft thresholding being rescaled using level dependent estimation of level noise. Decomposition is made at level 3 with the symmlet8 as the mother wavelet.

3 FEATURES EXTRACTION AND RANDOM FOREST CLASSIFICATION

Thus, each waveform is turned into a compact representation through a set of 30 features, in time, frequency and wavelet domains (Tab. 1). Besides common features such as amplitude, duration, energy, rise time, partial powers or peak frequency, other features derive from speech recognition and sound description studies. Wavelet features are actually a specific set of features using wavelet packet energy [5]. The energy percentage of the terminal nodes of the wavelet packet tree is computed, leading to 8 wavelet packet energy features.
The supervised classification is based on Random Forests which are an ensemble learning method that operate by constructing a multitude of decision trees during training, each capable of producing a response (vote) when presented with a new set of features during testing. The algorithm was originally developed by Leo Breiman and Adele Cutler in 2001 [6]. During the testing phase, each AE signal is run down each tree of the Forest, leading to T votes. The final decision can be obtained two different ways. The first one is simply the usual majority voting (MV) rule. In this work, another decision rule is introduced called security voting (SV) rule. In this special rule, one given AE signal is assigned to a specific class if more than 70% of the total number of trees voted for that class. The whole approach combining the waveform preprocessing and the RF supervised classification has been implemented into the software RF-CAM (“Random Forests Classification for Acoustic emission Monitoring”).

Table 1: The set of the 30 features. Those features are recalculated from waveforms. “L” = Low-pass filter, “H” = High-pass filter. Thus, “LLH” consists in cascading two low-pass filters and one high-pass filter.

<table>
<thead>
<tr>
<th>ID</th>
<th>Feature</th>
<th>Unit</th>
</tr>
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<tr>
<td>R1</td>
<td>Amplitude</td>
<td>V</td>
</tr>
<tr>
<td>R2</td>
<td>Duration</td>
<td>s</td>
</tr>
<tr>
<td>R3</td>
<td>Energy</td>
<td>V²</td>
</tr>
<tr>
<td>R4</td>
<td>Zero-crossings</td>
<td>-</td>
</tr>
<tr>
<td>R5</td>
<td>Rise time</td>
<td>s</td>
</tr>
<tr>
<td>R6</td>
<td>Temporal centroid</td>
<td>s</td>
</tr>
<tr>
<td>R7</td>
<td>Temporal decrease</td>
<td>α</td>
</tr>
<tr>
<td>R8</td>
<td>Partial Power 1 ([100; 200]kHz)</td>
<td>%</td>
</tr>
<tr>
<td>R9</td>
<td>Partial Power 2 ([200; 400]kHz)</td>
<td>%</td>
</tr>
<tr>
<td>R10</td>
<td>Partial Power 3 ([400; 700]kHz)</td>
<td>%</td>
</tr>
<tr>
<td>R11</td>
<td>Partial Power 4 ([700; 1000]kHz)</td>
<td>%</td>
</tr>
<tr>
<td>R12</td>
<td>Frequency centroid</td>
<td>Hz</td>
</tr>
<tr>
<td>R13</td>
<td>Peak frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>R14</td>
<td>Spectral spread</td>
<td>Hz</td>
</tr>
<tr>
<td>R15</td>
<td>Spectral skewness</td>
<td>-</td>
</tr>
<tr>
<td>R16</td>
<td>Spectral kurtosis</td>
<td>-</td>
</tr>
<tr>
<td>R17</td>
<td>Spectral slope</td>
<td>-</td>
</tr>
<tr>
<td>R18</td>
<td>Roll-off frequency</td>
<td>Hz</td>
</tr>
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<td>R19</td>
<td>Spectral spread to peak</td>
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<tr>
<td>R20</td>
<td>Spectral skewness to peak</td>
<td>-</td>
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<tr>
<td>R21</td>
<td>Spectral kurtosis to peak</td>
<td>-</td>
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<tr>
<td>R22</td>
<td>Roll-on frequency</td>
<td>Hz</td>
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<tr>
<td>R23</td>
<td>Wavelet Packet Energy 1 (LLL)</td>
<td>%</td>
</tr>
<tr>
<td>R24</td>
<td>Wavelet Packet Energy 2 (LLL)</td>
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<td>Wavelet Packet Energy 3 (LHL)</td>
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<td>%</td>
</tr>
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<td>R29</td>
<td>Wavelet Packet Energy 7 (HHL)</td>
<td>%</td>
</tr>
<tr>
<td>R30</td>
<td>Wavelet Packet Energy 8 (HHH)</td>
<td>%</td>
</tr>
</tbody>
</table>

4 VALIDATION ON GROUND TRUTH DATA

Ground truth data come from the synthetic dataset collected in [7]. Those data represent four clearly identified classes (2000 signals per class) and are described with a set of M = 9 features. A Training Set is built, comprised of 70% of those data (5600 signals taken at random), the remaining 30% (2400 signals) constitute the Testing Set. In order to test the robustness of both algorithms regarding mislabeled data and the introduction of noise and outliers, a new evaluation tool called the alter-class matrix (ACM) is used [8]. The ACM is a particular n-square matrix designed to alter the original training set in order to simulate uncertainty on labeled data for supervised classification. For example, the class C1 becomes C1alter, composed of 79% of waveforms from C1, 2% from C2, 15% from C3 and 4% from C4. Figure 1 shows the alteration of the class C1 from the Training Set, for different values of the trust
factor (100, 90 and 60). Forcing the data to be mislabeled using the ACM can also be seen as a random and progressive introduction of noise and outliers in the original data. In all these tests, RF is compared to the widely used and efficient k-Nearest Neighbor (k-NN) algorithm [9]. The following parameters have been set for the algorithms:

- Random Forests: The number of trees \( T = 200 \) has been set, the number of randomly selected features has been set to the recommended value for classification, i.e. \( m = \sqrt{M} \) where \( M \) is the total number of features.
- k-NN: The optimal value of \( k = 15 \) derives from the leave-one-out cross-validation (LOOCV) method [10], where the usual Euclidean distance is used. Recognition rates are computed for both RF and k-NN algorithms. They correspond to the ratio of the number of predicted labels to the number of true labels. Globally, RF outperforms k-NN up to 10% and is less sensitive to a slightly mislabeled library. For example, the recognition rates on synthetic data for both RF and k-NN algorithms are respectively 96.1% and 88.9 for a trust factor of 70. Moreover, k-NN is globally linearly sensitive to the increase of the number of waveforms and the number of features whereas RF is almost not influenced.

5 APLICATION TO THE REAL CORROSION DATA

Experiments are conducted on 304L stainless steel. Samples are immersed in a corrosive solution (with different values of NaCl (2g/L or 35g/L), pH (6.7, 8.3 or 10.5) and temperature (25 °C or 50 °C). In average, each corrosion experiment has been conducted twice under the same conditions. The pre-treatment (before immersion) of samples is performed step by step as follows: grinding to 400#, rinsing, chemical passivation (20 vol.% HNO3 during 1 hour, at room temperature), drying in air. Stainless steel sheet is then assembled by two formers made by polymethyl methacrylate (PMMA). This latter device allows two confined areas on both sides of the specimens in order to enhance crevice corrosion (Fig. 2). The open circuit corrosion potential (OCP) is continuously recorded owing to a saturated calomel electrode (SCE) as a reference (Fig. 2).
The AE acquisition system is a Mistras AEDSP embedded computer board. The sensors (R15) are applied on the surface of the specimen, outside the corrosive solution (distance sensors/sample = 40mm). R15 sensors have been chosen because of their good frequency sensitivity around 150 kHz. Sensor coupling is performed using vacuum grease. To ensure the repeatability of the results, assembly torque is controlled using a dynamometric key and set to 3Nm. Acquisition parameters were set as follows: peak definition time (PDT) = 200 $\mu$s, hit definition time (HDT) = 400 $\mu$s, hit lockout time (HLT) = 200 $\mu$s. Acquisition threshold depends on environmental noise, thus varying from 19dB to 28dB. An optimal sampling frequency equals to 4MSPS (and 4K points per waveform) has been set as a very good compromise between the size of the data to process (real-time constraint) and the robustness of the extracted features (reliability constraint). Then, a set of 30 features are extracted from recorded waveforms (Tab. 1).

Some experiments are performed with the addition of $\text{H}_2\text{O}_2$ in order to accelerate corrosion. The OCP drop shows that crevice initiates as soon as $\text{H}_2\text{O}_2$ is added. For the sake of illustration, experiments presenting no corrosion and performed at a higher temperature are depicted in Figure 3. The specimen exhibiting no corrosion presents higher activity than the corroded one because the corresponding test is conducted at 50°C, which induces a high acoustic activity due to the dilatation of the device and the generation of bubbles, together considered as noise. In order to build various data sets, pH and temperature values, NaCl concentration and $\text{H}_2\text{O}_2$ addition are controlled to obtain crevice corrosion for some experiments and no corrosion for the others. 13 out of 17 experiments (almost 75%) are used for the training set. In absence of corrosion, OCP does not decrease (Fig. 3a). However, even if there is no corrosion, some AE activity is observed all along the experiment. These signals are attributed to noise (i.e. dilatation phenomena and bubbles evolution within the liquid due to the temperature of the test (50 °C)). A first class (denoted as NC) is built from 1200 signals. Regarding the experiments involving crevice corrosion (Fig. 3b), AE activity starts prior to the addition of $\text{H}_2\text{O}_2$, and is mainly assigned to noise. After $\text{H}_2\text{O}_2$ addition, gathered signals are mainly assigned to corrosion and constitute a second class (denoted as CC), composed of 1167 signals. It has to be noticed that this CC class is not pure and also contains noise signals. The previous study on the use of the ACM for altered data shows that recognition results are satisfactory even if classes are altered up to 20%. Besides, since there is no class-privilege in real conditions, a special attention has been paid to build a well-balanced training set, for a total of 2367 waveforms. The remaining four experiments are used to construct the different testing sets. Two of them present no corrosion (namely NCa and NCb), the other two show crevice corrosion (namely CCa and CCb), for a total of 1311 waveforms. Preprocessing and features extraction have been applied to all waveforms.
The percentage of signals for the Majority Voting (MV) rule is given regarding the original total number of signals of the test set. The percentage of signals for the Security Voting (SV) rule is given regarding the number of remaining signals, after the security threshold of 70% is applied.

For each test (Table 2), the proper majority class has been recognized and results show that using SV leads to a reinforcement of the usual MV decision, when it comes to assign signals to a specific class. Moreover, for each test case, most of the signals corresponding to the minority class are discarded, thus strengthening the trend of the majority class.

Table 2: RF classification results of the proposed method for NC and CC experiments.
6 CONCLUSIONS

Results show that this approach performed the best on ground truth data and was also very promising on real data, especially for its reliability, performance and speed, which are serious criteria for corrosion monitoring in the chemical industry. The results associated to the usual majority voting (MV) rule were satisfactory in terms of finding the proper majority class. In order to take into account the industrial reliability constraint, another decision rule called security voting (SV) has been implemented as a confidence level (set to 70%), and reinforced the final decision process taken by the MV.

Future prospects to be considered are the enlargement of the learning library in order to identify other corrosion mechanisms such as pitting corrosion. Finally, this methodology which was developed and validated at the laboratory scale can be applied at the industrial scale, providing the construction of a consistent new learning library.

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REFERENCES


Damage Evaluation of RC Bridge Deck under Wheel Loading Test by Means of AE Tomography

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ABSTRACT: Remediation and replacement of deteriorated reinforced concrete (RC) bridge decks are severely concerned in Japan, and thus intensive studies for long-term operation of the decks are recently carried out. For implementing proper remediation program of the deck, damage evolution should be evaluated in advance. So far, damage grading has been conducted from crack patterns by naked eyes. This kind of visual investigation is well implemented for the correcting maintenance procedure, where the repair shall be conducted when the remarkable deterioration is found on the surface of the deck. However, to reduce the repair budget, leading to the decrease in the amount of road investment as well as life-cycle cost, the deterioration and damage should be evaluated before being visually identified on the surface. To this end, internal damage of RC decks due to fatigue is reproduced experimentally by wheel-loading apparatus. Then, the damage progress is quantitatively and visually evaluated by AE tomography analysis.

1 INTRODUCTION
Among road investment, large share has been reported for the bridge-deck replacement. Conventionally, fatigue damage has been discussed when the deterioration becomes remarkable as to be observed on the surface of the deck. So far, characteristics of surface cracks on the directions and the densities have been employed to determine the grade of the damage in the deck due to fatigue. This kind of visual investigation is well implemented for the correcting maintenance procedure, where the repair shall be conducted when the remarkable deterioration is identified on the surface.

In order to reduce the repair budget, leading to the decrease in the amount of road investment as well as life-cycle cost, deterioration and damage are preferably to be evaluated before being identified on the surface of the deck [1]. Bridge owners have long been wondering whether the investment might be reduced as internal damage is properly evaluated with nondestructive testing (NDT) approaches and the damage is reasonably quantified. To detect internal damage, the elastic wave tomography and AE tomography [2][3] are under development. As well known, X-ray tomography [4] is only one tool to visualize the internal damage, while it costs a lot and is time-consuming, in addition to bringing harmful situation against human health.

AE measurements are known to be effective to trace the damage continuously [5]. However, to locate AE sources, a multi-channel system is necessary. Thus, practical applications are even limited to important structures only. In addition, external environmental noises are problematic for that long-term monitoring on site. Therefore, real-time fatigue damage monitoring with AE technique has been conducted for experimental purposes [6].

In contrast to AE monitoring, signal excitation and detection are performed in ultrasonics, as at least one pair of input and output sensors are applied to explore internal damages. Locations of defects are estimated from propagation time, by assuming unique or spatially homogeneous velocity of ultrasonic wave. In the case that the wave-propagation length of the media is known, overall deterioration can be estimated from the wave-velocity calculated with propagation time. Also it is noted that AE source location is useful for evaluating damage positions/ areas. In the case, the wave-velocity is necessarily determined in advance, because the sources are located on the basis of arrival-time differences among sensors, assuming the unique velocity value.

Innovative AE tomography has been developed [3][8] for more than a decade, being able to determine the both of wave-velocity and AE sources even under the condition that the damage is evolving or exists within the materials of interest.

In this study, the fatigue evolution in RC decks is reproduced by wheel-loading apparatus. Three-dimensional (3D) AE tomography analysis is executed at proper periods through the test. Thus, internal progress of fatigue damage is visualized and quantified from distribution of the elastic-wave velocities, taking into account surface cracks observed.

2 WHEEL LOADING PROGRAM
To induce fatigue failure to an RC deck specimen, repeated loading with a steel wheel was conducted. The specimen is a plate of dimensions 3000 ×2000 ×210 mm, with steel reinforcement arranged as shown in Fig. 1. A steel wheel of 300 mm in diameter and 400 mm in width can be applied with the load up to 250 kN in the case of repeated loading and 534 kN in the case of static loading. In order to generate crack patterns actually observed in the decks, being different from the conventional wheel-loading apparatus, a movable loading-wheel [7] was developed on the
foundation. The wheel can move horizontally from ±500 mm to ±1000 mm. The repetition rate is to be set between 0.897 - 9.97 rpm/min. The motion of ±500 mm and the rate 8.97 rpm were applied to the test. Here, step-wise cyclic loadings are performed as shown in Fig. 2. In the 1st cycles, the load of 98 kN was repeatedly applied 100x10³ times, and then elastic-wave excitations were applied by using a steel hammer of 35 mm diameter for 3D AE tomography. In the 2nd cycles, then, the load of 127.4 kN were applied 200x10³ times. Again, elastic-wave excitations were performed after this loading step. The 3rd cyclic loadings were conducted 250x10³ times with 156.8 kN load, prior to the elastic-wave excitations. It is noted that the specimen reached the fatigue limit at 235x10³th loading step.

![Image](image1.png)

3 MEASURING CONDITIONS

Damage evolution could be visualized, plotting AE sources accumulated through the whole failure process. In structures in service, however, it is not easy to install AE sensors in defective conditions. Therefore, the tomography analysis is applied by employing elastic-wave excitations. As illustrated in Fig. 3, 32 AE sensors of 60 kHz resonant are placed at 10 locations on the top, 18 locations on the bottom and 2 each on the two sides. The excitations were driven by a hammer of 35 mm diameter at designated 18 locations on the top and 22 on the bottom surface. The wheel loadings were applied in the longitudinal direction, at the area between green lines in Fig. 3. During the load holding in Fig. 2, vertical loads were applied vertically at the central area denoted by a red rectangle.

Elastic-wave signals generated due to the excitations were amplified at the sensor-integrated pre-amplifier by 40 dB and recorded in AE monitoring system, of 48-channel with a 16 bit A/D conversion rate and 1 MHz sampling rate.

