

The Methodology for the Reliability Evaluation of the Signal Processing Methods Used for the Dispersion Estimation of Lamb Waves

Lina Draudvilienė¹ and Asta Meškuotienė²

Abstract—The applications of ultrasonic Lamb waves are becoming more and more frequent and diverse in industrial fields. These waves are used in non-destructive testing (NDT), structural health monitoring (SHM), for the assessment of the quality of materials, etc. However, due to the unusual properties of these waves, new or adapted signal processing methods are necessary to use for the analysis of such wave signals. Based on the requirements of ISO 17025, the work presents the methodology for verification of the signal processing methods used to reconstruct the dispersion curves of the phase and group velocities of Lamb waves. The key sequence of the mathematical and experimental stages, which must be passed to evaluate the reliability of the methods are developed. The present methodology includes the algorithm to optimally quantify the uncertainty, as to avoid additional testing, saving cost and time. The main characteristics and sources of the uncertainties, that mainly affect the accuracy of the obtained results are identified, analyzed, and presented. New standards for certification testing, inspection, and monitoring can be developed more easily and quickly based on the provided methodology in the future.

Index Terms—Dispersion curve, method verification, reliability, signal processing method, ultrasonic Lamb waves, uncertainty.

I. INTRODUCTION

NOWADAYS, the applications of the ultrasonic testing method based on ultrasonic Lamb waves are becoming more diverse and increasingly employed. These waves are used in non-destructive testing (NDT), structural health monitoring (SHM), also for the assessment of the quality of materials determining their elastic properties [1]–[7]. However, the Lamb waves have some limitations related to the properties of these waves such as: a dispersion phenomenon, multimodal behavior, convergence of modes, modes interlacing, mode splitting due to edges, and others [7]–[11]. One of the main limiting factors is the phenomenon of dispersion, which means that the velocity of waves varies depending on the frequency (f) and the object thickness (d) [12]. Velocity as a function of frequency determines the occurrence of two-phase and group

velocities and is characterized by dispersion curves [13]–[15]. Thus, these identified behavioral features suggest that the signal processing methods, commonly used for the analysis of ultrasonic waves, cannot be employed for these waves. Therefore, new signal processing methods are developed or adapted for the analysis of signals of Lamb waves [16]–[18]. However, usually the main hurdle in the adaptation of such novel analysis methods is the unknown reliability. In accordance with the protocols and requirements given in [19] and [20], each measurement method must be reliably, accurately, and precisely tailored to the intended purpose. Therefore, a verification, in order to verify and confirm that a laboratory has the ability to carry out those proposed methods, is needed [19], [20]. It is pertinent to perform a feasibility study after some new processing algorithm and/or method is proposed and developed to determine the performance characteristics [21]. Such tests should include system accuracy, linearity, limited detection, and other parameters. One can also perform environment testing to see what kind of conditions might be changed so as to ensure that a proposed method is still accurate [22]–[26]. It can be stated that a lack of such information complicates the application and utilization of the proposed new methods for certain task solving. As an example, the pharmaceutical industry is the driving force in the development of validation and verification practices [27]–[29]. A guide on bioanalytical method validation was published by the U.S. Food and Drug Administration (FDA) in 2001 in which a sensible compromise between thoroughness and cost-effectiveness is achieved [27]. However, different practices exist in other industries and sectors. Usually owing to the lack of adequate resources, generally accepted and cost-effective methodologies for validation and verification are used. It is, therefore, crucial that efforts are made to make such procedures optimal. So, the methodology of verification of a method is valuable for any routine testing that requires consistency and accuracy. On the contrary, research publications presenting novel signal processing methods for Lamb waves dispersion evaluation usually skips reliability topic. Most often phrases such as: “a good agreement,” “a good compliance,” “highest agreement is obtained,” “very accurate results,” “the measured dispersion curves agree well with the theoretical model,” and “correlated well with theoretical calculations” are encountered without substantial backing to them [17], [30]–[34]. This makes it difficult to interpret the distribution of the results and to

Manuscript received July 14, 2021; revised October 26, 2021; accepted November 3, 2021. Date of publication November 11, 2021; date of current version March 1, 2022. The Associate Editor coordinating the review process was Dr. Grazia Barchi. (Corresponding author: Lina Draudvilienė.)

Lina Draudvilienė is with the Ultrasound Research Institute, Kaunas University of Technology, 51423 Kaunas, Lithuania (e-mail: lina.draudvilienė@ktu.lt).

Asta Meškuotienė is with the Metrology Institute, Kaunas University of Technology, 51368 Kaunas, Lithuania (e-mail: asta.meskuotiene@ktu.lt).

Digital Object Identifier 10.1109/TIM.2021.3127625

evaluate the proposed method's accuracy and reliability. Making a comparison with the other methods to decide which is more appropriate to solve one or another problem becomes impossible. As a big number of different signal processing methods are used for the dispersion evaluation of Lamb waves, the common methodology for the reliability evaluation of the methods is necessary to be developed and presented. The general principles and sequence of the mathematical and experimental stages will facilitate the verification analysis of any signal processing method used for the dispersion evaluation of Lamb waves and expand understanding about the measurement reliability, peculiarities of method validation, and verification. These provisions will complement the general guidelines [19], [20], [28], [29] that present a discussion of the characteristics that should be considered during the verification or validation of procedures.

