KAUNAS UNIVERSITY OF TECHNOLOGY

EDGARAS VAŠTAKAS

GENERATION AND APPLICATION OF MECHANICAL DISPLACEMENTS FOR LOW FREQUENCY ACOUSTIC EMISSION TRANSDUCER CALIBRATION

Summary of Doctoral Dissertation
Technology Sciences, Measurement Engineering (10T)

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INTRODUCTION

Relevance of the topic

The majority of acoustic emission transducers (AET) are of piezoelectric type due to their simple construction and possibility to perform measurements under complex conditions (high temperature, environmental pollution, dust, etc.), and they are used in many areas as well. Transducer time and frequency-based characteristics depend on the properties of piezo ceramics and the construction of the transducer, and may vary considerably, depending on the operating conditions. Therefore, the calibration of such transducers is necessary.

The calibration of acoustic emission transducers is defined by the standard **E1106-86**. In this standard, a method is described, and recommendations for the equipment allowing measurement of the AET impulse and frequency responses are provided.

The AET impulse response is measured during the excitation of the AET, using a mechanical stress of order of microseconds, i.e., impulse, or spike. To prevent the impact of acoustic wave reflections on the measurement of the impulse response, the standard **E1106-86** recommends using a metal block. The mechanical effects (nanoscale displacements) are induced by breaking the borosilicate capillary tube. After its propagation through the metal block, the mechanical stress allows to measure the AET impulse and frequency responses while avoiding the impact of acoustic reflections from the walls of the block on the results of the measurement.

The block size is large in the low frequency range from 20 kHz to 100 kHz, and its mass can reach several tons. Borosilicate capillary tubes are used to generate the mechanical impact, which leads to a problem associated with the manufacture of such tubes, ensuring repeatability of production parameters, as well as the limited performance of the calibration system. The calibration is performed using a wave of Rayleigh type, regardless of the AET operating conditions. Therefore, the characteristics obtained using existing calibration equipment are correct when the transducer operating conditions are close to those which were present during calibration. If, during its real-world application the AET measures, the wave of other type that propagates in a material with substantially different acoustic impedance, then the transducer characteristics obtained during calibration are not comprehensive enough. For this reason, a different kind of calibration equipment is necessary, which could provide the possibility to measure the AET characteristics using different types of waves and to evaluate the characteristics of these transducers under different acoustic impedance.

Considering the shortcomings of the existing calibration equipment, a task to create a portable AET calibration equipment of a new type, with a greater measurement performance and allowing the evaluation of AET characteristics using different wave types and waveguides with different acoustic impedances, was formulated.

One of the main problems encountered was the reduction of the calibration equipment size. In the equipment described by the standard, a large metal block is used. The use of such block allows to avoid the impact of the wave reflections from the walls of the block on the results of the measurements. Block dimensions are selected so as to reach at least several wavelengths of the propagating wave of minimal frequency. When reducing the size of the calibration equipment, the introduction of such block becomes impossible. For this reason, the bar and plate type constructions of acoustic waveguides with considerably smaller dimensions were offered. The application of these waveguides permits the reduction of the calibration equipment size; however, the acoustic wave dispersion is unavoidable in the waveguides of such type. The mechanical impact triggered in the dispersive waveguides depends on the geometry of the waveguide (length, diameter, cross section shape, thickness – in plate case), and the properties of the transducer used for the excitation. Because of this reason, it is not possible to obtain nano-displacements of the order of microseconds when using the conventional methods of excitation in such waveguides. Therefore, deconvolution-based methods of mechanical displacement generation have been proposed and practically implemented. Considering the need to calibrate the AET using different types of waves, the waveguides of different construction types have been proposed and tested.

As it is necessary to know the magnitude of the displacement used to excite the transducer when performing the transducer calibration in absolute units, the analysis of methods applicable in measurement of micro displacements was conducted. Different nano displacement measurement methods have been tested, and the construction of the smart capacitive transducer for the measurement of micro displacements has been proposed.