![Image](image2.png)

4 THEORY OF AE TOMOGRAPHY

In AE tomography (hereafter referred to as AET), both of source locations and velocity distribution are simultaneously calculated. Here, the source location algorithm developed is briefly explained. Detailed tomographic procedure is to be referred to the other literature [8]. The location technique is based on the ray-trace algorithm [9], where relay points are assigned in each cell as illustrated in Fig. 4. Since the ray-paths are formed, connecting with segments among nodal points, its resolution depends on the mesh size. Namely, the high accuracy of source locations requires the finer mesh. This leads to the
increase in the number of degrees of freedom since the slowness, a reciprocal of velocity, shall be defined in each cell. In the ray-trace algorithm proposed, the relay points between the nodes are taken into account and then a new ray-path is formed with segments among the nodal points and relay points as shown in Fig. 5. As a result, the resolution of ray-trace is increased without the increase in the degrees of freedom. Because of the role of the relay points, relaying the signals, the relay points shall be distributed uniformly in the space. However, a non-uniform shape of cross section in a concrete structure does not allow uniform distribution of the relay points. To solve this problem, the relay points are installed by using iso-parametric mapping in the ray-trace algorithm. Since each cell is mapped onto an isosceles-right triangle, the relay points are uniformly installed in the mapped cell as shown in Fig. 6. This algorithm does not give exactly uniform distribution of the relay points in the case that the shape of the cell is skewed. Avoiding strongly skewed cells, the distribution of the relay points is improved and the source location is performed by applying this ray-trace algorithm. The procedure is briefly summarized in Fig. 7. The ray-traces are generated from a receiver as illustrated in Fig. 8. Travel times \( t_{ij} \) from receiver \( i \) to all nodal and relay points \( j \) are calculated. Since arrival time \( T_i \) at receiver \( i \) is estimated in the experiment, the possible emission time of the signal \( E_{ij} \) is computed by Eq. 1 at a nodal or relay point \( j \).

![Fig. 4 Conventional set of relay points.](image1)

![Fig. 5 Revised ray path in consideration of proposed relay points.](image2)

\[
E_{ij} = T_i - t_{ij} \tag{1}
\]

The step is applied to all receivers, and then the variance of the \( E_{ij} \) is computed as follow.

\[
\sigma_j = \frac{\Sigma(E_{ij} - m_j)^2}{N} \tag{2}
\]
in which

\[
m_j = \frac{\sum_i E_{ij}}{N}
\]  

(3)

where \( N \) is the number of receivers.

For the estimation of the source location, the variance \( \sigma_j \) is evaluated. If distribution of the slowness is identical to that of the real slowness, \( \sigma_j \) must be equal to zero at the source location and \( m_j \) must be exactly the emission time. Due to the discretization error of slowness distribution and insufficient resolution of ray-trace, generally \( \sigma_j \) is not equal to zero. Still, it is reasonably considered that \( \sigma_j \) could be the minimum. Hence, the source locations are to be determined as the nodal or relay points of the minimum variance \( \sigma_j_{\text{min}} \). Additionally, \( m_j \) is referred to as the possible emission time. It is noted that the accuracy of the source locations is controlled by the density of nodal and relay points because the source locations are assigned to a nodal or relay points in the proposed algorithm. Furthermore, by applying this technique to the iterative procedure on the identification of a wave-velocity structure, the source locations are updated in every iterative step, improving the accuracy of the source location. This approach can be applied to not only AE signals but also signals that are generated by elastic-wave excitations. Although the conventional tomography requires locations of sources, emission times and travel times to the receiver, source locations and emission times can be estimated from travel times to the receivers in the wave velocity distribution determined. Based on these facts, a tomographic procedure with estimation of source locations is developed and summarized in Fig. 9. In the first step, the source location and emission time are estimated. Here, the observed travel times are to be separated into groups, respectively, that are associated with individual excitation points. The source location and emission time are estimated for each travel-time group observed. In the second step, the ray-traces to all estimated source locations are calculated. Since the ray-traces are made for the all of estimated source locations, the travel times among the estimated source locations and the other nodal or relay points are derived. Eventually, theoretical travel times at receivers are obtained, given by adding the computed travel time \( t_j \) to the estimated emission time \( m_j \).

\[
T_i' = m_j + t_{ij}
\]  

(4)

In the third step, the slowness distribution is updated to eliminate the difference between the theoretical travel time and observed.

Recently, two-dimensional AE tomography (2D AET) mentioned above is upgraded into 3D AET [8]. The most difference between 2D AET and 3D AET is the ray-trace technique in the algorithm. In the ray-trace technique, the waves in 3D AET are expressed in Eqs. 5 and 6, which are to be expanded to 3D from Eq. 7 in 2D AET.

\[
a_1 x + b_1 y + c_1 z + d_1 = 0
\]  

(5)

\[
a_2 x + b_2 y + c_2 z + d_2 = 0
\]  

(6)

\[
a x + b y + c = 0
\]  

(7)

In the following, 3D AET is applied to the RC deck specimen damaged by the wheel-loading.

5 RESULTS OF 3D AET

In order to estimation of velocity distributions after loading times of 100x10^3, 200x 10^3, and 250x10^3, the target area (blue rectangular in Fig.3) for 3D AET analysis is divided into rectangular-parallelepiped cells, which consist of 25 (long axis direction) \times 11 (short axis direction) \times 5 (thickness direction) nodes. Results of 3D AET after three loading phases are given in Figs. 10, 11, and 12. After 100 x10^3 times loading, the velocity distributions are almost identical inside the specimen as shown in Fig. 10(a)-(d). The overall velocity is approximately 3500 m/s. It is found from the three-dimensional model in Fig. 10(d) that the velocity in the right side of the specimen tends to be lower. Following 200x10^3 times loading, a low velocity zone appears as illustrated in Fig. 11(a)-(d). The velocity of right side on the surface is of slower velocity than 3000 m/s. From Fig. 11 (d), it is realized that internal velocity distribution is not homogeneous as the previous stage. This implies a state in which soundness and fatigue damage parts are mixed up. Velocity distributions after 250x10^3 times are shown in Fig. 12(a)-(d). During this loading phase the specimen actually reached to the fatigue limit. The zones of the velocity lower than 2500 m/s extensively appear in the whole of specimen. Comparing with the velocity distributions after 100x10^3 and 200x10^3 times, the velocities drastically decrease. Low velocity zones could be particularly identified at wheel-running areas, suggesting the severe damage.
6 DISCUSSIONS
Cracks distributions observed at the bottom are shown in Fig. 13(a)-(c). After the loading of 100x10^3 times, many cracks are observed at the central area, and they are densely distributed in the right side. Although the lower velocities are identified (Fig. 10 (c)) in the densely cracked area, they are not particularly low. Thus, fatigue damage is considered to be severe at this stage. In comparison of crack distribution after 200x10^3 times with that after
100x10^3 times, densely cracked areas are found in the center and right portions. The fact clearly reflects the velocity structure in Fig. 11 (c). The lower velocity zone than 3000 m/s exists on the right side. It is considered that the fatigue failure could start around. This suggests that the progress of fatigue failure is associated with not only the intensity of the load, but also the variation in the quality of concrete placement.

Cracks and the velocity areas lower than 2700 m/s distribute all over the bottom side after loading of 250x10^3 times. The low velocity areas are clearly confirmed in Fig. 12(a)-(d), surely reflecting deterioration by fatigue damage. In addition, the velocity change rate from 200x10^3 to 250x10^3 times was more rapidly than that from 100x10^3 to 200x10^3 times. According to this study, the application of 3D AET to real RC decks is promising to carry out the preventive maintenance effectively.

![Fig. 13 Overlay map on the bottom surface by velocity distribution and crack situation.](image)

(a) 100 x10^3 times  
(b) 200 x10^3 times  
(c) 250 x10^3 times (after fatigue limit)

7 CONCLUSIONS

3D AET is applied to a quantitative study on internal fatigue damage of RC deck. The damage was reproduced by the wheel-loading apparatus and tomographic analyses are conducted at three loading phases. With the tomographic approach, it is clearly demonstrated that internal velocity-distributions change in the RC deck specimen due to fatigue loading. Since the decrease in the velocities of RC decks suggest the generation of internal cracks, damaged areas are to be identified by 3D AET visually. Thus, progress of fatigue damage in RC decks is readily inspected by this procedure.

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REFERENCES

Source of AEs from IG-SCC of Face Centered Cubic Metals under Static or Dynamic Straining

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ABSTRACT: Stress Corrosion Cracking (SCC) of Face Centered Cubic (FCC) metals such as sensitized Type -304 and -316 by tetra-thionic acids and 70Cu/30Zn brass by ammonia vapor are intergranular (IG) type. These SCCs produce no AE when static SCC test are done. However, when we employ a dynamic strain test such as strain increasing test, these SCCs produce AEs even if it is done in non-corrosive environment. Detail SEM observation of fracture surfaces suggests that the coincident twin/austenitic grain boundaries with low energy are broken mechanically by dynamic loading and produce AEs. This paper discusses relationship between the extrusions observed on the fracture surface and the coincident grain boundaries.

1 INTRODUCTION

Among the environmental assisted cracking, active path corrosion type stress corrosion cracking (APC-SCC) has been recognized to emit no AE[1][2][3]. Typical example of the APC-SCC is the chloride SCC of austenitic stainless steel and transgranular (TG) type cracking. Though a very few AE can often be monitored for a limited material -environment combination, these AEs are mostly from the cracking of the corrosion products in the SCC, and not the primary AE from the initiation and propagation of the SCC[4]. Independently on the crack types (TG or IG), we never monitor the primary AEs as long as a static loading such as bent beam testing is utilized. Authors have, however, reported that the primary AEs can be monitored for the IG-SCC when a continuously increasing load such as CERT (constant extension rate testing) is employed. We do not necessary need the CERT for producing the primary AEs, rather the dynamic loading or stepwise or continuously increasing loading is enough. The authors have called these AE behaviors as the unique AE so far[5]. However we do not understand the source mechanism of the unique AE.

Once Takemoto estimated that the AE are possibly produced by fracture of the “weakly bond intact portion” of the grain boundary for the IG-SCC of Type-304 steel[6]. He also reported that the “extrusion like projections” were often observed on the grain boundary. However we could not understand what is the extrusion and how the extrusion is produced by what mechanism. This research aims to study the possible source mechanism of AEs which are monitored during the crack opening operation or dynamic loading of the member which previously suffered IG-SCC. We estimate the source mechanism of the AEs, based on the detail fractographic observation of the fresh fracture surface produced by the crack opening operation. We insist an importance of the twin/austenite low energy grain boundary or coincident grain boundary in producing AEs.

EXPERIMENTAL

Two kinds of material/environment combinations, sensitized stainless steels: Type-304 and -316 strips (2~3mmT-20mmW-67mmL) in 1 mass% tetra-thionic acid solution (pH=2) and as-received 70Cu-30Zn brass in ammonia vapor (mainly 8% vapor) are tested. SCCs were induced into these strips by three point bending (static loading) SCC test and then washed by an ultrasonic washer three times and dried by hot air at being loaded. Some strips were kept in a desiccator for more drying. These strips were then submitted to a crack opening operation in air mainly, but for special aims in dry nitrogen gas or the corrodant. The crack opening aims to open the closed cracks in front of open SCC, and was done by turning the central bolt of the bending device continuously. Thus the crack opening operation is dynamic or continuously load increasing type. AEs were monitored by the two resonant type small sensors (PAC PICO) attached on the convex surface of the bent strip, and amplified to 40dB by a preamplifier and stored in a personal computer as digital data. Signals were analyzed by a home-made ADAS system.
3 RESULTS AND CONSIDERATION

3.1 IG-SCC of sensitized Type-304Steel by tetra-thionic acid

Using the procedure of Figure 1, we first studied how long the closed IG-SCC was. Here the closed SCC implies the grain boundaries which could not be recognized as the crack by transverse microscopic observation.

The SCC strip tested by three point bending at arc height(AH) of 0.6 mm was longitudinally cut into two pieces by wire discharge cutting. One strip(A) was submitted to the AE monitoring and transverse microscopic observation after the crack open operation, and another one(B) to microscopic observation without opening operation. Figure 2 compares the crack depth before and after the opening operation. It can be seen that closed crack length reaches to 0.42 mm in this case. Figure 3 compares the SEMs of open (the left) and closed crack. The surface of newly produced by the opening operation are free from thick film (tarnish film of FeS) while that of the open crack possesses thick film. We can not obtain any fractographic information from the open crack but can from clear fracture surface. Figure 4 shows AE behavior during the static SCC test and the crack opening operation. We monitored no AE during 22 hours of the static SCC test (three point bending test), but 37 signals during the opening operation in air. Above the arc height (AH) of 1.3 mm, we again observed no AE since the attacked grains (closed crack) was completely opened. Figure 5...
shows SEM of transverse surface after the opening operation (Specimen A of Fig. 1). There observed both the deeply attacked grain boundary and not attacked boundary. The former grain boundary corresponds to the random grain boundary or high energy boundary. Contrary, non-attacked portion corresponds to the coincident grain boundary with low energy. It is reported that the coincident boundaries are often produced at twin/austenite grain boundary\[7\]\[8\]. This boundary seems to correspond to the “intact boundary” in authors previous report \[6\]. We also observe grain rotation and steps between the grains. We monitored fluctuation of the strain using the strain gage mounted over the cracks, and found rapid fluctuation with strain amplitude of 100×10^-6 frequently. This means that the grains in the closed crack region actively move and rotate and produce AEs when the intact portion or the coincident grain boundary was mechanically fracture. Figures 6, 7 and 8 are SEMs of the fracture surface produced by the opening operation.

As the Figure 6 is the fractography of the grain falling from the random grain boundaries, we do not observe any extrusion. Contrary, Figure 7 of the new fracture surface produced by the crack opening operation, we observe many extrusions. These extrusions are considered to be produced by tearing-off of the twins from the austenitic grain boundaries. We also observe the open sub-cracks or the open crack to the fracture surface, around the grains with the extrusions. This is because the grain colony with many extrusions are mechanically separated from the neighboring grains. Figure 8 shows small size cracks and intact portion (size in few micrometers) on the grain boundary. We observe many extrusions on the grain a.

We next studied the fluctuation of corrosion potential during the step-wise load increase at the end of static SCC test in the tetra-thionic solution. As shown in Figure 9, we observed both the RD (Rapid drop) type corrosion and AE generation during the step increasing of AH. This strongly implies that new electrochemically active fresh surfaces are produced by mechanical breaking of the coincident grain. Amplitude of the corrosion drop reaches 8mV.
3.2 IG-SCC of sensitized Type-316 by tetra-thionic acid

Sensitized Type-316 strip (700 °C x 2 hours), as well as the cold-rolled and then sensitized ones, show higher resistance against the tetra-thionic SCC than the Type-304 steel. However we observe the same AE behavior as those for the Type-304, i.e., no AE during the static SCC test, but AEs of 30 to 60 counts during the crack opening operation. Here the authors show only the SEMs of the opened fracture surface. Figure 10 is SEM of the sensitized Type-316 of as-received strip and shows more star-fish type extrusions than the Type-304. Higher resistance of the Type-316 seems to be due to the frequent extrusions or the low energy boundaries. We can produce only one IG-SCC for the cold rolled (35%) and sensitized (700 °C x 2 hours) strips in pH=1.8 after 456 hours. We did not monitor AE during static SCC test but detected AEs during the crack opening operation. Figure 11 shows a number of extrusions in newly produced fracture surface, but no extrusion in the static SCC surface. The coincident grain boundary of the twins produced by cold working seems to be resistant to the IG-SCC.

![Figure 10: SEM of the fracture surface produced by crack opening operation in air of the sensitized type-316 steel previously suffered IG-SCC by static SCC test](image1.png)

![Figure 11: SEM of the fracture surface produced by crack opening operation in air of the 35% cold rolled and then sensitized (700 °C x 2 hrs) type-316 steel](image2.png)

3.3 IG-SCC of as-received 70Cu/30Zn brass in ammonia vapor

Among the brasses, 70%Cu/30%Zn brass shows IG-SCC in ammonia vapor from 2.5 mass % to 8 mass % at room temperature. We mainly studied IG-SCC of 70Cu/30 Zn brass in 8% ammonia vapor. Contrary the 60Cu/40Zn brass does not suffer TG-SCC and emit no AE during both the static SCC test and crack opening operation. Figure 12 compares the crack length before and after the opening operation. The crack opening operation extends the SCC depth from 0.94 mm to 1.65 mm. Fractographic observation, Figure 13, revealed that the fracture surface by the static SCC is covered by thick corrosion products, but that by the opening operation is free from the products which makes detail SEM observation possible.

