**PRODUCTION & MANUFACTURING | RESEARCH ARTICLE**

Effect of ultrasonic coupling media and surface roughness on contact transfer loss

Darjo Zuljan

**Abstract:** The study identifies and evaluates differences in contact transfer losses with different coupling media and surface roughnesses $Ra$ between 0.1 and 7 µm. The study was designed based on the non-destructive ultrasonic pulse-echo technique (UT) with a straight-beam probe (piezoelectric). The study is based on the findings of research that has been carried out stating that both the coupling media and surface roughness influence the results of UT tests to a considerable degree. The ultrasonic coupling media that are most commonly used in industry were selected: water, glycerine, UCA-2 M contact gel, U47 contact gel, mineral oils, and wallpaper paste. The selected coupling media have statistically significant influence on the ultrasonic contact transfer losses and thus also on testing results. It was found that the glycerine coupling media has the lowest contact transfer loss among the selected coupling media. The signal amplitude contact transfer differences were measured to establish the relative contact transfer losses. The observed variations in signal amplitude with reference to the types of coupling media and different surface roughnesses (from 0.1 to 7 µm) are higher than those reported by the International Atomic Energy Agency (IAEA) (2018). The contribution of the present study is the use of signal amplitude contact transfer differences to measure relative contact transfer losses since in this way the influence of parameters such as the type of ultrasonic apparatus, type of ultrasonic probe, temperature, and material of the specimen on our measurements was eliminated.

**ABOUT THE AUTHOR**

Dr. Darjo Zuljan, was born in 1963 in Slovenia. He received his doctorate in the field of Production Cybernetics, Machining Systems and Robotic at the Faculty of Mechanical Engineering, University of Ljubljana in 1997. He is Associate Professor of University of Primorska, Faculty of Education. His research activities focus on technology literacy. Since 2007 he has been the head of non-destructive testing (NDT) Personnel Qualification of the Welding Institute, Ljubljana, Slovenia. His research fields are NDT – visual testing (VT), penetrant testing (PT) and ultrasonic testing (UT) methods.

**PUBLIC INTEREST STATEMENTS**

The study with the title *Effect of ultrasonic coupling medium and surface roughness on contact transfer loss* refers to the field of non-destructive ultrasonic pulse-echo technique testing (UT), widely used in industry for the detection and evaluation of internal discontinuities in materials. The influence of the differences in coupling media and between different surface roughnesses was measured and discussed. The coupling media (water, glycerine, UCA-2M contact gel, U47 contact gel, mineral oils, and wallpaper paste) that are frequently used at UT were selected for analysis. Surface roughnesses, with $Ra$ values 0.1, 0.8, 1, and 7 µm, were selected for analysis since they are most often present in welded structures. Results of this research help controllers to correct UT results. The results obtained have practical importance for inspectors when inspecting structures and will be useful as corrections, and for high-level inspectors who plan instructions and procedures for inspections.
1. Introduction
Ultrasound can be used in a wide field of applications: high-intensity ultrasound (cleaning, machining, drilling, soldering), chemical and electrical use, medical applications (imaging, diagnosis, ultrasonic microscopy, therapy, and surgery), non-destructive material testing, flow meters, and ranging and navigation. Ultrasonic testing (UT) is a family of non-destructive testing techniques based on the propagation of ultrasonic waves in the object or material tested. The sound waves travel through the material with a certain corresponding loss of pressure and are reflected at interfaces. The reflected beam is displayed and then analyzed to define the presence and location of flaws or discontinuities (International Atomic Energy Agency, 2018, pp. 134–149; Bar-Cohn & Mal, 1989; Krautkrämer & Krautkrämer, 2013; Workman et al., 2007).

Small defect sizing using ultrasound is a complex task. In the daily routine of ultrasonic operators, defect sizing is done by comparing the signal (echo) maximum amplitude of a natural defect to the maximum amplitude generated by an artificial defect (large planar reflectors, flat-bottomed holes (FBH), side-drilled holes (SDH), notches of various cross-sections) at the same distance from the transducer as the natural defect (Kleinert, 2016, pp. 1, International Organization for Standardization, 2014a). International Organization for Standardization (2014b) notes that “adaptation of these techniques for the sizing is limited to the case where the dimension of the zone on the scanning surface corresponding to the signal amplitude reduction below the evaluation level is less than the probe dimension projected on the scanning surface” (p. 8).

The correct calibration of the range and sensitivity setting of ultrasonic devices is crucial for the correct evaluation of the indications in the test samples. Range and sensitivity settings are thus carried out prior to each testing. Checks are also carried out whenever a system parameter is changed or changes in the equivalent settings are suspended. The range setting of the ultrasonic devices is calibrated using an International Institute of Welding calibration block (V1) (International Organization for Standardization, 2014c; International Atomic Energy Agency, 2018, pp. 207–222).