Based on the results presented in this work, a new type low-frequency AET calibration stands, and tools for the measurement of micro displacements have been suggested. The measurement uncertainties of the proposed calibration equipment were evaluated. The results of the work have been implemented in the project “Smart acoustic emission transducers”.

The aim and objectives

The objective of the work is to investigate the possibilities of application of mechanical effects generated in dispersive waveguides to calibrate the low-frequency AET and to create measures for their calibration.

To achieve the objective of the work, the following tasks have been formulated:

1. Propose methods and measures for obtaining mechanical displacements of the desired waveform in dispersive waveguides. To demonstrate their suitability for AET calibration.
2. Suggest waveguide constructions and evaluate the application possibilities of these constructions with aim to calibrate AET.
3. Offer and explore potential measurement tools for the measurement of mechanical displacement of the specified shape. To evaluate uncertainties of the proposed measurement tools introduced during the calibration of AET.

Research methods

The tasks formulated in order to achieve the work objective were being solved analytically, and the results have been verified experimentally. The dispersive properties of waveguides have been calculated according to mathematical expressions presented in the literature. Predetermined displacement calculation and evaluation algorithms have been implemented using Matlab software.

Experimental investigations were conducted in Kaunas University of Technology laboratories of Metrology Institute, Faculty of Mechanical Engineering and Mechatronics, and Prof. K. Baršauskas Ultrasound Research Institute.

Evaluation of measurement uncertainties has been conducted according to the method presented in the literature.

Scientific novelty

- The possibilities to obtain predetermined mechanical effects in the bar and plate type structures have been demonstrated.
- New methods of obtaining predetermined mechanical effects have been proposed. Comparison of methods used to generate mechanical effects has been accomplished.

Practical value

The results of the work have been implemented in the project, “Smart acoustic emission transducers”. Using the results obtained in this work, the calibration of the manufactured AET has been performed.

Approbation of the results

The following items have been published in relation with the dissertation topic: two scientific papers in the journals cited in the database of Institute for Scientific Information, and one paper in conference proceedings; tree presentations in international conferences. Practical results of the work have been implemented in the project, “Smart acoustic emission transducers”.

Statements presented to defense

1. Proposed excitation methods allow to generate arbitrary type displacements in dispersive waveguides. Hence, it is possible to manufacture new types of stands which haven’t been used for AET calibration before. One of the key features of these stands is the application of bar, plate, and grid type array waveguides.
2. New type of AET calibration stands expand the transducer characteristic measurement abilities. Increase in the measurement speed, compared to existing solutions’ limitations, reduces the size of calibration stands and allows for measurements with different acoustic impedances.
3. Mechanical displacements, necessary for AET calibration measurement with absolute unit’s problem, are solved by applying a new type capacitive transducer with self-calibration possibilities.

The structure and scope of the dissertation

This doctoral dissertation consists of an introduction, 4 chapters, conclusions, and a list of references. The total volume is 102 pages, in which 68 figures, 13 tables, 63 mathematical expressions, and a list of 61 titles of references are presented.

In the First chapter, the AET calibration examples are presented, providing the ground to decide on the need to provide more detailed calibration data. The AET calibration methods are analyzed, and advantages and shortcomings of these measurement methods are discussed.

In the Second chapter, the problems arising when attempting to obtain predetermined displacements in bars and plates are shown, along with the influence of dispersion on the displacements that are generated. The solutions are proposed, allowing to compensate for the dispersion influence and to obtain predetermined displacements in bars and plates. Additionally, the predetermined displacement evaluation criteria are proposed and the visualization of displacements are performed.

In the Third chapter, the systems for measuring the AET characteristics using longitudinal and surface waves are proposed.

In the Fourth chapter, an analysis of the uncertainties of measurement systems is conducted.

Each chapter ends with conclusions.

In the end of the work, the final conclusions of the investigations carried out are presented.

