COUPLANTS AND THEIR INFLUENCE ON AE SENSOR SENSITIVITY

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Abstract

The removal of air from the interface between a measurement surface and an AE sensor is crucial to the transmission of ultrasonic energy. The acoustic impedance of air is around 5 orders of magnitude lower than that of the two contacting surfaces, allowing for very little transmission of acoustic energy at the frequencies typical of acoustic emission (AE). The use of a couplant can greatly improve this transmission by around 2 times at 100 kHz and more than 10 times at 500 kHz; a typical gel-based couplant having a high acoustic impedance around 4 orders of magnitude higher than that of air. The effectiveness of a given couplant is dependent on its acoustic impedance, acoustic absorption, application thickness and viscosity. Each of these can have a strong influence on the sensitivity response of the sensor and can ultimately change the way the sensor responds to different wave modes. This paper considers a number of ultrasonic/AE couplants and compares the sensor response for each couplant to longitudinal and shear waves, demonstrating that a high-performance ultrasonic couplant can improve sensor sensitivity significantly above 400 kHz compared with a grease-type couplant.

Introduction

When attaching an AE sensor to a measurement surface, a couplant material is used to remove any air from the interface, introduced due to the microstructure and surface roughness of the two contacting surfaces. The reason for doing this is that the acoustic impedance of air is much lower than that of the sensor face or material surface and will cause considerable loss in transmission. Piezo-ceramic has relatively high acoustic impedance, as does steel (a typical measurement surface) making them a relatively good match. However, the acoustic impedance of air is around 5 orders of magnitude lower than that of piezo-ceramic or steel and so introducing a couplant layer with an acoustic impedance higher than that of air, which displaces the air between the two surfaces, can increase transmission substantially [1]. For AE applications, there is a range of couplants to choose from depending on the requirements dictated by the application. The properties of the chosen couplant can have a significant effect on the output generated by the sensor and thus the quality of the measurement. Couplants with high acoustic impedance have been shown to produce substantially better ultrasonic transmission than standard couplants [2] and are used in ultrasonic applications to improve the signal-to-noise ratio. For AE and vibration applications, studies have compared the properties of common couplants and have made recommendations based on transmission and ease of use etc. [3].

Whilst couplants no doubt improve the transmission between the contact surface and the sensor, they do introduce a certain amount of variability [4] and different couplants can provide different transmission properties as a function of frequency [5]. During calibration, this can have an effect not only on the apparent sensitivity of the sensor but also its frequency response. For the calibration of an AE sensor, a single couplant is usually selected and the sensitivity of the sensor as a function of frequency is usually stated using the selected couplant [6-13]. This paper considers the effect of couplant choice on the stated sensitivity of the sensor during calibration.
Couplant Requirements

When selecting a couplant for use during an AE measurement or monitoring application, a number of factors need to be considered, of which acoustic transmission is just one. The most important factors might be long-term stability depending upon length of measurement, removal and reapplication of the sensor, the mounting surface condition or shape, sources of vibration which could displace the sensor, mounting surface temperature, etc. There are a number of couplant types to choose from, typically liquid, gel or grease. Other types of couplants based on compounds or adhesives can be used, which provide bonding of the sensor to the surface.

Generally, the acoustic performance of a couplant is dictated by the acoustic impedance, acoustic absorption and the couplant thickness. In addition to these, the ability of the couplant to force air bubbles from the contacting layer is extremely important and this often requires a relatively low viscosity. Equally important is the wetting ability of the couplant. This is related to the surface tension of the couplant and describes the level of molecular contact between a couplant and the compressing surfaces. This is often related to viscosity and good wetting fluids, like water, can often result in less air between the couplant and the two compressing surfaces.

Acoustic emission sensors have a dominant response to particle motion normal to the surface and for this type of measurement the properties described above are most applicable. However, if detecting particle motion is parallel to the sensor face (shear motion), which is a common requirement in plate structures, the viscosity of the couplant will become a more important transmission property. A high-viscosity couplant or a rigid bond will provide greater transmission of these in-plane particle motions than couplants with the conventional properties described above.

Measurements and Results

A number of couplants were selected for testing. Glycerin, propylene glycol, ultrasound gel and silicone grease are compared in this paper. Glycerin and propylene glycol were selected as these are considered high-performance ultrasonic couplants, particularly glycerin, which provides a layer of relatively ‘high-impedance’ couplant. Ultrasound gel was also used as this couplant is routinely used for AE sensor calibration at the National Physical Laboratory [9, 10], providing good transmission but only suitable for relatively short measurement periods. The main advantage of this type of gel is its extremely good wetting properties, which combined with a relatively low viscosity, result in very low air content in the coupling layer. Silicone grease was also used in the comparison as this and other similar performing greases are widely used in practical AE applications due to their stability with time and their non-drip consistency. A dry contact was also used for reference purposes to demonstrate the effect of using no couplant. Two sets of measurements were performed. Firstly, a longitudinal sensor calibration was performed against a velocity interferometer to obtain the sensor sensitivity in V/mm/s as a function of frequency. This calibration was performed for each couplant on the same sensor to show the effect of the couplant on the sensitivity response of the sensor. Secondly, a relative comparison was performed between each couplant showing how the sensor’s response to a normal incidence shear wave is affected by the couplant. For the shear-wave measurements, a couplant designed specifically for shear wave transmission (Panametrics shear-wave couplant) was used in place of the glycerin.

