

THE USE OF BIOLOGICAL MATERIALS AS COUPLING AGENTS IN ACOUSTIC ANALYSES OF MATERIALS

Andrzej Wesółowski

Department of Systems Engineering, University of Warmia and Mazury
ul. Heweliusza 14, 10-900 Olsztyn
e-mail: ika@uwm.edu.pl

Abstract. The objective of this study was to investigate the effects of organic materials used as coupling agents in acoustic analyses of biological materials. Ultrasonic wave propagation velocity was tested in steel with the application of coupling agents frequently applied in industry: Sonagel W, ŁT machine lubricant, 4W-40 motor oil and wallpaper adhesive. Ultrasonic wave propagation velocity is generally known, therefore, it was treated as a standard value. Ultrasound velocity was then determined for steel using the following organic materials as coupling agents: mains water, distilled water, liquid honey, crystallised honey, butter and vegetable oil. The evaluation criterion was the thickness of natural layer formed at the contact point between the head and the tested material which influenced measurement results, and the substances used in industry, in particular Sonagel W, liquid honey and butter were found to be such substances.

Key words: biological materials, ultrasonic non-destructive testing, coupling agent

SYMBOLS

c – ultrasonic wave velocity, (m s^{-1}),
 d – absolute error in determinations of ultrasonic wave velocity, (m s^{-1}),
 h – distance between heads (height of sample), (m),
 n_{\min} – minimal number of replications,
 S – standard deviation,
 t – ultrasound wave transmission time, (s),
 t_{α} – Student's t-distribution for confidence level coefficient $1-\alpha = 0.95$,
 g – thickness of coupling layer, (m),
 λ – wavelength, (m),
 ρ – density, (kg m^{-3}),
 D – penetration depth,
 R – reflection coefficient.

INTRODUCTION

Ultrasonic non-destructive tests are widely applied in aviation, motor, defence, and petrochemical, power engineering, construction, rail and metallurgical industries. They are performed to evaluate the macrostructure and microstructure of materials by detecting, identifying and describing macrostructural discontinuity and microstructural anomalies (Lewńska-Romicka 2001). Precise measurements require stable and effective acoustic coupling between the material and ultrasonic heads. Various coupling agents are applied for this purpose. The use of additional material between the emitter and the material and between the material and the receiver could disrupt measurements and falsify the results. In laboratory tests, it is assumed that longitudinal ultrasonic waves move in a perpendicular direction to the thin, flat and parallel surface of the couplant. Ultrasonic vibrations penetrate the layer, while some waves bounce off its surface. Penetration is characterised by the penetration depth coefficient D , and reflection – by the coefficient of reflection from the layer R . The couplant's effect on the reflection and penetration of ultrasonic waves is negligible in three cases (Obraz 1983):

1. When the thickness of the coupling layer is significantly lower than the wavelength (λ).

$$g \ll \lambda / 2\pi \quad (1)$$

2. When the thickness of the coupling layer meets condition (2):

$$g = n\lambda / 2 \quad \text{where: } n = 1, 2, 3... \quad (2)$$

3. When the thickness of the coupling layer meets conditions (3) and (4):

$$g = (2n - 1)\lambda / 4 \quad \text{where: } n = 1, 2, 3... \quad (3)$$

$$\rho_0 c_0 = \sqrt{\rho_1 c_1 \rho_2 c_2} \quad (4)$$

Then reflection coefficient $R = 0$.

In line with formula (5), the coefficient of penetration depth D takes on the maximum value of $D = 1$.

$$D = 1 + R \quad (5)$$

The above illustrates a theoretical situation in which ultrasonic waves propagate across the coupling layer without penetration loss. As regards smooth surfaces, such as metals, the required coupling layer is thin enough to exert a negligible effect on the measurements. The above does not apply to biological materials

which have a highly varied structure, even within the same genus or species. Most biological materials do not have a smooth surface, and a thicker coupling layer is required to guarantee correct coupling. The above creates problems in positioning the coupling layer relative to the surface of the heads and the sample. An additional difficulty is posed by the fact that most biological materials attenuate ultrasonic waves. For this reason, ultrasonic methods can be effectively applied only to samples with relatively small thickness. In this case, the effect of the coupling layer effect on ultrasonic measurements cannot be regarded as negligible. A certain solution is offered by contact-free methods which eliminate the use of coupling agents, but ultrasonic heads are relatively ineffective and expensive. In contact-free tests, such as the EMAT (Electromagnetic-and-Acoustic) technology, the voltage generated by the piezoelectric transducer is around one thousand times lower than in contact evaluations (Szelażek 2010).