1. EXISTING ACOUSTIC EMISSION TRANSUCER CALIBRATION SYSTEMS

The simplified system for the measurement of AET characteristics is presented in Fig. 1. The acoustic emission transducer is being affected by the known mechanical pulse. The mechanical force is then converted using the piezo effect into proportional voltage, which is measured and registered using the equipment dedicated for this purpose.

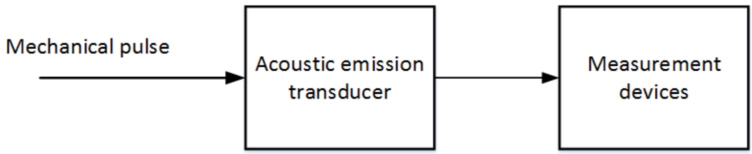


Fig. 1. Simplified structural diagram of acoustic emission transducer calibration system

In the literature, the following methods for the measurement of AET characteristics are presented:

- Method described in the standard **E1106-86**.
- Method described in the standard **E 1781-98**.
- Method described in the standard **E976**.
- Reciprocity calibration method.
- Surface-to-surface AET calibration method.
- Step force AET calibration method.
- Spark impulse AET calibration method.
- Method based on the use of white noise.

The methods listed above permit the measurement of AET frequency-related characteristics. The measurement results are presented in a form of transducer sensitivity over a certain range of frequency (measurement units V/m/s, V/nm, or V/Mpa).

The problem emerging due to such AET representation concerns insufficiently informative results of the measurement. Usually the measured AET frequency response does not allow itself to be associated with the time-based characteristic of the transducer, which normally is not provided. Measurements are carried out for one type of wave and under certain acoustic impedance. This makes it impossible to assess the application possibilities of such AET for alternative service conditions.

2. ARBITRARY WAVEFORM ACOUSTIC SIGNALS GENERATION IN WAVEGUIDES

When attempting to reduce the size of the AET calibration equipment and to expand the measurement capabilities, the microsecond-order mechanical stress generation problem in the bar and plate type waveguides has been encountered.

In the standard **E1106-86**, the mechanical stress is generated by breaking the capillary tube. Such mechanical stress generation technique does not allow the predetermined effects to be generated, and it is difficult to ensure the repeatability of the generated displacements as well. The method also limits the speed of performance of calibration equipment and results in increased dimensions of the equipment. When using this method, the acoustic waves are excited in the metal block type structures, where their dimensions allow the eliminating of the influence of acoustic wave reflections and wave dispersion on the results of the measurement.

Without the use of acoustic wave delay tract, which is a metal block as defined by the standard **E1106-86**, wave reflections would be obtained during the measurement, interfering with the measurement of the AET impulse response. The use of such a block in the portable calibration equipment is not possible. For this reason, bar and plate type waveguides were suggested as a block replacement, allowing for a considerable reduction of calibration equipment size.

When the bar or plate type waveguides are used to delay acoustic waves, dispersion of waves is unavoidable. It means that the conventional excitation methods, such as breaking of the capillary tube, do not result in short mechanical stress necessary to measure the impulse response.

The problems of generating short signals in dispersive environments are also encountered in optical fiber systems, non-destructive testing, underwater acoustics, etc. With an aim of solving this problem, signal processing methods are used, which enable the evaluation of the emerging wave dispersion and the correction of the excitation signal in the desired spot of the dispersive environment, in order to obtain the effect pulse of the desired waveform.

The signal decomposition and time reversal, mirror methods that are currently being used to compensate for the dispersion. Due to its simplicity, the time reversal mirror method can be applied in systems with limited computational performance, although it exhibits a series of disadvantages compared to the method of decomposition.

In order to obtain the mechanical effect of the desired waveform in dispersive waveguides, both methods have been tested. The time reversal mirror method does not estimate the signal attenuation in the waveguide, and is also less resistant to noise. For this reason, when using the time reversal mirror method, it is possible to obtain the several-microsecond impulse from a long mechanical impact stress with a duration of several of microseconds, but the shape of this pulse can hardly be predicted. Also, due to the low resistance to interference, the additional background noise is possible. The deconvolution-based method does not assess the number of bits available in the digital-to-analog converter, which, in some cases, cause additional noise and shape distortion of the synthesized effect.