1.1. Calibration block (V1) and reference blocks (RB)
The ultrasonic measuring system shall be calibrated on one or more calibration blocks, reference or specific blocks representative of the object to be measured, i.e. having comparable dimensions, material, structure, and surface roughness. When amplitudes of echoes from the object are compared with echoes from a calibration block, certain requirements relating to the material, surface condition, temperature of the block, possibility of chemical reactions between test surfaces and coupling medium, cleaning requirements, and geometry shall be observed. Where possible, the reference block shall be made of material with acoustic properties which are within a specified range with respect to the material to be examined and shall have a surface condition comparable to that of the object to be examined. If these characteristics are not the same, a transfer correction shall be applied (Kleinert, 2016; International Organization for Standardization, 2019, p. 3).

1.2. Ultrasonic transducers and coupling medium
An ultrasonic transducer is the active element of the probe which converts electrical energy into sound, and vice versa, and the term typically refers to piezoelectric transducers (IAEA, 1999) or capacitive transducers (Maity et al., 2019a, 2019b, 2018a, 2018b; Savoia et al., 2012). Ultrasound propagates in different materials which are made of atoms (or molecules) that are connected to each other by an interaction force. Electromechanical transducers are far more versatile and include piezoelectric and magnetostrictive devices. Non-destructive material testing involves the use of ultrasonic echolocation to gather information on the integrity of mechanical structures.
A proper coupling media should be used between the probe (piezoelectric) and the specimen to improve the transmission of ultrasonic energy between them.

Acoustic contact between probe (probes) and material has to be provided, normally by the application of a coupling medium. A proper coupling media should be used between the probe and the test specimen to achieve the transmission of ultrasonic energy by eliminating air. The coupling media should be selected to suit the surface conditions and the irregularities of the surface to ensure adequate coupling. Contact transfer losses represent the reduction of sound transmission across the interface between a probe and a test object. Different coupling media can be used, but their type shall be compatible with the materials to be examined. Examples include water (possibly containing some agent, e.g., wetting, anti-freeze, corrosion inhibitor), contact paste, oil, cellulose paste (containing water), glycerine, petroleum greases, silicone grease, wallpaper paste, and various commercial paste-like substances. The characteristics of the coupling media shall remain constant throughout the verification, calibration operations, and examination. The coupling media shall be suitable for the temperature range in which it will be used. If the constancy of characteristics cannot be guaranteed during calibration and examination, a transfer correction shall be applied (Bar-Cohn & Mal, 1989, p. 543; Workman et al., 2007, pp. 221–223; International Organization for Standardization, 2014a, p. 5, 2019, p. 3; International Atomic Energy Agency, 2018, pp. 203–204; Kumar, 1996).

1.3. Ultrasonic transfer loss
During propagation, an ultrasonic wave suffers from three different losses (International Organization for Standardization, 2014c, p. 35):

- Divergence losses ($V_D$) caused by the probe and the material. With distance the sound pressure decreases;
- Attenuation losses ($V_A$) caused by the material of the test object (absorption and scattering);
- Contact transfer losses ($V_{CT}$) caused by the contact matching of the probe to the test object via a coupling medium.

To measure these contact transfer losses the divergence losses and attenuation losses have to be eliminated. To keep these $V_A$ and $V_D$ losses constant during the measurement, a set of experimental schemes made of the same material are used with the same probe under constant coupling conditions (load, rest time, temperature).

Li and Nordlung (1993) showed the effects of coupling on acoustic transmission. The purpose of this study was to examine the pulse wave transmission of aluminium foils and a few liquid media as an acoustic coupling medium. Li and Nordlung (1993) noted that “the coupling condition is one of the most important factors influencing the transmissibility of pulse waves. Considering the technical difficulty in obtaining a perfect coupling condition with metal foil, it is recommended to use viscous liquids as acoustic coupling media in pulse wave measurements” (p. 69). Kumar et al. (2005) described the effects of coupling conditions on signal (echo) parameters. A detailed analysis was given on various echo parameters, such as peak frequency, amplitude, their ratios, etc., for first and second back wall echoes. Netshidavhini and Mabuza (2012) described the effects of various coupling media on carbon steel and aluminium materials using ultrasonic testing. Their study shows that coupling media are a requirement for all contact ultrasonic testing to be successful. According to their findings, coupling media has major effect on transfer losses, and the most suitable coupling media is honey, useful to obtain better results during defect detection. This study also shows that coupling media with high acoustic impedance and high transmission coefficient are most effective for defect detection. Nagy and Adler (1987) analyzed surface roughness-induced contact transfer losses of reflected and transmitted ultrasonic waves. The transmitted wave is shown to be attenuated in a way similar to the reflected one, and their transfer losses ratio is found to be independent of frequency in the considered cases of slight surface roughness. The surface roughness-induced transfer losses mainly depend on
the RMS (Root Mean Square) roughness, but, in the case of strong roughness, it becomes increasingly dependent on the surface profile as well.

A survey of existent studies makes it clear that several studies focused on the effect of coupling media and surface roughness on ultrasonic test results. We have established that each study examined different aspects of the study topic (different types of probes, different frequencies used, different test techniques, different surface roughnesses). All these studies confirm that coupling media and surface roughness affect test results.

