Through-Transmission Characteristics of AE Sensor Couplants

Kanji Ono
Department of Materials Science and Engineering,
University of California, Los Angeles (UCLA),
Los Angeles, CA 90095

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 µm. 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 µm 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.

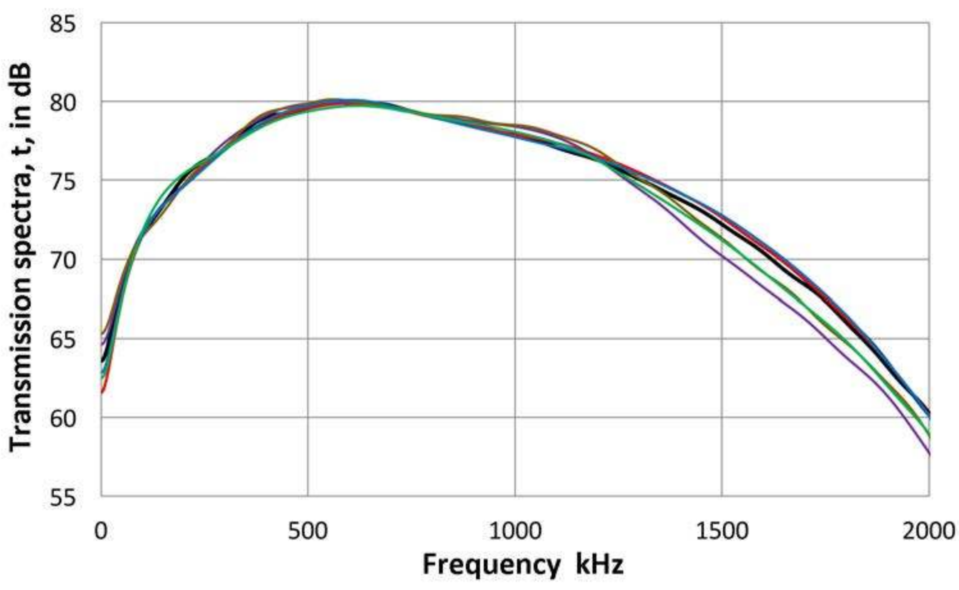

Fig. 1 FFT magnitude spectra of received signals through couplant, or t vs. frequency, f. Vaseline: dark blue curve, motor oil: red, Nonaq: blue, High vacuum grease: purple, Stopcock grease: brown, SC-6 resin: green. V103 transmitter and FC500 receiver.

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 Δt 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 ~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 ~1 dB lower than Vaseline.

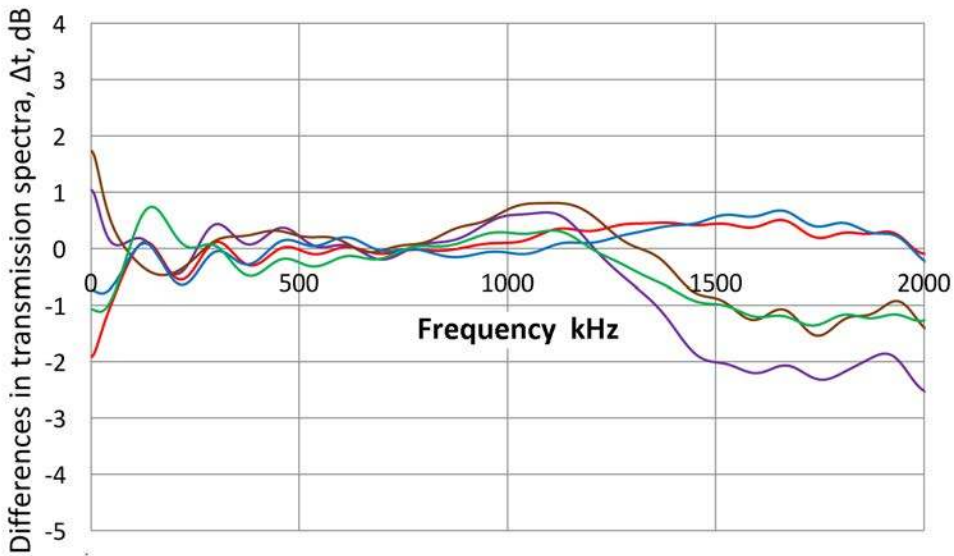

Fig. 2 Differences in transmission spectra, Δt, of received signals through couplant using Vaseline spectrum as reference. Motor oil: red, Nonaq: blue, High vacuum grease: purple, Stopcock grease: brown, SC-6 resin: green. V103 transmitter and FC500 receiver.