The measurements were performed on a 410-mm diameter hemi-spherical aluminium block with a flat top of approximate diameter of 50 mm, for mounting the sensor under test. The flat
top is also polished flat to provide a suitable optical reflection for calibration of the sensor against a laser interferometer. In this case, the polished surface also acts as an idealised coupling surface and resulted in reduced variability between couplings. A Panametrics V189-RB 0.5 MHz, 1.5-inch diameter NDT source transducer was bonded with cyanoacrylate to the base of the hemisphere as shown in Fig. 1. The interferometer was aligned with its optical beam normal to the surface of the flat top along the central axis of the block. The Panametrics V189-RB transducer was excited with a 1-μs pulse generated by an Agilent 33220A function generator. Following propagation through the block, the out-of-plane displacement component of the longitudinal wave was measured using the interferometer. The output from the interferometer was captured at a sample rate of 25 mega-samples per second using a TDS 5054 oscilloscope with the trigger synchronised with the function generator. A total of 3000 time averages were used to measure the interferometer output to improve the signal-to-noise ratio. Once the velocity history of the surface had been established using the interferometer, a PAC S9208 sensor (with 40 dB pre-amplification and a 20 kHz high-pass filter) was then coupled to the flat top of the hemisphere, with the selected couplant, in place of the interferometer laser beam. The sensor was chosen due to its broadband response up to 1 MHz. The same procedure was then followed to capture the voltage output from the sensor with 100 time averages being used. This process was repeated for each couplant. To improve repeatability and allow comparison between the different couplants, the position of the sensor on the surface was fixed using a three-point guide and held in place with a constant mass of approximately 6 N. Using a constant force does mean that a more viscous couplant might result in a thicker layer and less air removal. To counter this, an increasing force was applied during installation of the sensor, whilst simultaneously monitoring the sensor output. Once the apparent maximum output was achieved, the force was reduced to the holding force of 6 N, ensuring that the sensor output did not drop during this reduction. This approach ensures that the maximum acoustic performance is established for each couplant and reduces variability between re-couplings. It is however acknowledged by the authors, that this may not represent a realistic scenario for in-situ use.

For the shear-wave measurements, a Panametrics V152-RB 0.5 MHz, 1.0-inch normal incidence shear-wave transducer was used to generate a shear wave at the sensor after propagation through the block shown in Fig. 1, with a velocity or displacement component parallel to the surface. This transducer was also bonded to the transmission surface using cyanoacrylate to provide a rigid bond for optimum shear-wave transmission. For these measurements, only the sensor outputs were measured. In this configuration it was not possible to calibrate the response of the

Fig. 1. Measurement configuration for out-of-plane motion.
sensor to the velocity component parallel to the surface as the interferometer measures only the normal velocity component of the surface, although calibration to this in-plane component using optical interferometry has been reported in the literature [10-11].

For both the longitudinal and shear wave measurements, the sensor was coupled a number of times using each couplant. This was done to establish both the overall variability of re-coupling the sensor and to establish the maximum peak-to-peak signal level achievable with each couplant.

The sensor measurement in Fig. 2 shows the longitudinal-wave arrival following a 32-µs propagation time through the aluminium block. At around 64 µs, a direct shear wave arrives, which is generated from the edges of the transducer. Although this is difficult to identify from the sensor output, it is identifiable from the interferometer measurements (not shown). The direct echo does not arrive until around 96 µs and is just visible at the end of the time waveform shown in Fig. 2. To obtain the magnitude sensitivity, the quotient of the spectra of the sensor-output voltage and the interferometer velocity output is calculated. However, to ensure that the sensitivity is calculated for only the longitudinal-wave arrival, the time waveforms are time-gated before the shear-wave arrival as indicated in Fig. 2.