The aim of this work is to develop a methodology for verification of the signal processing methods applied to reconstruct the dispersion curves of the phase and group velocities of Lamb waves and the accuracy assessment according to the requirements of ISO 17025. To achieve this goal, it is necessary: to create an algorithm for the determination of general principles and sequence of key steps to estimate the results of signal processing methods; to identify, analyze, and present the main characteristics and sources of uncertainties that mainly affect the accuracy of obtained results.

II. PROCESS OF THE METHODOLOGY REALIZATION

Validation of a newly developed method is an important and a necessary part of the proposed algorithm as it would help to avoid costly and time-consuming practices and ensure the understanding of the methods' capabilities. The methodology includes the following main aspects:

- 1) Development of an algorithm for a process of the verification procedure of signal processing methods. The extent of the process depends on many factors: a type of method and equipment used, type of a tested object, procedure steps, or even the user's experience and training [27], [35].
- 2) General mathematical verification and interpretation of the experimental results. The purpose is to determine the mathematical model, input and output parameters, which affect the final method accuracy.
- 3) Optimization of selected uncertainty components for uncertainty quantification. The quantitative expression (quantitative equation) is related to the measurement value according to the parameters on which it depends [35].

In order to evaluate the metrological parameters of signal processing methods used for the dispersion evaluation of the phase and group velocities of Lamb waves, there are two main stages: mathematical and experimental. Verifications are recommended to be performed according to the flowchart Fig. 1.

A deeper analysis of both mathematical and experimental verifications and interrelation between them is presented in Sections II-A and II-B.

A. Mathematical Verification

Mathematical verification of a signal processing method used for the phase and group velocity dispersion evaluation of the Lamb waves consists of several main steps.

First, the uncomplicated object, which can be easily described mathematically, is recommended to be used. That object could be an aluminum or steel plate.

Second, reference method, for the obtained results comparison, needs to be selected. It is recommended to use analytical and/or semi-analytical methods such as: semi-analytical finite element (SAFE) [36], DISPERSE [37], and/or others. Then, the dispersion curves of the phase and group velocities of the A_n and S_n modes of Lamb waves are obtained using the geometry parameters and the material properties (Young's modulus, Poisson ratio, and density) of the object selected for the study.

The third step is the frequency range selection. The Lamb waves possess an infinite number of modes in the higher frequency ranges. For that reason, the investigation frequency range should be selected based on the obtained plots of the dispersion curves by the reference method. It is recommended to use the frequency range where only fundamental asymmetric A_0 and symmetric S_0 modes exist. Based on the selected frequency range, the input parameters such as excitation signal $u_0(t)$, the wave propagating distance x , and the step between two-point dx are chosen.

The fourth step is to obtain the simulated signals using the signal processing method. It is recommended to use the simplified complex transfer function for that purpose [38]

$$u_x(t) = \text{IFT}[\text{FT}[u_0(t)] \cdot H(jf, x)] \quad (1)$$

where $u_x(t)$ is the output signal; $u_0(t)$ is the input signal; the IFT denotes the inverse Fourier transform; and $H(jf, x)$ is the complex transfer function of the object

$$H(jf, x) = e^{-\alpha(f)x} e^{-j\omega \frac{x}{c_{ph}(f)}} \quad (2)$$

x is the propagation distance; $\alpha(f)$ is the frequency-dependent attenuation coefficient which is not used since the Lamb waves attenuation is very low for metal objects; ω is the angular frequency; and j is the basic imaginary unit $j = (-1)^{1/2}$. The set number of the propagating signals is obtained, and they can be displayed in the B-scan images.

The fifth step is the verification of the signal processing method's application. Using the collected output signals $u_x(t)$ at different distances and applying the particular proposed signal processing methods, the segments of the phase and/or group velocity dispersion curves are obtained [39], [40]. The reconstructed dispersion curve relates the velocity values and corresponding frequencies.

The final step is the calculation of the standard deviation by the comparison of the results obtained using the mathematical simulation and reference method. It is important that the comparison of the obtained velocity values would be performed at the same frequency. The standard deviation of the calculated velocity error indicates the reliability of the method at the theoretical level, and it should be involved in the uncertainty budget.