![Figure 12: Transverse IG-SCC of 70/30 brass by 8% ammonia vapor](image3.png)

![Figure 13: SEM of fracture surface of the brass attacked by 8% ammonia vapor and then crack opening operation in air](image4.png)
Figure 14 shows AE behavior during the static SCC test and crack opening operation. We also did not monitor AE during the static SCC test but monitored much AE signals during the crack opening. There found to be two types of AEs, i.e., high frequency signals with frequency components from 300 to 500 kHz and low frequency component below 150 kHz, as shown in Figure 15. Number of high frequency signals is slightly larger than those of low frequencies.

Examples of SEM of the new fracture surface are shown in both Figures 16 and 17. Figure 16 represents extrusions on the grains and open sub-crack around the grain with extrusions. Detail SEM observation revealed that there are another type of fracture as shown in Figure 17. We observe twin at the center of the photo, and quasi-cleavage fracture in the size of less than 25 \(\mu\)m. As the brass is much brittle than the austenitic stainless steel, this alloy is likely to suffer transgranular brittle fracture. This type of fracture is considered to correspond the mechanical cleavage fracture, suggested by the Film Induced Cracking (FIC)[9]. We did not observe the cleavage fracture started by brittle de-alloyed film during static loading, however, there is a possibility of the cleavage brittle fracture when we use dynamic strain increasing. We also monitored AE signals during the crack opening operation in ammonia vapor. It is not clear which signal with high frequency or low frequency is produced by which type of fracture shown in Figures 16 and 17.

Figure 18 represents another example of brittle fracture which contains both the extrusion like projection and transgranular (TG) cleavage fracture. TG cleavage fracture suggests that the ammonia vapor impregnates into the cleavage plane and weakened the cohesion strength.

The AE behavior shown in Figure 14 is not limited to the ammonia SCC of the 70/30 brass. In the Mattson’s solution...
(pH=7.2, NH₄OH+(NH₄)₂SO₄+CuSO₄ solution, recommended method by ASTM), as shown in Figure 19, the 70Cu/30Zn brass emits no AE during the static SCC test but emits AEs during the crack opening operation.

5 CONCLUSIONS

Acoustic emission behavior is studied for the inter-granular SCC of sensitized Type-304 and -316 stainless steels in tetra-thionic acid and 70Cu/30Zn brass and ammonia vapor. Conclusions are summarized below:

1) We monitored no AE during static bending SCC test for both material/environment combinations, however monitored AEs during the crack opening operation (continuously load increasing or step wise load increasing) in air and in corrosive environment.

2) AEs from APC-SCC can be monitored only the dynamic loading to the IG-SCC. We can not monitor any primary AEs from transgranular type SCC.

3) Detail SEM observation suggests that the AEs during the crack opening operation are produced by mechanical fracture of the coincident grain boundary in case of both austenitic stainless steels and brass, and possibly by the quasi-cleavage transgranular fracture for the 70Cu/30Zn brass.

4) The intact grain boundary in our previous paper is considered to be the portion of low energy coincident grain boundary, such as the twin band/austenite grain boundary. The extrusion-like projections observed on the separated grain surfaces in non-corrosive environment appears to be the fracture trace of the coincident grain boundary.

5 REFERENCES


Detection of Acoustic Emission Signals with the Fabry-Perot Interferometer Type Optical Fiber Sensor

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ABSTRACT: In order to improve the convenience in handling for measuring acoustic emission (AE) signals with optical fibers, an application of the Fabry-Perot interferometer to optical fiber AE sensor was investigated. The Fabry-Perot interferometer made of a pair of fiber Bragg gratings was adhered to the inside of a cylindrical sensing block for detecting the out-of-plane component of the displacement caused by AE waves. It was demonstrated that the proposed sensor could detect artificial AE signals due to steel ball dropping. Characteristics of the sensor were discussed by comparing with the result of the piezoelectric sensor.

1 INTRODUCTION
Various type of optical fiber acoustic emission (AE) sensors that are known to have advantages of robustness against electromagnetic noise, resistance to water, applicability in high temperature, etc. have been proposed in order to overcome difficulties in using conventional piezoelectric AE sensors [1-9]. AE measurement with interferometer type sensors is performed by paying attention to the change of the light intensity so that only the light source and the optical detector are required to construct the monitoring system, while the sensors based on other principles sometimes need equipment to examine wavelength shift, traveling time of the light, etc. One of the weak points of optical fiber sensors in comparison with the conventional piezoelectric sensors is the cost of the equipment for operation. Therefore, interferometer type sensors seem to be suitable from this point of view.

We have developed the Mach-Zehnder interferometer type optical fiber AE sensor with a cylindrical sensing block for the purpose of usability, such as detecting component and portability, same as conventional piezoelectric AE sensors [7]. However, handling of a reference fiber which composes the interferometer significantly affects the stability of sensing so that the ingenuity of fiber holding or the extra equipment avoiding the influence of disturbance are sometimes required. Since the Fabry-Perot interferometer is constructed without the reference fiber, the sensor based on the Fabry-Perot interferometer is preferable from the viewpoint of the sensing stability due to fiber handling. Although some Fabry-Perot interferometer type AE sensors have been already proposed [1,3], those sensors seem to be not always convenient because of requiring precise assembly to construct the interferometer. In this study, the Fabry-Perot interferometer made of fiber Bragg gratings (FBGs) was applied to the AE sensor in order to improve the convenience in handling, and the proposed sensor was used to detect artificial AE signals caused by dropping the steel ball.

2 PRINCIPLE AND STRUCTURE OF THE SENSOR
2.1 Principle of the Fabry-Perot interferometer
The schematic of the Fabry-Perot interferometer type optical fiber sensor is shown in Figure 1. Some power of light provided into the fiber is reflected at the point where made a half mirror, while the rest power of light is transmitted to the endpoint of the fiber and is reflected by a full mirror. Therefore, the interference is occurred caused by the phase difference in accordance with the change of the distance between the two mirrors. The intensity of the interference light is described in Equation 1.

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\left(\frac{4\pi \Delta l}{\lambda}\right)$$ (1)

where: $I$: Intensity of the interference light [mW], $I_1$: Intensity of the reflected light at the half mirror [mW], $I_2$: Intensity of the reflected light at the full mirror [mW], $\Delta l$: Change of the distance between the half mirror and the full mirror [nm], $\lambda$: Wavelength of the light [nm]

![Figure 1: Schematic of the Fabry-Perot interferometer type optical fiber sensor](image)
This means that the AE sensor can be made by preparing a structure that the distance between the half mirror and the full mirror is changed according to AE waves.

2.2 Structure of the sensor

In order to prepare the mirrors of the Fabry-Perot interferometer, it is known that FBGs, diffraction gratings that only reflect the light of the specific wavelength called Bragg wavelength, are applicable. In this study, the single mode UV coated silica fiber of 0.25 mm in diameter introducing FBGs at the position where keep a distance of 2 mm from the end of the fiber as shown in Figure 2 was used. Each length of the FBG is 1 mm and the distance between two FBGs is 1 mm. The reflectivity of the FBG located at the connector side was set to 50 %, therefore that acts as the half mirror. On the other hand, the other FBG located at the pigtail side acts as the full mirror because the reflectivity was set to 91 %. The Bragg wavelength and the bandwidth of the reflection represented by the parameter called the full width at half maximum (FWHM) of both FBGs were 1548.94 nm and approximately 0.35 nm, respectively.

A pair of polycarbonate blocks as shown in Figure 3 that were longitudinally halved the cylindrical geometry was used for making the sensing block. The interferometer part of the fiber mentioned above was adhered to the grooved block (Figure 3(a)) with cyanoacrylate adhesive by putting the fiber on a half-round groove. Then, this block and the non-grooved block (Figure 3(b)) were tightly bonded facing the flat surfaces with cyanoacrylate adhesive. By attaching the bonded block to the specimen, AE waves are propagated to the block in the longitudinal direction by way of the bottom of the block so that the out-of-plane component of the displacement caused by AE waves can be detected. Since the fiber related sensing was settled on the central axis of the cylindrical geometry, the sensor is expected to have no directivity. It is also notable that the sensor is convenient for handling since the whole interferometer part is embedded in the block. Figure 4 shows the appearance of the proposed sensor.
3 DETECTION OF ARTIFICIAL AE SIGNALS

In order to examine the validity of the strategy for sensing described in Chapter 2, we attempted to measure artificial AE signals by using the proposed sensor. The sensor was attached to the center of an aluminum alloy plate (120 x 120 x 20 mm) with high vacuum silicone grease and a steel ball (ø10 mm, 4.2 g) was dropped from 40 mm height above the opposite side of the plate. The light transmitting in the optical fiber was provided by a DFB light source (Appointech, B1000; central wavelength: 1549 nm, spectral width: 0.4 nm, output power: 0 dBm) with an isolator avoiding the influences of the Fresnel reflection, and the signals of the interference light were recorded to a digital storage oscilloscope by the sampling rate of 1 μs via an O/E converter (Thorlabs, PDA10CF). The experiment replacing the conventional wide band type piezoelectric AE sensor (NF Corporation, AE-900S-WB) in the experimental setup was also conducted for the purpose of comparison with the results.

An example of the AE signal detected by the proposed Fabry-Perot interferometer type sensor is shown in Figure 5. It is found that the remarkable change in the amplitude is observed around the time of 150 μs. This fact implies that the proposed sensor could successfully detect the AE signal. Figure 6 shows result of the experiment using the piezoelectric sensor. It is found that there is a tendency of the waveform to change in a period of several hundreds μs after arrival of the initial motion of the AE wave. Similar behavior is also found in Figure 5 so that the proposed sensor could be used to examine the same phenomenon detected by the piezoelectric sensor. The amplitude of the waveform detected by the proposed sensor, however, is considerable low rather than that of the piezoelectric sensor. One of the reasons for low amplitude signals detected by the proposed sensor is due to the fact that the Fabry-Perot interferometer made of FBGs is only workable to the narrow bandwidth filtered light around the Bragg wavelength. Further discussion on improving sensitivity is required to apply the proposed sensor for monitoring AE associated with fracture. On the other hand, the Fabry-Perot interferometer is preferable from the viewpoint of sending stability due to fiber handling because the sensor has no reference fiber, while the Mach-Zehnder interferometer type sensor requires the reference fiber which should be fixed in order to avoid the vibration caused by either of AE signals and disturbance. Consequently, it is reasonable to conclude that the Fabry-Perot interferometer type sensor made by proposed method can improve usability of the interferometer type optical fiber AE sensors.

Figure 5: AE signal detected by the proposed Fabry-Perot interferometer type optical fiber sensor

Figure 6: AE signal detected by the piezoelectric sensor
4 CONCLUSION

The Fabry-Perot interferometer type optical fiber AE sensor was proposed for the purpose of improvement the convenience in handling. The Fabry-Perot interferometer was made of a pair of FBGs and it was adhered to the inside of a cylindrical sensing block in order to detect the out-of-plane component of the displacement caused by AE waves and have no directivity. It was demonstrated that the proposed sensor could detect the artificial AE signals caused by dropping the steel ball form the result of the experiment comparing with the piezoelectric sensor.

REFERENCES


Remote imaging of plate-like structures with E-camera

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ABSTRACT: This study presented the principle of defect imaging technique from a remote location and its experimental results. The experimental system consists of a fiber laser for generating narrow band burst waves and a laser Doppler vibrometer for detecting flexural vibration in a plate-like structure. Because a defect image can be obtained at an extremely high speed using the system, we call this E-camera. The experimental results showed that defect images for aluminum alloy plate and pipe with complex geometries can be obtained in the measurements from the distances about 2.3 meters and 6.0 meters.

1 INTRODUCTION

Thin walled large structures are widely used for pipes, bridges, wings and body of aircrafts, and automobile bodies. To maintain such large structures, in addition to visual inspection, non-destructive testing with X-ray and ultrasonic is periodically implemented for essential parts. In ultrasonic non-destructive testing, ultrasonic pulse echo technique is generally used, in which plate thickness is measured using a contact ultrasonic transducer by the flight time of pulse echo signal. Although the conventional widely-used technique is reliable and highly accurate in thickness measurements, it is not suitable to inspect whole areas of large structures due to its small measurement area underneath a transducer.

Guided wave inspection has been considered recently as an effective inspection technique for such large plate-like structures. Guided waves are ultrasonic modes propagating along such waveguides as plates, pipes, bars, and railway rails. Guided wave inspection has been highly expected as an efficient technique for long range inspection. However, there still have some issues, one of which is that defect echoes cannot be obtained for a defect in a desired size due to the use of low-frequency range for long-range propagation.

Therefore, the authors have developed defect imaging for plate-like structures using a scanning laser source technique [1-3]. Because the imaging technique is established with a non-contact and fast measurement and has a potential to be a very easy imaging technique like optical and infrared cameras, we call it E-camera. This paper describes the principle of defect imaging with E-camera first and introduces some results of the defect imaging.

2 PRINCIPLE OF DEFECT IMAGING WITH E-CAMERA

In E-camera, a pulse fibre laser and a laser Doppler vibrometer (LDV) are used for generating elastic waves and for detecting the waves, respectively. The laser source of elastic wave is rastered by galvano mirror scanners and then distributions of an amplitude peak or a Fourier spectrum peak are obtained from the waveforms at all rastering points. Then a phenomenon that generation energy of flexural vibration is enhanced when a laser source is located on a defect or in the vicinity of a defect was observed and distributions of the vibration energy correspond to a defect image. The authors analysed the energy enhancement using semi-analytical finite element calculations and normal mode expansion theory [1, 3]. Figure 1 shows the schematic figure of the principle: (a) for a plate with a widely spread defect like erosion and corrosion and (b) for a plate with a non-volume crack stretching in the thickness direction. In (a), when the laser beam is irradiated on an intact thick area, small flexural vibration is generated. On the other hand, if the laser source is located at a thin defected area, the detected signals at the LDV become large. It is shown in ref. [1] that this phenomenon appears at the frequency range below the cut-off frequency of A1 mode. In (b), if laser beam is irradiated in the vicinity of a reflective object like a crack, the interaction of a pair of evanescent waves from the laser source and the reflection object generates extra vibration energy. On the other hand, if the laser source locates far from the reflection object, the interaction of the evanescent waves becomes small and the energy enhancement cannot be seen. The energy enhancement caused by the interaction of evanescent modes was discussed in ref. [3].
3 EXPERIMENTAL SET-UP

Figure 2 shows experimental set-up used in this study. A fiber laser was used for generating elastic wave instead of an Nd: YAG laser that is generally used for elastic wave generation. The fiber laser equipment can radiate laser pulses at a high repetition rate and the laser pulses can be controlled by modulation signals provided to the laser equipment. In this study, narrowband burst waves were generate using a fiber laser with external modulation signals in order to improve signal to noise ratio (SNR) in the frequency domain. Using the high repetition fiber laser in the scanning laser source technique, surface damage by laser radiation can be avoided as well as the improvement of SNR.

The elastic waves generated by the laser radiation propagated through various paths in the plate-like structure and were detected by the LDV. An appropriate band-path filter and Fourier transform were performed to the received signals in a personal computer, and then frequency peak distributions were obtained. Here, modulation signals consisting of three rectangular signals at three different frequencies were used, and three distributions were obtained for the frequency bands. Then, spurious images were reduced by taking the average of the three distributions [2].
4 RESULTS

Figures 3 (a) - (c) show defect images obtained by laser irradiation over the region of 80 mm × 80 mm behind the artificial defect at 1 mm increment, and the plate specimen used is illustrated in (d). Schematic figures of modulation signals used are also shown. The distance between the test plate and the experimental system was about 2.3 m. (a) is a defect image for the modulation signals at the repetition rate of 200 Hz (the time interval of 5 ms). The modulation signals consisted of three rectangular waves with the time duration of 1 ms connecting in series. The defect image was an averaged distribution of the three distributions at three frequency bands. The measurement time resulted in about 33 s (=5 ms (200 Hz) × 81 × 81).

Increasing the repetition rate provides shorter measurement time. (b) and (c) are defect images for the repetition rates of 600 Hz and 1000 Hz, respectively. Although the measurement time became about (b) 11 s and (c) 6.6 s, the images were more largely distorted at the higher repetition rate. Two reasons can be considered in the image distortions. The first one is reduction of SNR. Increasing the repetition rate resulted in the use of shorter time duration of the modulation signals, which caused the reduction of SNR in frequency range. The second one is the superposition of waves at previous steps on the wave at the current step. Because waves generated at the previous steps cannot be reduced sufficiently in the short time interval of modulation signals, reverberations in a plate were received by the LDV. For example, the vertical lines in (b) and (c) near the left edge were caused by the waves generated at the right side.
Next, Figures 4 (a)-(c) show the images for an aluminum alloy branch pipe for different receiving points as in Figure 4 (d). The distance between the measurement system and the branch pipe was about 6.0 m. Rastering at the repetition rate of 80 Hz and in 2 mm increment resulted in the measurement time of about 12 minutes. The artificial pipe thinning was appeared in dark regions, which proved that the E-camera can visualize defects in such a pipe with complex geometries.