![Fig. 2. Sensor output time waveform for longitudinal wave measurements.](image)

Figure 3 shows the calibration results of the S9208 AE sensor for its velocity sensitivity to the longitudinal wave when coupled using the high-impedance glycerin, propylene glycol, ultrasound gel, silicone grease and a dry contact with no couplant. In each case, the sensitivity is derived from the maximum signal level achievable with each couplant. At lower frequencies, below 400 kHz, the couplant appears to have very little effect on the sensitivity of the sensor, with the variability observed between 200 kHz and 400 kHz being almost within the variability due to re-coupling which was around 5% to 15% depending on the couplant. However, above 400 kHz there is greater difference in sensitivity, particularly at frequencies where the sensor exhibits resonance behaviour, which cannot be explained by re-coupling variability. This shows that the glycerin, propylene glycol and particularly the ultrasound gel do provide the greatest sensitivity. Conversely, silicone grease provides poorer sensitivity at the higher frequencies, up to as much as 65% less than the ultrasound gel, for the best coupling achievable with each couplant. This indicates that ultrasound gel has a lower attenuation coefficient at the higher frequencies than
silicone grease as both have comparable acoustic impedance. The ultrasound gel could also benefit from good wetting, good air removal properties and a thinner coupling layer. These differences do have implications for couplant choice when providing the calibration sensitivity of the sensor and even more so when performing broadband or high-frequency AE measurements. A poor choice of couplant could not only have a negative impact on the signal-to-noise ratio, but could ultimately change the shape of the AE-event waveform being investigated. The dry contact also shows a large reduction in sensitivity as expected - around a 50% reduction at 100 kHz and substantially more at higher frequencies. This is to be expected due to the high acoustic absorption in air (which effectively fills the gaps in the sensor-surface contact) at ultrasonic frequencies and the very high impedance mismatch. The sensor measurement in Fig. 4 shows a shear-wave arrival following a 64-µs propagation time through the aluminium block. This wave mode is generated at the source transducer such that it arrives with its particle velocity parallel to the sensor surface. A small longitudinal-wave arrival can also be seen arriving after a delay of 32 µs. Although small, it is assumed that a direct echo of the longitudinal wave arrives at around 96 µs and so the time waveforms are time-gated between 64 µs and 96 µs as shown in Fig. 4.
Figure 5 shows the response of the S9208 AE sensor to the 1-µs pulse generated by the V152-RD normal-incidence shear-wave transducer when coupled using the propylene glycol, ultrasound gel, silicone grease and a dry contact with no couplant. In addition to these, a Panametrics shear-wave couplant, which is specifically designed to have a very high viscosity to maximise shear-wave transmission, was included in the comparison. It should be noted that Fig. 5 cannot be compared with Fig. 3 to assess the sensors longitudinal and shear wave response as Fig. 3 is a sensitivity derived from the quotient of the spectra of the sensor and interferometer signals, whereas Fig. 5 only considers the direct output spectrum of the sensor.

The shear-wave couplant clearly provides the greatest transmission of the shear wave in this case, but, more interestingly, the dry contact is now not so poor when compared to the use of a couplant. The dry contact is in fact comparable to the silicone grease. The most probable reason for this is that for good shear-wave transmission acoustic impedance and absorption are no longer the dominant factors. The transfer of shear forces between atoms is likely to dominate and for this to be most effective, a rigid contact is necessary. Although the effective contact area for the dry contact would be significantly reduced by the microstructure of the two surfaces, the small contacting area is sufficiently rigid to provide transmission comparable to a low rigidity/viscosity couplant, which provides a full area contact in this case. However, the measurements were performed on a polished metal surface, which should allow for a good dry contact. The type of measurement surfaces encountered in practice would likely perform very poorly for a dry contact. For the shear-wave measurements however, the couplant effect on frequency response is less clear. The ultrasound gel and propylene glycol provided surprisingly good transmission of the shear wave given their very low viscosity. The silicone grease performed less effectively but has the benefit that it does not drip or dry up with time, which can be a problem with liquid-based couplants. The silicone grease also had the lowest re-coupling variability of less than 8% in both sets of measurements. The performance of couplants for shear waves with particle motion parallel to the surface also represents their performance to symmetric Lamb waves. Similarly the longitudinal wave results presented with particle motion normal to the surface will be representative of couplant performance for anti-symmetric Lamb waves, which propagate in plate structures [14].

Conclusions

The effect of couplant on the calibration of the velocity sensitivity response of an AE sensor to a longitudinal wave (out-of-plane) has been considered and shows the effect of the couplant to
be broadly unnoticeable within the re-coupling variations. However, at higher AE frequencies above 400 kHz, the properties of the couplant become more important. At these higher frequencies, silicone grease reduced the sensitivity of the sensor by up to 65% compared with a high-performance ultrasonic couplant such as propylene glycol. Although this has implications for the accuracy of the sensitivity calibrations for AE sensors, it will also have an impact on AE measurements. A poor choice of couplant could significantly reduce signal-to-noise ratio in broadband or high-frequency AE measurements and could lead to distortion of the waveform being measured.

In addition to this, shear-wave measurements have shown that for the measurement of wave modes with particle motion parallel to the surface, such as symmetric Lamb waves, there is no real benefit in using couplants conventionally considered to be ‘high-performance’ ultrasonic couplants. Given that both planes of particle motion would be encountered in typical AE applications, a balanced choice should be made between the requirement for out-of-plane and in-plane particle motion and required mechanical/material/chemical properties.

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References