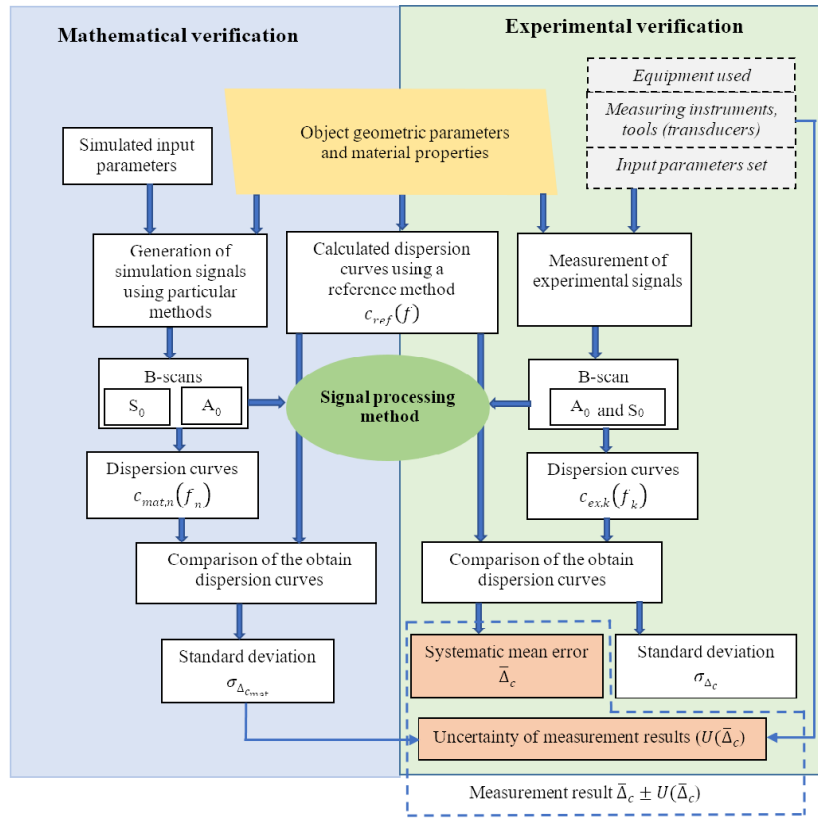


Fig. 1. Algorithm for the evaluation of the metrological parameters of the signal processing methods used for the dispersion estimation of Lamb waves.

The calculation and explanation of $\sigma_{\Delta_{c_{mat}}}$ are given in Table I. The absolute error and the average of absolute errors can be calculated as follows:

$$\Delta_{c_{mat,n}} = c_{mat,n}(f_n) - c_{refn}(f) \quad (3)$$

$$\bar{\Delta}_{c_{mat}} = \frac{1}{N} \sum_{n=1}^N \Delta_{c_{mat,n}} \quad (3a)$$

where $n = 1, \dots, N$, n th point of the dispersion curve obtained by the mathematical simulation, N is the number of points in a segment of the dispersion curves obtained by the mathematical simulation, $c_{refn}(f)$ are the phase/group velocities at the corresponding frequency obtained according to the reference dispersion curve, $c_{mat,n}(f_n)$ are the phase/group velocities at the corresponding frequency of the reconstructed dispersion curve obtained by the mathematical simulation.

In order to complete the assessment of any method reliability, experimental investigations are necessary.

B. Experimental Verification

The experimental investigations are necessary for the complete assessment of any method's reliability. In order to evaluate quantitative characteristics of method accuracy, a systematic error of the experimental values from conventional true value has to be estimated [41], [42]. Equipment of different complexity can be used for the realization of different methods. It may affect not only the systematic error but also the total uncertainty. The equipment includes a measuring system

with specific software for the generation of input parameters and for processing the results. The main equipment consists of the wide band ultrasonic system for generating and receiving the Lamb waves, ultrasonic transducers for the excitation and reception of propagating ultrasonic wave signals, and a scanner. The measuring instruments are needed to calculate the density, dimensions, and measuring distance of the object and/or to determine the other parameters necessary for the test.

In order to determine the applicability of the methodology, it is necessary to define the limits of suitability. The standard deviation of the mathematical verification is one of the sources of combined standard uncertainty shown in Fig. 1. It can be determined under the following three conditions:

- 1) The experimental verification is performed using the experimentally collected signals propagating in an object with the same material parameters (Young's modulus, Poisson's ratio, and density) and geometry as it is used in the investigation of the mathematical verification.
- 2) The investigation is performed in the same frequency range.
- 3) The same referent method for the comparison of the obtained experimental results is used.

The measurement technique should ensure the acquisition of signals along the wave propagation direction. The number of the collected signals depends on the selected measured distance x and the step between two measurement points dx . The set number of the propagating signals is obtained. The B-scan of the normal component of the particle velocity on

TABLE I
SUMMARY OF UNCERTAINTY BUDGET FOR MEASUREMENT OF VELOCITY

Sources of combined standard uncertainty	Equation of standard uncertainty	Remarks	Distribution	Sensitivity coefficient of standard uncertainty
Mathematical model	$\sigma_{\Delta c_{mat}} = \sqrt{\frac{\sum_{n=1}^N ((\Delta c_{mat,n}) - \bar{\Delta c}_{mat})^2}{(N-1)}}$	N is the number of points in a segment of mathematical reconstructed dispersion curve, n^{th} – the point of the segment, $\Delta c_{mat,n}$ (Formula 3) are the errors of velocities of the reconstructed dispersion curve from the simulated signals, $\bar{\Delta c}_{mat}$ (Formula 3a) is the average of errors of velocities.	Gaussian	1
Velocity (dispersion curve)	$\sigma_{\Delta c} = \sqrt{\frac{\sum_{k=1}^K (\Delta c_k - \bar{\Delta c})^2}{K-1}}$	K is the number of points in a segment of experimentally reconstructed dispersion curve, k^{th} – the point of the segment, Δc_k (Formula 4) are the errors of velocities of the reconstructed dispersion curve from the experimental signals, $\bar{\Delta c}$ (Formula 4a) is the average of errors of velocities.	Gaussian	1
Uncorrected error for frequency range or fluctuations of the Lamb wave's frequency f	$\sigma(\Delta c_{max}) = \frac{\Delta c_{max}}{3}$	Δc_{max} is the maximum deviation from the average velocity error for a single point	Gaussian	1
Distance between two points	$\sigma(dx) = \pm \frac{\Delta dx}{\sqrt{3}}$	Δdx is the error of step setting, t is the duration of pulse excitation	Rectangular	$1/t$
Plate thickness	$\sigma(x_i) \text{ or } \sigma = \pm \frac{\Delta x_i}{\sqrt{3}}$	x_i , Δx_i are the density ρ , the Young modulus E , the Poisson's ratio ν , the plate thickness d or their variations respectively	Gaussian or rectangular	$W_i(x_i) = \frac{\Delta F(x_i)}{\Delta x_i}$
Density				
Young modulus				
Poisson's ratio				