![Receiving point](image1)

(a) Upper receiving point

![Receiving point](image2)

(b) Right end receiving point

![Receiving point](image3)

(c) Left end receiving point

(d) A pipe specimen used

Figure 4 Images of a branch pipe for different receiving points.

5 SUMMERY

This study described the principle of E-camera that enables to obtain defect images from a remote position, and then presented experimental results for a plate and a branch pipe. In both cases, artificial defects created on the back surface of a laser emission region were well visualized.

Because this technique does not require scanning a receiving laser, the measurements for defect imaging are relatively easy once a receiving point is determined. Therefore automatic inspection and fast imaging like optical camera are expected in the future.

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REFERENCES


High-precision source location of AE event using automatic error correction of signal rising time

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ABSTRACT: Correspondence between the signal arrival time and ultrasonic wave mode is often unclear under noisy environment. In this study, a novel signal analysis method for high-precision source location of AE event is developed. Multiple arrival times are detected by AIC picker. Correspondence between the detected arrival time and ultrasonic wave modes is established in the consideration of experimental conditions. Contribution ratio of each data of signal arrival time to the total error is checked. Low quality data including large error is eliminated and miss correspondence between the signal arrival time and ultrasonic wave mode is corrected.

1 INTRODUCTION

Determination of arrival times of AE wave to each sensor is essential for source location of AE events. In the simplest method, trigger time of AE hit, i.e. the time when AE waveform crosses a preset threshold voltage can be regarded as the arrival time. However, this method is not so precise in many cases. Meanwhile, manual determination enables better precision than the threshold crossing method. However, automatization is impossible in this method because the diagnostic criterion of the arrival times is obscure. Here, Akaike’s Information Criterion (AIC) picker is one of solutions of this problem, i.e. realization of precise and automatic arrival detection. Maeda et al. developed a direct computation method of AIC value from seismic waveform [1]. Kurz et al. applied Maeda’s method to AE waveform [2]. Sedlak developed two-steps AIC picker for better precision [3]. In Sedlak’s method, AIC picker is applied twice around the trigger time. In the first step, AIC picker is applied to AE waveform before and after several tens of microseconds of the trigger time. Then, in the second step, AIC picker is applied again to a smaller range of waveform around the detected arrival time in the first step. Current version of our in-house developed AE measurement system “Continuous Wave Memory” (CWM) includes the Maeda’s and Sedlak’s algorithms.

AE wave is an elastic wave which propagates in solid materials. Therefore, multiple modes of waves with different velocities are included in AE waveform. For example, longitudinal wave, transversal wave and some types of surface waves are observed in bulk specimen. Lamb wave is dominant in thin plate. Lamb wave includes symmetric (S) and asymmetric (A) modes where the top and bottom surfaces vibrate symmetrically and asymmetrically, respectively. Therefore, discrimination of these modes is important for precise AE source location. When the signal-to-noise ratio (SNR) is sufficiently high, a sharp rising edge can be observed in waveform and the earliest signal arrival can be detected easily. However, often SNR is low in practical AE measurement and precise detection of arrival times becomes difficult. Therefore in this study, a novel arrival detection method with automatic error detection and correction was developed for high-precision source location of AE events.

2 SIGNAL PROCESSING METHODS

2.1 Detection of multiple arrival times of AE wave with AIC picker

Waveforms from AE sensors via amplifiers were continuously sampled and recorded to hard disk drives by previously mentioned CWM system. A noise reduction filter was applied in frequency domain, i.e. spectrum subtraction method. At first, the filtered continuous waveforms were scanned to detect AE hits and events by cross-trigger method. Then, an arrival time was decided by two-steps AIC picker. The first AIC picker detected a tentative arrival time between -60 µs and +40 µs of the trigger time. After that, was revised by the second AIC picker between -30 µs and +20 µs of . Furthermore, two more arrival times and were detected by two-steps AIC pickers before and after 100 µs of . These default values may be appropriate for the most cases, but they can be changed as needed. In conclusion, three arrival times, i.e. , and , were automatically detected around the trigger time for one AE hit. An example of this result is shown in figure 1. Figure 1(a) showed a waveform after applying of noise filter. Figure 1(b) and (c) showed the first and second picking of arrival times, respectively.

After that, some connection between three arrival times and modes of AE wave is needed. In some cases, different modes of AE wave have different frequency characteristics and the arrival times can be easily assigned to certain modes. However, this becomes difficult when a resonant type of sensor is used. In such case, modes of AE wave and area of AE source were limited by reasonable estimation. Then, minimum and maximum time differences of arrival times of two modes can be calculated by each sensor.
2.2 Automatic error detection and correction

In this study, source location of an AE event was conducted by this equation

\[(t_i - t) v_j = |p_i - p|\]  

(1)

where \(i\) is the number of sensor, \(j\) is mode of wave, \(t_i\) is an arrival time of wave, \(v_j\) is a wave velocity and \(p_i\) is position of a sensor, respectively. These variables are known. Meanwhile, there are unknown variables: \(t\) is the generation time of AE and \(p\) is the location of the AE event. The values of \(t\) and \(p\) are decided by least-squares method, i.e. AE event source was located at the position with least mean square error. However, signal processing in chapter 2.1 may include several types of errors. For example, the detection of signal arrival is sometimes inaccurate. At least one of the three arrival times is ineffective and points a fluctuation of noise because only two modes are detectable at most in many cases. Furthermore, there are some miss connection among the arrival times and wave modes.

Therefore, a novel error detection and correlation process was introduced in this study. When the mean square error is larger than a preset threshold value, each contribution ratio of \(t_i\) to the total error is checked and one sensor which causes largest error is chosen. Then, a different connection among the arrival times and wave modes are tried to diminish the error. If the error is not diminished in any connection pattern, this \(t_i\) data is removed from the calculation of source location. Consequently, low quality data with large error on detection of the signal arrival time is eliminated. Miss estimation of correspondence between the signal arrival time and ultrasonic wave mode is corrected.

3 EXPERIMENTAL PROCEDURE

AE monitoring during friction stir welding (FSW) of magnesium alloy was conducted as a verification experiment of the error detection and correction process in the previous section. A schematic diagram of the specimen and welding is shown in figure 2. The center 100 mm on the long side of two plates was welded with 800 mm/min speed and 1000 rpm of the welding tool. These welding conditions were chosen to generate welding defects and AE events should be concentrated at the welding point. Four of AE sensors (type M304A, Fuji Ceramics Corporation, Japan) were attached on the top surface of the specimen. AE waveforms were amplified 86 dB by a head internal amplifier of the sensor and an external amplifier (type A2001, Fuji Ceramics Corporation, Japan). The amplified waveforms were continuously recorded to hard disk drives by CWM system with 10 MHz of sampling frequency, 12-bit resolution and ±5 V range. A high pass filter with 100 kHz of cut-off frequency was applied by the internal software of CWM system to reduce noise caused by vibration. AE events were
detected with four threshold voltages (100, 200, 400 and 800 mV) to detect more number of AE events in fluctuate noise level environment during FSW.

Three arrival times were detected automatically for one AE hit. The detection method was the same as mentioned in the previous section. The mainly detected modes of AE wave were assumed to S0 and A0 modes of Lamb wave because the specimen was a thin plate. Then, the wave velocities of S0 and A0 modes of lamb wave in this specimen were calculated as $5.2 \times 10^3$ m/s and $3.1 \times 10^3$ m/s lamb from the material, thickness of the specimen and the frequency of Lamb wave. In this study, the frequency of Lamb wave was assumed as 200 kHz, which was the same as the resonant frequency of the sensors. Then, the assumed time difference between the arrivals of S0 and A0 modes was 4.2 to 17.6 $\mu$s, when the AE source location was limited on the welding line, i.e. $-50 \leq x \leq +50$ mm and $y = 0$ mm. Therefore, connection among the three arrival times ($t_1$, $t_0$ and $t_2$) and two modes (S0 and A0 modes of lamb wave) was conducted. Therefore, maximum eight data (4 ch × 2 modes) of wave propagation was obtained. After that, error detection and correction was conducted as previously mentioned method. When the mean square error was over than 2.0 $\mu$s², one sensor of the biggest factor of error was checked and corrected. At least four data must be remained to make 2D location of event. When the mean square error cannot be smaller than 2.0 $\mu$s² after this processing, this event will be ignored. The default value of threshold of the mean square error may be appropriate for the most AE events, but they can be changed as needed.

**Figure 2: Schematic diagram of AE monitoring during FSW**

4 RESULTS AND DISCUSSION

A continuous axial defect was observed on the welding line from the start point to the end point. Therefore, many AE events are expected to be located at the welding point during FSW. The result of source location of AE events was shown in figure 3. In this figure, vertical and horizontal axes are position on the welding line and time in welding, respectively. Each bubble plot represents one AE event and its radius reflects the maximum amplitude. Furthermore, the oblique line in the figure shows the welding points during the experiment. The algorithm of source location is the same in the conventional method without error detection and correction (figure 3(a)) and the new method with error detection and correction (figure 3(b)). Location dispersion around the welding points became smaller in the new method. Standard deviation of source location, i.e. root mean square of distance between the location of an AE event and the welding position at the time of AE generation were about 22 mm and 8 mm in the case of figure 3(a) and (b), respectively. It shows the effect of the error detection and correction.
Figure 3: Result of source location of AE events (a) without and (b) with error detection and correction.

5 CONCLUSIONS

A novel signal analysis method for high-precision source location of AE event is developed. Three arrival times are detected by AIC picker. Correspondence between the detected arrival time and ultrasonic wave modes is considered measurement conditions. Contribution ratio of each data of signal arrival time to the total error is checked. Low quality data with large error is eliminated and miss correspondence between the signal arrival time and ultrasonic wave mode is corrected. All signal processing is automatic and is done in real-time. The effect of this new signal analysis method was verified by defect monitoring during FSW test of magnesium alloy plates.

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REFERENCES

Influence of pre-compression on tensile behavior in wrought AZ31 studied by the acoustic emission technique

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ABSTRACT: Deformation mechanisms in extruded AZ31 Mg alloy during one cycle loading (pre-compression followed by tension) are discussed in term of the acoustic emission (AE) response. Due to a fiber texture of the alloy, the level of pre-compression stress significantly influences the subsequent tensile behavior resulting in S-shape of deformation curve. The obtained AE results are correlated to the deformation curves and the differences in the AE count rate were used to reveal changes in underlying deformation mechanisms. Twinning during the pre-compression was followed by detwinning during the tensile loading.

1 INTRODUCTION

Wrought Mg alloys have been intensively studied due to their low density and high damping capacity. Therefore, they can fulfill requirements of many applications in the automotive and aerospace industry. However, their use is often limited due to inherent anisotropy of mechanical properties caused by their hcp lattice, texture and homogeneity of materials. Specific crystallographic textures are developed during formation processes, e.g. extrusion, rolling and forging. The strong basal texture of extruded Mg alloys, having basal planes almost parallel to the extrusion direction (ED), favor the occurrence of {10-12}<-101-1> twins during compression along ED [1]. Thus, a distinct tension-compression asymmetry at the yield strength (YS) during loading along the extrusion direction (ED) in Mg alloys is linked with the formation of those twins [2]. Twinning is a key mechanism of plastic deformation in Mg alloys. Twins significantly influences the material behavior especially during cyclic loading, when twinning – detwinning mechanism induces important changes in the deformation behavior [2]. Tensile loading of the pre-compressed Mg alloy leads to disappearing of {10-12} twins due to an easier activation of the detwinning process than the twinning one [2]. Extensive experimental research was focused on the role of twinning and detwinning also in fatigue behaviour [3,4]. It is, therefore, essential to get more insight into individual mechanisms of deformation (dislocation slip, twinning, twinning - detwinning) during a single cyclic loading with respect to given texture and homogeneity of material. Obtained results can contribute to analyze deformation behavior during repeated loading for several cycles and strain path changes, when twin-twin junctions can form, and they have been shown to play a crucial role in increasing strain hardening and controlling microstructure evolution.

The acoustic emission (AE) studies can be performed concurrently with the deformation tests, allowing the real time monitoring of active deformation mechanisms. The differences in AE signal characteristics can be used to distinguish different types of deformation processes. For example, in [5] a comprehensive set of AE data for basal slip and twinning was obtained during uniaxial compression of Mg single crystals along <11-22> and <11-20> axis respectively.

The main idea of the paper is to study an influence of pre-compression stress on subsequent tensile behavior of extruded AZ31 alloy during a single cyclic test. Active deformation mechanisms during loading are discussed in term of the AE response. Obtained results for Mg single crystals [5] are used for an interpretation of the AE signal in polycrystalline Mg alloy.

2 EXPERIMENTAL PROCEDURES

Wrought Mg alloy AZ31 (Mg + 3 wt%Al + 1 wt%Zn + 0.3 wt%Mn) was fabricated using indirect extrusion at 300°C with an extrusion rate (profile exit speed) of 5 m/min. The extrusion ratio was 1:30, which resulted in round bars with a diameter of 17 mm. The extruded profile exhibits a bimodal microstructure with an average grain size of 20 ± 1 μm. There are larger grains elongated in ED, along with a distinct fraction of grains with smaller sizes. The investigated alloy is characterized by a prismatic fiber texture with the highest intensity at the <10-10> pole. Thus, a distinct alignment of basal planes parallel to ED, that is, the c-axis is perpendicular to ED, is a characteristic feature of this texture.

Samples (gauge length of 15 mm, diameter of 8 mm) with screw heads on both ends were machined from the round extruded bar parallel to ED. Deformation tests (pre-compression followed by tension, i.e., one cycle tests) were carried out using the universal testing machines Zwick Z50 at room temperature (RT) and at an initial strain rate of 10^-3 s^-1.

The AE activity during mechanical testing was monitored by a computer-controlled PCI-2 device, supplied by Physical Acoustic Corporation (PAC). AE was acquired using a miniaturized MST85 (Dakel-ZD Rpety, Czech Republic) piezoelectric transducer with a diameter of 3 mm and with a flat response in the frequency band from 100 to 600 kHz. The sensor was attached to the sample surface using silicon grease and a spring. A preamplifier
with a gain of 40 dB was used. The full scale of the A/D converter was ±10 V (100 dB). To obtain a comprehensive set of AE parameters, a threshold level detection of 26 dB was applied.

3 RESULTS
To study an influence of the pre-loading level on subsequent tensile test, the samples were firstly pre-compressed up to a stress of 130 MPa, 150 MPa and 200 MPa, respectively, and then subjected to tensile loading up to fracture. For sample pre-compressed up to 200 MPa the resulting stress and the concurrently measured AE signal voltage are plotted against time (Figure 1). Data for whole test is presented in Figure 1a, whereas detail of the tensile part is presented in Figure 1b. As AE response for all three samples is similar the results for samples pre-compressed up to 130 MPa and 150 MPa are not presented here. It can be seen that yielding occurs at a compressive stress of 124 MPa. The plastic flow continues with an increasing (plotted negative) slope of the deformation curve. After the pre-compression and unloading, the tensile curves exhibit a characteristic sigmoidal shape (S-shape), which is typical for compression test of extruded Mg alloys. The deformation curve is correlated to the concurrent AE measurement through measuring time. The AE signal is very strong during pre-compression, especially in the region of the compressive yield strength (CYS). In contrast, during tensile loading, smaller AE amplitudes were observed (Figure 1).

Results of tensile parts of the tests after pre-compression up to various level of the stress are shown in Figure 2. It can be seen that the higher the compressive stress is the more pronounced is the S-shape of the tensile curve, see Figure 2a. The AE streaming data were parameterized and represented as the AE count rate – the count number per time unit [6] at a given threshold voltage level. Such parameterization offers important information about collective dynamic processes which occur during plastic deformation. In order to find the link between the particular deformation stages and the AE response, the true stress vs. true strain and AE count rates vs. time are correlated and presented in the same plot (Figure 2b-d for samples pre-compressed up to 130 MPa, 150 MPa, 200 MPa, respectively). During pre-compression, the AE count rates exhibit similar maximum at the CYS in all three cases (not presented here). During subsequent unloading from pre-compression level of stress to zero stress any detectable AE is not produced. In contrast, during the tensile loading, the AE count rate exhibits distinct changes with increasing strain (Figure 2b-d). Evolutions of the AE count rate are different with respect to different level of pre-loading. Changes in the AE activity could be related to the inflection points on the deformation curves. In all three cases of pre-compression, the maximum of the AE count rate occurs when stress-strain dependences are saturated. With applying higher pre-compression stress, an additional AE count rate peak, related to the plateau after yielding (S-shape), is observed. The AE count rate peaks become more pronounced with increasing level of pre-loading (Figure 2c-d). At the terminate stage of the deformation test a strong decrease in the AE count rate is observed in all three cases.