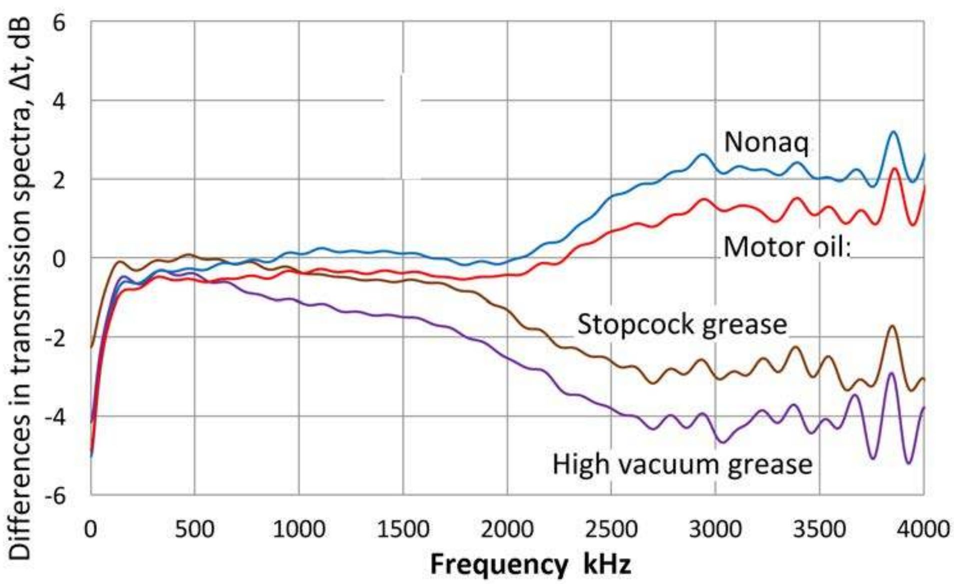

Fig. 3 Differences in transmission spectra, Δt, of received signals through couplant using Vaseline spectrum as reference up to 4 MHz. Motor oil: red, Nonaq: blue, High vacuum grease: purple, Stopcock grease: brown. NDT Systems C16 transmitter and FC500 receiver.

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).

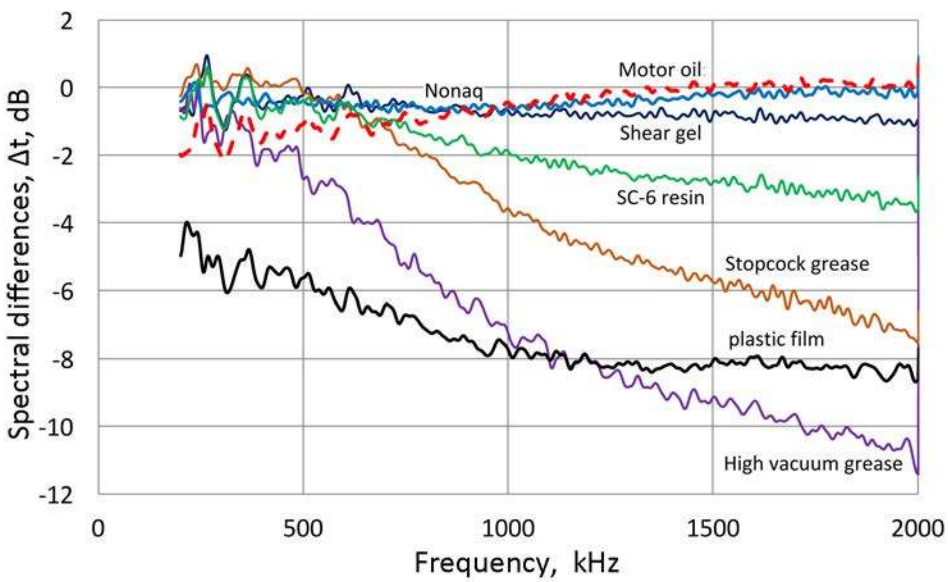

Fig. 4 Differences in transmission spectra of received signals, Δt, through couplant using Vaseline spectrum as reference. Non-optimum sensor installation for viscous couplants. Motor oil: red, Nonaq: blue, Shear gel: dark blue, High vacuum grease: purple, Stopcock grease: brown, SC-6 resin: green, plastic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

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.

