ACTA IMEKO
ISSN: 2221-870X
March 2026, Volume 15, Number 1, 1 - 6

Impact of contact force on the ultrasonic signal amplitude in carbon steel: A systematic evaluation

A. Justen[1], E. W. Santos[1], T. C. Dourado[1], S. A. Miqueletti[1], R. P. B. Costa-Félix[1]

[1] *Laboratory of Ultrasound (LABUS), Directory of Scientific and Industrial Metrology (DIMCI), National Institute of Metrology, Quality, and Technology (INMETRO), Duque de Caxias – RJ, Brazil*

ABSTRACT
Ultrasonic testing is widely used in industrial non-destructive evaluation; however, the influence of transducer contact force on signal stability during conventional contact measurements is still insufficiently documented for metallic specimens. This study investigates the effect of applied contact force on ultrasonic wave velocity and signal amplitude in SAE 1020 carbon steel, using a 5 MHz contact transducer and a controlled loading device. Three cylindrical specimens were tested under increasing, decreasing, and cyclic force protocols within a range of 2 to 20 kgf. The results showed negligible variation in ultrasonic velocity throughout the investigated force range, whereas signal amplitude increased markedly at low forces and reached a plateau near 10 kgf. These findings indicate that contact force primarily affects coupling efficiency and signal amplitude, rather than bulk wave velocity, under the present experimental conditions. The proposed procedure contributes to improved repeatability and supports more reliable contact-based ultrasonic measurements in industrial practice.

Section: RESEARCH PAPER

Keywords: ultrasound; transducer contact force; signal amplitude; carbon steel; non-destructive testing; Industry 4.0

Citation: A. Justen, E. W. Santos, T. C. Dourado, S. A. Miqueletti, R. P. B. Costa-Félix, Impact of contact force on the ultrasonic signal amplitude in carbon steel: A systematic evaluation, Acta IMEKO, vol. 15 (2026) no. 1, pp. 1-6. DOI: 10.21014/actaimeko.v15i1.2021

Section Editor: Carlos Hall, PósMQI/PUC-Rio, Rio de Janeiro, Brazil

Received December 1, 2024; **In final form** March 4, 2026; **Published** March 2026

Funding: This work was supported by the Fundação Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, CAPES-BRAZIL.

Corresponding author: A. Justen, e-mail: alexjusten46@gmail.com

1. INTRODUCTION

Ultrasonic testing (UT) is one of the most established techniques in non-destructive testing (NDT), being widely employed for flaw detection, thickness evaluation, and material characterization in metallic components. The reliability of contact-based ultrasonic measurements depends not only on the intrinsic properties of the inspected material, but also on operational variables, such as coupling condition, surface finish, probe positioning, and contact pressure applied during testing. These factors can directly affect signal transmission, signal amplitude, and measurement repeatability [1]-[3].

Although ultrasonic inspection is extensively applied to steel components, the effect of contact force on signal behavior is still less systematically documented than other measurement variables, particularly in practical contact measurements using conventional piezoelectric probes. This issue is important because insufficient or poorly controlled force may alter coupling efficiency and contribute to variability in amplitude-based analyses. Therefore, defining a stable force range is important for improving repeatability and reducing operator-dependent effects in ultrasonic inspection procedures [4]–[7].

The objectives of this research are as follows:

1. To determine the effect of varying contact forces on ultrasonic amplitude and velocity in carbon steel;
2. To establish a minimum force threshold that ensures optimal coupling conditions;
3. To propose refined measurement protocols for improved accuracy and repeatability.