4 DISCUSSION
In Mg alloys plastic deformation starts in grains favorably oriented for \(<a>\) dislocation glide in the basal and prismatic plane [1]. Thus, collective movement of dislocations produces detectable AE signals even before achieving the macroscopic YS (Figure 1a). To retain the compatibility of plastic deformation during the compression test, with respect to very high CRSS for the activation of non-basal slip systems [1], the occurrence of twins is required. Due to strong basal texture of extruded AZ31 Mg alloy, where the basal planes are almost parallel to ED, the \{10-12\}<101-1> twin system activates with applying the compression stress along ED. The plastic deformation proceeds by basal slip in grains reoriented due to twinning and, after reaching CRSS for...
activation of non-basal slip systems, it proceeds also by \( \langle c+a \rangle \) dislocation slip. Therefore, the twin nucleation was found as the main deformation mechanism at the macroscopic yield, and it significantly influences the YS. Thus, the observed low CYS and the strong AE signal are unequivocal signs of the activity of this mechanism. This is supported by the investigations conducted on Mg single crystals [5], where twinning was associated with burst AE signals with high amplitudes and basal slip was accompanied by a low amplitude AE signal. Moreover, in [7] it was concluded that the twin nucleation is an excellent source of AE, contrary to the twin growth, which does not contribute to the AE response. Other combined studies, provided by EBSD technique and light microscopy [8], AE with neutron diffraction [9], have shown that \( \{10-12\} \langle -101-1 \rangle \) twins nucleate at the beginning of plastic deformation.

The AE signal, observed shortly after the YS, has significantly lower amplitudes. This drop in the AE signal amplitudes indicates a change in the dominant deformation mechanism, and it is connected with the transition from the twin nucleation to dislocation slip and twin growth. Nevertheless, a few twins could still nucleate during increase in the compression load.

Unloading from the pre-loading compressive stress (cf. Figure 1a) to zero stress does not produce any detectable AE signals, which corresponds to the closing of dislocation sources. Furthermore, twin thinning may be an active relaxation mechanism during unloading. Similar to the growth or thickening of twins, detwinning or thinning is basically a movement of twin boundaries, and therefore no detectable AE signal [7] is expected as a result of this mechanism.

The subsequent tensile loading re-opens dislocation sources, and therefore, collective dislocation motion produces detectable AE signals. The AE response during entire tensile loading is significantly lower than during pre-compression (Figure 1). Basically, two opposite processes influence the AE activity during tensile loading. Namely, the increasing number of detwinned grains supports the AE activity through the rise in the flight distance and the free length of moving dislocations. On the other hand, the increasing dislocation density implies a stronger barrier for their movement, and therefore generally reduces the AE signal in the tensile part of the test.

According to Christian and Mahajan [10], a higher stress is required for nucleation than for the propagation of twins. Therefore, during reverse loading, detwinning is easily activated due to the already existing twin

![Figure 2](image_url) True stress vs. true strain (a) curves for the tensile loading of pre-compressed AZ31 Mg alloy. Deformation curves correlated with the acoustic emission count rate for the tensile loading of AZ31 Mg alloy after pre-compression up to 130 MPa (b), 150 MPa (c), 200 MPa (d).
boundaries. Based on this, the lower YS for the reverse tension than that for the pre-compression could be explained (Figure 1a for sample pre-compressed up to 200 MPa). Unlike the usual shape of the tensile curve, after pre-compression, the deformation curve for the tensile part is very similar to the compression part of the curve and it has S-shape. Twinning and detwining, due to their strong polar nature, result in large reorientations of the crystal lattice (86.3°), which macroscopically gives rise to the characteristic S-shape stress–strain behavior, preceding the terminate strain-hardening region. A similar behavior was also observed during cyclic testing in the textured AZ31 sheet [2].

From analysis of tensile deformation curve and AE responses, it can be seen that detwining process is more significant in case of high pre-compression (up to 200 MPa) and negligible for sample pre-compressed up to 130 MPa just achieving CYS. It is suggested that in last case, twin volume fraction is too small for massive detwining process and it can not significantly influence shape of the deformation curve. Therefore, an additional AE count rate peak related to S-shape of deformation curve (Figure 2c-d) is associated with collective dislocation motion in grains after detwining.

For all three cases the upcoming decrease in the AE count rates at terminate stage of deformation is connected with the decrease in the free path of moving dislocation due to an increase of dislocation density resulting in the strain hardening of the material. Similar effect can be seen for Mg single crystal compressed along <11-20> axis [5].

5 CONCLUSIONS

To study in detail possible deformation mechanisms, such as dislocation slip and twinning, twinning-detwining, during cyclic loading rather than damage process a single cyclic test consisting of pre-compression followed by tension were performed. Especially the influence of pre-compression stress of subsequent tensile loading was analyzed. The transition between different deformation mechanisms, such as dislocation slip, twin nucleation, twin growth and detwining, at different stages of the deformation test were discussed in term of the AE response. Detwining has a similar influence on the deformation behavior to twinning: S-shape of the deformation curve. During twin growth and detwining, the AE response shows events with lower amplitudes than during twin nucleation. Thus, the AE activity during tensile loading is a result of collective dislocation processes, while neither thickening nor thinning of twins obviously do not contributes to the AE response. For samples pre-compressed up to 150 MPa and 200 MPa an increase in the free length of moving dislocations during twin thinning (detwining) leads to an increase in potential dislocation movement in detwinned grain fraction; therefore, an additional AE count rate peak is observed.

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REFERENCES

Visualization of internal damage in RC slab with single side access attenuation tomography

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ABSTRACT: An innovative non-destructive testing method is developed and introduced for inspecting the interior of concrete. The method is based on the phenomenon of attenuation, which corresponds to the gradual loss in amplitudes of waves traveling through a heterogeneous medium. In the case of concrete, the attenuation is particularly high in the presence of defects, such as cracks or air voids. Ingeniously, single-side measurements of acoustic emission (AE) activity are employed for reconstructing distribution of the wave attenuation rate in the tested concrete and thus locating damaged areas. The present method is successfully applied to a panel of a reinforced concrete slab of a bridge in service.

1 INTRODUCTION

Acoustic emission (AE) testing is one of non-destructive testing (NDE) methods available for investigating the internal features of civil engineering structures. AE techniques have been extensively used for bridge examination [1-3]. AE phenomena correspond to the release of internal energy in the form of elastic waves when cracks are nucleated and extend (referred to as primary AE activity) or internal fretting on cracked surfaces (referred to as secondary AE activity) [4]. A sensing system for recording AE activity has been already published [5]. Sources of AE events, namely cracks, are located from the measured arrival times of their associated waves [6, 7]. Their cracking modes can be determined through the moment tensor analysis [8, 9].

Nowadays, AE source location is ingeniously combined with a travel-time tomography to reconstruct the wave velocity distribution inside concrete [10]. Indeed, the decrease in the wave velocity substantially corresponds to the presence of such defects as cracks or air voids [11].

Amplitudes of elastic waves tend to decrease while they are traveling through media such as concrete. This phenomenon is well known as an attenuation, resulting from heterogeneous nature of concrete and from wave characteristics of diffraction, dispersion and scattering at the boundaries in addition to geometrical spreading [12]. The presence of defects in concrete, such as cracks or air voids, could enhance the attenuation [13]. It has been shown that the attenuation was more sensitive to the presence of defects than the velocity distribution [14]. H.K. Chai et al. [15] employed the attenuation of ultrasounds for imaging the interior of concrete. Their method has been proven to be effective for locating damages in concrete. However, it has one disadvantage to require an access to at least two sides of the tested specimen. In the case of bridge slabs, it is generally not possible to measure at the two sides because of traffic. Accordingly surface waves have been employed to investigate the interior damage of concrete [16]; however, specific depths could not so far be identified with this technique.

In the present paper, an innovative method is developed for reconstructing distribution of the attenuation rate inside a reinforced concrete element from single-side measurements of AE activity. Applied results of this method to a panel of a reinforced concrete (RC) bridge slab is discussed.

2 ALGORITHM FOR ATTENUATION TOMOGRAPHY

2.1 General principle

The attenuation rate in a particular medium can be defined as the amplitude decay undergone by an elastic wave traveling in this medium, per unit of distance. It is generally expressed in decibels per meter (dB/m). The increase in the attenuation rate generally indicates the presence of defects in concrete, such as cracks or air voids.

For computing the attenuation tomography, the method combines a conventional AE source location algorithm with an algorithm of tomographic reconstruction, known as a SIRT algorithm (Simultaneous Iterative Reconstruction Technique).

The process is summarized in Figure 1. It is noted that AE activity can be measured from only one side of the tested member. First, the source locations of all AE events are used as input, where a constant wave velocity across the tested member is assumed for calculation. Second, the amplitude at the source of the considered AE event is
estimated on the basis of the amplitudes recorded by the sensors. Third, the attenuation rates along all the wave paths between the source and the receiving sensors are computed.

![Flow chart to compute attenuation tomography](image)

Figure 1: Flow chart to compute attenuation tomography

### 2.2 Source location algorithm

The algorithm for AE source location is based on the Ingleda’s method, which is used in seismic engineering for locating the epicenter of earthquakes [6, 7]. By assuming a constant wave velocity inside the tested specimen, the source location of an AE event is determined from the arrival times of their associated elastic waves at the locations of several sensors.

### 2.3 Estimation of the peak amplitude at the source

For each AE event, the peak amplitude of the elastic wave at the source is unknown. Consequently, it must be approximated to calculate the attenuation rate along the considered wave paths. In the tomography algorithm, the attenuation rate is generally estimated from a relation represented in Figure 2. First, the peak amplitude of the signal recorded by each sensor is plotted as a function of the distance between the source and the sensors. Second, a linear regression between the peak amplitude of the elastic wave and the distance from the source is computed. The peak amplitude at the source is referred to as equal to the value for the case that the distance is equal to zero.

![Estimation of the peak amplitude of the elastic wave at the source](image)

Figure 2: Estimation of the peak amplitude of the elastic wave at the source

### 2.4 SIRT algorithm for attenuation tomography

In the tomography based on the attenuation, the area of interest and analyzed must be divided into mesh elements characterized by their own attenuation rates. Then, a first estimate on distribution of the attenuation rates is to be provided as input. By comparing the measured attenuation rate along each wave path to its calculated value of the assumed distribution, the SIRT algorithm could lead to proper distribution of the attenuation rates.

First, the measured attenuation rate along each ray path is estimated from Equation 1.
\[ AR_{\text{measured},i} = \frac{A_{\text{source}} - A_{\text{sensor},i}}{\sum_j N_j d_{ij}} \]  

Where:
- \( AR_{\text{measured},i} \): measured average attenuation rate along the wave path from the source to the \( i \)th sensor
- \( A_{\text{source}} \): estimated peak amplitude of the elastic wave associated to the considered AE event at its source
- \( A_{\text{sensor},i} \): peak amplitude of the elastic wave measured at the \( i \)th sensor
- \( N_j \): mesh number of elements crossed by the wave path from the source to the \( i \)th sensor
- \( d_{ij} \): length of the wave path from the source to the \( i \)th sensor in the \( j \)th element

Second, the attenuation rate along each wave path based on distribution of the attenuation rates in the mesh elements is computed by Equation 2.

\[ AR_{\text{calculated},i} = \frac{\sum_j M_i AR_{j} d_{ij}}{\sum_j M_i d_{ij}} \]  

Where:
- \( AR_{\text{calculated},i} \): calculated average attenuation rate along the wave path from the source to the \( i \)th sensor (dB/m)
- \( AR_{j} \): attenuation rate in the \( j \)th element (dB/m)
- \( M_i \): mesh number of elements crossed by the ray path from the source to the \( i \)th sensor

Afterwards, the difference between the measured and the calculated attenuation rates is calculated for each wave path by using Equation 3.

\[ \Delta AR_i = AR_{\text{measured},i} - AR_{\text{estimated},i} \]  

In a similar manner to Equation 11, the differences of the attenuation rates on all the wave paths are estimated by Equation 4.

\[ \Delta AR_j = \frac{\sum_{i=1}^{N} \Delta AR_i d_{ij}}{\sum_{i=1}^{N} d_{ij}} \]  

Where \( N \) is the number of wave paths crossing the \( j \)th element. The attenuation rate in each element is then updated with Equation 5.

\[ AR_{j,\text{updated}} = AR_{j} + \Delta AR_j \]  

The procedure from Equation 2 through Equation 5 is repeated until the convergence is reached.

3 EXPERIMENT AND MEASUREMENT PROCEDURE

3.1 Sensor array

Figure 3 shows the plan view of the bridge and the location of the investigated panel. The panel of dimensions 3750 mm x 2650 mm x 235 mm was tested. The bottom surface of the slab segment is given in Figure 6. As seen, a few cracks are observed. Therefore, it was estimated that the panel (slab segment) was not severely deteriorated according to the visual inspection.

Fifteen AE sensors were placed on the bottom surface of the panel. Figure 7 shows their arrangement. The resonant frequency of AE sensors employed were 30 kHz. The signals detected were amplified by 40 dB by sensor-integrated preamplifier and the signals exceed the threshold of 53 dB were recorded. AE activity under normal traffic loads was monitored for seven days, resulting in total AE events of 53,800,520. The wave velocity for AE source location was initially set at 3300 m/s, which was the average of experimentally measured values at the investigated panel.

![Figure 3: Location overview of the investigated panel and sensor array](image-url)
3.2 Panel removal and core sampling
RC slabs studied herein were fully replaced in November 2015 as other panels in the vicinity of the tested one were so deteriorated as to be replaced. In the course of renovation process, they were cut into parallelepiped pieces. The slab segment corresponding to the investigated panel was preserved for further investigation.

4 RESULTS AND DISCUSSION
The attenuation rate distribution in the investigated panel were computed within the area covered by the sensor array. Parallelepiped-shaped elements of dimensions 375 mm x 350 mm x 60 mm are applied for the meshes. Results are presented in Figure 4 in comparison with the core samples.

![Figure 4: Comparison between the attenuation rate distribution computed and the core samples.](image)

It can be observed that the attenuation rate at the center of the panel is the highest. It suggests that the central part of the panel suffers larger and/or denser cracks than other areas. Furthermore, it appears that the attenuation rates are higher than 40 dB/m at the area, where the core samples have large horizontal cracks (C4, C5, C6 and C7). In contrast, the attenuation rates are lower than 40 dB/m at the area, where the uncracked core samples (C2, C3, C8 and C9) are taken out. These results show that single-side attenuation tomography can be applied to identify severely cracked portions and areas in RC slabs of the bridge in service.

5 SUMMARY
In this paper, an innovative non-destructive method for inspecting the interior of concrete is introduced and applied to the RC slab of a bridge in service. The method, referred to as single-side attenuation tomography, which is based on the principle that the elastic waves traveling through concrete are to impinge on the cracks. It could provide the tomogram on the attenuation rates inside the tested specimen.

To summarize, single-side attenuation tomography must be understood as a very practical non-destructive testing method for identifying the parts of a reinforced concrete member which are very likely to present serious damages. If the tomograms cannot be used, in the present state, for directly assessing the structural safety of the tested specimen, they provide essential information for guiding further investigation.

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REFERENCES

Acoustic Emission modeling from the source to the detected signal: model validation and identification of relevant descriptors

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ABSTRACT: The interpretation of data measured by Acoustic Emission (AE) is largely based on empirical correlations between the respective characteristics of the source and the measured signal. The main limitation is that changes due to the acquisition chain are not well known. Therefore, the aim of this work is to build a quantitative relationship between the AE sources and the detected signal by unravelling the effect of the different stages of the acquisition chain. For this purpose, an AE modelling, in which each part is considered individually, is carried out. This will serve to understand the effects of different parameters on the signal waveform, such as the type of damage, the geometry of the specimen and the effect of the piezoelectric sensor.

1 INTRODUCTION

Acoustic Emission (AE) is a method for non-destructive evaluation allowing real time detection of damage mechanisms. As a consequence, it appears as a well-suited technique to retrace damage evolution in metals and composite materials. In fact, microscopic events occurring in the material during damage are at the origin of ultrasonic waves, which propagate up to the surface. Using AE sensors, it is possible to measure the surface vibrations due to the propagated waves. The analysis of the recorded signal gives some information about the source mechanisms, which are responsible for the wave generation. The common practice consists in describing the measured signal through some appropriate parameters (rise time, peak amplitude, centroid frequency, peak frequency, etc.), and regrouping signals into clusters thanks to classification algorithms [1]. The objective is to identify separate clusters corresponding to a different source mechanism. However, the wave originating from the source is altered during propagation. Hence, the main limitation of the AE techniques is that changes due to the acquisition chain are not well known. First, it is modified by the propagation medium itself (phase displacement, reflections, dispersion) [2] and then, by the recording system. All these transformations make the interpretation of the signals very difficult. In other words, we would like to discern the role of the source from the effect of the transformations due to the propagation medium and the recording system on the measured signal. An experimental study alone cannot provide a satisfying answer. Therefore, the aim of this work is to build a quantitative relationship between the AE sources and the detected signal by unravelling the effect of each stage of the acquisition chain, namely the source, the propagation medium and the detection system. For this purpose, an AE modelling is carried out using the finite element method (FEM) code ABAQUS®. In this case each stage of the acquisition chain is considered individually.