Polymers can also be used as coupling agents. Polymers are elastic solids whose acoustic parameters are very similar to water, and those properties eliminate the need for the repeated application of coupling fluid. The absence of fluid discharge during measurements further contributes to acoustic coupling (Ginzel and Ginzel 1996). Ultrasonic heads can be dry operated to eliminate the use of couplants. The coupling effect is achieved by adjusting the ultrasound emitter and receiver. The above method supports acoustic measurements in porous materials such as cement, sandstone and chalk (Peński 2009). Methods that rely on couplants cannot be used to analyse the acoustic properties of hygroscopic materials such as chalk. Cutter-heads can also be applied to eliminate the coupling agent (Polish Patent 142739).

The above methods produce highly promising results, nevertheless, they are still at the testing stage. The vast majority of tests are performed with the involvement of conventional methods. In traditional ultrasonic evaluations, mechanical vibrations with frequency higher than 20 kHz are applied to the analysed material and, having penetrated the sample, they are measured by the receiver. The signal oscillogram is analysed to determine the condition of the evaluated material. The contact surface between the head and the sample is generally uneven and porous, and it contains air. Air has acoustic impedance of $0.0004 \cdot 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$, and steel – $46 \cdot 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$. Such significant differences in impedance produce very high reflection coefficients at the couplant-sample interface, and only 0.6% of wave energy penetrates the contact surface. The use of water with acoustic impedance of $15 \cdot 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$ improves the reflection coefficient 50-fold. Water cannot be applied to hygroscopic materials, which is why oils, solid lubricants, paint adhesives, liquid salt, honey, glycerine, vaseline, fillers and fats of different density are used. Adhesives that conduct electricity, such as epoxy glue and phenyl salicylate, are recommended for industrial tests. Aluminium and steel foil are also used as coupling agents (Rao and Ramana 1992, Li and Nordlund 1993, Tao and King 1990,

Couvreur and Thimus 1996, Azeemudin *et al.* 1994, Siggins 1993, Rummel and van Heerden 1981). No differences were noted between the results produced by viscous liquid couplants and foil (Couvreur and Thimus 1996). Research results have demonstrated that the transmission of transverse ultrasonic waves across foil is significantly affected by pressure, which obstructs evaluations and could produce unreliable results (Li and Nordlund 1993). The use of viscous liquid materials as coupling agents is thus recommended. The use of highly differentiated materials affects measurements and the results obtained.

The objective of this study was to determine the effect of various coupling agents on measurements of ultrasonic wave velocity. Special emphasis was placed on substances which are suitable for measurements of biological materials.

MATERIALS AND METHODS

Materials

The effect of various coupling agents applied in ultrasonic measurements was evaluated. A steel sample was used to validate the generated results. The sample had the shape of a cylinder with the height of 29.81 ± 0.01 mm. Coupling agents were divided into two groups. The first group comprised materials which are used in metal tests but cannot be applied in evaluations of biological materials on account of their toxicity: sonagel W (SON), ŁT machine lubricant (ML), 5W-40 motor oil (MO) and wallpaper adhesive solution of 12.5 g adhesive/250 ml water (ADH). The second group of non-toxic materials included mains water (MW), distilled water (DW), liquid honey (LH), crystallised honey (CH), butter (BUT) and vegetable oil (VO).

Measurements were performed at a temperature of 21°C. Coupling agents were stored at the above temperature for 6 h prior to testing.

Measuring devices

Coupling agents were evaluated in a specially designed test stand (Fig. 1) comprising a pulsar receiver (Panametrics 5800PR), dual-channel digital oscilloscope (Tektronix TDS 1012B), a ruler coupled with software (Suwmix), self-designed measuring module, set of ultrasonic heads (M02 2L0°20C INCO), and a PC.