2. MATERIAL AND METHODS

2.1. Materials

Three cylindrical SAE 1020 carbon steel specimens were tested, all with a diameter of 76 mm and lengths of 25 mm, 40 mm, and 76 mm, respectively. The specimen surfaces were machined to reduce surface irregularities and to improve consistency in contact measurements. Since surface condition affects ultrasonic transmission and amplitude response,

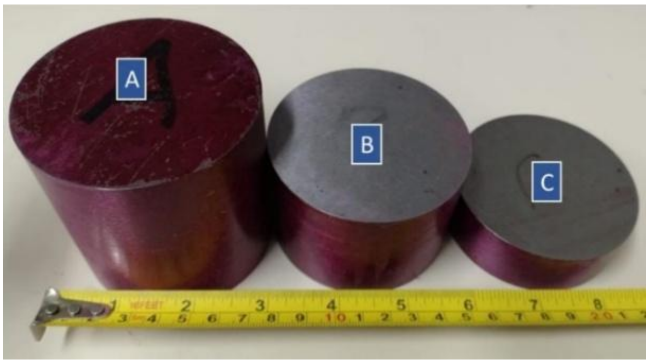

Figure 1. Steel blocks SAE 1020.

minimizing roughness-related variability was important for isolating the specific effect of applied contact force [6], [8], [9].

Figure 1 shows the three cylindrical specimens of SAE 1020 carbon steel with the dimensions of 76 mm in diameter and 76 mm (Figure 1, A), 40 mm (Figure 1, B), and 25 mm (Figure 1, C) in length, respectively.

2.2. Equipment

Figure 2 illustrates the experimental setup, including the 5 MHz transducer (Olympus V309-SU, USA), the oscilloscope (Agilent DSO-X 3012A), the force gauge (IMPAC IP-500, Brazil). The following equipment was employed to perform the ultrasonic measurements:

1. **Oscilloscope:** Agilent DSO-X 3012A
2. **Signal generator:** Agilent 33500B
3. **Transducer:** 5 MHz (Olympus V309-SU, USA)
4. **Force gauge:** IMPAC IP-500 (Brazil)
5. **3D-printed** aligment system
6. **Desktop:** Labview 2014 program.

Figure 2 shows the diagram of the experimental setup, depicting the transducer and oscilloscope connected to the specimen. This figure illustrates the arrangement used for the ultrasonic measurements, with the transducer applied to the surface of the steel blocks and the oscilloscope recording the signals.

2.3. 3D printed system for force application

To maintain consistent contact force during measurements, a custom 3D-printed alignment and force application system was developed. This system was designed to allow the precise and reproducible application of force on the transducer, ensuring uniform coupling between the transducer and the material surface throughout the tests.

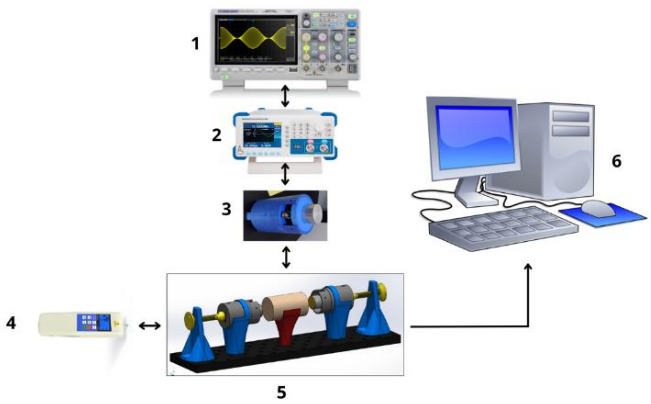

Figure 2. Experimental setup.

Figure 3. 3D-printed alignment system.

A detailed image of the 3D-printed alignment system is shown in Figure 3. This system features adjustable settings to ensure the desired force is applied consistently during each measurement cycle. The system was optimized to prevent human error in force application and maintain accurate results.

2.4. Experimental protocols

Three contact force protocols were employed in this study:

1. **Increasing force:** The force was gradually increased from 2 kgf to 20 kgf.
2. **Decreasing force:** The force was gradually decreased from 20 kgf to 2 kgf.
3. **Cyclic force:** Alternating between increasing and decreasing forces.

These protocols were designed to explore the effects of force variation on both the ultrasonic signal amplitude and velocity.

Figure 4 shows a flowchart illustrating the experimental protocol, with a visual representation of the step-by-step application of force and measurement collection. This helps clarify the sequence of operations for each experimental condition.