2. Empirical part

2.1. Aim and objectives of the study

Based on the studies performed and on valid standards it is known that different coupling media and different surface roughnesses have significant influences on the UT test results without, however, their characteristics having been identified, so our focus was on determining them in a way that will be useful to ultrasonic controllers. The aim of the quantitative experimental study is to analyze and evaluate contact transfer losses with different coupling media and with different surface roughnesses Ra (values between 0.1 and 7 µm). When there is a change of a coupling media or surface roughness, standards (American Society of Mechanical Engineers, 2015; International Organization for Standardization, 2014a) recommend a re-calibration of ultrasonic devices, without mentioning the values of these changes.

For the purpose of our study the following hypotheses were set:

H1). The coupling media selected for the study (water, glycerine, UCA-2 M contact gel, U47 contact gel, mineral oil, wallpaper paste) show statistically significant differences regarding ultrasound attenuation.
H2). In the study, the selected surface roughnesses (Ra values are 0.1, 1, and 7 μm) show statistically significant differences regarding ultrasound attenuation.

H3). The lowest ultrasound attenuation appears in glycerine.

A t-test for independent samples was used to check whether average values of ultrasound attenuation in different coupling media and different surface roughnesses show statistically significant differences.

Knowing the coupling media enables us to correctly choose and work precisely with ultrasonic devices. The purpose of finding the differences in contact transfer losses is to determine the ultrasonic transfer correction when changing the coupling media or in changing the surface roughness without re-calibrating the ultrasonic device.

2.2. Work methodology
In the study, the contact transfer loss of the coupling media was measured with a straight-beam probe in the reflection of ultrasound from an SDH with a diameter of 3 mm. The contact transfer loss in the coupling media was measured by simulating the conditions of the ultrasonic controller in an industrial setting (Figure 1). We used the CN4R-10 straight-beam probe with longitudinal waves with the PE technique. For the purpose of the research, 720 measurements were carried out. To ensure the same conditions throughout the study, the ultrasonic probe was weighted with a 0.2 kg weight.

2.3. Equipment used
For the purpose of the experiment, the following equipment was used:

- Ultrasonic device: OLYMPUS EPOCH 650;
- Straight-beam probe: OLYMPUS PANAMETRICS NDT TM, CN4R-10. 4 MHz, No.: 645576.
- International Institute of Welding (I.I.W) calibration block (V1): S355J0, GE59108-5115, EN 12223 and Ra<0.8 μm;
- Reference block (RB): S355J0, Ra = 0.1 μm, Ra = 1 μm and Ra = 7 μm—sandblasted surface;
- Reference reflector: 3 mm SDH;
- Weight: 0.2 kg;
- Room temperature: 21°C.

Coupling media used:

- Water;
- Glycerine, KEFO d.o.o.;
- UCA-2 M contact gel, Chemell;
- U47 contact gel, PASTA DI ACCOPPIAMENTO CGM, Cigiemme s.r.l.;
- Mineral oil (MO) for vacuum pumps, WIMAG K1L;
- Wallpaper paste (WPP), METYLAN normal HENKEL in water, mixing ratio 1:80.

A coupling media was added to the measurement site as needed. The duration of the experiment was 6 hours. Measurement of the amplitude with the coupling media used was carried out at the following time intervals: 15 min, 30 min, and 1, 1.5, 2, 2.5, 3, 4, and 6 hours.
2.4. Data processing
The obtained data were processed with the IBM SPSS Statistics Version 25 statistical software. The data were processed at the descriptive and inferential statistical levels. For the purpose of checking differences, the paired-sample t-test for independent samples was applied.

2.5. Research results and discussion
Contact transfer losses were detected by a straight-beam probe with a pulse-echo technique (PE) in the reflection of ultrasound from SDH as shown in Figure 1. The path of ultrasound s (mm) was calibrated using a V1 block so that there were two reflections from SDH on the A-scan. The first reflection of the ultrasound from SDH was strengthened to 80% of the vertical scale of the ultrasonic device A-scan. The position of the ultrasonic probe was adjusted to achieve an amplitude of 80% of the scale at the minimum gain and record the signal amplitude. The signal amplitude record (dB) represents the ultrasonic transfer losses when passing through the calibration block, the coupling medium, and the surface roughness. In order to compare the contact transfer losses between the various coupling media, the difference in the contact transfer loss was calculated. We decided to calculate signal amplitude contact transfer differences in order to eliminate the influences on the measurements by the type of ultrasonic apparatus, type of ultrasonic probe, temperature, and material of the test specimen. We built on the assumption that, similar to the evaluation of small reflectors (DAC, DGS techniques), by measuring the difference of signal amplitude between natural indication and reference reflectors (side-drilled holes, flat-bottomed holes, notches), we can evaluate a coupling media by measuring signal amplitude differences between the coupling media and glycerine as the reference coupling medium.

The signal amplitude contact transfer difference between the coupling media was calculated using Equation (1):

\[ V_{CT} = V_1 - V_2 \]  

(1)

Whereby:

\[ \Delta V_{CT} \text{(dB)} \] — Signal (echo) amplitude contact transfer difference;

\[ V_1 \text{ (dB)} \] — Signal amplitude when using the coupling media 1;

\[ V_2 \text{ (dB)} \] — Signal amplitude when using the coupling media 2.