The results of the research have shown limited application possibilities of the above-mentioned methods with an aim to generate the mechanical effects of the desired shape in waveguides. For this reason, the modified method of decomposition has been proposed and tested. As the literature references do not present any criteria applicable in the evaluation of obtained predetermined effects, the quality criterion Q of the desired waveform signal has been offered for the purpose of such evaluation. This criterion also allowed a comparison of the methods for obtaining the mechanical effects of the order of microseconds in dispersive environments.

2.1 Arbitrary waveform acoustic signals generation in dispersive waveguides

The decomposition-based method is implemented according to formula (1). Methods that use decomposition require a theoretical signal $y(t)$ or $Y(j\omega)$. The signal $y(t)$ duration has to be limited by the transfer function $H(j\omega)$frequency bandwidth, which, in turn, depends on the construction of the piezo ceramic transducer and the waveguide dimensions. For the implementation of this method, as also in the time reversal case, the measurement of the system's impulse response and the possibility to generate complex excitation signals are necessary. When the impulse response of the system is known, the output signal is found by calculating the composition integral.

$$y(t)=\int_{-\infty}^{\infty} h(\tau)x(t-\tau)d\tau; \tag{1}$$

where $y(t)$ – output signal, $x(t)$ – input signal, $h(\tau)$ – impulse response of the system.

The composition integral in the time domain corresponds to the multiplication in the frequency domain, and therefore, the system's output signal spectrum in frequency domain, when the system's transfer function is known, is found according to (2).

$$Y(j\omega) = H(j\omega) \times X(j\omega); \tag{2}$$

where *X(jω)* – complex-number excitation signal spectrum (system input signal), *Y(jω)* - complex spectrum of arbitrary waveform signal (system output), *H(jω)* – complex spectrum of the impulse response.

The excitation signal *x(t)* induces the system's reaction *Y(jω)* and, when the transfer function of the system and the spectrum of the arbitrary waveform are known, is found according to (3). Such method for calculating the excitation signal is the application of the signal decomposition, having a number of drawbacks. The main problem arising with this method of calculation is the division by *H(jω)*. The ratio between the minimal and maximal values of *H(jω)* may exceed 60 dB, and some values may be equal to zero. In such a case, undesired noise is obtained when calculating the excitation signal. It also does not assess the capabilities of the excitation equipment, or the number of bits of the digital-to-analog converter. As a possible solution, the formula (4) has been proposed, in which the window function is used.

$$x(t) = IFFT\left(\frac{Y(j\omega)}{H(j\omega)}\right); \tag{3}$$

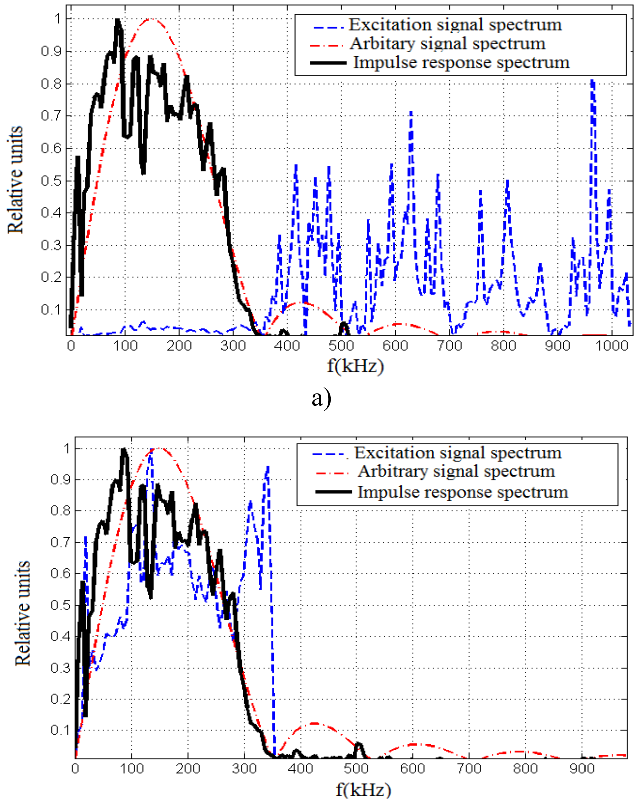
where *IFFT* is the inverse Fourier transformation.

