CONSIDERATIONS FOR SELECTION OF ADVANCED AE TRANSDUCERS

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INTRODUCTION

The most popular sensors used in Acoustic Emission are based on designs from the 1960s and work surprisingly well under a wide range of conditions. Because of overall utility of the common AE sensor designs and in light of the demands upon them (rugged, high sensitivity, immunity to environmental noise), it is easy to overlook and accept the limitations of these sensors. The basic calibration method used by most AE sensor manufacturers, the face-to-face calibration which results in the familiar sensitivity versus frequency curves, serves many applications well, especially laboratory applications. In structural testing there is much more happening in the wave than is actually expressed in these basic sensitivity curves, and often the sensor themselves are far less effective than in that laboratory case. The 1990s has seen the development of new AE sensor designs. These designs not only possess the capabilities of today's popular sensors, but do away with some historical drawbacks and provide for opportunities that are not to be found in the mainstream sensor lines. Advanced sensor considerations discussed in this DECI report are (1) aperture size and its effect on structural coupling and (2) AE sensors tailored to coupling specific structural wave modes and analysis methods, such as Modal Ratio.

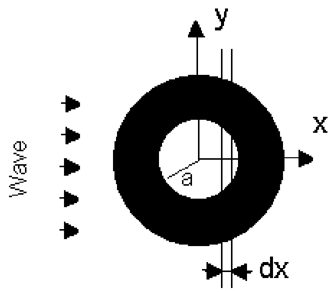
APERTURE EFFECTS

The importance of aperture effects of AE sensors to AE measurements depends on the structure that is propagating the AE wave. If the propagating AE wave that the sensor detects can be described as diffuse, aperture effects can be ignored. On the other hand, if the AE wave propagation arrives as a plate wave, aperture effects are critical. The first case will be described more fully before proceeding to how the sensor aperture affects the second case.

If the transducer is in the near vicinity of the crack and multiple reflections of the AE signals occur within the specimen, a diffuse acoustic field is produced. The frequency content of the AE signal is very broad and therefore very high frequency response transducers can effectively record the data. For this application the aperture of the transducer is of no significance due to the diffuse acoustic field. Test coupons used in the laboratory, such as fracture toughness specimens, are examples where the diffuse field can be assumed and aperture effects can be ignored. For diffuse field cases, the face-to-face ultrasonic calibration used in most manufacturer's calibration curves for sensors closely represent what a sensor will be monitoring.

When monitoring for cracks in structures, the diffuse field will not develop and sensor response will depend on the aperture size. There are two key differences from the diffuse field case that change the situation: propagation distance (crack to sensor) and the thickness of structural members. In many cases sensors can be several feet away from the crack. Also, the wave energy is channeled into guided wave modes. The structures most often resemble plates, so Lamb modes can be expected. Most of the energy will fall into just a few modes, so all but a few modes can be safely ignored. Those modes which are most important: extensional wave having characteristics similar to the S_0 symmetrical Lamb wave, a shear wave, and a dispersive flexure wave having characteristics similar to the A_0 anti-symmetrical Lamb wave. Each mode has its own characteristics according to time, frequency and direction of particle motion, so the waves will separate from one another in time and they will have distinct frequency characteristics. The large aperture face-to-face calibration curves that work well with describing AE response under diffuse field conditions are insufficient to describe how an AE sensor will respond to time, frequency and direction of motion of plate wave modes.