In a similar way, by measuring signal amplitude differences between the actual surface roughness and the reference surface roughness at \( Ra = 0.1 \mu m \), we can evaluate the influence of surface roughness on transfer losses. The purpose of measuring signal amplitude difference is to determine the error size (dB) made by the controller when changing the coupling media or when changing the roughness of the surface without re-calibrating the ultrasonic device. With the wallpaper paste or U 47 contact gel coupling medium, the drying begins after 90 minutes. Drying of the coupling media increases transfer losses in the coupling media and is therefore not allowed. The wallpaper paste or the U47 contact gel can only be used for up to 90 minutes, after which we suggest complete removal and the application of a fresh coupling medium.

2.6. Signal amplitude difference for different pairs of coupling media on the V1 block
Table 1 shows the results of the t-test for checking the differences in the signal amplitude for the various pairs of coupling media on the V1 block. A statistically significant difference in signal amplitude was found between most of the analyzed pairs of coupling media on the V1 block with the surface roughness (Ra) of 0.8 \( \mu m \) (t between 3.79 and 105.943, p < .001). It was confirmed that the ultrasonic coupling media differs according to the ultrasonic properties analyzed. The high signal amplitude difference occurred between mineral oil and glycerine (5.9 dB) and water and
Table 1. Results of the t-test of the signal amplitude difference (ΔV<sub>CT</sub>) for different pairs of coupling media on V1 block (Ra ≤ 0.8 µm)

| Pairs of coupling media | Paired sample test (Paired difference) |  |
|-------------------------|--------------------------------------|--|
|                         | M (dB) | SD (dB) | 95% CI | t     | df | p    |
| MO—Glycerine            | 5.9    | 0.321   | 5.81 6.04 | 105.943 | 32 | < .001 |
| Water—Glycerine         | 4.5    | 0.194   | 4.40 4.54 | 132.382 | 32 | < .001 |
| WPP—Glycerine           | 4.3    | 0.167   | 4.22 4.34 | 147.566 | 32 | < .001 |
| U47—Glycerine           | 4.0    | 0.210   | 3.91 4.06 | 109.324 | 32 | < .001 |
| MO—UCA-2M               | 3.5    | 1.198   | 3.09 3.94 | 16.866  | 32 | < .001 |
| UCA-2M—Glycerine        | 2.4    | 1.057   | 2.03 2.78 | 13.097  | 32 | < .001 |
| Water—UCA-2M            | 2.1    | 0.921   | 1.73 2.39 | 12.873  | 32 | < .001 |
| WPP—UCA-2M              | 1.9    | 0.992   | 1.52 2.22 | 10.842  | 32 | < .001 |
| MO—U47                 | 1.9    | 0.282   | 1.83 2.03 | 22.09   | 32 | < .001 |
| U47—UCA-2M             | 1.6    | 1.090   | 1.19 1.96 | 8.335   | 32 | < .001 |
| MO—WPP                 | 1.6    | 0.383   | 1.50 1.78 | 13.79   | 32 | < .001 |
| MO—Water               | 1.5    | 0.440   | 1.29 1.61 | 18.980  | 32 | < .001 |
| Water—U47              | 0.5    | 0.263   | 0.38 0.57 | 10.534  | 32 | < .001 |
| WPP—U47                | 0.3    | 0.247   | 0.20 0.37 | 3.79    | 32 | < .001 |
| Water—WPP              | 0.2    | 0.159   | 0.13 0.24 | 6.905   | 32 | < .001 |

CI = confidence interval; LL = lower limit; UL = upper limit.
Table 2. Results of the t-test of the signal amplitude difference ($\Delta V_{\text{st}}$) for different pairs of coupling media on RB block (Ra = 0.1 \text{ \textmu m})

| Pairs of coupling media | Paired sample test (Paired difference) |
|-------------------------|----------------------------------------|
|                         | $M$ (dB) | $SD$ (dB) | $95\%$ CI | $t$ | $df$ | $p$ |
| Water—Glycerine         | 7.15     | 0.940     | 6.81–7.49 | 43.041 | 31 | <.001 |
| MO—Glycerine            | 6.60     | 1.185     | 6.17–7.02 | 31.482 | 31 | <.001 |
| WPP—Glycerine           | 5.39     | 0.926     | 5.06–5.73 | 32.964 | 31 | <.001 |
| U47—Glycerine           | 4.82     | 0.382     | 4.68–4.96 | 71.322 | 31 | <.001 |
| Water—UCA-2 M           | 4.74     | 1.260     | 4.29–5.20 | 21.298 | 31 | <.001 |
| MO—UCA-2 M             | 4.19     | 1.420     | 3.68–4.70 | 16.705 | 31 | <.001 |
| WPP—UCA-2 M            | 2.99     | 0.528     | 2.79–3.18 | 31.995 | 31 | <.001 |
| U47—UCA-2 M            | 2.41     | 0.569     | 2.21–2.62 | 24.032 | 31 | <.001 |
| UCA-2 M—Glycerine       | 2.40     | 0.560     | 2.20–2.60 | 24.285 | 31 | <.001 |
| U47—Water              | 2.32     | 1.089     | 1.93–2.72 | 12.087 | 31 | <.001 |
| MO—U47                 | 1.77     | 1.247     | 1.32–2.22 | 8.046  | 31 | <.001 |
| Water—WPP              | 1.75     | 1.608     | 1.17–2.33 | 6.175  | 31 | <.001 |
| MO—WPP                 | 1.20     | 1.581     | 0.63–1.77 | 4.302  | 31 | <.001 |
| WPP—U47                | 0.57     | 0.955     | 0.22–0.91 | 3.387  | 31 | .002  |
| MO—Water               | 0.55     | 1.527     | 0.00–1.10 | 2.049  | 31 | .049  |