$$\overline{X}(j\omega) = \frac{Y(j\omega) \times L(j\omega)}{H(j\omega)}; \tag{4}$$

where *L(jω)* is the window function.

The frequency range and type of the window function is selected by considering the spectrum of the impulse response and the spectrum of the arbitrary waveform signal. The rectangular window is used in the simplest case. This solves the problem of the resulting high-frequency noise. An example use of such window is given in Fig. 2.

The provided window function application example illustrates the advantages of window function use, although such a solution is possible only in some certain scenarios. There may be situations when the spectrum of the transfer characteristic contains amplitude irregularities, in which case a simple window function (rectangular, Tukey, etc.) does not resolve the problem of division by small values of *H(jω)*.



a)

b)

Fig. 2. Application of the window function: a) signal spectrums without window function b) signal spectrums when using window function

When attempting to solve the problem of division by small values of *H(jω)*, it is offered in literature to calculate the excitation signal using formula (5). The problem is solved by introducing coefficient *k*.

$$X(j\omega) = \frac{Y(j\omega)H^*(j\omega)}{|H(j\omega)|^2 + k^2}; \quad (5)$$

where *X (jω)* – spectrum of excitation signal, *k* - constant, *H(jω)* – system impulse response spectrum, $H^*(j\omega)$ – complex conjugate values of the system impulse response, *Y(jω)* – Fourier transform of the driving signal of arbitrary waveform.

The constant *k*, which is added to *H(jω)* (5), is the same for all frequencies. Therefore, a different method for calculation of excitation signal has been offered, expressed by (6). According to this formula, the window function is calculated, the values of which are selected by considering the ratio of amplitudes of the transfer characteristic.

$$X(j\omega) = \frac{Y(j\omega)L(j\omega)}{H(j\omega)} = \left(\frac{Y(j\omega)}{H(j\omega)}\right) \times \left(1 - \frac{C_{max}}{C(j\omega)}\right)^{W}; \quad (6)$$

where *L(jω)* is window function, $C(j\omega) = \left|\frac{Y(j\omega)}{H(j\omega)}\right|$, *W*–1...10, number must be chosen according to the resulting value of Q Eq.(11).

Another solution developed during the research is the correction of the spectrum samples amplitude based on limit coefficient Eq. (7). The solution can be used alongside deconvolution or time reversal mirror methods.

$$X_i(j\omega) = \begin{cases} \frac{X_i(j\omega)}{r_i}, when\ r_i > l, \\ X_i(j\omega), when\ \ r_i < l. \end{cases} \quad (7)$$

where $X_i(j\omega)$ is the excitation signal spectrum frequency sample, $r_i = \frac{|X_i(j\omega)|}{mean|X(j\omega)|}$, and *l* is the limit coefficient.

Deconvolution based methods require the calculation of theoretical arbitrary signal *y(t)* or *Y(jω)*. Duration *y(t)* is limited by transfer functions $H(j\omega)$ bandwidth, which is determined by piezo ceramic excitation actuator used and also by properties of the dispersive waveguide. In order to obtain the shortest possible acoustic signal, an arbitrary signal duration optimization parameter z_{min} was presented. In order to calculate the optimization parameter, first *N* possible, different duration signals *y(t)*need to be calculated Eq. (8).

$$y(t)_g = \left(\frac{sin(t \times g)}{(t \times g)}\right)^2, when\ g = 0.1 \ldots N; \quad (8)$$

where N – number of signals, g – signal index.