the surface of the object is obtained for both A_0 and S_0 modes. Then, the proposed signal processing technique is applied and the dispersion curves $c_{ex,k}(f_k)$ are obtained. A systematic error calculation can be performed by comparing the segments of the dispersion curves reconstructed in both ways in the same frequency range. Then, the systematic error and the average of the errors are obtained

$$\Delta c_k = c_{ex,k}(f_k) - c_{refk}(f) \quad (4)$$

$$\bar{\Delta c} = \frac{1}{K} \sum_{k=1}^K \Delta c_k \quad (4a)$$

where, K is the number of points in a segment of experimentally reconstructed dispersion curve, $k = 1, \dots, K$, k^{th} point of the segment, $c_{ex,k}(f_k)$ are the phase/group velocities at the corresponding frequency of the reconstructed dispersion curve from the experimental signals, and $c_{ref}(f)$ are the phase/group velocities at the corresponding frequency obtained according to the reference dispersion curve. The calculation and explanation of the experimental standard deviation $\sigma_{\Delta c}$ are given in Table I. It is recommended to express these characteristics in relative terms. Section III analyzes the main sources of uncertainties. The summarized overall uncertainty budget is presented.

III. ANALYSIS OF UNCERTAINTIES

A list of sources of uncertainties relevant to the signal processing methods used for the phase and group velocities dispersion evaluation is advised to be developed and recorded. This list would reflect the final stage of the study of the

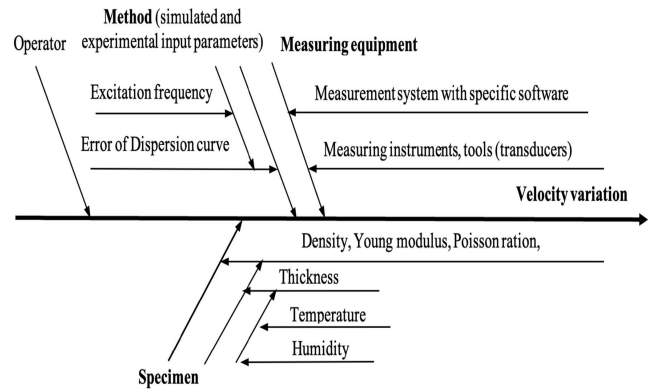


Fig. 2. Cause and effect diagram to visualize the possible uncertainty components for phase and group velocities evaluation of the Lamb waves by using contact measurement method.

suitability of the proposed signal processing method for its use. Thus, key recommendations and research steps, as well as systematized components of uncertainty, would help in the introduction of new signal processing methods.

The assessment of the components with the greatest influence on the overall standard uncertainty is recommended to be focused on [39], [43]–[47]. Typical sources of the uncertainty are submitted using a cause-and-effect diagram in Fig. 2.

Uncertainty sources can be divided into three main groups: 1) method implementation; 2) measuring instruments; and 3) specimen parameters, which include the mechanical parameters affected by environmental conditions and geometric parameters. Therefore, the next step is to quantify the

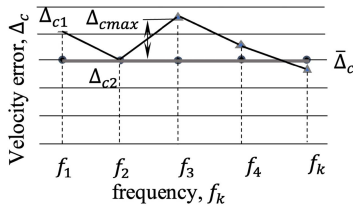


Fig. 3. Calculation of the mean absolute error of the reconstructed segment of the velocity dispersion curve.

uncertainty arising from these sources. Thus, this information can be obtained using different means: in the laboratory, from the device specifications, test reports, and scientific literature. Main uncertainty sources and most influential components related to the individual measurement stages are presented below. Operators are assumed to be trained to work with measuring equipment. Based on this reason, the uncertainty source of the human error is neglected in this article.

A. Method Implementation

It is assumed that a methodical error is evaluated during the mathematical verification. Obtained segments of the dispersion curves can be used to assess the uncertainty of the measurement model $\sigma_{\Delta_{c_{mat}}}$ (see Table I). It is equal to the standard deviation of the dispersion curves.

Using the developed signal processing method, the dispersion curves in the given frequency range are reconstructed. According to the segments of the reconstructed dispersion curves, two main uncertainty components should be evaluated: the standard deviation σ_{Δ_c} and the uncorrected error for a frequency range or the frequency fluctuations of the Lamb waves $\sigma(\Delta_{c_{max}})$ (see Table I). Owing to this, the mean values of the velocity errors $\bar{\Delta}_c$ and the deviations from the average value for separate points Δ_{ck} should be calculated. Maximum deviation from the average velocity error is fixed $\Delta_{c_{max}} = \max(\Delta_{ck} - \bar{\Delta}_c)$ by evaluating the combined uncertainty across the whole frequency range (see Fig. 3). In this way, the deviation for the uncorrected error for the frequency range calculation is obtained (see Table I). It is assumed that the frequency fluctuations of the Lamb waves are evaluated. This component includes limitations of the application of the method due to the resolution.

B. Measuring Instruments

Measurement systems with specific software and tools (transducers) configure the experimental parameters and have very different operating principles and specifications. The operating frequency band of the transducers used in the experiment affects the frequency range of the reconstructed dispersion curve which has been discussed above.