CI = confidence interval; LL = lower limit; UL = upper limit.

glycerine (4.5 dB). The low signal amplitude difference occurred between water and wallpaper paste (0.20 dB) and wallpaper paste and the U47 contact gel (0.3 dB). It was noted that glycerine had the lowest transfer loss (between contact media analyzed).

2.7. Signal amplitude difference for different pairs of coupling media on the RB block

Table 2 shows the results of the t-test for checking the differences in the signal amplitude for the various pairs of coupling media on RB block with a surface roughness of Ra = 0.1 \text{ \textmu m}. The highest signal amplitude difference occurred between the water and glycerine pair of coupling media (7.15 dB). The lowest signal amplitude difference occurred between mineral oil and water (0.55 dB) and between wallpaper paste and the U47 contact gel (0.57 dB). It was found that glycerine had the lowest ultrasound transfer loss (Tables 1-4).

A statistically significant difference in signal amplitude was found between most of the analyzed pairs of coupling media on the RB block with the surface roughness (Ra) of 0.1 \text{ \textmu m} (t between 4.302 and 43.041, p < .001). The ultrasonic properties of all ultrasonic coupling media are statistically significantly different.

Table 3 shows the results of the t-test for checking the differences in the ultrasonic contact transfer loss for the various pairs of coupling media on RB block with a surface roughness of Ra = 1 \text{ \textmu m}. A statistically significant difference in signal amplitude was found between most of the


Table 3. Results of the t-test of the signal amplitude difference ($\Delta V_{\text{ct}}$) for different pairs of coupling media on RB block (Ra = 1 µm)

| Pairs of coupling media | Paired sample test (Paired difference) |
|-------------------------|---------------------------------------|
|                         | $M$ (dB) | $SD$ (dB) | 95% CI | $t$ | $df$ | $p$ |
| MO—Glycerine            | 3.90     | 0.48      | 3.75 4.05 | 52.24 | 40 | <.001 |
| U47—Glycerine           | 2.82     | 1.52      | 2.34 3.29 | 11.90 | 40 | <.001 |
| Water—Glycerine         | 2.81     | 1.27      | 2.40 3.21 | 14.14 | 40 | <.001 |
| MO—UCA-2 M              | 2.56     | 1.01      | 2.24 2.88 | 16.17 | 40 | <.001 |
| MO—WPP                 | 2.42     | 0.99      | 2.10 2.73 | 15.55 | 40 | <.001 |
| WPP—Glycerine           | 1.48     | 0.98      | 1.17 1.79 | 9.70  | 40 | <.001 |
| U47—UCA-2 M             | 1.48     | 2.11      | 0.81 2.14 | 4.49  | 40 | <.001 |
| Water—UCA-2 M           | 1.47     | 1.03      | 1.14 1.79 | 9.10  | 40 | <.001 |
| UCA-2 M—Glycerine       | 1.33     | 0.94      | 1.04 1.63 | 9.10  | 40 | <.001 |
| U47—WPP                | 1.33     | 1.50      | 0.86 1.81 | 5.68  | 40 | <.001 |
| Water—WPP              | 1.32     | 0.791     | 1.57 1.07 | 10.73 | 40 | <.001 |
| MO—Water               | 1.09     | 1.27      | 0.68 1.49 | 5.48  | 40 | <.001 |
| MO—U47                 | 1.08     | 1.43      | 0.62 1.53 | 4.83  | 40 | <.001 |
| WPP—UCA-2 M            | 0.14     | 1.06      | -0.19 0.48 | 0.86 | 40 | .394 |
| U47—Water              | 0.00     | 2.01      | -0.62 0.64 | 0.03 | 40 | .975 |

CI = confidence interval; LL = lower limit; UL = upper limit.

analyzed pairs of coupling media on the RB block with the surface roughness (Ra) of 1 µm ($t$ between 4.83 and 52.24, $p < .001$). The highest difference in contact transfer losses occurred when comparing mineral oil and glycerine (3.90 dB) and the U47 contact gel and glycerine (2.82 dB). The lowest difference in contact transfer losses occurred with the wallpaper paste and the UCA-2 M contact gel (0.14 dB). No differences in contact transfer losses occurred with the U47 contact gel and water (0.00 dB). It was found that the difference between wallpaper paste and UCA-2 M contact gel was not statistically significant ($p = .394$), and the same was found for the difference between U47 contact gel and water ($p = .975$).