Signal spectrums are calculated according to Eq. (9).

$$Y(j\omega)_g = FFT\left(y(t)_g\right). \tag{9}$$

When spectrums of $Y(j\omega)$ are known, possible $H(j\omega)$ and $Y(j\omega)$ spectrum overlappings are calculated according to Eq. (10).

$$z_g = \left|\left|\sum_{i=1}^{N} \frac{Y_{max}}{Y_i(j\omega)_g}\right| - \left|\sum_{i=1}^{N} \frac{H_{max}}{H_i(j\omega)}\right|\right|; \tag{10}$$

where $Y_{max}=\max(Y(j\omega)_g)$, $H_{max}=\max(H(j\omega)_g)$, z_g – numbers representing spectrum overlapping.

Minimal value of parameter z_g represents best possible overlapping of spectrums $H(j\omega)$ and $Y(j\omega)$. This parameter is obtained using signal index g_{min} Eq. (11), which then can be used for calculation of arbitrary signal $y(t)$ Eq. (12).

$$z_{min}(g) = \min\left(z_g\right) \rightarrow g_{min}, \tag{11}$$

$$y(t) = \left(sinc(t \times g_{min})\right)^2 \rightarrow FFT\left(y(t)\right) = Y(j\omega). \tag{12}$$

Signal y(t) calculated, using index g_{min}, obtained from Eq (11), represents the shortest possible signal duration in the system with transfer function of *H(jω)*.

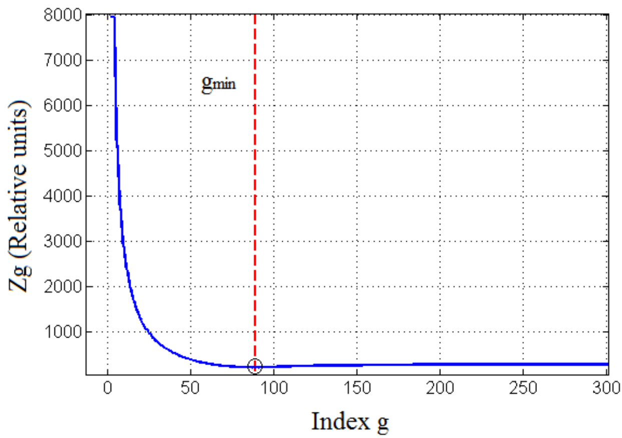


Fig. 3. Values of spectrums' overlapping and minimum index

Spectrums' overlapping evaluation examples for signals of two types – full and half-period sinusoid – are shown in Fig. 4.