The measuring module guarantees the concentricity of ultrasonic heads regardless of their diameter and distance (Wesołowski 2011). Distance is measured with the accuracy of 0.01 mm. The system supports measurements of wave transmission time with the accuracy of 0.001 μ s.

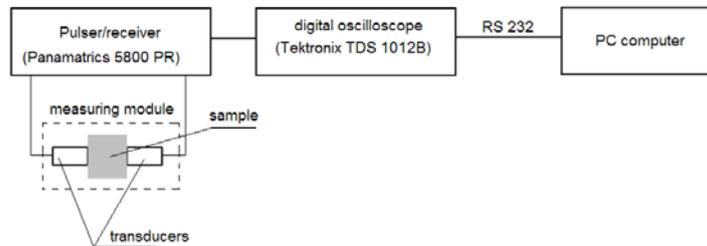


Fig. 1. Test stand (source: own elaboration)

METHODS

The minimum number of measurements for every tested material and coupling agent was determined with the use of formula (6):

$$n_{\min} \geq (S^2 \cdot t_{\alpha}^2 / d^2)^{\frac{1}{2}} \quad (6)$$

It was assumed that the absolute error in determining ultrasonic velocity would not exceed 3 m s^{-1} . If ultrasonic wave propagation velocity in steel is observed in the range of $5600\text{-}6000 \text{ m s}^{-1}$ (Blitz 1967, Deputat 1979, Matauschek 1961, Obraz

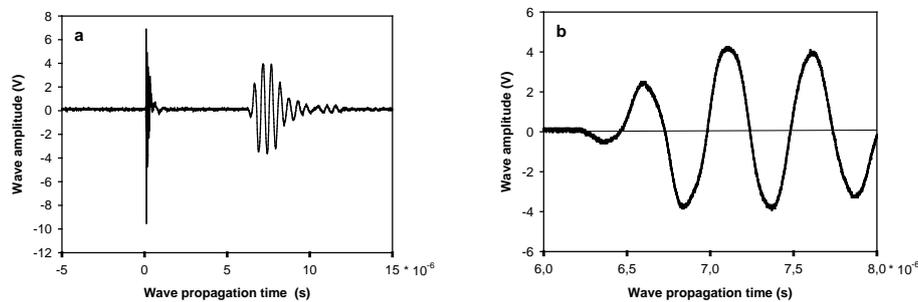


Fig. 2. Sample oscillograms

1983), the allowable absolute error accounts for 0.06% of the smallest value. Tests were carried out with the use of the transmission method and two heads with the frequency of 2 MHz. Prior to every measurement, the material was covered with a fresh layer of the coupling agent, and the sample position relative to the heads was altered. The distance between the heads was determined for every measurement. Wave transmission time was detected by the zero-crossing method. Sample oscillograms are presented in Figure 2. Measurement parameters and head frequencies were carefully selected to produce legible oscillograms which did not require addi-

tional processing.

The place of signal release by the receiver (marked with an arrow) and the signal received by the head are shown in Figure 2a. The signal received by the head at reduced voltage and increased time base is presented in Figure 2b.

Ultrasonic wave velocity was determined with the use of formula (7).

$$c = h/t \quad (\text{m s}^{-1}) \quad (7)$$

RESULTS AND DISCUSSION

Ultrasonic wave propagation velocity

The average values of ultrasonic wave velocity in steel are presented in Table 1. When crystallised honey, butter and vegetable oil were used as coupling agents, the absolute error of the obtained results was much higher in comparison with other couplants. The noted value of absolute error does not exceed the allowable limit. Propagation velocity values are consistent with the referenced data.