Table 4 shows the results of the t-test for checking the differences in the ultrasonic contact transfer loss for the various pairs of coupling media on RB block with a surface roughness of $Ra = 7$ µm. A statistically significant difference in signal amplitude was found between most of the analyzed pairs of coupling media on the RB block with the surface roughness (Ra) of 7 µm ($t$ between 6.55 and 48.98, $p < .001$). There was no statistically significant difference ($p = .451$) between the WPP and water coupling medium, on the surface with the surface roughness (Ra) of 7 µm. We assume that this occurred due to the composition of WPP, consisting of the METYLAN normal HENKEL glue and water, mixing ratio 1:80. The properties of most ultrasonic coupling media differ. It was found that the glycerine coupling media at surface roughness (Ra) 0.1 µm had the lowest contact transfer loss; therefore, it was chosen for the reference to calculate the signal amplitude difference (Table 6). It was found that the coupling media analyzed had different
Table 4. Results of the t-test of the signal amplitude difference ($\Delta V_{\text{CT}}$) for different pairs of coupling media on RB block (Ra = 7 µm)

| Pairs of coupling media | Paired difference | Paired sample test |
|-------------------------|-------------------|--------------------|
|                         | $M$ (dB) | $SD$ (dB) | $95\%$ CI $LL$ $UL$ | $t$ | $df$ | $p$ |
| MO—Glycerine            | 10.40 | 1.20 | 9.96 10.83 | 48.98 | 31 | < .001 |
| WPP—Glycerine           | 7.49 | 1.36 | 7.00 7.98 | 31.00 | 31 | < .001 |
| Water—Glycerine         | 7.40 | 1.48 | 6.87 7.94 | 28.23 | 31 | < .001 |
| U47—Glycerine           | 6.51 | 1.40 | 6.01 7.02 | 26.32 | 31 | < .001 |
| MO—UCA-2 M              | 6.06 | 1.07 | 5.67 6.45 | 31.90 | 31 | < .001 |
| UCA-2 M—Glycerine       | 4.34 | 1.35 | 3.85 4.82 | 18.12 | 31 | < .001 |
| MO—U47                  | 3.88 | 1.08 | 3.49 4.27 | 20.21 | 31 | < .001 |
| WPP—UCA-2 M             | 3.15 | 0.38 | 3.01 3.29 | 46.00 | 31 | < .001 |
| Water—UCA-2 M           | 3.06 | 0.59 | 2.85 3.28 | 29.34 | 31 | < .001 |
| MO—Water                | 2.99 | 1.17 | 2.56 3.41 | 14.37 | 31 | < .001 |
| MO—WPP                  | 2.90 | 1.22 | 2.46 3.35 | 13.41 | 31 | < .001 |
| U47—UCA-2 M             | 2.17 | 0.48 | 2.00 2.34 | 25.35 | 31 | < .001 |
| WPP—U47                 | 0.97 | 0.63 | 0.75 1.20 | 8.75  | 31 | < .001 |
| Water—U47               | 0.89 | 0.77 | 0.61 1.17 | 6.55  | 31 | < .001 |
| WPP—Water               | 0.08 | 0.62 | −0.14 0.31 | 0.76  | 31 | .451  |

CI = confidence interval; LL = lower limit; UL = upper limit.

Signal amplitudes when compared to the glycerine coupling medium ($\Delta V_{\text{CT}}$ between 1.33 and 10.4 dB) (Tables 3 and 5). By calculating the paired difference of signal amplitude, the influences of the ultrasonic device, probe, material (S355J0), and temperature on the signal amplitude were eliminated.

2.8. Signal amplitude difference on the RB block and the V1 block with varied surface roughness

Table 5 shows the results of the analysis of the paired differences of signal amplitude on the RB and V1 block with varied surface roughness. A high paired difference of signal amplitude ($\Delta V_{\text{CT}}$ between 11.32 and 15.81 dB) occurred with the majority of the coupling media on the reference block with the roughnesses (Ra) of 0.8 µm and 7 µm. A statistically significant difference in signal amplitude was found between all the analyzed pairs of coupling media on the RB and V1 blocks with the surface roughnesses (Ra) of 0.1, 0.8, 1, and 7 µm; they appear due to differences in roughness.

From the results of the t-test, it was found that the signal amplitude differences, with surface roughnesses Ra = 0.1, 0.8, 1 and 7 µm and with different coupling media, were statistically significant ($t$ between 3.59 and 227.93, $p$ between < .001 and .001). When the surface roughness changes (Ra = 0.1, 0.8, 1 and 7 µm) during the test, the ultrasonic device has to be re-calibrated.
Table 5. Results of the t-test of the signal amplitude difference (ΔV<sub>CT</sub>) for different pairs with varied surface roughness on RB and V1 blocks