3. RESULTS AND DISCUSSION

3.1. Uncertainty calculus

The uncertainty in ultrasonic measurements was calculated following the guidelines provided by the Guide to the Expression of Uncertainty in Measurement (GUM) [10]. The uncertainty in the measured quantities was determined using the propagation of uncertainty formula, where each source of error was considered.

The uncertainty sources considered include the following:

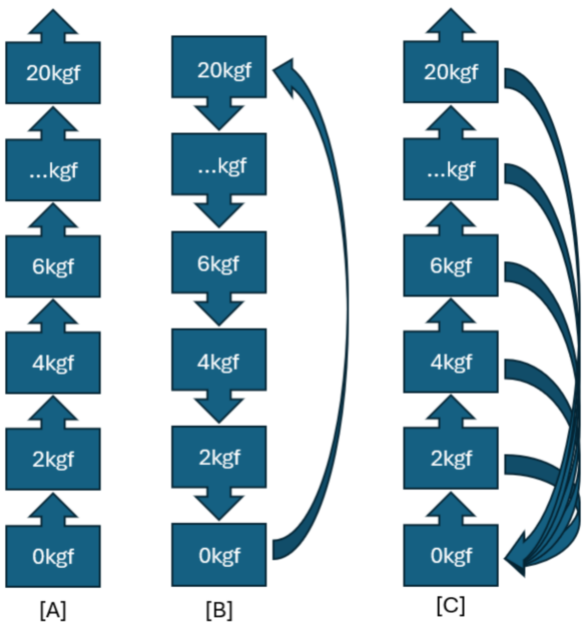

Figure 4. Experimental protocol.

1. **Force measurement:** The force gauge used in this study had a specified uncertainty of ± 0.05 kgf;
2. **Time of Flight (TOF):** The uncertainty in the time measurement from the oscilloscope was calculated as ± 0.001 µs, based on the resolution of the oscilloscope;
3. **Amplitude measurement:** The uncertainty in amplitude was considered as ± 0.02 V, given the oscilloscope's precision.

3.2. Uncertainty of applied force (U_{force})

The uncertainty in the applied force U_{force} is determined based on the calibration of the force gauge and the resolution of the measurement system. The formula used to calculate the uncertainty of force is:

$$U_{\text{force}} = \sqrt{U_{\text{calibration}}^2 + U_{\text{resolution}}^2}\,, \tag{1}$$

where:

- $U_{\text{calibration}}$= 0.05 kgf (uncertainty of the force gauge),
- $U_{\text{resolution}}$= 0.01 kgf (resolution of the force gauge, assumed based on the instrument's specifications).

Thus, the uncertainty in the applied force is:

$$U_{\text{force}} = \sqrt{0.05^2 + 0.01^2}\ \text{kgf} = 0.051\ \text{kgf}\,. \tag{2}$$

3.3. Uncertainty of time of flight (U_{TOF})

The uncertainty in the time of flight U_{TOF} is based on the resolution of the oscilloscope used to measure the time of flight of the ultrasonic wave. The formula to calculate the uncertainty of time of flight is:

$$U_{\text{TOF}} = \frac{\Delta t}{\sqrt{N}}\,, \tag{3}$$

where:

- $\Delta t = 0.001\ \mu s$ (measurement uncertainty, based on the oscilloscope's resolution),
- $N = 10$ (number of measurements taken).

Thus, the uncertainty in time of flight is:

$$U_{\text{TOF}} = \frac{0.001}{\sqrt{10}} = 0.000316\ \mu\text{s}\,. \tag{4}$$

3.4. Uncertainty of amplitude ($U_{amplitude}$)

The uncertainty in the amplitude measurement $U_{\text{amplitude}}$ is calculated based on the oscilloscope's resolution, which was specified as 0.02 V. The formula used is:

$$U_{\text{amplitude}} = \frac{\Delta A}{\sqrt{M}}\,, \tag{5}$$

where:

- $\Delta A = 0.02$ V (uncertainty in amplitude measurement),
- $M = 10$ (number of measurements performed).