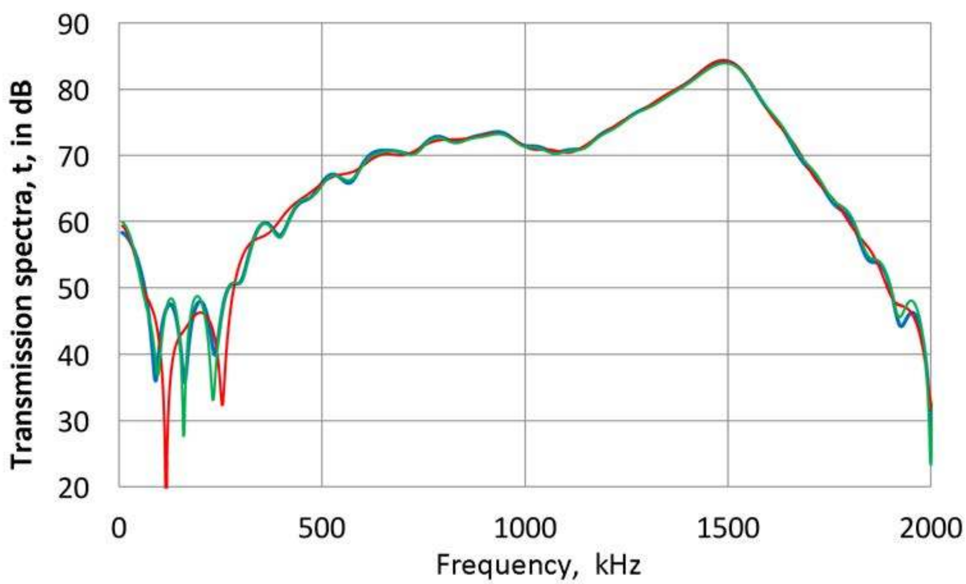

Fig. 5 Transmission spectra, t, of received signals through couplant. Vaseline reference: blue curve, epoxy resin (as mixed): green, epoxy resin (cured for 30 min): red. FC500 transmitter and Automation Ind. 1 MHz-1/2".

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.

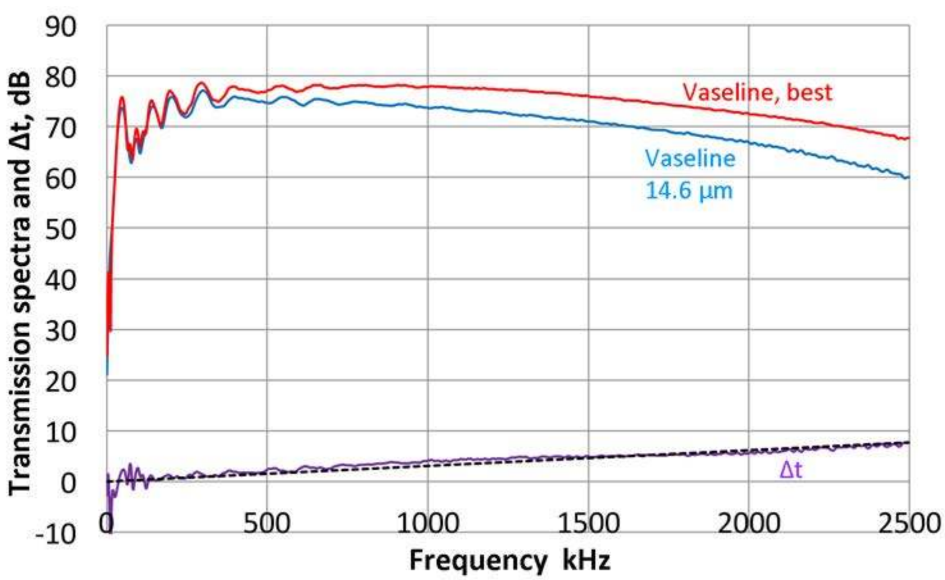

Fig. 6 Transmission spectra, t, of received signals through Vaseline couplant. Vaseline reference: red curve, Vaseline couplant after normal mounting: blue. Spectral difference, Δt, between normal and reference installation is plotted in purple curve, which follows linear frequency dependence in black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

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 m^2 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 m^2, 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.