Table 1. Average ultrasonic wave propagation velocity in steel for various coupling agents and the average coupling layer

Coupling agent	Velocity (m s^{-1})	Error (m s^{-1})	Thickness of coupling layer (m)
Sonagel W	5735	0.6	$5 \cdot 10^{-5}$
Machine lubricant	5705	0.4	$2 \cdot 10^{-5}$
Motor oil	5687	0.2	$2 \cdot 10^{-5}$
Wallpaper adhesive	5710	0.2	$2 \cdot 10^{-5}$
Mains water	5684	0.2	$4 \cdot 10^{-5}$
Distilled water	5734	0.1	$2 \cdot 10^{-5}$
Liquid honey	5732	0.3	$3 \cdot 10^{-5}$
Crystallised honey	5621	0.9	$70 \cdot 10^{-5}$
Butter	5750	1.0	$3 \cdot 10^{-5}$
Vegetable oil	5698	2.9	$2 \cdot 10^{-5}$

Thickness of coupling layer

Due to the variability of biological materials, repeatability of acoustic coupling conditions is difficult to achieve, therefore, conditions that meet relations (2) and (3) are impossible to achieve during the test. For this reason, the analysis was carried out based on condition (1). Wavelength $\lambda_{steel} = 2.9 \cdot 10^{-3}$ m was calculated based on formula (8), and the average ultrasonic wave propagation velocity in steel was adopted at $c_{aver. steel} = 5706 \text{ m s}^{-1}$.

$$\lambda = c/f \quad (\text{m}) \quad (8)$$

The boundary value of coupling layer thickness, below which its influence on the results would be negligible, was determined for condition (1). The said value has to be significantly lower than $g = 4.5 \cdot 10^{-4}$ m. It was assumed that the boundary value should be at least 10-fold lower, i.e. lower than $g = 4.5 \cdot 10^{-5}$ m. The thickness of the analysed coupling layers is shown in Table 1. The obtained results were similar to the boundary values, and they had to be additionally validated to indicate whether the reported thickness of the coupling layer could be regarded as negligible. The only exception was crystallised honey whose thickness significantly exceeded the boundary value. The effect exerted on the results by the additional layers between the heads and the sample has to be taken into account when using crystallised honey. The above poses an additional problem in analysis. Nonetheless, unlike liquid couplants, crystallised honey does not drip, making it a suitable agent in tests involving inclined or vertical surfaces. The average values of ultrasonic wave propagation velocity in steel for the applied coupling agents were processed statistically. The noted values are not characterised by normal distribution, therefore non-parametric tests were used to compare many independent samples, even though they are weaker than parametric tests. The hypothesis claiming that selected coupling agents do not affect ultrasonic wave propagation velocity in steel was verified by the Kruskal-Wallis test. Three homogenous groups were identified (Tab. 2), and none of them created grounds for rejecting the hypothesis under verification.

Table 2. Homogenous groups for a steel sample

Group	Coupling agents
I	sonagel, distilled water, liquid honey, butter
II	machine lubricant, wallpaper adhesive, vegetable oil
III	motor oil, mains water.

Significant differences were noted between the average values of ultrasonic wave propagation velocity, even for substances which are commonly used as coupling agents in industry: sonagel W, motor oil, machine lubricant and wallpaper adhesive. Those differences can be ignored in ultrasonic conductive materials, but they have to be taken into account in materials that strongly attenuate ultrasound, i.e. most biological materials. Sonagel is produced especially for ultrasonic tests, which is why it was classified as a model substance. In the group of tested biological substances, only liquid honey and butter supported the achievement of average propagation velocities which did not differ significantly from the values reported for sonagel (Tab. 2).

The data presented in Figure 3 validates the results of homogenous group analysis. Due to a considerable distance between extreme values for crystallised honey and butter, those materials were eliminated from the list of suitable coupling agents. Homogenous groups are clearly separated, which indicates that the tested substances had a varied effect on acoustic measurements.