| Coupling media | Pairs RB, Ra—V1 (RB), Ra | Paired sample test | Paired difference |
|----------------|--------------------------|--------------------|-------------------|
|                |                          | M (dB)             | SD (dB)           | 95 % CI LL UL | t      | df    | p     |
| Water          | RB, Ra = 7—V1, Ra = 0.8  | 14.27              | 0.39              | 14.12 14.41   | 205.07 | 31    | <.001 |
|                | RB, Ra = 7—RB, Ra = 1    | 12.5               | 0.79              | 12.21 12.78   | 89.38  | 31    | <.001 |
|                | RB, Ra = 1—RB, Ra = 0.1  | 0.6                | 1.03              | 0.28 1.02     | 3.59   | 31    | .001  |
| Glycerine      | RB, Ra = 7—V1, Ra = 0.8  | 11.32              | 1.37              | 10.83 11.82   | 46.62  | 31    | <.001 |
|                | RB, Ra = 7—RB, Ra = 1    | 8.35               | 1.54              | 7.79 8.90     | 30.67  | 31    | <.001 |
|                | RB, Ra = 1—RB, Ra = 0.1  | 4.55               | 1.14              | 4.96 4.13     | 22.5   | 31    | .001  |
| UCA ~2 M       | RB, Ra = 7—V1, Ra = 0.8  | 13.25              | 0.91              | 12.93 13.58   | 82.15  | 31    | <.001 |
|                | RB, Ra = 7—RB, Ra = 1    | 10.9               | 0.84              | 10.68 11.29   | 73.85  | 31    | <.001 |
|                | RB, Ra = 1—RB, Ra = 0.1  | 3.84               | 1.12              | 3.43 4.25     | 19.273 | 31    | <.001 |
| U47            | RB, Ra = 7—V1, Ra = 0.8  | 13.85              | 0.61              | 13.63 14.07   | 126.51 | 31    | <.001 |
|                | RB, Ra = 7—RB, Ra = 1    | 12.5               | 0.78              | 12.28 12.84   | 90.81  | 31    | <.001 |
|                | RB, Ra = 1—RB, Ra = 0.1  | 2.02               | 0.72              | 1.76 2.28     | 15.88  | 31    | <.001 |
### Table 5. (Continued)

| Coupling media | Pairs | M (dB) | SD (dB) | 95% CI | t  | df | p     |
|----------------|-------|--------|---------|--------|----|----|-------|
|                |       |        |         | LL     | UL |    |       |
| MO             | RB, Ra = 7—V1, Ra = 0.8 | 15.81 | 1.11    | 15.40  | 16.21 | 79.93 | 31   | <.001 |
|                | RB, Ra = 7—RB, Ra = 1    | 14.8  | 1.13    | 14.46  | 15.28 | 14.56 | 31   | <.001 |
|                | RB, Ra = 1—RB, Ra = 0.1  | 1.83  | 1.41    | 1.32   | 2.34  | 7.32  | 31   | <.001 |
| WPP            | RB, Ra = 7—V1, Ra = 0.8  | 14.54 | 0.36    | 14.41  | 14.67 | 227.93 | 31 | <.001 |
|                | RB, Ra = 7—RB, Ra = 1    | 14.2  | 0.62    | 14.00  | 14.45 | 128.8 | 31   | <.001 |
|                | RB, Ra = 1—RB, Ra = 0.1  | 0.76  | 0.88    | 0.44   | 1.08  | 4.90  | 31   | <.001 |

CI = confidence interval; LL = lower limit; UL = upper limit; Ra (µm) = Surface roughness; V1 = Calibration block; RB = Reference block.
sensitivity setting), which is confirmed by the recommendations of standards (American Society of Mechanical Engineers, 2015; International Organization for Standardization, 2014a).

2.9. Variations of signal amplitude difference with types of coupling media and varied surface roughness on RB block with respect to glycerine

When establishing the influence of the type of coupling media and surface roughness on transfer losses, glycerine as a coupling media and surface roughness of 0.1 µm were selected as the reference, since they have the lowest contact transfer losses. Table 6 shows the variation of signal amplitude contact transfer difference (ΔV_{CT \text{Glycerine, Ra = 0.1 µm}}) with types of coupling media and varied surface roughness reference block with respect to glycerine and surface roughness of 0.1 µm. Specific contact transfer losses (Equation (2)) are determined by measuring signal amplitude contact transfer difference.

\[ V_{CT \text{Glycerine, Ra = 0.1 µm}} = V_1 - V_{\text{Glycerine, Ra = 0.1 µm}} \]  \hspace{1cm} (2)

Whereby:

\[ \Delta V_{CT \text{Glycerine, Ra = 0.1 µm}} \text{ (dB)} \]—Signal (echo) amplitude contact transfer difference with respect to glycerine and surface roughness 0.1 µm;

\[ V_1 \text{ (dB)} \]—Signal amplitude at a different type of coupling media and a different surface roughness;

\[ V_{\text{Glycerine, Ra = 0.1 µm}} \text{ (dB)} \]—Signal amplitude at glycerine coupling media with respect to RB block surface roughness 0.1 µm.

| Surface roughness (µm) | Ra = 0.1 | Ra = 1 | Ra = 7 |
|------------------------|----------|--------|--------|
|                        | M  | SD  | M  | SD  | M  | SD  |
| Pairs of coupling media|       |      |     |      |     |      |
| Glycerine-Glycerine (Ra = 0.1) | 0.0 | 0.36 | 3.9 | 1.55 | 12.9 | 1.35 |
| UCA-2 M-Glycerine (Ra = 0.1) | 2.4 | 0.48 | 5.2 | 2.16 | 17.2 | 0.37 |
| WPP-Glycerine (Ra = 0.1) | 5.4 | 0.70 | 5.4 | 1.57 | 20.4 | 0.34 |
| U47-Glycerine (Ra = 0.1) | 4.8 | 0.49 | 6.7 | 0.69 | 19.4 | 0.85 |
| Water-Glycerine (Ra = 0.1) | 7.2 | 1.11 | 6.7 | 2.16 | 20.3 | 0.42 |
| MO-Glycerine (Ra = 0.1) | 6.6 | 1.07 | 7.8 | 1.49 | 23.3 | 1.09 |