Both the extensional and flexure waves produce OOP displacements at the plate surface as they travel down the plate. These displacements activate the piezoelectric crystal contained in the transducer, producing the acoustic emission (AE) signal. If the aperture of the transducer coupled to the surface is small compared to the wave length of the traveling wave, the frequency content and amplitude of the signal can be accurately measured. If the aperture of the transducer is large compared to the wave length the efficiency of the transducer is compromised. Breckenridge et al (Ref.1) published a report in 1986 showing a theoretical method of calculating the aperture effects of a transducer when attempting to detect surface waves, when the transducer is some distance from the source of the wave. Their analysis is shown in figure 1A, the results are plotted in figure 1B for Raleigh velocity in steel of 2,500 m/sec.



$$U(t) = \frac{B}{pa^2}\int_{-a}^{a}\cos(kx - wt)\sqrt{a^2 - x^2}\,dx = [2J_1(ka)/ka]B\cos wt$$

with the propagation vector u(x,t)=$B\cos(kx-wt)$

where $k = \frac{w}{c}$

and c is the Raleigh velocity

Figure 1A: Aperture Calculation

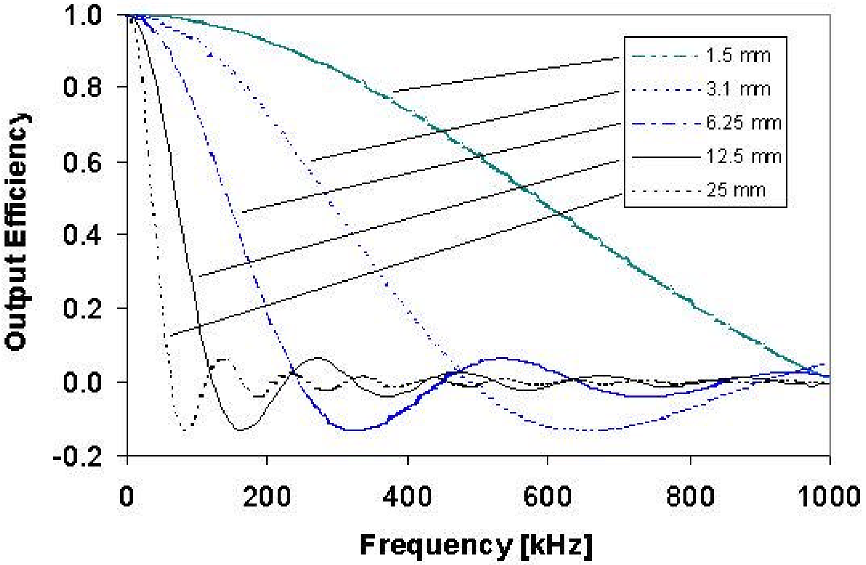


Figure 1B: Calculated aperture effects based on Breckenridge Model. A value of 1 is the response of a transducer with zero aperture (point).

So how does aperture size effect AE sensors when the AE field is not diffuse, paying particular attention to 150 kHz, the frequency used for many acoustic emission tests? The aperture size of many AE transducers lie between 0.5 inch (12.5mm) and 1.0 inch (25mm). For this range of aperture sizes, we can see in figure 1A that there is a great loss in relative output efficiency in response for frequencies above 100 kHz. DECI offers a range of sensors with different aperture sizes, shown in figure 2. The DECI SE1000-HI transducer has an aperture size of 0.060 (1.5mm). From figure 1B it is calculated to have an efficiency of approximately 80% at the 400 kHz frequency and almost 100% efficiency at 150 kHz. Not only is the efficiency high, the SE1000-HI reproduces frequency results to a high degree of accuracy.

Figure 2. Several DECI Sensors arranged by aperture size

An experimental example shows the ability of the SE1000-HI to faithfully reproduce frequencies. The goal here is to compare the separation in time/frequency of the separate modes as predicted by Lamb group velocities. AE waves are generated by both IP and OOP sources by pencil lead breaks. As Lamb theory predicts frequency characteristics to vary with thickness, three thicknesses of steel plates are used. A trigger sensor is used to facilitate measuring the velocity. The signal is split into high (HF, figure 3A) and low (LF, figure 3B) frequency components as the HF components will show the extensional and shear waves and the LF components will show the flexure waves. Because the SE1000-HI is both high-fidelity and is able to resolve fine frequency resolution by virtue of the small aperture, several experimental results can be extracted that correlate to Lamb theory:

- Extensional wave velocity in the high frequency channel (figure 3A) remains the same for all three thicknesses of the steel bars.
- The amplitude and frequency of the extensional wave is higher for the thinner bar.
- Both the amplitude and frequency content of the signal decreases, as the bar gets thicker
- Both the frequency and velocity of the flexure wave (3B) varies with thickness; the thicker bar having the highest velocity and the lowest frequency content

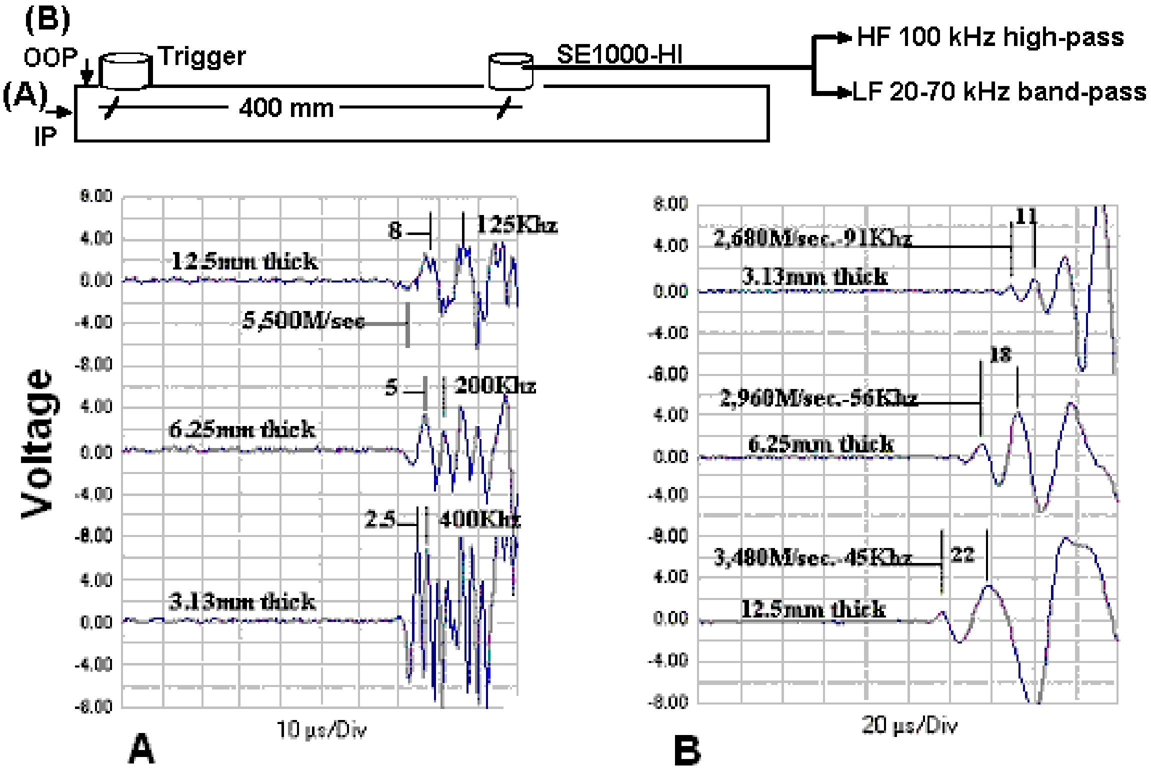


Figure 3 Small Aperature Response (SE1000-HI) to (A) IP Source at high frequencies and (B) OOP Source at low frequencies for three steel bars with varying thickness

This experiment allows for the time separation (velocity measurements) and frequency content (filtering) to be correlated in AE from structures. What remains is the how to make use of the direction of motion, which is the next topic.

Building Sensors to Exploit Aperture Effects (Modal Ratio)

As guided structural waves (plate waves) have distinct modes, AE sensors can be built to exploit frequency response as both in-plane (IP) sources and out-of-plane (OOP) sources generate extensional waves, shear waves, and flexure waves. Sensors built with large apertures cannot exploit more advanced AE monitoring techniques. The model number SE9125-M transducer is the pre-eminent sensor aimed at exploiting aperture effects in sensor design.