In this paper, once we validate our FE Model for wave propagation, we study the effects of the geometry, of the type of sources and finally of the sensor.

2 MODEL VALIDATION

For obvious reasons, we first perform validation tests of the FE model by comparing experimental and numerical results. In the experimental setup, pencil lead breaks are introduced onto the surface of aluminium specimens having three different shapes shown in Figure 1, the thickness for all specimens being 3.7 mm. The EPL16 specimen has the exact shape of the dumbbell test pieces typically used in the laboratory for material characterisation in general and AE tests in particular. Other shouldered test bars EPL3 and EPL80 were especially designed to mimic the behaviour of a thin rod and a plate respectively, for which analytical solutions of guided propagating modes are easily calculable. The signals are detected by means of a laser vibrometer, which measures the out-of-plane velocity on a surface point. Here we have not used a piezoelectric sensor in order to avoid its effect on the signal waveform, in particular the so-called aperture effect, so that we can isolate the signal recorded from the transformations due to the sensor.
Concerning the FE modelling, loads by the pencil lead breaks are modelled as displacement sources according to [3]. A 3D geometry has been built for each specimen (EPL3, EPL16 and EPL80), where the material is considered homogeneous, isotropic and perfectly elastic (Young modulus = 180GPa, Poisson ratio = 0.49 and density = 2170 kg/m³), the damping is taken into account by Rayleigh parameters. The dumbbells have been meshed with 3D hexagonal C3D8R elements. The average size of one element respects the following criterion:

\[
l_e = \frac{\lambda_{\text{min}}}{R} \quad \text{with} \quad \lambda_{\text{min}} = \frac{C_R}{f_{\text{max}}}
\]  

(1)

Where \(C_R\) : the Rayleigh wave speed in the material, \(f_{\text{max}}\) : the maximum frequency, which is usually set at 1 MHz in AE, \(\lambda_{\text{min}}\) : the minimum wavelength and \(l_e\) : the average size of one element. The resolution parameter \(R\) was set to 10 for the elements located around the source, to 6 in the gauge section and to 4 in the shoulders.

The measured velocity has been compared to the simulated out-of-plane velocity, a good agreement is observed between the two curves for each case as shown on Figure 2. The green lines indicate the time at which oscillations of simulated signals start, while the red lines indicate the time up to which experimental and simulated signals are comparable.

Figure 2: Simulated and experimental velocity: a) EPL80 specimen, b) EPL3 specimen, c) EPL16 specimen
This validation allows us to use the model of propagation medium for other numerical studies. So the next point treated in this paper is the impact of the geometry on the recorded waveform.

3 EFFECT OF GEOMETRY

In the three geometries (EPL3, EPL16 and EPL80), the same displacement history (with a chirp signal showed in Figure 3) is introduced on the surface in order to rather equally stimulate all frequencies up to 1.2 MHz. This simulation allows us to identify the different modes of propagation by presenting the 2D Fast Fourier Transform (FFT2D). Those simulated modes are compared to theoretical modes calculated for plates and beams in the case of EPL80 and EPL3 specimen respectively.

Figure 3: the Chirp source in terms of time and frequency

The results are presented as 2D Fast Fourier Transform shown in Figure 4; this way to present the results allows us to identify the excited modes so that we can compare the simulated results to theoretical calculation. Here the results show that the propagation medium geometry affects the propagated signals. Knowing that, in these geometries, the signal propagates only following specific modes, we deduce that for the large specimen (EPL80) the plate modes are stimulated, while for the thin one (EPL3) the beam modes are stimulated. In the intermediate specimen (EPL16), for which the FFT2D is more complex, and the identification of modes is practically impossible: this geometry cannot be assigned neither to a plate nor to a beam.

Figure 4: FFT2D for the three geometries excited by the same source simulated on the surface, a) the large specimen (width = 80mm), b) the fine specimen (width=3mm) and c) the medium specimen (width=16mm)

This study shows us that AE tests done on a classical specimen e.g. EPL16 (Figure 1) in the laboratory cannot replace an industrial case from a geometry perspective. 

In the following part, we will study the effect of the type of source on the recorded signal.
4 EFFECT OF TYPE OF SOURCES

In this part, we are interested in simulating physical sources. Three sources corresponding to three different damage mechanisms have been modelled as buried point sources, according to [4], in three identical specimens (of equal thickness = 3.7 mm). The sources are located in the gauge section, in the median plan and the centre of the specimen width. They are modelled as dipole forces as shown in Figure 5, representing the expansion, fracture in-plane shear mode and the fracture-opening mode. The sources rise time is 1 μs, the particle velocity is calculated on the section of the specimen from the epicentre to its end. The results are presented in the form of FFT2D (wave number in terms of frequency).

Figure 5: The modeled sources: expansion, fracture in-plane shear mode and the fracture-opening mode

The Figure 6 shows the FFT2D results for the different types of damage. The stimulated modes are not the same in the three cases neither the stimulated frequency range. These results highlight an acoustic signature for each kind of source.

Figure 6: FFT2D of the same geometry stimulated by different type of sources; a) expansion, b) fracture in-plan shear mode and c) fracture opening mode

All studies above are done without considering the piezoelectric AE sensor. This latter, depending on its type, is known by having resonant frequencies and limited bandwidth. So, in the last part we will take into account the sensor effect on the recorded signals.
5 EFFECT OF PIEZOELECTRIC SENSOR

The last study in this paper concerns the effects of the sensor on the signals. The strategy is to study the AE signals without considering the sensor, then adding the sensor effect and compare results. The results without sensor are based on simulation results. The sensor is taken into account by its transfer function experimentally determined by the reciprocity method [5]. This transfer function is added in the post-processing phase in the Fourier domain, following the equation 2:

$$S_{\text{sensor}}(f) = M(f) \times S_{\text{surf}}(f)$$  \hspace{1cm} (2)

Where $S_{\text{sensor}}(f)$: the signal spectrum, $M(f)$: the sensitivity function and $S_{\text{surf}}(f)$: the spectrum of the simulated signal retrieved from the surface representing the sensor’s sole at the sensor position.

In this part, the analysis is based on a traditional study of AE signals i.e. descriptor analysis. To obtain several AE signatures as results, different kind of sources and different geometries are considered.

- **Sources** (Figure 7): the fracture opening mode (S1) and fracture in-plan shear mode (S2)
- **Geometries** (Figure 1): EPL3, EL16 and EPL80

![Sources S1: fracture opening mode and S2: fracture in-plan shear mode applied to the three geometries](image)

In order to have a good EA descriptors analysis, we selected relevant descriptors. The criteria for this selection are:

- the descriptor is constant regardless of the distance from the source
- it is independent of specimen geometry
- its value depends on the characteristics of the source

Based on those criteria, the pertinent descriptors selected are the zero-crossing rate (temporal descriptor) and frequency centroid.

The left panel in Figure 8 – left shows the results of classification in terms of the pertinent descriptors without sensor. We can clearly identify two classes. Each class is assigned to a different source. However the right panel of the same figure shows the results of classification after considering the sensor (in this case: a typical commercial
PACμ80 sensor from Euro Physical Acoustics). We observe an overlapping of classes, which highlights the transformation of classification results due to the piezoelectric sensor.

![Figure 8: Classification result without considering sensor (left panel) and after considering the μ80 sensor effect (right panel)](image)

Finally, this last result presents what we see in our screen as recorded signal when using sensor but the result without sensor presents what kind of improvement in terms of clustering could actually be obtained when deconvolving the sensor effect on the signals.

CONCLUSIONS
The aim of using the modeling of AE is to understand the transformations of the signal from the source to the acquisition system. Firstly, comparing simulated results to experimental ones validates the propagation medium model. Then the model is used to study the effect of the geometry, the effect of sources and the effect of sensors. Each of these parameters has its own intervention on the signal and this paper showed how they affect the recorded signals.

This paper basically treats the case of isotropic homogenous material. It is considered as a first step in the modeling of Acoustic Emission, before addressing the problem of anisotropic materials. The modeling of AE in composite material is ongoing in view of its significance to understand the different type of sources generally observed during the degradation of such more complex materials.

REFERENCES

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**ABSTRACT:** AEs in living plants are related to the drought stress which induces the cavitation. The irrigation management is important factor to cultivate the tomato plants under suitable drought stress. In this study, the response to irrigation of miniature-tomato plants was evaluated using AE method. We proposed that the change of AE occurrence rate before and after the irrigation \(RD\) represented the stress response to the change of the drought stress. The AE measurement of hydroponic miniature-tomato with high-frequency irrigation revealed that the \(RD\) was influenced by the irrigation schedule. Furthermore, the average value of \(RD\) was deeply related to the yield and the sugar content of the fruits.

1 INTRODUCTION

AEs in plants are accompanied by cavitation events that occur in xylem elements [1]. Cavitation accompanies ultrasonic AEs, which can be detected by an AE sensor attached to the stem or trunk. Many studies on diagnosis of living tree has been done using AE measurement owing cavitation [2,3]. Qiu and Okushima [4], furthermore, analyzed the relationship between AE and transpiration rate of tomato plant by measurement of AE, leaf temperature and transpiration rate. They found that the influence of the change of transpiration rate on the AE behavior depended on the drought stress level. Takakura et al. also proposed the concept of the speaking plant approach (SPA) to evaluate dynamic responses of plants to changes in their environment and examined developed a chlorophyll fluorescence imaging system for tomato plants cultivated in greenhouses [5]. Such a combination of several sensing techniques, i.e. a spectrum of a leaf, transpiration rate (weight of water in a pot) and AE at stem, was successful to evaluate water or drought stress response of plants to environmental changes. The measurements of the spectrums of leaves and the weight of the pots, however, are not suitable for the practical use in agricultural greenhouse because of high cost and delicate handling. The AE method is widely used for monitoring of industrial structures because the low-cost and robust devices have been developed. Additionally, the stress response of the plants could be evaluated by only AE method if the environmental changes can be detected. The AE and irrigation is good combination to evaluate the stress response of a plant because the irrigation drastically eases the drought stress of the plant while the AE behavior is deeply related to the drought stress. The authors, therefore, studied the AE behavior of miniature tomato plants to develop a technique for the health monitoring of plants using AE measurement and irrigation control [6]. Consequently, irrigation control of the miniature tomato using the AE change ratio before and after irrigation \(RD\) (response to drought stress change) was successful for deficit irrigation of the miniature tomato

\[
RD = \frac{N_{after} - N_{before}}{N_{before} + N_{after}} \tag{1}
\]

where \(N_{before}\) and \(N_{after}\) represent AE events before and after irrigation, respectively.

\[RD < 0\]
\[RD > 0\]

![Figure 1: Schematic of evaluation of irrigation response using \(RD\).](image)

\[\text{Irrigation}\]

\[\text{Irrigation}\]

\[\text{Time}\]

\[\text{Time}\]

\[\text{AE rate}\]

\[\text{AE rate}\]

\[\text{RD < 0}\]

\[\text{RD > 0}\]
can be treated as the irrigation response of a plant as shown in figure 1. The plant shows a forward response when \( RD < 0 \) because both of the drought stress and AE rate were decreased. In our model, the forward response means that the plant is well irrigated and the drought stress is moderate because the occurrence of cavitation was restrained. In contrast, the backward response (\( RD < 0 \)) means that the plant needs water and the drought stress is severe because the irrigation accelerated the occurrence of cavitation. Drought stress significantly influences on the yield and the sugar content of fruits at tomato cultivation. Hence, \( RD \) could be used for the prediction of yield and sugar content of the fruits because the \( RD \) is deeply related to the drought stress of tomato plants [7]. In this study, the hydroponic cultivation system for tomato plants with high frequency irrigation was fabricated to investigate the influence of the irrigation condition on the \( RD \) behavior. The AEs at the stem of tomato plants were continuously detected during cultivation and the response of \( RD \) against the change of the irrigation time was discussed.

2 EXPERIMENTAL PROCEDURES

2.1 Experimental material

A miniature tomato (Chika, Takii Seed) was used in this study. The seeds were germinated in a tray and mixed with vermiculite. The plants were placed in a temperature-controlled room where the temperature was set at 24 and 20 °C for day and night, respectively. The lighting intensity was set to 240 \( \mu \text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1} \) at the base of the shoot; the lighting cycle ran for 12 h each day. Well-grown plants at one month after transplanting the seedlings were examined and measured. All lateral shoots were removed when they appeared during the measurement, and the plants were pinched above the third truss with two true leaves over the truss. The seedlings were planted in a small pot and grown using a hydroponic cultivation system, as shown in Figure 2. Irrigation was done by spraying the nutrient solution to the roots through mist nozzles using a water pump from a tank below the shoots. Root cutting was down at the interval of 10-14 days for a root-zone restriction. The plants were cultivated for 75-88 days while AE measurement.

2.2 AE measurement

A high-precision vibration sensor (VS-BV203, NEC TOKIN) was selected as an AE sensor because of reducing cost. A pair of AE sensors were attached to the same stem of a miniature tomato to measure AE owing to cavitation in xylem tissues. The center-to-center distance between each sensor was set to 2-5 cm. The AE sensor was fixed using a stainless-steel hose clamp. AE signals were detected by an oscilloscope (PicoScope 4424, Pico Technology) with a sampling rate of 10 MHz, and the waveforms were recorded using a PC. The thresholds for AE measurement were set to 3 mV for the AE sensor. \( RD \) was evaluated every hour by following procedures. Firstly, sums of \( N_{\text{before}} \) and \( N_{\text{after}} \) up to 1 hour before were calculated when \( T_{\text{AE}} \) was set to 10 min or \( T/2 \) if \( T \leq 20 \) min as shown in Figure 3. Then \( RD \) was calculated using sums of \( N_{\text{before}} \) and \( N_{\text{after}} \) and equation 1 (\( RD \) was treated as being lost when \( N_{\text{before}}+ N_{\text{after}} = 0 \)).
Irrigation control was carried out by a PC and a relay circuit as shown in figure 2. Constant and fluctuated section were selected for the irrigation condition of the plants. For the constant section, the irrigation interval and time were fixed to 30 and 15 min, respectively. For the fluctuated section, the irrigation time or interval was fluctuated using a fuzzy control. The concept of the irrigation control was to cultivate the tough plants against change of drought stress, i.e. $RD=0$. Then the program was designated to increase and decrease the irrigation frequency when $RD>0$ and $RD<0$, respectively. Unfortunately, the fuzzy control in this study did not work properly for several causes (electrical troubles, computer freezing up and bugs of the program) although the fuzzy control was programmed to change the parameter according to the value of $RD$. The irrigation condition was treated as being randomly changed for the fluctuated section in this study. The irrigation condition was listed in table 1. The irrigation time and interval time were changed for F1 and F2, respectively.

### Results and Discussion

Figure 4 to 6 show the behaviors of AE occurrence rate and irrigation time of C, F1 and F2 section. In fluctuated sections F1 and F2, the relationship between the AE occurrence rate and the amount of irrigation time was not recognized though the both were largely fluctuated. Hourly behavior of $RD$ of F1 was significantly scattered as shown in figure 7 because the number of the detected AE was not enough to calculate the precise value of $RD$. Then, an average value of $RD$ was calculated by separating for each period $T$ for the entire measurement period. Figure 8 shows the behaviors of $RD$ and $ITT$ of F1 section when $T=24$ h. The $RD$ showed slight similar behavior with the $ITT$ (same rising peaks at 44, 70 and 80 d were observed).