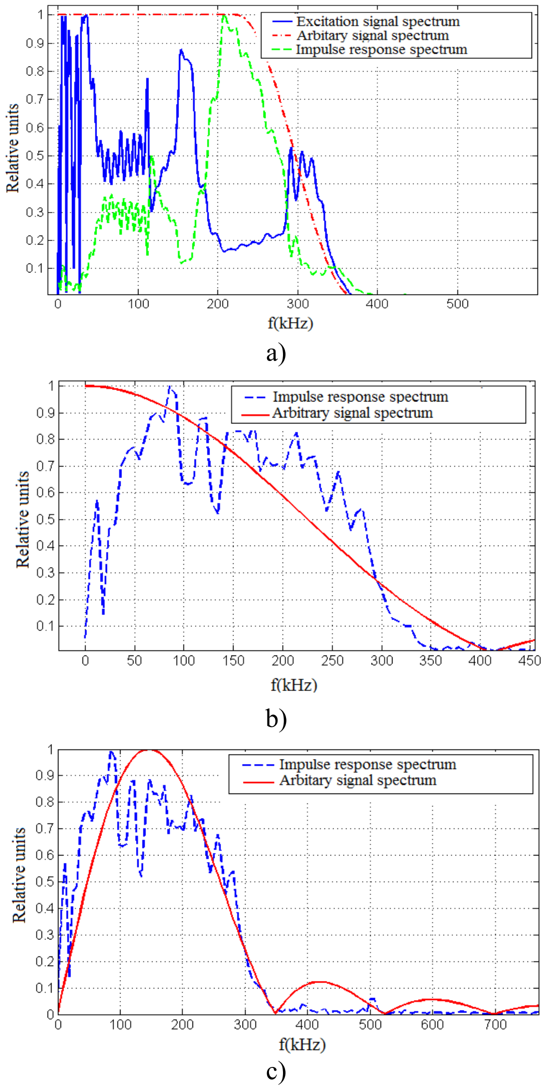


Fig. 4. Overlappings of the arbitrary waveform signal and impulse response spectrums in different waveguides: a) *sinc* type signal b) half-period sinusoid signal c) full-period sinusoid signal

2.3 Wave visualization

During the calibration of AET, the acoustic wave delay tract allows avoiding of the wave reflection impact on the measurement result. It is considered that a minimal delay time for the low-frequency AET calibration (starting with the AET excitation, until the return of the reflected signal) must be not less than 100 μs. At least several signal wavelengths from the transducer with minimum frequency excitation must be accommodated along the direction of wave propagation. It was determined experimentally that the dimensions of the bar-type waveguides have to be chosen according to formula (14), while in case of the plate-type waveguide, the length of a single edge is found using expression (15).

$$l_{bar} \geq 3\lambda_{max}; \tag{14}$$

where l_{bar}– length of the bar-type waveguide, λ_{max} – maximum wavelength used for calibration.

$$l_{plate} \geq 6\lambda_{max}; \tag{15}$$

where l_{plate}– length of the plate-type waveguide, λ_{max} – maximum wavelength used for calibration.

To ensure the synchronicity of the mechanical pulse used for calibration across all the transducer aperture area, the necessary diameter of the bar-type waveguide must be evaluated. It was determined experimentally that this diameter has to be selected according to formula (16).

$$D_b > \frac{\lambda_{min}}{2}; \tag{16}$$

where D_b – diameter of cylindrical waveguide, λ_{min} – minimum wavelength used for calibration.

The excitation signal *x(t)* is calculated using impulse response *h(t)*measured at one point of the waveguide. Thereafter, the desired arbitrary impact function *y(t)*can be calculated at the measurement point of the impulse response *h(t)*, by using methods of decomposition or time reversal mirror. The problem arising independently of the excitation method is related to the continuity of the impulse response on the surface of the waveguide used for AET calibration.

When calculating the excitation signal, none of the examined methods estimates that the impact function *y(t),* obtained at the adjacent points of the waveguide, may differ from the one obtained at the impulse response measurement point.

In order to evaluate the influence of non-continuity of the impulse response *h(t)*on the predetermined impact function *y(t)*, the bar and plate type waveguide surface vibration scan was carried out.

The ending of the steel bar-type waveguide with a diameter of 24 mm was scanned. The measurements were accomplished according to the block diagram presented in Fig. 6. The excitation signal *x(t)* was calculated for the central point according to the modified method of decomposition, formula (6). The excitation signal frequency band was selected according to formula (14).