Thus, the uncertainty in amplitude will be:

Table 1. Ultrasonic velocity for different contact forces.

Sample	Force range in kgf	Velocity in m/s
Sample A	2–20	5929.64–5929.87
Sample B	2–20	5940.76–5940.91
Sample C	2–20	5941.80–5941.95

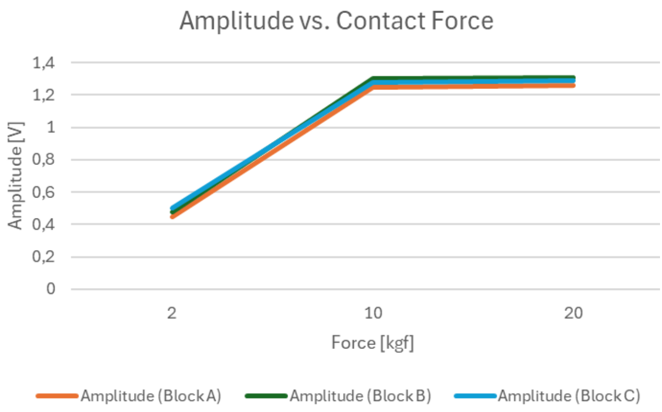

Figure 5. Amplitude vs. contact force.

Table 2. Amplitude for different contact forces.

Force in kgf	Amplitude Block A	Amplitude Block B	Amplitude Block C
2	0.45 V	0.48 V	0.50 V
10	1.25 V	1.30 V	1.28 V
20	1.26 V	1.31 V	1.29 V

$$U_{\text{amplitude}} = \frac{0.02\ \text{V}}{\sqrt{10}} = 0.00632\ \text{V}\,. \tag{6}$$

3.5. Ultrasonic velocity

Across all specimens, no significant changes in ultrasonic velocity were observed with varying contact forces. Table 1 shows the velocity values for each sample.

Under the present experimental conditions, these results indicate that the applied contact force did not materially affect bulk wave propagation velocity in SAE 1020 carbon steel. Therefore, within the tested interval, contact force had a limited influence on time-of-flight-based velocity estimation when compared with its effect on signal coupling [2], [4], [11].

These results confirm that ultrasonic velocity in carbon steel is primarily governed by the material's inherent properties, as supported by previous studies.

3.6. Signal amplitude

Signal amplitude increased substantially between the lowest force level and approximately 10 kgf, after which a plateau trend was observed. This behavior is consistent with improved acoustic coupling, as the applied pressure reduces interfacial gaps and enhances transmission efficiency between the transducer and the specimen surface. In practical terms, the main effect of contact force in the present configuration was observed in amplitude stabilization, rather than in wave velocity [4]–[6], [12].

Figure 5 illustrates the amplitude versus contact force for the three samples, highlighting the stabilization threshold; the values are given in Table 2. This figure clearly shows the point where the amplitude begins to plateau, indicating the optimal force for consistent measurements.

The results from the increasing force protocol demonstrated smoother transitions to the stabilization region than the decreasing and cyclic protocols.

These results align with findings from earlier works, suggesting that the coupling medium and transducer alignment are critical at lower forces.

3.7. Practical implications

The results indicate that contact force should be treated as a controlled operational variable in manual ultrasonic testing procedures. The identification of a stabilization region near 10 kgf suggests that the adoption of minimum force thresholds may improve repeatability and reduce measurement scatter in contact-based inspections, especially when signal amplitude is used as an interpretative parameter [5], [6], [12].

4. CONCLUSION

This study has provided a systematic exploration of the effects of varying contact forces on ultrasonic signal properties—specifically amplitude and velocity—in carbon steel, addressing a critical yet underexplored aspect of non-destructive testing (NDT). Through rigorous experimentation involving precise force application via a novel 3D-printed alignment system, we have demonstrated that ultrasonic velocity remains largely invariant to changes in contact force, underscoring its reliability as a metric governed primarily by intrinsic material properties. This consistency aligns with established principles in ultrasonic wave propagation through homogeneous materials, reinforcing velocity's utility in defect detection, material characterization, and integrity assessments across industries such as manufacturing, aerospace, and infrastructure maintenance.