Wave modes are generated in different proportions depending on whether the source is IP or OOP. Measuring the amplitude of the signals in the high and low frequency channels and dividing the high frequency peak amplitude by the low frequency peak amplitude results in a ratio (the Modal Ratio) that allows us to determine the source of the AE signal, i.e., IP or OOP. Since extraneous noise signals are usually OOP in nature and crack growth signals are IP in nature, this Modal Ratio provides a method of filtering out extraneous noise signals in real time and only recording data due to crack growth.

In order to maintain good dynamic range when measuring the Modal Ratios, a special transducer was designed that would provide a Modal Ratio of approximately 1 for OOP sources in a wide range of different plate thickness. The SE9125-M has accomplished this balance between OOP and IP by using a “false” aperture provided by bonding a small mass in the center of a larger aperture resonant piezoelectric crystal. This results in sensitivity to the displacements produced by the low frequency flexure wave, while the remainder of the crystal is excited by the high frequency extensional wave displacements and the shear components of the wave that couple into the crystal and excite the radial mode of crystal which due to its dimensions are cross coupled to the thickness mode. A design based on these principles accomplished the desired balance between IP and OOP sensitivity and a patent was obtained for the resulting sensor, the SE9125-M.

The mode dependencies can be shown experimentally. Figure 4A and 4B show how dramatically different two AE sources, IP and OOP, are when monitored with the SE9125-MI transducer in a structural environment. These signals were recorded from a 500 X 500 mm aluminum plate 4.7mm thick. As shown, the IP and OOP Sources were made with 0.3mm pencil lead breaks on the edge of the plate at mid depth made and on the top of the plate respectively. Both sources were near the trigger transducer.

From the IP source (Figure 4A), the top trace is the high frequency channel (HF) and the lower trace is the low frequency channel (LF).

- The extensional velocity of 5,000m/sec is observed for the first arrival signal.
- The signal occurring at 80 microseconds is the arrival of the shear wave with a velocity of 3,125m/sec. The later arriving signals are due to reflections at the boundaries of the plate.
- No signal is observed in the LF channel (lower trace). This is due to the fact that the lead break was made at mid depth in the plate. When this symmetry occurs no anti-symmetrical (flexure wave) is created. Placing lead breaks off-center results

in a weak flexural wave whose amplitude is dependent on the depth from which the signal originates. The amplitude of the flexure wave is less than that of the extensional and shear wave. Therefore if one calculates the HF/LF Modal ratio, the value is greater than 1 when using the SE9125-M transducer. The modal ratio of the data in figure 4A would be infinite due to the fact that no LF signal is present.