M (dB); SD (dB).
A simple comparison of the efficiency of coupling between the coupling media and a surface roughness can be made. Signal amplitude contact transfer differences are dependent on the coupling media and surface roughness. For glycerine at surface roughness between $Ra$ from 0.1 to 7 $\mu$m and glycerine at surface roughness $Ra = 0.1 \mu$m, the signal amplitude contact transfer differences are between 3.9 and 12.9 dB. For mineral oil at surface roughness between $Ra$ from 0.1 to 7 $\mu$m and glycerine at surface roughness $Ra = 0.1 \mu$m, the signal amplitude contact transfer differences are between 6.6 and 23.3 dB. The measured values of the signal amplitude contact transfer difference ($\Delta V_{CT}$ glycerine, $Ra = 0.1 \mu$m) are high for all coupling media compared. During equipment calibration or during specimen testing, the type of coupling media should therefore be the same for results to be dependable. To get reliable results during the test, the surface roughness of the reference block and that of the test sample should be the same. If changes in surface roughness occur during testing, corrections can be read from Table 6 for more reliable results. The measured values of the signal amplitude contact transfer difference ($\Delta V_{CT}$ glycerine, $Ra = 0.1 \mu$m) are higher when compared to the results of International Atomic Energy Agency (2018, p. 204).

3. Conclusion

Knowing the properties of a coupling media and surface roughness is essential for calibrating ultrasonic devices. The research confirmed and evaluated the recommendations of the related standards (American Society of Mechanical Engineers, 2015; International Organization for Standardization, 2014c) on the re-calibration of ultrasonic devices for the purposes of non-destructive testing. The conclusions drawn below refer to the evaluation of signal amplitude contact transfer differences.

From the results of the t-test, it was found that in all analyzed pairs of coupling media used on the RB block with the surface roughness $Ra$ from 0.1 to 7 $\mu$m, the signal amplitude differences were statistically significant ($p < 0.049$). This confirms hypothesis 1, assuming that the coupling media selected for the study (water, glycerine, UCA-2 M contact gel, U47 contact gel, mineral oil, wallpaper paste) show statistically significant differences regarding ultrasound attenuation. This means that ultrasonic coupling media differ in their ultrasonic properties. A change of the coupling medium has a significant influence on contact transfer losses and the results of ultrasound testing. A high signal amplitude contact transfer difference occurred between mineral oil and glycerine (10.4 dB) and wallpaper paste and glycerine (7.74 dB) on a reference block with a surface roughness of 7 $\mu$m. The ultrasonic device should always be re-calibrated after a change of the coupling medium during testing. A comparative analysis of signal amplitude parameters showed that the glycerine coupling medium has the lowest contact transfer loss among the selected coupling media, which confirms hypothesis 3 that the lowest ultrasound attenuation appears in glycerine. The wallpaper paste and the U47 contact gel are usable for up to 90 minutes, and after this they must be removed from the surface, followed by a fresh application of the coupling media. The use of water and wallpaper paste as a coupling media causes corrosion of the surface.

The change in surface roughness ($Ra = 0.1, 0.8, 1$ and $7 \mu$m) had a significant influence on contact transfer losses ($t$ between 3.59 and 227.93, $p$ under .001). This confirms hypothesis 2, that the surface roughnesses selected in the study ($Ra = 0.1, 0.8, 1,$ and $7 \mu$m) show statistically significant differences regarding ultrasonic attenuation.

The signal amplitude contact transfer differences between glycerine at a surface roughness ($Ra$) from 0.1 to 7 $\mu$m and glycerine at a surface roughness of 0.1 $\mu$m are between 3.9 and 12.9 dB. The signal amplitude contact transfer differences between mineral oil at a surface roughness ($Ra$) from 0.1 to 7 $\mu$m and glycerine at a surface roughness of 0.1 $\mu$m are between 6.6 and 23.3 dB. The ultrasonic device should always be corrected or re-calibrated after a change in the roughness of the surface. The measured values of the signal amplitude contact transmission difference are high for all compared connecting media, if we know that the 4 dB difference between quality classes is
defined in the standard of Non-destructive testing of welds—Ultrasonic testing—Acceptance levels (International Organization for Standardization, 2018). The comparison of our results with the results of the International Atomic Energy Agency (2018, p. 204) leads to the conclusion that the type of coupling medium (glycerine, water, and mineral oil) and the surface roughness (Ra from 0.1 to 7 µm) have a considerable influence on contact transfer losses. These conclusions will be useful as guidelines, especially for inspectors who use ultrasonic testing for non-destructive inspection of structures, and for high-level inspectors who plan inspection instructions and procedures.

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