In contrast, signal amplitude exhibited a pronounced sensitivity to contact force, increasing with applied force up to a stabilization threshold of approximately 10 kgf. Beyond this point, further force increments yielded diminishing returns, highlighting an optimal range for efficient transducer–specimen coupling without risking mechanical damage. Slight variations in amplitude across different steel blocks further emphasized the influence of material-specific factors such as surface roughness and alignment, advocating for standardized protocols in NDT practices to enhance measurement reproducibility.

4.1. Significance and innovations

A pivotal innovation of this work is the development of the 3D-printed alignment system, which minimized human error and ensured consistent force application, thereby elevating the accuracy and reliability of ultrasonic measurements. This affordable, customizable tool exemplifies how emerging technologies such as 3D printing can democratize high-precision experimentation, offering scalable solutions for both laboratory and field applications. Additionally, the comprehensive uncertainty analysis—encompassing force application, time-of-flight, and amplitude—quantified error sources and provided expanded uncertainties at a 95 % confidence level, offering valuable insights for refining measurement protocols and mitigating variability in real-world scenarios.

These findings hold substantial implications for industrial NDT, where the precise control of contact force can optimize signal quality, reduce measurement errors, and improve safety standards in critical applications. Beyond engineering, the principles extend to medical ultrasound imaging, where consistent coupling is essential for diagnostic accuracy. By establishing force thresholds and highlighting amplitude's force-dependence, this research contributes to more efficient, damage-minimizing testing methodologies, ultimately advancing the field toward greater precision and reliability.

4.2. Broader implications and final thoughts

In summary, this investigation advances our understanding of the role of contact force in ultrasonic testing, confirming the robustness of velocity while delineating the force-sensitive behavior of amplitude. The integration of innovative tools and rigorous uncertainty evaluation not only validates the results but also sets a benchmark for future studies. As industries increasingly rely on NDT for quality assurance and safety, these insights pave the way for enhanced protocols that balance efficacy with practicality. Ultimately, this work underscores the importance of controlled experimental conditions in unlocking the full potential of ultrasonic techniques, fostering safer and more reliable material evaluations in diverse sectors.

4.3. Overview of future directions

Building on the foundational insights from this study, future research should extend the investigation of the impact of contact force on ultrasonic signals to broader contexts, materials, and variables. This will not only validate and generalize the current findings but also address gaps in non-destructive testing (NDT) applications, particularly in challenging environments. Recommendations are structured to prioritize feasibility, innovation, and practical impact, with considerations for interdisciplinary collaboration. By pursuing these avenues, researchers can enhance ultrasonic testing's robustness, reduce uncertainties, and adapt methodologies to real-world complexities.

4.3.1. Expansion to diverse materials

A primary recommendation is to replicate and expand the experiments on materials with varying surface characteristics, such as concrete, rock, composites, or alloys with high roughness. For instance, testing on concrete—common in civil engineering—could reveal how porosity and irregularities amplify the effect of force on amplitude, potentially leading to tailored thresholds for infrastructure inspections.

Pros and cons analysis:

- **Pros:** This would provide industry-specific guidelines, improving safety in construction (e.g., bridge assessments) and reducing false positives in defect detection.
- **Cons:** Materials like composites may introduce anisotropy, complicating velocity measurements and requiring advanced modeling; however, this could be mitigated with finite element simulations.

Practical suggestions: Start with controlled lab tests using standardized samples, then progress to field trials. Collaborate with materials scientists to incorporate surface profilometry for quantifying roughness.

4.3.2. Investigation of coupling agents and transducer frequencies

Explore the interplay between contact force, coupling agents (e.g., gels, oils, or dry couplings), and transducer frequencies. Higher frequencies might exacerbate amplitude sensitivity to force in rough materials, while alternative agents could lower the stabilization threshold.