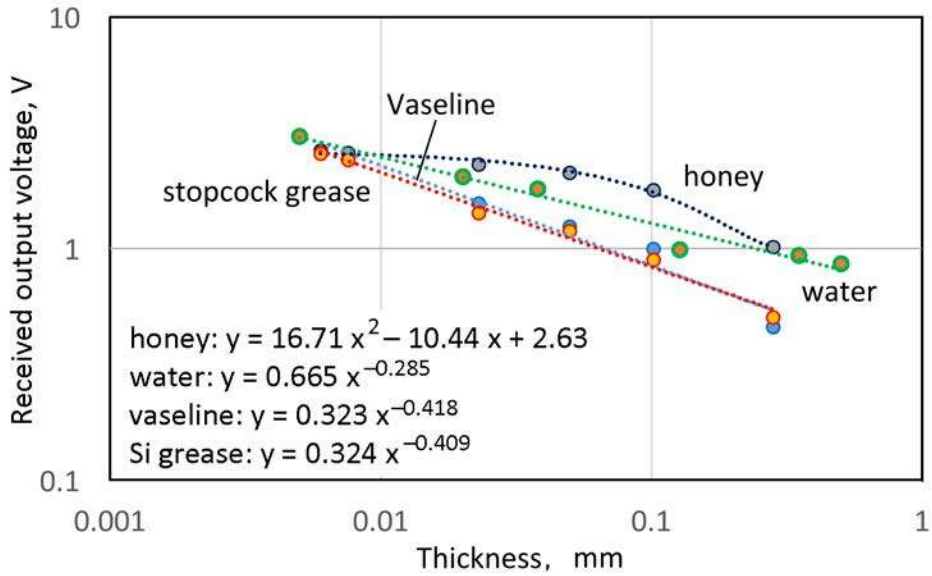

Fig. 7 Thickness dependence of output voltage of received signals through honey (dark blue), water (green), Vaseline (blue), stopcock grease (red). FC500 transmitter and Olympus V104 receiver.

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.

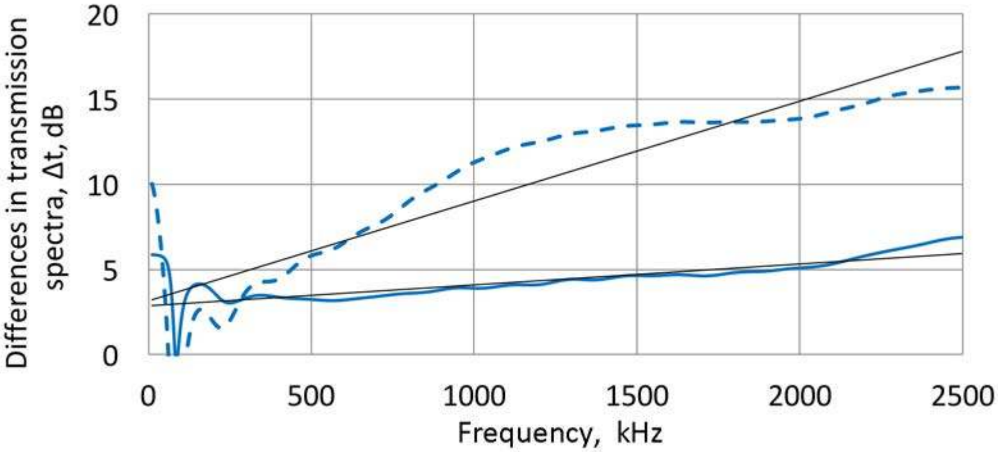

Fig. 8a Spectral difference, Δt, between reference installation and through 0.04 mm (solid) and 0.13 mm (dashed) layer of water. Δt curves follow nearly linear frequency dependence in black lines with offset. FC500 transmitter and Olympus V104 receiver.