<table>
<thead>
<tr>
<th>Irrigation Condition</th>
<th>Section Name</th>
<th>Irrigation Interval</th>
<th>Each Irrigation time</th>
<th>EC of fertilizer</th>
<th>Cultivation Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>C</td>
<td>30 min</td>
<td>15 min</td>
<td>0.2 - 0.6 mS/cm</td>
<td>81 d</td>
</tr>
<tr>
<td>Fluctuated</td>
<td>F1</td>
<td>3-30 min</td>
<td>10 s - 20 min</td>
<td>0.2 - 0.6 mS/cm</td>
<td>85 d</td>
</tr>
<tr>
<td>Fluctuated</td>
<td>F2</td>
<td>3-30 min</td>
<td>15 s</td>
<td>0.2 - 0.6 mS/cm</td>
<td>75 d</td>
</tr>
</tbody>
</table>

---

![Figure 3: Schematic of definition of $T_i$ and $T_{AE}$.](image)

![Figure 4: AE behavior and irrigation fluctuation for C section](image)
Figure 5: AE behavior and irrigation fluctuation for F1 section

Figure 6: AE behavior and irrigation fluctuation for F2 section

Figure 7: RD behavior for F1 section

Figure 8: Behavior of $\overline{RD}$ and $ITT$ at $T=24$ h for F1 section

Figure 9: Relationship between $T$ and the average of $\Delta RD$ when $ITT$ was increased ($\Delta ITT>0$) and decreased ($\Delta ITT<0$) at (a) F1 and (b) F2 section.
To identify the influence of the irrigation change on the RD, the change of $RD$ against the fluctuation of irrigation time was investigated when $T$ was varied from 1 to 168 h. Firstly, the differential value of $RD$ and $ITT$ from the previous period in each section $\Delta RD$ and $\Delta ITT$ was calculated. Then, the average values of $\Delta RD$ for $\Delta ITT>0$ and $\Delta ITT<0$ were derived, respectively to find the trend of $\Delta RD$ against the fluctuation of $ITT$. The behaviors of the average value of $RD$ when $\Delta ITT>0$ and $\Delta ITT<0$ in F1 and F2 sections were shown in figure 9.

The $\Delta RD$ showed the reverse polarity to the $\Delta ITT$ when $T<12$ h in F1 section while the polarity of $\Delta RD$ coincided with that of $\Delta ITT$ regardless of $T$ in F2 section. The cavitation rate (AE rate) is decreased usually after the irrigation when the drought stress is eased because the amount of the irrigation is increased. Hence, a well-irrigated plant should demonstrate negative value of $\Delta RD$ when $\Delta ITT>0$ in short period as shown in F1 section. Furthermore, the average values of the irrigation time of C, F1 and F2 sections were 709, 347 and 54 min/d, respectively. F2 section, therefore, suffered the severe deficit irrigation. These results suggest that the plants of F2 suffered severe drought stress and eventually the behavior of $\Delta RD$ was different between F1 and F2 in short term.

On the other hand, figure 9 also indicate that there is the positive relation between the RD and the amount of irrigation in long period for both of F1 and F2. Such a tendency might be related to the growth of the examined plants because the increase of the amount of irrigation (fertilizer) should promote the plant’s growth following the increase of transpiration rate which increases the cavitation vulnerability.

The $\Delta RD$ was related to the yield $YD$ and the average sugar contend $AS$ of the fruits after experiment as shown in figure 10. The $YD$ was decreased compared with F1 section while $AS$ was not changed as shown in figure 10. Consequently, these results suggest that $RD$ could be controlled by the irrigation control if the polarity of $\Delta RD$ against $\Delta ITT$ was inverted in short period as observed in F1 section. Furthermore, the control of $RD$ can be expected to optimize of $YD$ and $AS$ of tomato plants. The effect of irrigation control using RD on the improvement of yield and sugar content of fruits in tomato cultivation, therefore, will be studied in future works.

Figure 10: Influence of $RD$ on yield ($YD$) and average sugar content ($AS$) of fruits when $T$ is whole measurement period. Circles, squares and triangle represent C, F1 and F2, respectively.

4 CONCLUSIONS

This study investigated the influence of the irrigation condition on the behavior of the AE change ratio before and after irrigation $RD$ as the irrigation response of a tomato plant. The hydroponic cultivation system for tomato plants with high frequency irrigation was fabricated and the AEs at the stem of tomato plants was continuously were detected during cultivation. The daily average value of $RD$ was slightly related to the irrigation time though the hourly value of $RD$ was largely scattered. The change of $RD$ showed the same polarity to the fluctuation of irrigation time when calculating period $T$ was longer than 12 h when the irrigation time was fluctuated (F1 and F2 sections). On the other hand, The change of $RD$ showed the different tendency between the F1 and F2 sections while the yield of the fruits of F2 was decreased compared with F1. Consequently, $RD$ could be controlled by fluctuating the irrigation condition unless the plants suffers severe deficit-irrigation and might be useful parameter to optimize the yield and sugar content of the fruits of tomato plants.

REFERENCES


In-situ investigation of deformation mechanisms in various magnesium alloys by X-ray diffraction and acoustic emission

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ABSTRACT: The influence of the LPSO (long period stacking ordered) phase orientation on the deformation mechanisms of magnesium alloys has been investigated by X-ray diffraction (XRD) and acoustic emission (AE) measurements. The adaptive sequential k-means analysis (ASK) method, offering identification of the dominant deformation process (basal, non-basal slip, twinning) in a given time period, has been used for AE data evaluation. The results indicate that the kinking mechanism exhibits a significant dependence on the orientation of the LPSO phase with respect to the loading axis.

1 INTRODUCTION

1.1 Current development in field of high-strength magnesium alloys

Magnesium alloys, having excellent strength to weight ratio, represent a highly interesting material for transportation industry, where the fuel saving achieved through weight reduction belongs to the most important tasks. Nevertheless, their widespread application is limited by several factors, as generally low formability and yield strength at ambient temperature, strong degradation of mechanical properties above 200 °C. There are several ways for improving the mechanical performance of magnesium alloys, including grain size refining and alloying, which leads precipitation formation, which enhance the stability of the microstructure.

The Mg-Zn-RE LPSO (LPSO – long period stacking ordered) structures are fundamentally long-period stacking variants of a hexagonal-closed-packed (hcp) structure of the Mg crystal. The recent investigations shows, that yield strength exceeding 300 MPa can be achieved using technologically simple hot-extrusion process for this class of materials [1]. The high-temperature properties of Mg/LPSO alloys are also very promising – only a slight decrease of strength was found in the temperature range of 20 - 300 °C.

Despite the efforts of the scientific community in the last decades the elucidation of the deformation mechanisms of magnesium alloys with LPSO phase is still a challenging task. There is a general agreement that there are two main processes besides the dislocation slip, which contribute to the plasticity: formation of “deformation kinks” and twinning.

Deformation kinks form, when a large stress acts parallel to basal slip planes. Owing to the low critical resolved shear stress (CRSS) for basal slip, avalanche-like motion of (0001) basal dislocations takes place, accompanied by elastic buckling of planes. During the ongoing loading, basal dislocations with opposite sign nucleate. They start to move against the dislocations from the first “wave”, which leads to the kink formation.

The kink formation significantly depends on materials parameters (e.g. shape and orientation of LPSO phase, grain size, texture) and experimental conditions (loading direction, temperature etc.). The role of the non-basal slip in the kink formation has not yet been clarified. However, the activation of \( \{10\overline{1}0\}\{\overline{1}1\overline{2}0\}\) prismatic slip has been reported, but rather at higher testing temperatures [2].

Deformation twinning is the main mechanism accommodating deformation out of the basal plane, particularly at temperatures below 200 °C. In magnesium, the \( \{10\overline{1}2\}\) -type extension twinning, associated with extension along the c-axis and reorientation of the lattice by 86.3° and \( \{10\overline{1}1\}\) -type compression twinning, resulting in contraction along the c-axis and tilting of the lattice by 56° are the most often reported and studied twinning
mechanisms. In the case of Mg/LPSO alloys, twinning was found to operate for particular sample compositions and texture. However, revealing the conditions for its activation needs further investigation.

1.2 Experimental methods exploitable for investigation of Mg/LPSO alloys

Owing to their complex microstructure the experimental study of the deformation mechanisms in Mg/LPSO alloys is rather difficult. The deformation kinks, slip bands and twinning are usually studied by light optical microscopy (LOM). In addition, there are several investigations of the dislocation structure performed by transmission electron microscopy (TEM). However, the study of less populated dislocation types (e.g. prismatic or 2nd order pyramidal ones) by TEM is not an easy task. The SEM experiments are usually limited to documenting of the microstructure by means of secondary and/or back-scattered electrons; the orientation mapping using electron-backscattered diffraction (EBSD) technique is scarce. Generally, the microscopic methods usually examine only a small volume of the material and the results are not always representative for the whole specimens.

Statistically representative data about the dislocation structure and twinning in magnesium alloys can be obtained from both diffraction experiments and acoustic emission (AE) tests [3]. The total twinned volume is determined from the intensity variations of particular peaks, caused by the crystal lattice reorientation during the twinning [4]. The diffraction measurements can take place both in ex-situ and in-situ regime. In the latter case, the combination of the diffraction experiments with the AE testing can result in a complex characterization of the plasticity [5].

The acoustic emission (AE) is an efficient experimental tool for in-situ testing of deformation mechanisms in magnesium alloys. The main advantages of the method are a fine time resolution and sensitivity to twin nucleation and collective dislocation motion. Nevertheless, the differentiation between the particular signal types is a difficult task due to their simultaneous appearance. Various statistical methods (k-means, fuzzy c-means, neuron analysis) have been worked out to analyse the AE data. The recent one, the so called adaptive sequential k-means analysis (ASK) by Pomponi and Vinogradov [6] appears very promising for determination of the dominant deformation mechanisms at the various stages of deformation in magnesium alloys.

2 EXPERIMENTAL

2.1 Material

The Mg97Y2Zn1(at.%) alloy was fabricated by melting in an electric resistance furnace using high purity Mg and Zn elements and a Mg-Y master alloy. Ingots were cast by pouring the liquid metal into a cylindrical steel mould of diameter 42 mm. Cast billets were extruded to flat bar at 400 ºC with a reduction ratio of 18:1. This rectangular bar was sectioned to 6x4x4 mm³ sized specimen, which were used for compression tests.

2.2 Microstructural characterization

Prior the optical microscopy, the specimens were sequentially ground on SiC grinding papers (800, 1200, 2000, 4000) with water. Then coarse polishing was performed using 3-µm and 1-µm diamond abrasive. In the next step the specimens were etched with nital 5% and electrolytically polished in a solution of picric acid (100 ml ethanol, 18 ml H2O, 6 ml glacial acetic acid, 12 g picric acid 98%) for 7s. Texture analysis was performed by the back-Schulz reflection method, using a SIEMENS TM Kristalloflex D5000 x-ray diffractometer equipped with an Eulerian cradle.

2.3 In-situ acoustic emission (AE) and synchrotron diffraction (SD)

The deformation test has been performed in compression at room temperature, using a strain rate of 10⁻³ s⁻¹. In the case of ED the test was stopped after reaching 20% of strain in order to avoiding the destroying of the AE sensor. A miniature (2 mm in diameter) broadband AE sensor (flat frequency response in the range 100 – 500 kHz) from Dakel company was mounted on the specimen using vacuum grease and a clamp. The AE was amplified by 40 dB in the frequency range 100 – 1200 kHz using a 2/4/6-type preamplifier manufactured by Mistras Corporation. The AE acquisition (PCI-2 board from Mistras Corp.) took place in a so-called data streaming regime, where the data were recorded continuously with 18 bits amplitude resolution and 2 MHz sampling rate.
In-situ synchrotron diffraction experiments were carried out during separate compression test on the beamline EDDI at BESSY, Berlin, Germany. The energy range of the synchrotron white beam was from 10 to 135 keV. The diffraction angle was around $2\theta = 9.74^\circ$. The resulting gauge, determined by slit setting, was a rhomboid prism of 0.5x0.5x5.6 mm. The gauge volume was always positioned in the centre of the cylinder. The sample was tilted within the scattering plane between $\varphi = 0^\circ$ (axial direction) and $\varphi = 90^\circ$ (radial direction), where $\varphi$ is defined as the angle between the scattering vector and the extrusion axis. The use of a white beam allowed the entire diffraction pattern to be collected for each $\varphi$ angle. Individual diffraction peaks were obtained for each diffraction pattern and fitted with a Gaussian curve to determine the peak position and peak intensity.

3 RESULTS AND DISCUSSION

3.1 Initial microstructure

Figure 1 shows the microstructure in the extrusion direction (ED) and transverse direction (TD). The LPSO phase, having long fiber shape, has deformed during the extrusion process. Its volume fraction was estimated as 19%. The magnesium matrix exhibits a bimodal grain structure, consisting of dynamically-recrystallized (DRX) grains and non-recrystallized grains elongated along the extrusion direction.

![Figure 1: Typical microstructure of the initial state in a) extrusion direction (ED); b) transversal direction (TD).](image)

The loading direction is parallel with the vertical axis of the figure.

Figure 2 shows the recalculated (0002) and $(10\bar{1}0)$ pole figures of the magnesium phase measured in the section perpendicular to the extrusion direction. The alloy shows a strong fiber texture with the basal plane parallel to the extrusion direction. This texture component is given mainly by non-recrystallised grains, as it has been shown by several authors [1].

![Figure 2: (0002) and $(10\bar{1}0)$ pole figures of the initial specimen showing a strong fiber texture](image)

The deformation curves for the particular directions and the corresponding AE response are plotted in Fig. 3. It is obvious that the yield strength is higher for the ED specimen. Similarly the AE signal is more intensive in this direction. In order to reveal the background of this behavior, ASK analysis was applied on the continuously recorded AE data stream.
Raw AE signals recorded during compression tests were further analyzed using the adaptive sequential k-means (ASK) procedure. The main steps of the procedure can be summarized as follows:

- The recorded waveform streaming data are sectioned into consecutive frames. In our case a single frame corresponds to a 2 ms long “time window”. (see schematic drawing in Fig. 4)
- For each frame, the Fast Fourier Transformation (FFT) of the signal is done, which is used for the calculation of the Power spectral density (PSD) function.
- PSDs in the consecutive frames are analyzed one-by-one. The features of the PSD in the first frame define Cluster 1. All other clusters are defined with respect to this initial cluster. The conditions for new cluster forming are based on k-means method.

When the clustering procedure is completed, a dominant AE source mechanism is assigned to each cluster. This assignment consists of two basic steps:

1. Checking the time of the appearance of the elements in a given cluster. The elements in Cluster 1 belong to the background noise, since the recording of AE data is always launched before the starting of the deformation test.
2. Checking characteristic features of the PSDs, as energy, frequency distribution etc.

Finally, the increment of the number of elements with time (Cumulative Number of Elements) can be plotted, which describes the activity of particular deformation mechanisms in time.
Based on the above mentioned algorithm, 4 main clusters have been identified. In order to facilitate the cluster assignment to the deformation mechanisms, we constructed the Energy vs. Median Frequency cross-plot (Fig. 5). It is obvious that for both specimens orientations the characteristic features of the clusters are similar. The evolution of the number of elements in the particular clusters is plotted in Fig. 6.

Using information given by Figs. 5 and 6, the following mechanisms can be assigned to the clusters:

- **Cluster 1 – Background noise** (color code in figures – black)
  Since the elements in this cluster appear before launching of the straining, this cluster naturally belongs to the background noise. They are typically low energy, broad frequency signals, as it was reported by several authors [7].

- **Cluster 2 – Dislocation slip** (color code in figures – red)
  The number of events in this cluster starts to increase from the very beginning of the deformation. This behavior corresponds to the basal slip, which has the lowest critical resolved shear stress (CRSS) [8]. As the deformation progresses, further dislocation mechanisms (prismatic and pyramidal slip) contributes to this cluster. However, this analysis could not distinguish them properly. The dislocation cluster has a characteristic tear shape, which is given by shortening of the mean free path for dislocation movement at higher stresses, where the dislocation density is larger than that at the beginning.

- **Cluster 3 – Twinning** (color code in figures – green)
  The elements in this cluster have high energy and a relatively narrow frequency range. Such a feature is characteristic for burst-type twinning signal. Also the appearance of this cluster in the early stage of the straining indicates the twinning origin of elements, since the CRSS of $\{10\overline{1}2\}$-type extension twinning is as low as several MPa [8].

- **Cluster 4 – Kinking** (color code in figures – blue)
  The average energy level of the signals is slightly higher compared to cluster 2 (dislocation slip). The cluster has a tear shape, but the frequency range is narrower than that for the dislocation slip. This cluster becomes dominant in the frequency spectrum from approximately 40 MPa. These features indicate the kinking-origin of this cluster. As it is mentioned in the introduction, the kinking is caused by avalanche-like motion of basal dislocations. Such a mechanisms produces a relatively high energy signals [9], which is in good agreement with our experimental data. Owing to the structure of the LPSO phase, the initiation of kinking requires higher stresses [1].