Studies have shown that the distance between two measurement points (for example the scanning step) has an impact on the results [39], [40], [46]. So, it is recommended to estimate the uncertainty component based on the distance between two points dx . Then, the standard uncertainty $\sigma(dx)$ can be calculated as shown in Table I. Transmitter produces by a pulse

with the duration of t which corresponds to the excitation of appropriate frequency waves. The change of Δt is affected by the corresponding variation of Δdx , which is very small. Therefore, the time component is not discussed.

The impact of the electrical noise on the equipment used is very difficult to assess. Because of this reason, it is recommended to reduce the errors by performing signal averaging. For example, averaging eight signals reduces random noise 2.5 times [40], [45].

C. Specimen Parameters

Temperature affects the measurement result [48], as it affects the geometrical parameters of the object, mechanical material properties. Typically, the properties of the material are determined at a temperature of 20 °C. The uncertainty of the temperature fluctuations is small and may be neglected when using a contact method at a sufficiently short distance in a controlled laboratory environment [39], [47]. In any case, the experiments have to be performed under normal working conditions (20 °C \pm 2 °C). Therefore, the laboratory temperature ought to be monitored using a calibrated thermometer.

Based on the carried out investigations, the mechanical and geometric parameters such as density ρ , Young's modulus E , Poisson's ratio ν , and plate thickness d affect the variation of the velocities [39], [40]. Due to this reason, the knowledge of the material properties and geometry of the objects under investigation is necessary. Experimental results or some assumptions and/or manufacturers' specifications can be used for uncertainty analysis of these components [45], [48]. Standard uncertainties can be calculated using the rectangular or Gaussian distribution accordingly (see Table I). In the cases where it is difficult to describe the model function, the sensitivity coefficients can be evaluated not mathematically, but experimentally [46], [47]. In this case, the sensitivity coefficient is calculated instead of standard expression [46] $W_i(x_i) = (\partial F(x_i)/\partial x_i)$ using the equation [46]: $W_i(x_i) = (\Delta F(x_i)/\Delta x_i)$, where Δx_i is the small change of the variable x_i , $\Delta F(x_i)$ is the change of function caused by variation Δx_i and it is evaluated as follows:

$$\Delta F(x_i) = \frac{[F(x_i) - F(x_i - \Delta x_i)]}{2} + \frac{[F(x_i - \Delta x_i) - F(x_i)]}{2}. \quad (5)$$

Based on the discussed main sources of the combined standard uncertainties, the overall uncertainty budget is summarized and presented in Table I. The probability distributions and formulas are also assigned, and they are listed in Table I.

During the calculation of the uncertainty components, the preference should be given to the experimental data or simulation using theoretical assumptions. When the sum of individual effects is important, it is necessary to consider the individual contributions from all individual effects separately. As most equipment calibration uncertainties will be negligibly small when compared with the overall precision and uncertainty in the bias; this needs only to be verified.

As observed in the uncertainty evaluation [39], [46], [47], the dominant influences are attributed to the repeatability of velocity, frequency fluctuations of the Lamb waves, and

cover more than 50% of the overall uncertainty. Presented combined standard uncertainty is sensitive to the parameters of the mathematical model, plate thickness (especially in the measurement of small geometrical parameters), and the distance between two points.

Each source is quantified and incorporated into a final expanded uncertainty using the standard formula [45] $(\Delta c) = k \times (\sum_{i=1}^N W_i^2 \sigma^2(x_i))^{1/2}$, where W_i is the sensitivity coefficient, $\sigma(x_i)$ is the standard uncertainty. Expanded uncertainty is based on the standard uncertainty multiplied by a coverage factor of $k = 2$, which provides a confidence level of 95%.

IV. CONCLUSION

The work presents the methodology of reliability evaluation of signal processing methods used to reconstruct the dispersion curves of the phase and group velocities of Lamb waves. The reliability of the method is associated with the systematic error and measurement uncertainty evaluation. According to the requirements of ISO 17025, method validation and verification are carried out by quantitative assessment of its accuracy. The methodology provides the main characteristics and sources of uncertainties, which mainly affect the accuracy of the obtained results. The present methodology includes an algorithm for estimating the optimal uncertainty. Based on the presented algorithm, two different tests, using simulated and experimental parameters are recommended to be performed for the verification of the proposed method. In both cases, the results obtained must be compared with the calculated dispersion curves by the reference method. The results of the mathematical verification are used for the calculation of the mathematical model uncertainty. The experimental results are used to calculate key characteristics such as the systematic average error and the expanded uncertainty. The expanded uncertainty covers all the significant components that have been identified.

The verification methodology with the evaluated budget of uncertainties can be applied equally within different industries. Using the presented calculations, the analysis can be minimized, saving cost and time. New standards for certification testing, inspection, and monitoring can be developed based on the provided methodology in the future.