Real-world examples: In medical ultrasound, water-based gels are standard; adapting this to industrial NDT could minimize force needs, as seen in automotive welding inspections where low-force couplings prevent surface damage.

Pros and cons analysis:

- **Pros:** Optimizing agents could reduce mechanical stress on delicate specimens, enhancing sustainability and cost-effectiveness.
- **Cons:** Some agents may degrade over time or in harsh environments (e.g., high temperatures), increasing

uncertainty; testing in simulated conditions would address this.

Practical suggestions: Conduct comparative studies with frequencies from 1 MHz to 10 MHz, using the 3D-printed system for consistency. Quantify improvements via signal-to-noise ratio metrics.

4.3.3. Integration of advanced technologies

Incorporate machine learning for predictive modeling of force-amplitude relationships or integrate sensors for real-time force monitoring in automated NDT systems. This could evolve the 3D-printed alignment into a smart device with IoT capabilities.

Real-world examples: In aerospace, AI-driven ultrasonics are used for composite aircraft inspections; extending this to force optimization could automate quality control in manufacturing lines.

Pros and cons analysis:

- **Pros:** Automation would boost efficiency and reproducibility, ideal for high-volume industries such as oil and gas pipelines.
- **Cons:** Initial development costs and data requirements might be barriers; start with open-source ML frameworks to lower entry points.

Practical suggestions: Partner with tech firms for prototype development, validating through uncertainty analyses similar to this study's.

4.3.4. Methodological enhancements and uncertainty reduction

Refine uncertainty propagation models to include environmental factors such as temperature and humidity, which could indirectly affect coupling efficiency.

Pros and cons analysis:

- **Pros:** Enhanced models would yield more reliable 95 % confidence intervals, critical for regulatory compliance in safety-critical fields.
- **Cons:** Adding variables increases complexity; use Monte Carlo simulations to manage this without excessive computational demands.

Practical Suggestions: Develop standardized protocols via international collaborations (e.g., with ISO standards bodies) and publish open datasets for community validation.

4.3.5. Broader interdisciplinary applications

Extend findings to non-engineering fields, such as geophysics for seismic wave studies or biomedical engineering for tissue imaging, adapting force thresholds accordingly.

AUTHORS' CONTRIBUTION

A. Justen played a pivotal role in the development and implementation of the 3D printing system designed for precise force application during the ultrasonic measurements. This innovative system ensured consistent and reproducible force application on the transducer, significantly enhancing the accuracy of the results. In addition, A. Justen was responsible for conducting the ultrasonic measurements on the steel blocks, ensuring that the testing protocols were followed accurately. This hands-on involvement was critical to the success of the experiment and to obtaining reliable data for the study. Furthermore, A. Justen collaborated with S. A. Miqueletti in performing the uncertainty calculations, providing a thorough assessment of the measurement limitations.

E. W. Santos provided essential technical support throughout the study, ensuring that the measurement systems and equipment operated smoothly. He was actively involved in the preparation of the experimental setup, assisting with the calibration and troubleshooting of instruments. His expertise was invaluable in ensuring the correct application of the experimental protocols and in providing guidance during the measurements. E.W. Santos also assisted in the data collection process, helping to ensure that the measurements were accurate and that the results could be reliably analyzed.

T. C. Dourado's role in the study was primarily in the partial supervision of the measurement process. He provided oversight and expert advice throughout the experimental procedures, ensuring that the measurements were conducted according to best practices. T.C. Dourado's experience in the field helped to refine the experimental protocols and ensure the proper alignment and calibration of the equipment. His guidance was critical to ensuring the accuracy and reliability of the collected data.

S. A. Miqueletti, alongside A. Justen, was responsible for performing the detailed uncertainty calculations for the study. These calculations were crucial for understanding the reliability and precision of the measurement results. S.A. Miqueletti carefully evaluated the sources of uncertainty, including the force measurement, time of flight, and amplitude, and used the propagation of uncertainty formula to quantify the overall uncertainty. This meticulous work was integral to the quality of the study, providing a clear understanding of the potential sources of error in the experimental setup.