If we compare the time evolution of the number of elements in the particular clusters (Fig. 6), we can see that noise and dislocation slip clusters behave similarly. The dominancy of background noise terminates as the deformation starts. The dislocation slip has a large jump at the onset of the straining, as a consequence of the basal slip. There is a further jump on this curve in the vicinity of the macroscopic yield, which is caused by activation of non-basal $<$+a$>$-slip in the prismatic and pyramidal planes [5]. The twinning is more significant in ED. This feature is evident also from Fig. 7, where the AE data are plotted together with diffraction data. It is obvious that there are more twins nucleated in ED (cf. AE data – green line) and their volume is significantly larger (cf. diffraction data – red scatter). This behavior can be elucidated with the initial texture, where in ED both large and small grains are favorably oriented for twinning. In contrast, only the non-recrystallized large grains can undergo twinning in TD. Consequently, both number and volume fraction of twins are larger in ED. There is also a difference in kinking activity. Since the stiff, elongated LSPO phase is aligned with the ED, load transfer takes place from the matrix to the LSPO during compression of ED specimens. This mechanism is less effective in TD case [10]. After reaching
a certain level of stress, kinking takes place. Again, owing to the orientation of the LPSO phase, kinking requires lower stress in ED, and it progresses gradually. In TD, kinking can be observed from approx. 80 MPa and its onset is more dramatic (Fig. 7).

Figure 7: Change of the intensity of (0002) diffraction peak and evolution of number of twinning elements as a function of true stress for a) ED; b) TD specimen

4 CONCLUSIONS

The dependence of the deformation mechanisms with respect to the specimen orientation was investigated in Mg97Y2Zn1(at.%) alloy having LPSO phase. The following conclusions can be drawn:

- Higher yield stress and strength was observed for ED - which is given by more effective load transfer from matrix to LPSO phase.
- There is a significant difference in the twinning activity – owing to the initial texture more grains are involved in twinning process in ED. Consequently, both the twinned volume and the number of nucleated twins is larger for this specimen. In contrast, the dislocation slip seems to be similar for both directions.
- The onset of kinking is shifted to higher stresses in TD.

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REFERENCES

Acoustic emission and damage evolution at mean temperature under air of a SiC/[Si-B-C] composite subjected to cyclic and static loading: towards lifetime prediction

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ABSTRACT: The low density and the high tensile strength of Ceramic Matrix Composites (CMC) make them a good technical solution to design aeronautical structural components. To fully understand damage mechanisms and be able to design components, its behavior has to be analyzed during fatigue tests. The aim of the present study is to consider the possibility of predicting rupture time from acoustic emission monitoring. New indicators of damage are defined, based on acoustic energy. These indicators highlight critical times or characteristic times allowing an evaluation of the remaining lifetime.

1 INTRODUCTION

Ceramic matrix composites (CMC) seem to be adequate materials to design new generation of civil aircraft engines because of their low density and high tensile strength at high temperature. That is why damage mechanisms have to be identified, through cyclic fatigue tests.

The aim of the study consists in analyzing and comparing material behavior under cyclic and static fatigue loadings, at the same temperature and under air, to determine the effects of a cyclic loading on damage and lifetime. CMCs seem to be promising material for aeronautical applications, even if their constituent materials are brittle, the strain at failure is rather high due to considerable matrix cracking and cracks deflection at interfaces [1]. However, the behavior of these materials is affected by oxidation of interphases, fibers and the ultimate failure is governed by slow crack growth in fibers [2]. Self-healing material has been developed to protect fibers against oxidation, which increased largely the lifetime of material. Nevertheless, under air and for temperature under 550°C, self-healing is not significant enough to fully protect the material. It’s therefore important to understand the material behavior for those temperatures. As specified above, the lifetimes under these types of loadings are rather long, which makes it hard to realize tests on laboratory equipment. This kind of studies needs to be done with a limited number of tests, thus the use of different techniques to monitor the damage in real time is mandatory. Acoustic emission (AE) appears to be a good candidate in this case. The aim of AE is to record transient elastic waves on the material created by damage mechanisms. There are several studies referring to this kind of method for different types of CMCs under tensile tests [3-5]. For fatigue tests, damage can be analyzed from different points of view, first by linking each acoustical event to the damage mechanism which generated it [5-6]. This process needs clustering algorithms [7].

Another approach consists in considering the evolution of released energy [8-10]. It is generally accepted that the energy of an AE signal is related to the energy released by the source. Consequently, AE energy gives information about material damage; it is then possible to point out precursory elements to ultimate failure or to simulate AE energy evolution with a power law to determine lifetime.

A main purpose of this paper is to consider the possibility of predicting rupture time of CMC from damage evolution recorded by AE technique. The objective of this approach is to propose a method based on acoustic energy in order to evaluate the remaining lifetime during long-term-mechanical tests. The approach is based on the determination of energy released and identification of a critical point in energy release during mechanical test. So beyond this characteristic point, the criticality can be modeled with a power-law in order to evaluate time to failure.

In this study, new indicators of damage have been defined, based mainly on acoustic energy analysis. These indicators highlight critical times or characteristic times allowing an evaluation of the remaining lifetime. Moreover, the clustering of acoustic emission, using a supervised clustering method based on random forest approach [11], makes possible to get a real-time detection of each damage phenomena and to identify the mechanism responsible for this critical time.

2 EXPERIMENTAL PROCEDURE
2.1 Materials and mechanical tests

Fatigue tests have been realised at a temperature of 450°C under air. The material is a ceramic matrix composite reinforced with Nicalon SiC fibers, coated with PyC and embedded in a self-healing [Si-B-C] matrix. The reinforcement architecture is a stack of several layers of 2D satin fabrics linked together by strands of fibers in the third direction. In this study all the specimens have a dog-bone shape with a thickness of 4 mm and a gauge section...
of 60 mm x 16 mm. For static fatigue tests, specimens were first loaded at constant loading rate of 1kN/min, and periodically (every 6 or 12 hours) unloading-reloading cycles were carried out in order to determine the secant elastic modulus. Cyclic fatigue tests were conducted under a tensile/tensile sinusoidal loading with constant amplitude and a frequency of 2 Hz. Strain is measured using an extensometer. In the case of static fatigue tests, the imposed stress increases every Ti (time for 18% of Nf, number of cycles to failure) with a step corresponding to 6% of tensile strength. At the same time cyclic fatigue tests are realized with imposed stress oscillating at a frequency of 2 Hz between 0 and a constant maximum value which is incremented of 6% every 18% of Nf (Fig. 1). Moreover, cyclic fatigue tests with constant amplitude were conducted under a tensile/tensile sinusoidal loading and a frequency of 2 Hz until composite fracture.

Figure 1. Applied stress for a. Incremental static fatigue test b. Incremental cyclic fatigue test

2.2 Acoustic emission monitoring

Two piezoelectric sensors (Micro80, Mistras Group) are maintained on the specimen surface. Medium viscosity vacuum grease is used to ensure a good coupling between the specimen and sensors. Each sensor is connected to the data acquisition system (PCI2, Mistras Group) via a preamplifier with a 40 dB gain and 20-1200 kHz bandwidth (Mistras Group).

During tests, AE is recorded with 2 piezoelectric sensors, one on each side of the reduced section. The position of a detected source can be determined linearly knowing the wave velocity in the material.

The AE wave velocity has been calibrated before the test $C_{0e}$, according to a pencil lead break procedure: several breaks were performed on the specimen at several locations $x$ between the two sensors. The velocity $C(e)$ of an extensional wave in a thin plate is proportional to the square root of the elastic modulus $E$ of the material. Since $E$ decreases as damage occurs in the material, it is important to take into account the evolution of $C(e)$ during the mechanical test in order to better evaluate the location of the AE sources. As proposed by Morsher [4], the initial modulus during unloading $E(0)$ was measured during a cycled tensile test, where hysteresis loops were obtained at different strains. The velocity $C_d(e)$ was then determined by using equation 1:

$$\frac{C(e)}{C_{0e}} = \sqrt{\frac{E(e)}{E_0}}$$

(1)

2.3 Damage indicators

The energy of the recorded AE events represents a part of the elastic energy released by damages of CMC specimens. Thus, the evolution of elastic energy released by analysing the energy of AE events may be investigated. The source energy $E(n)$ is then defined as the square root of the product of the amounts of energy received at both sensors $E_1(n)$ for each source:

$$E(n) = \sqrt{E_1(n) \times E_2(n)}$$

(2)
The first indicator is based on the coupling of mechanical energy \( U_m \) and acoustic energy \( U_{AE} \) denoted Sentry Function \( F \), initially introduced by Minak [12, 13]:

\[
F = \ln \frac{U_m}{U_{AE}} \tag{3}
\]

where \( U_m \) is strain energy and \( U_{AE} \) the cumulated acoustical energy \( \sum E_n \). \( F \) can be function of time or strain. It is defined as soon as the first acoustical event is recorded. Strain energy is calculated measuring the area under the force-displacement curve. To determine only the effects of tension, unloading/loading loads are not taken into consideration. The function is calculated every \( k \) acoustic sources (\( k \approx 0.1\% \) of number of signals).

The coefficient of emission \( R_{AE} \) is defined as the increment of energy \( \Delta E \) recorded during an increment of time \( \Delta t \), divided by the total energy emitted during the initial loading of the sample:

\[
R_{AE}(t) = \frac{1}{E_{loading}} \frac{\Delta E}{\Delta t} \tag{4}
\]

where \( E_{loading} \) is the cumulative AE energy for all the signals recorded during the initial loading up to the nominal load of the test, \( \Delta E \) is the cumulative AE energy for all signals recorded during the interval \([t; t + \Delta t]\).

In this study the energy rather than the signal strength is used to define the severity. It is defined as the average energy.

\[
S_r = \frac{1}{J} \sum_{n=1}^{m} E_n(n) \tag{5}
\]

\( J \) is an empirical constant.

The indicator denoted \( R_{LU} \), is defined by the ratio of the liberated energy during the loading part of a cycle and the energy recorded during the unloading part of this cycle.

\[
R_{LU} = \frac{\Delta E_{loading}}{\Delta E_{unloading}} \tag{6}
\]

3 RESULTS AND DISCUSSION

Results of fatigue tests are summarized in Table 1. To compare the results of static and cyclic fatigue tests, the behavior of the material during a tensile test is used as a reference. Thereafter, \( \sigma_R \) and \( \varepsilon_R \) will respectively represent ultimate tensile strength and strain at failure. For both types of loading, stress at failure is lower than \( \sigma_R \), nevertheless it is twice as high for static loading than for cyclic loading which means that cyclic loading has an effect on the material lifetime. Considering the strain at failure, the value is also lower for a cyclic loading than for a static loading. In addition, the elastic modulus decreases greatly before ultimate fracture of the composite while it tends to an asymptotic value for a static loading and does not reach the limit value \( E_{fract} \). Moreover, the mean distance between matrix cracks in the longitudinal yarns is higher under cyclic fatigue, showing to saturation of matrix cracks could occur at a lower interfacial shear stress, decreased probably by progressive wear induced by cyclic loading.

Under cyclic fatigue (Tab. 1), a greater proportion of recorded signals and a more significant release of energy were obtained at a given time than under static fatigue for the same values of temperature and maximum load. Thus this remark may point out an increase of damage due to loading cycles.

The figures 2a and 2b represent the evolution of the sentry function \( F \) during static and cyclic loading. In both cases, a third part appears for an average time of 90% of the total test duration. The function is then decreasing. The signals which have created this decrease are probably generated by fibers breakages since they are localized in the area where the specimen failed. The evolution of the sentry function during the cyclic fatigue test shows a part (part 1.b) where the function is decreasing significantly. This is caused by the important increase of acoustic energy, whereas the strain remains constant. It appears that cyclic loading generates different types of damage since the
function does not show this type of variation for a static loading or a tensile test. The variations of this function in
different cases exhibit different levels of damage on the composite: matrix cracking and fibers breakages for fatigue
tests. Furthermore it shows that a cyclic loading has more critical damage effect than a static loading when the
maximum stress is higher than 36 % of σR. In addition, during incremental fatigue test, this indicator reveals the
fatigue limit (Fig. 2).

Now a focus is done on results obtained for cyclic loading at constant amplitude just behind this critical value.
The evolution of $R_{AE}$ coefficient versus time is given in Fig. 3. For the cyclic fatigue tests at constant amplitude,
the evolution of the coefficient $R_{AE}$ is very different from that observed in static fatigue. In both cases for the static
fatigue, $R_{AE}$ decreases first, down to a minimum value, and then increases up to the failure of the composite. On
average, the minimum of $R_{AE}$ appeared at 55% of the rupture time. The minimum of the coefficient $R_{AE}$ indicates
the beginning of the critical damage phase and provides an estimate of the remaining lifetime. In previous studies,
the restart of activity prior to final rupture is attributed to the avalanche fibers ruptures. For the cyclic fatigue, a
minimum value is not observed but a significant change of slope is visible for all mechanical tests at approximately
20-25% of the total test duration. This characteristic time could certainly be used in order to evaluate time to failure.

Table 1. Results of static and cyclic incremental fatigue tests

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<th>Cyclic fatigue (x3)</th>
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<td>Stress at failure</td>
<td>84 % of $\sigma_R$</td>
<td>36-42 % of $\sigma_R$</td>
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<tr>
<td>Strain at failure</td>
<td>$\varepsilon_R$</td>
<td>0.36 % of $\varepsilon_R$</td>
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<tr>
<td>Elastic modulus at failure</td>
<td>$E_f \cdot v_f$</td>
<td>1.5 $E_f \cdot v_f$</td>
</tr>
<tr>
<td>Number of AE sources</td>
<td>9500</td>
<td>2.57 $10^6$</td>
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<tr>
<td>Cumulated acoustic energy</td>
<td>2.2 $10^8$ (attoJ)</td>
<td>6.4 $10^{10}$ (attoJ)</td>
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matrix cracks spacing /
matrix cracks spacing after tensile test

1
1.6

![Diagram a)](image)

![Diagram b)](image)
Figure 2: Coupling of mechanical energy and acoustic energy (Sentry function) for a) an incremental cyclic fatigue test and b) an incremental static fatigue test.

Figure 3: Evolution of the coefficient $R_{AE}$ a) for static fatigue test at constant stress with time b) for cyclic fatigue tests at constant amplitude with the number of cycles.

Figure 4: a) Evolution of the coefficient $R_{LU}$ during cyclic fatigue at constant amplitude and highlight of two characteristic times at 25% and 47% of the lifetime duration (LT lifetime) on SiC/i[Si-B-C] composites, b) Evolution of the severity.

Moreover, it is interesting to notice that the coefficient $R_{LU}$ highlights two characteristic times before 50% of rupture time (Fig. 4a), the coefficient $R_{LU}$ is again upper to 1 after the last characteristic time. After this characteristic time, the increase of the coefficient $R_{LU}$ is linked to a significant increase of the severity of the signals recorded during the loading part (Fig. 4b). While for the signals recorded during the unloading phases, the severity remains constant. Moreover, the coefficient $R_{LU}$ goes through a minimum around 25% of rupture time.

A supervised classification technique can also be used to analyze AE signals recorded during fatigue of CMC composites in order to establish a link with the damage mechanism. This technique requires a data base of signals that have been labelled: the training set. This training set was created by merging data collected during tensile test. As described in the previous study, the analysis of AE signals, observation of microstructures and analysis of the mechanical behaviour of the composite led to the identification of 4 types of AE signals and to the following labelling of classes:

Class A: cluster A contains signals from two damage mechanisms which are chronologically well separated: seal coat cracking and tow breaks,

Class B: cluster B contains also signals from two damage mechanisms which are chronologically well separated: longitudinal matrix cracking and individual fibre breaks in the fracture zone just before failure,

Class C: Cluster C contains signals with relatively short duration, short rise time and low amplitude when compared to the others: transversal matrix cracking.

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Class D: this cluster is the last one to be activated and it becomes more active as strain increases and the D-type signals have a longer rise time when compared to other signals: sliding at fibre/matrix interfaces, fibre/matrix debonding.

An additional class denoted E was introduced into the library. It corresponds to signals recorded under fatigue, during unloading steps of cycles after the cycle 2000e and for applied stresses lower than $\sigma_{\text{max}}/2 - 10$ MPa. These signals are associated to the friction generated in cyclic fatigue.

In order to establish the training set of labelled signals for the supervised analysis, the same amount of signals (2000 signals) in each class (A, B, C, D and E) was used. The cluster analysis with RFCAM algorithm pointed out different damage mechanisms generated by cyclic loading, which are mainly debonding and friction at matrix/fiber and matrix/matrix interfaces. Moreover, with this analysis a link is established between the characteristic time at 25% and the beginning of the matrix cracking.

4 CONCLUSIONS
Comparison between static and cyclic tests shows that cyclic loading with an amplitude higher than 36% of $\sigma_R$ has significant effects on damage and on material lifetimes. Some new damage indicators are defined based on AE energy activity and dissipated mechanical energy. These new indicators show the evolution of damage during long term tests and can be used to propose new predictive laws of lifetimes. A link is established between a characteristic time at 25% and the beginning of the matrix cracking for the cyclic fatigue tests.

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