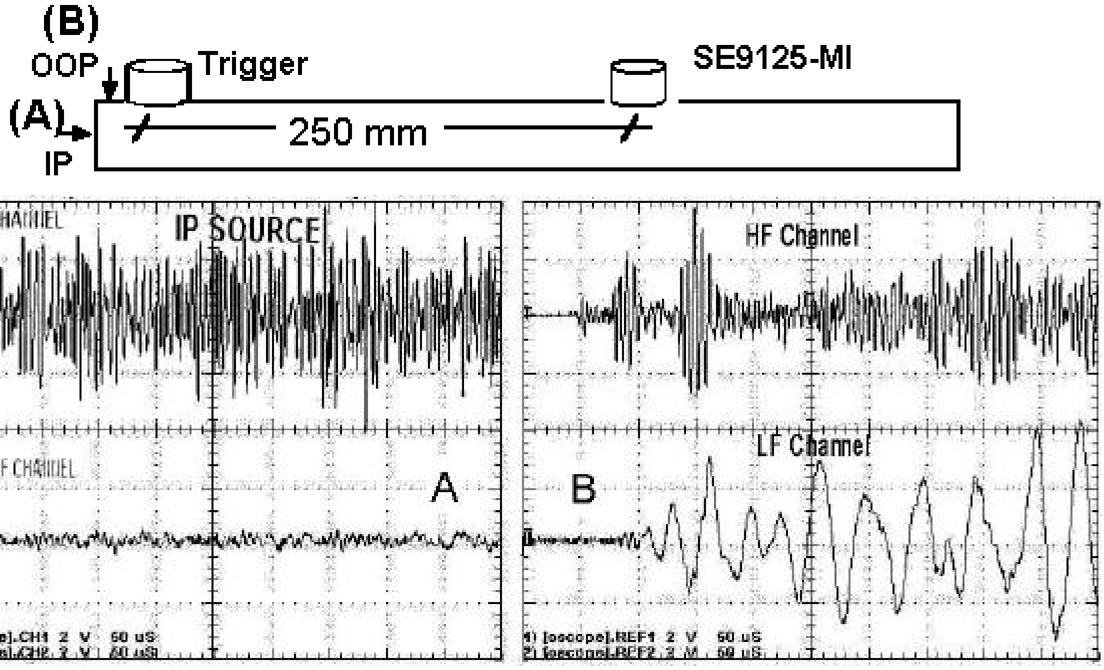


Figure 4: Comparison of High Frequency and Low Frequency Responses for False Aperture sensor (SE9125-M) with (A) IP source and (B) OOP source 4A The time base for the figure is 50 microseconds per division.

Showing a source at the exact middle plane points shows a difficult case. At exactly mid depth, the LF component we have become accustomed to seeing with the plate waves is no longer present. The signal might be interpreted as from EMI , thermal effects or high frequency airborne noise striking the transducer directly. In practice, the crack signals do not occur alone and when one actually occurs exactly on the middle plane, there will be others near this plane.

From the OOP lead break (Figure 4B), note the following:

- In the HF channel that a weak extensional wave is present at 50 microseconds, and a strong shear wave is still present at 80 microseconds. *The large signal at approximately 150 microseconds is due to reflections from the end of the plate. For field situations the plates are usually much larger that the plate used in this experiment and the Modal ratio would be calculated based on the amplitude of the shear wave in the HF channel divided by the amplitude of the flexure wave in the LF channel.*

- This Modal ratio is usually 1 or less for OOP sources using the SE9125.M transducer.
- The high amplitude flexure wave created by the OOP source in the LF channel, has an arrival time of approximately 100 microseconds for this thickness of material, which calculates to a velocity of 2,500 meters/sec.

The AESMART 2000 system specializes in making use of the advanced characteristics of the small aperture sensors. It was the AESMART that was used in these experiments. Incoming signals are split into both high and low frequency components to facilitate the identification of extensional and flexure waves detected by SE9125-M (and a few other) sensors. The modal ratio is calculated from peak amplitude of each channel. The software will default a modal ratio from infinity to a value of 60 when the low frequency signal is not present. The AESMART 2000 makes two important time difference measurements:

- Arrival time difference between trigger and signal sensor,
- Arrival time difference between when the HF signal crosses a set threshold and the LF signal crosses a set threshold. (designated as the LF-HF delta T).

Since this time is based on two different velocities it is proportional to the distance the source is from the data transducer. The LF-HF time difference along with the Modal ratio can be used to assure that the signal is a plate wave (except for crack growth at mid depth explained above) and not signals produced within the transducer by EMI or thermal noise.

Summary

The acoustic emission transducer is the most important component of an acoustic emission testing system. It matters not how sophisticated the hardware and software of the acoustic emission testing system if the information it receives from the transducer is of poor quality. When selecting a transducer for a particular test one must first of all consider what is desired to be measured and the physical geometry of the object on which the transducer is placed.

Since their introduction in the mid 1990s, sensors with small apertures have proven themselves in field work not only in places where the older designs have had difficulties, but also where the older designs have not been successful at all.

Reference: Breckenridge, F.R., Proctor, T.M., Hsu, N.N. Eitzen, Some Notions Concerning the Behavior of Transducers, Progress in Acoustic Emission, The Japanese National Society of NDI, 1986.