R. P. B. Costa-Félix was the final supervisor and reviewer of the entire article. As the lead supervisor, he provided invaluable guidance throughout the research process, from the conceptualization of the study to the analysis and interpretation of the results. R.P.B. Costa-Félix played a key role in reviewing the entire manuscript, ensuring that the article adhered to scientific standards and that the conclusions were well-supported by the data. His thorough review and expertise helped elevate the quality of the final publication.

All authors approved the final version of the manuscript and agree to be accountable for its content.

ACKNOWLEDGEMENTS

The authors thank the Brazilian National Council for Scientific and Technological Development (grants 307.562/2020-4), the Research Support Foundation of the State of Rio de Janeiro (grant E-26/210.687/2019, E-26/211.170/2019, and E-26/201.153/2021 [RCF]), and Norte Energia S.A. (grant P&D ANEEL PD-07427-0421/2021).

REFERENCES

[1] ASM International, ASM Handbook, Volume 17: Nondestructive Evaluation of Materials, ASM International, 2018. DOI: 10.31399/asm.hb.v17.9781627081900

[2] J. Krautkrämer, H. Krautkrämer, Ultrasonic Testing of Materials, 4th ed., Springer, Berlin, Heidelberg, 1990. DOI: 10.1007/978-3-662-10680-8

[3] D. E. Bray, R. K. Stanley, Nondestructive Evaluation: A Tool in Design, Manufacturing and Service, CRC Press, 2018. DOI: 10.1201/9781315272993

[4] F. L. di Scalea, R. E. Green Jr., Experimental observation of the intrusive effect of a contact transducer on ultrasound propagation, Ultrasonics, 37 (1999) 3, pp. 179-183. DOI: 10.1016/S0041-624X(98)00059-6

[5] M. Mihaljević, H. Cajner, B. Runje, Analysis of the couplant influence on the ultrasonic thickness measurement of the steel grade S355J0, Materialwissenschaft und Werkstofftechnik, 48 (2017) 8, pp. 803-813.
DOI: 10.1002/mawe.201700050
[6] D. Zuljan, Z. Zhou, Effect of ultrasonic coupling media and surface roughness on contact transfer loss, Cogent Engineering, 9 (2022) 1.
DOI: 10.1080/23311916.2021.2009092
[7] T. Han, J. Fan, Ultrasonic measurement of contact stress at metal-to-metal interface based on a real rough profile through modeling and experiment, Measurement, 217 (2023), 113046.
DOI: 10.1016/j.measurement.2023.113046
[8] J. Kim, H.-P. Ha, K.-M. Kim, K.-Y. Jhang, Analysis of the Influence of Surface Roughness on Measurement of Ultrasonic Nonlinearity Parameter Using Contact-Type Transducer, Applied Sciences, 10 (2020) 23, 8661.
DOI: 10.3390/app10238661
[9] Z. Wang, X. Cui, H. Ma, Y. Kang, Z. Deng, Effect of Surface Roughness on Ultrasonic Testing of Back-Surface Micro-Cracks, Applied Sciences, 8 (2018) 8, 1233.
DOI: 10.3390/app8081233
[10] JCGM, Evaluation of Measurement Data — Guide to the Expression of Uncertainty in Measurement, JCGM 100:2008, 2008.
DOI: 10.59161/JCGM100-2008E
[11] ASTM E213-20, Standard Practice for Ultrasonic Testing of Metal Pipe and Tubing, ASTM International, 2020.
DOI: 10.1520/E0213-20
[12] R. Xu, R. E. Beltrán-Gutiérrez, M. Käding, A. Lange, S. Marx, J. Ostermann, Frequency dependent amplitude response of different couplant materials for mounting piezoelectric sensors, NDT & E International, 141 (2024), 102993.
DOI: 10.1016/j.ndteint.2023.102993