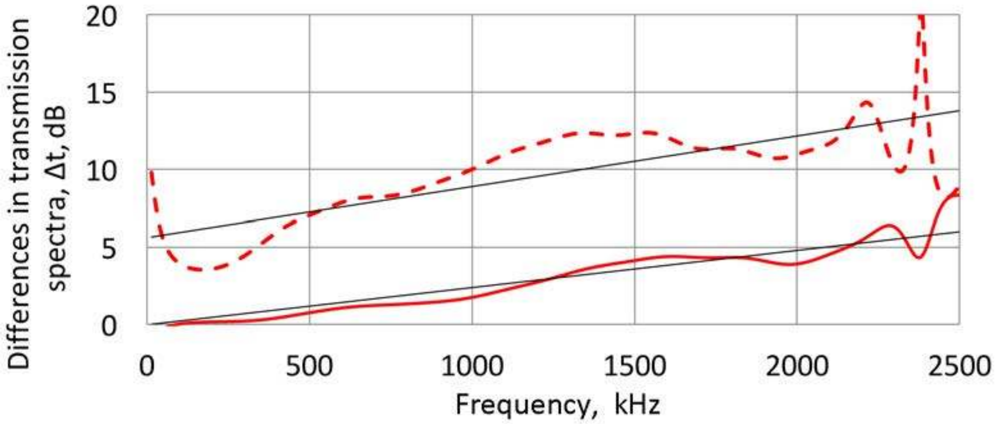

Fig. 8b Spectral difference, Δt, between reference installation and through 0.05 mm (solid) and 0.28 mm (dashed) layer of honey. Δt curves follow nearly linear frequency dependence in black lines without offset (0.05 mm) or with offset (0.28 mm). FC500 transmitter and Olympus V104 receiver.

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/2πf (V is the wave speed), or d << V/2πf, we have an approximate expression for T from Krautkramer [7] as

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

where f is the frequency, Z_g are the acoustic impedance of the gap medium with $Z_g << Z$. 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.

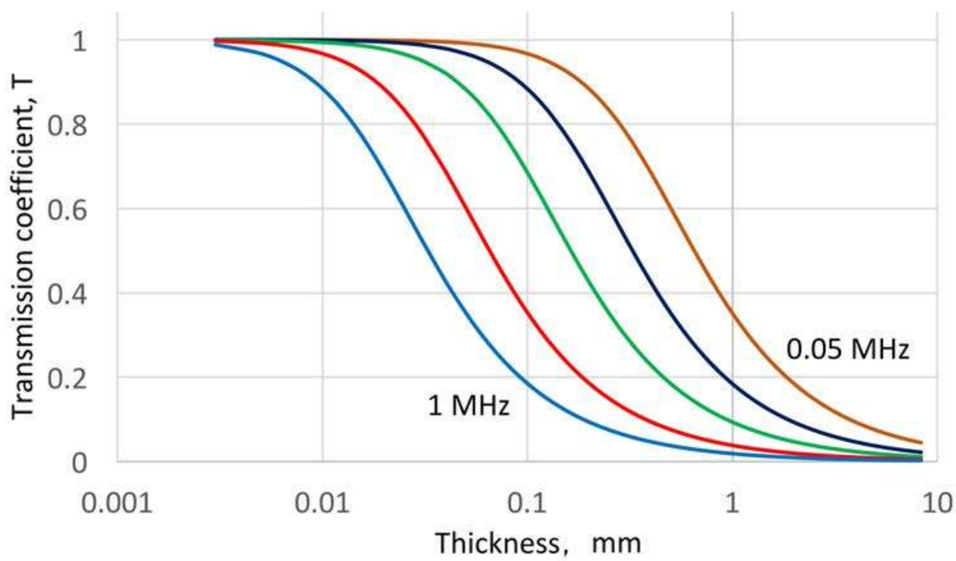

Fig. 9a Transmission coefficient, T, through a gap filled with water vs. gap thickness.
f = 1 MHz (blue curve), 0.5 MHz (red), 0.2 MHz (green), 0.1 MHz (dark blue) and 0.05 MHz (brown).