REFERENCES

- [1] W. J. Staszewski, S. Mahzan, and R. Traynor, "Health monitoring of aerospace composite structures—Active and passive approach," *Compos. Sci. Technol.*, vol. 69, nos. 11–12, pp. 1678–1685, Sep. 2009, doi: 10.1016/j.compscitech.2008.09.034.
- [2] K. A. Tiwari and R. Raisutis, "Identification and characterization of defects in glass fiber reinforced plastic by refining the guided Lamb waves," *Materials*, vol. 11, no. 7, p. 1173, Jul. 2018, doi: 10.3390/ma11071173.
- [3] R. Kažys, R. Šlitteris, L. Mažeika, O. Tumšys, and E. Žukauskas, "Attenuation of a slow subsonic A0 mode ultrasonic guided wave in thin plastic films," *Materials*, vol. 12, no. 10, p. 1648, May 2019, doi: 10.3390/ma12101648.
- [4] J. Zhang, Z. Wu, Z. Yang, K. Liu, K. Zhou, and Y. Zheng, "Excitation of guided wave modes in arbitrary cross-section structures by applied surface tractions," *Smart Mater. Struct.*, vol. 29, no. 6, Jun. 2020, Art. no. 065010, doi: 10.1088/1361-665X/ab85a1.
- [5] G. Sha, H. Xu, M. Radziński, M. Cao, W. Ostachowicz, and Z. Su, "Guided wavefield curvature imaging of invisible damage in composite structures," *Mech. Syst. Signal Process.*, vol. 150, Mar. 2021, Art. no. 107240, doi: 10.1016/j.ymssp.2020.107240.
- [6] A. A. Eremin, E. V. Glushkov, N. V. Glushkova, and R. Lammering, "Evaluation of effective elastic properties of layered composite fiber-reinforced plastic plates by piezoelectrically induced guided waves and laser Doppler vibrometry," *Compos. Struct.*, vol. 125, pp. 449–458, Jul. 2015, doi: 10.1016/j.compstruct.2015.02.029.
- [7] S. S. Bang, Y. H. Lee, and Y.-J. Shin, "Defect detection in pipelines via guided wave-based time–frequency-domain reflectometry," *IEEE Trans. Instrum. Meas.*, vol. 70, pp. 1–11, 2021, doi: 10.1109/TIM.2021.3055277.
- [8] W. Wang, Y. Bao, W. Zhou, and H. Li, "Sparse representation for Lamb-wave-based damage detection using a dictionary algorithm," *Ultrasonics*, vol. 87, pp. 48–58, Jul. 2018, doi: 10.1016/j.ultras.2018.02.011.
- [9] C. Xu, Z. Yang, B. Qiao, and X. Chen, "A parameter estimation based sparse representation approach for mode separation and dispersion compensation of Lamb waves in isotropic plate," *Smart Mater. Struct.*, vol. 29, no. 3, Mar. 2020, Art. no. 035020, doi: 10.1088/1361-665X/ab6ce7.
- [10] M. Barski and P. Pajtk, "Determination of dispersion curves for composite materials with the use of stiffness matrix method," *Acta Mech. Autom.*, vol. 11, no. 2, pp. 121–128, Jun. 2017, doi: 10.1515/ama-2017-0019.
- [11] B. Feng, A. L. Ribeiro, and H. G. Ramos, "Interaction of Lamb waves with the edges of a delamination in CFRP composites and a reference-free localization method for delamination," *Measurement*, vol. 122, pp. 424–431, Jul. 2018, doi: 10.1016/j.measurement.2017.10.016.
- [12] Z. Wang, S. Huang, S. Wang, Q. Wang, and W. Zhao, "Multihelical Lamb wave imaging for pipe-like structures based on a probabilistic reconstruction approach," *IEEE Trans. Instrum. Meas.*, vol. 70, pp. 1–10, 2021, doi: 10.1109/TIM.2020.3038474.
- [13] H. Chen, G. Zhang, D. Fan, L. Fang, and L. Huang, "Nonlinear Lamb wave analysis for microdefect identification in mechanical structural health assessment," *Measurement*, vol. 164, Nov. 2020, Art. no. 108026, doi: 10.1016/j.measurement.2020.108026.
- [14] P. Ochoa, V. Infante, J. M. Silva, and R. M. Groves, "Detection of multiple low-energy impact damage in composite plates using Lamb wave techniques," *Compos. B, Eng.*, vol. 80, pp. 291–298, Oct. 2015, doi: 10.1016/j.compositesb.2015.06.010.
- [15] L. Zeng, J. Lin, J. Bao, R. P. Joseph, and L. Huang, "Spatial resolution improvement for Lamb wave-based damage detection using frequency dependency compensation," *J. Sound Vib.*, vol. 394, pp. 130–145, Apr. 2017, doi: 10.1016/j.jsv.2017.01.031.
- [16] Z. Su, L. Ye, and Y. Lu, "Guided Lamb waves for identification of damage in composite structures: A review," *J. Sound Vib.*, vol. 295, nos. 3–5, pp. 753–780, Aug. 2006, doi: 10.1016/j.jsv.2006.01.020.
- [17] F. Schöpfer *et al.*, "Accurate determination of dispersion curves of guided waves in plates by applying the matrix pencil method to laser vibrometer measurement data," *CEAS Aeronaut. J.*, vol. 4, no. 1, pp. 61–68, Apr. 2013, doi: 10.1007/s13272-012-0055-7.
- [18] H. Jia, Z. Zhang, H. Liu, F. Dai, Y. Liu, and J. Leng, "An approach based on expectation-maximization algorithm for parameter estimation of Lamb wave signals," *Mech. Syst. Signal Process.*, vol. 120, pp. 341–355, Apr. 2019, doi: 10.1016/j.ymssp.2018.10.020.
- [19] *EUR-FA Guide: Protocol for Verification Studies of Single Laboratory/In-House Validated Methods*, Eur. Union Reference Lab., Feed Additives Eur. Commission-Joint Res. Centre, Belgium, 2014, pp. 1–26. Accessed: May 15, 2021. [Online]. Available: <https://ec.europa.eu/jrc/sites/default/files/EURLFA-technical%20guide%20for%20validation%20and%20verification%20v2014.pdf>
- [20] *ALACC Guide How to Meet ISO 17025 Requirements for Acknowledgments Method Verification*, AOAC Int., USA, 2007, p. 18. Accessed: May 15, 2021. [Online]. Available: <https://documents.net/reader/full/how-to-meet-iso-17025-requirements-for-method-verification>
- [21] B. Magnusson and U. Örnemark, Eds., "Eurachem guide: The fitness for purpose of analytical methods—A laboratory guide to method validation and related topics," 2nd ed., Eurachem, U.K., 2014, p. 64. Accessed: May 15, 2021. [Online]. Available: https://www.eurachem.org/images/stories/Guides/pdf/MV_guide_2nd_ed_EN.pdf
- [22] R. Gorgin, Y. Luo, and Z. Wu, "Environmental and operational conditions effects on Lamb wave based structural health monitoring systems: A review," *Ultrasonics*, vol. 105, Jul. 2020, Art. no. 106114, doi: 10.1016/j.ultras.2020.106114.