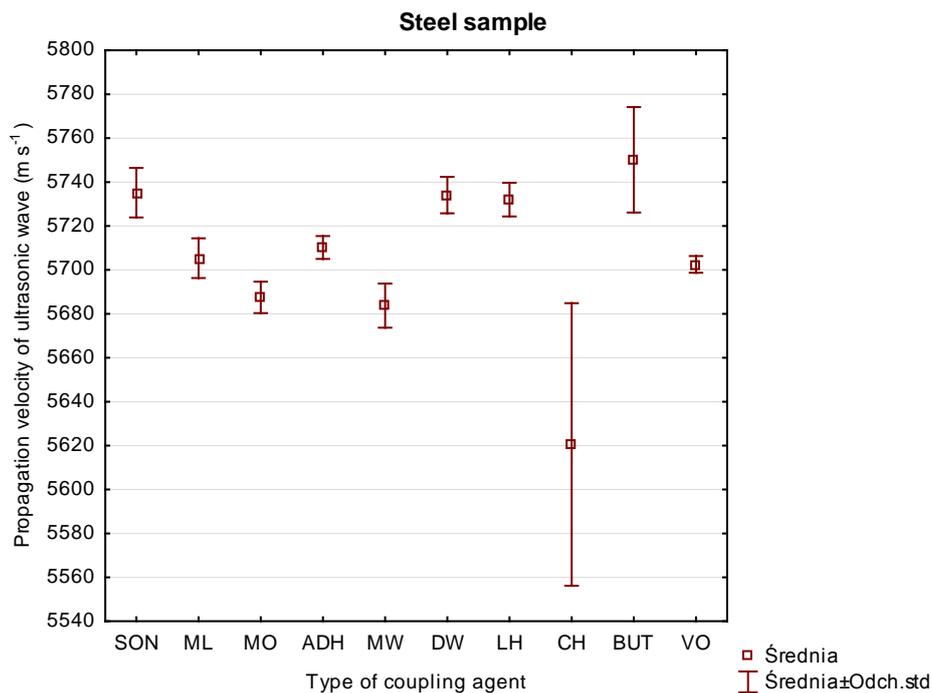


Fig. 3. Ultrasonic wave velocity subject to the applied coupling agent

Toxic materials were eliminated from the analysis. When mains water, distilled water, vegetable oil and liquid honey were used, the couplant effect on ultrasonic wave velocity in steel was negligible.

CONCLUSIONS

1. The type of acoustic coupling agent significantly affects the measurements of propagation velocity in material samples. If couplants influence measurements of relatively homogenous and smooth-surfaced materials such as steel, they can be expected to exert an even greater impact on evaluations of biological materials.

2. If sonagel W is a model acoustic coupling agent in industrial applications, then liquid honey or butter can be used alternatively in analyses of biological materials. Biological materials have to deliver a high level of acoustic coupling without exerting harmful effects on human health.

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ZASTOSOWANIE MATERIAŁÓW BIOLOGICZNYCH, JAKO OŚRODKI SPRZĘGAJĄCE W POMIARACH AKUSTYCZNYCH MATERIAŁÓW

Andrzej Wesołowski

Katedra Inżynierii Procesów Rolniczych, Uniwersytet Warmińsko-Mazurski
ul. Heweliusza 14, 10-900 Olsztyn
e-mail: ika@uwm.edu.pl

Streszczenie. Celem pracy było wykazanie przydatności wybranych materiałów organicznych, jako substancji sprzęgających w badaniach akustycznych oraz ocena ich wpływu na wyniki tych badań. Przeprowadzono pomiary prędkości propagacji fali ultradźwiękowej w stali stosując znane i stosowane w przemyśle ośrodki sprzęgające: sonagel W, smar maszynowy LT, olej silnikowy 4W-40, klej do tapet. Prędkość propagacji fali ultradźwiękowej w stali jest ogólnie znana i dlatego potraktowano ją, jako wzorzec. Następnie, również dla stali przeprowadzono pomiary prędkości fali ultradźwiękowej stosując, jako ośrodki sprzęgające materiały pochodzenia organicznego: wodę destylowaną i wodociągową, miód płynny i skryształizowany, masło, olej roślinny. Kryterium oceny tych substancji była grubość warstwy, jaką tworzą one naturalnie na styku głowicy i materiału badanego, która wpływa na wyniki pomiarów w taki sam sposób jak stosowane ogólnie w przemyśle substancje, szczególnie sonagel W. Stwierdzono, że substancjami takimi są miód płynny i masło.

Słowa kluczowe: materiały biologiczne, nieniszczące badania ultradźwiękowe, ośrodek sprzęgający