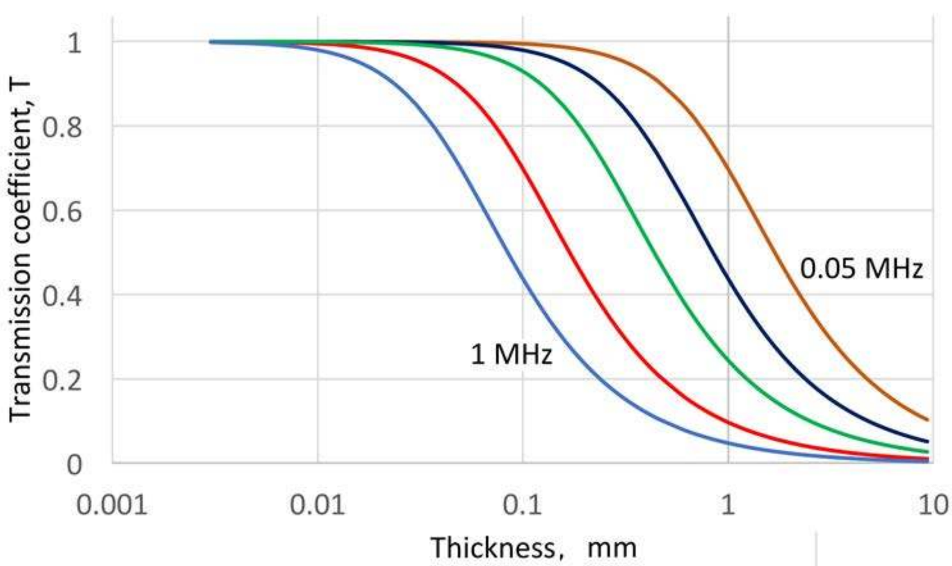

Fig. 9b Transmission coefficient, T, through a gap filled with honey vs. gap thickness. f = 1 MHz (blue curve), 0.5 MHz (red), 0.2 MHz (green), 0.1 MHz (dark blue) and 0.05 MHz (brown).

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 E+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 at –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.

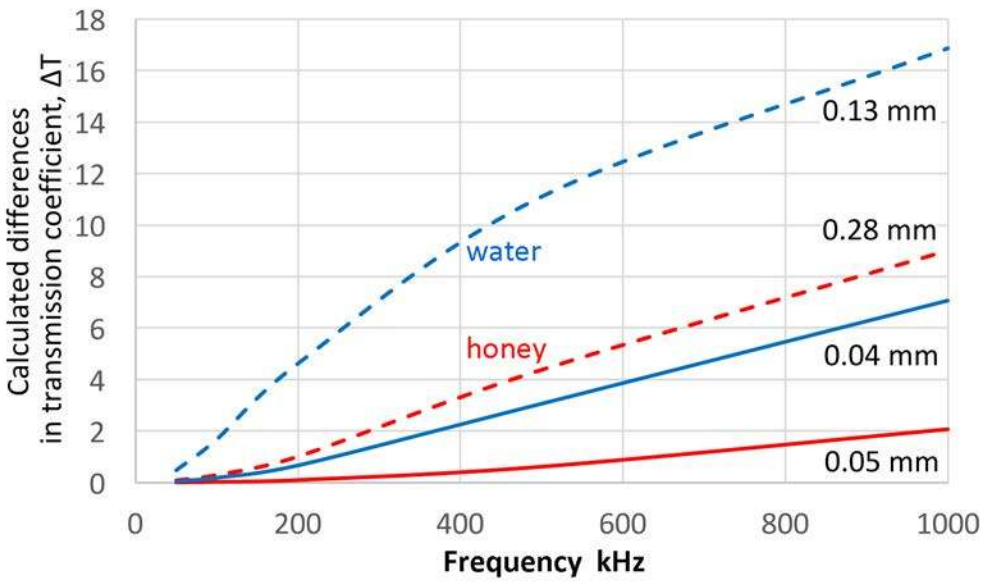

Fig. 10 Calculated differences in transmission coefficient, ΔT, through a gap filled with water and honey vs. frequency. Water thickness = 0.04 mm (blue curve), 0.13 mm (blue dash); honey thickness = 0.05 mm (red), 0.28 mm (red dash).

The reduction in transmission coefficient, ΔT, is higher at higher frequencies. Figure 10 gives the frequency dependence of ΔT 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 ΔT values are 3 to 5 dB higher than the observed values of transmission loss for water at 1 MHz: ΔT's are 7 and 17 dB (4 and 12 dB observed). For honey ΔT'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 µs and the pulse duration is ~2 µs. 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 µm. 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 µm 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.

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