- [23] S. Shoja, V. Berbyuk, and A. Boström, "Guided wave-based approach for ice detection on wind turbine blades," *Wind Eng.*, vol. 42, no. 5, pp. 483–495, Oct. 2018, doi: [10.1177/0309524X18754767](https://doi.org/10.1177/0309524X18754767).
- [24] J. Moll, C. Kexel, S. Pötzsch, M. Rennoch, and A. S. Herrmann, "Temperature affected guided wave propagation in a composite plate complementing the open guided waves platform," *Sci. Data*, vol. 6, no. 1, pp. 1–9, Dec. 2019, doi: [10.1038/s41597-019-0208-1](https://doi.org/10.1038/s41597-019-0208-1).
- [25] O. Putkis, R. P. Dalton, and A. J. Croxford, "The influence of temperature variations on ultrasonic guided waves in anisotropic CFRP plates," *Ultrasonics*, vol. 60, pp. 109–116, Jul. 2015, doi: [10.1016/j.ultras.2015.03.003](https://doi.org/10.1016/j.ultras.2015.03.003).
- [26] A. J. Croxford, J. Moll, P. D. Wilcox, and J. E. Michaels, "Efficient temperature compensation strategies for guided wave structural health monitoring," *Ultrasonics*, vol. 50, nos. 4–5, pp. 517–528, Apr. 2010, doi: [10.1016/j.ultras.2009.11.002](https://doi.org/10.1016/j.ultras.2009.11.002).
- [27] E. Theodorsson, "Validation and verification of measurement methods in clinical chemistry," *Bioanalysis*, vol. 4, no. 3, pp. 305–320, Feb. 2012, doi: [10.4155/bio.11.311](https://doi.org/10.4155/bio.11.311).
- [28] G. Abdel and M. El-Masry, "Verification of quantitative analytical methods in medical laboratories," *J. Med. Biochem.*, vol. 40, no. 3, pp. 225–236, 2021, doi: [10.5937/jomb0-24764](https://doi.org/10.5937/jomb0-24764).
- [29] P. Ravisankar, C. N. Navya, D. Pravalika, and D. N. Sri, "A review on step-by-step analytical method validation," *IOSR J. Pharm.*, vol. 5, no. 10, pp. 7–19, 2015.
- [30] G. Hayward and J. Hyslop, "Determination of Lamb wave dispersion data in lossy anisotropic plates using time domain finite element analysis. Part I: Theory and experimental verification," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 53, no. 2, pp. 443–448, Feb. 2006, doi: [10.1109/TUFFC.2006.1593383](https://doi.org/10.1109/TUFFC.2006.1593383).
- [31] C.-H. Chung and Y.-C. Lee, "Nondestructive determination of elastic constants of thin isotropic plates based on poly(vinylidene fluoride-trifluoroethylene) copolymer ultrasound focusing transducers and Lamb wave measurements," *Jpn. J. Appl. Phys.*, vol. 48, no. 4, Apr. 2009, Art. no. 046506, doi: [10.1143/JJAP.48.046506](https://doi.org/10.1143/JJAP.48.046506).
- [32] R. Watkins and R. Jha, "A modified time reversal method for Lamb wave based diagnostics of composite structures," *Mech. Syst. Signal Process.*, vol. 31, pp. 345–354, Aug. 2012, doi: [10.1016/j.ymssp.2012.03.007](https://doi.org/10.1016/j.ymssp.2012.03.007).
- [33] M. S. Harb and F. G. Yuan, "A rapid, fully non-contact, hybrid system for generating Lamb wave dispersion curves," *Ultrasonics*, vol. 61, pp. 62–70, Aug. 2015, doi: [10.1016/j.ultras.2015.03.006](https://doi.org/10.1016/j.ultras.2015.03.006).
- [34] H. Nishino, T. Tanaka, K. Yoshida, and J. Takatsubo, "Simultaneous measurement of the phase and group velocities of Lamb waves in a laser-generation based imaging method," *Ultrasonics*, vol. 52, no. 4, pp. 530–535, Apr. 2012, doi: [10.1016/j.ultras.2011.11.005](https://doi.org/10.1016/j.ultras.2011.11.005).
- [35] K. Kapil, "Method development and validation of analytical procedures," Dev Bhoomi Inst. Pharmacy Res., Dehradun, India, 2011, doi: [10.5772/19894](https://doi.org/10.5772/19894).
- [36] Ş. Sorohan, N. Constantin, M. Găvan, and V. Anghel, "Extraction of dispersion curves for waves propagating in free complex waveguides by standard finite element codes," *Ultrasonics*, vol. 51, no. 4, pp. 503–515, May 2011, doi: [10.1016/j.ultras.2010.12.003](https://doi.org/10.1016/j.ultras.2010.12.003).
- [37] B. Pavlakovic and M. J. S. Lowe, "Disperse user's manual," Non-Destructive Test. Lab., Dept. Mech. Eng., Imperial College London, 2013, p. 207. Accessed: May 15, 2021. [Online]. Available: <https://www.scribd.com/document/410429651/disperse-manual-pdf>
- [38] P. He, "Simulation of ultrasound pulse propagation in lossy media obeying a frequency power law," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 45, no. 1, pp. 114–125, Jan. 1998, doi: [10.1109/58.646916](https://doi.org/10.1109/58.646916).
- [39] L. Draudvilienė, A. Meskuotienė, L. Mazeika, and R. Rausutis, "Assessment of quantitative and qualitative characteristics of ultrasonic guided wave phase velocity measurement technique," *J. Nondestruct. Eval.*, vol. 36, no. 2, Jun. 2017, doi: [10.1007/s10921-017-0404-x](https://doi.org/10.1007/s10921-017-0404-x).
- [40] L. Draudvilienė, A. Meskuotienė, R. Rausutis, and H. Ait-Aider, "The capability assessment of the spectrum decomposition technique for measurements of the group velocity of Lamb waves," *J. Nondestruct. Eval.*, vol. 37, no. 2, pp. 1–13, Jun. 2018, doi: [10.1007/s10921-018-0484-2](https://doi.org/10.1007/s10921-018-0484-2).
- [41] R. N. Kacker, "Measurement uncertainty and its connection with true value in the GUM versus JCGM documents," *Measurement*, vol. 127, pp. 525–532, Oct. 2018, doi: [10.1016/j.measurement.2018.05.105](https://doi.org/10.1016/j.measurement.2018.05.105).
- [42] H. Huang, "Comparison of three approaches for computing measurement uncertainties," *Measurement*, vol. 163, Oct. 2020, Art. no. 107923, doi: [10.1016/j.measurement.2020.107923](https://doi.org/10.1016/j.measurement.2020.107923).
- [43] A. N. Kalashnikov and R. E. Challis, "Errors and uncertainties in the measurement of ultrasonic wave attenuation and phase velocity," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 52, no. 10, pp. 1754–1768, Oct. 2005, doi: [10.1109/TUFFC.2005.1561630](https://doi.org/10.1109/TUFFC.2005.1561630).
- [44] R. Grimberg, A. Savin, R. Steigmann, M. D. Stanciu, and J. Grum, "Determination of elastic properties of CFRP using Lamb waves resonant spectroscopy," in *Proc. 2nd Int. Symp. NDT Aerosp.*, 2010, pp. 1–8.
- [45] *Evaluation of Measurement Data—Supplement 1 to the 'Guide to the Expression of Uncertainty in Measurement'—Propagation of Distributions Using a Monte Carlo Method*, document JCGM 101:2008, 2008.
- [46] L. Draudvilienė, A. Meskuotienė, O. Tumsys, L. Mazeika, and V. Samaitis, "Metrological performance of hybrid measurement technique applied for the Lamb waves phase velocity dispersion evaluation," *IEEE Access*, vol. 8, pp. 45985–45995, 2020, doi: [10.1109/access.2020.2974586](https://doi.org/10.1109/access.2020.2974586).
- [47] B. H. Crespo, C. Courtney, and B. Engineer, "Calculation of guided wave dispersion characteristics using a three-transducer measurement system," *Appl. Sci.*, vol. 8, no. 8, p. 1253, Jul. 2018, doi: [10.3390/app8081253](https://doi.org/10.3390/app8081253).
- [48] Q. Xie *et al.*, "Imaging gigahertz zero-group-velocity Lamb waves," *Nature Commun.*, vol. 10, no. 1, pp. 1–7, Dec. 2019, doi: [10.1038/s41467-019-10085-4](https://doi.org/10.1038/s41467-019-10085-4).

Lina Draudvilienė received the M.Eng. degree in telecommunication engineering and the Ph.D. degree in measurements engineering from the Kaunas University of Technology, Kaunas, Lithuania, in 2008 and 2012, respectively.

In 2008, she worked as an Engineer with the Ultrasound Research Institute, Kaunas University of Technology, and then as a Junior Researcher, where she has been a Researcher with the Ultrasound Research Institute since 2014. She is the coauthor of over 20 scientific articles. Her research interests include ultrasonic guided waves measurements, non-destructive testing, structural health monitoring, material characterization, and signal processing.

Asta Meškuotienė received the M.Eng. degree in mechanic engineering and the Ph.D. degree in measurements engineering from the Kaunas University of Technology, Kaunas, Lithuania, in 1995 and 2002, respectively.

In 2002, she worked as an Engineer with the Institute of Metrology, Kaunas University of Technology, and then as a Researcher, where she has been a Senior Researcher since 2008. Her research interests include mass, pressure, density, length, volume measurements, and signal processing, development of the traceability system of the above-mentioned measurement quantities, development of verification and calibration methods and expertise, and quality infrastructure systems.

Dr. Meškuotienė is a Technical Expert of the National Accreditation Bureau and a member of the Technical Committee No. 34 "Metrology" of the Lithuanian Standards Board and the Metrology Expert Council of the National Metrology Institute.