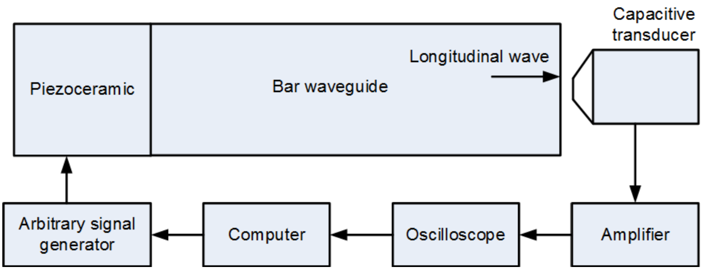


Fig. 6. Equipment connection block diagram

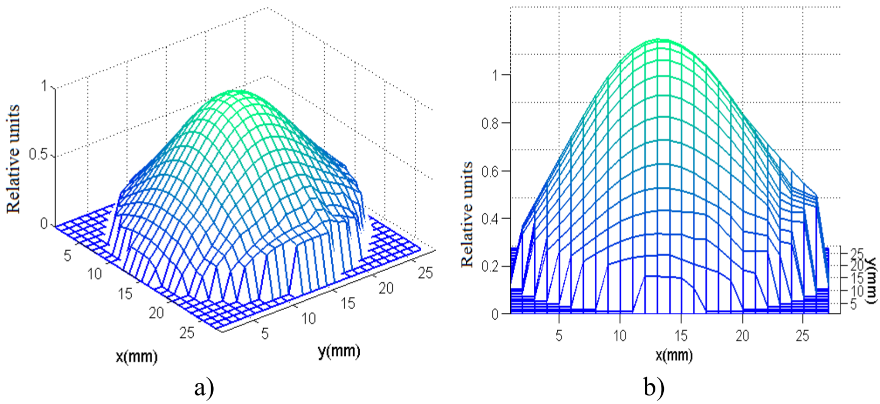


Fig. 7. Scanned vibrations of the ending of the steel bar with diameter of 24 mm for the excitation signal *x(t)*frequency band of 270 kHz: a) surface deformation under maximal vibration amplitude; b) surface deformation x-z axis

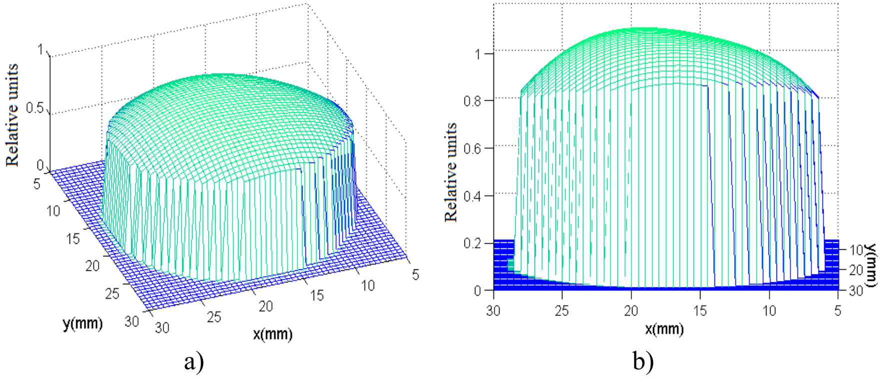


Fig. 8. Scanned vibrations of the ending of the steel bar with diameter of 24 mm for the excitation signal *x(t)* frequency band of 150 kHz: a) surface deformation under maximal vibration amplitude; b) surface deformation x-z axis

Generation of arbitrary mechanical pulse waveforms used for AET calibration is necessary not only in bars, but also in plate-type structures. In order to prove that predetermined displacements may be obtained, not only in a certain area of the bar but in plate as well, a surface scan of the 5 mm thick steel plate was carried out. The measurements were conducted according to the block diagram presented in Fig. 9.

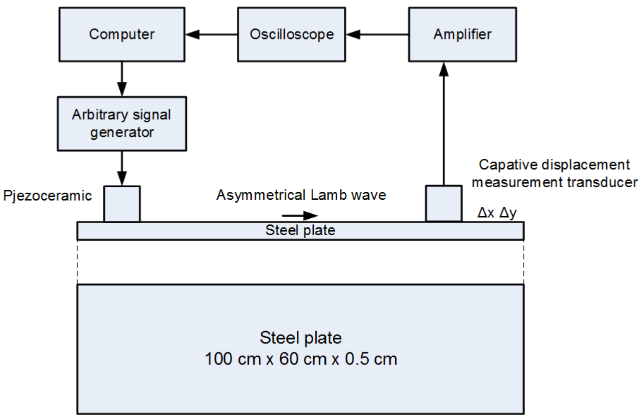


Fig. 9. Equipment connection block diagram

The excitation signal was calculated using formula (6), and the sinusoid full period type mechanical impact pulse was generated using the modified decomposition method. Results are presented in Fig. 10; here, the 2500 mm^2 plate area has been scanned, and the generated impact *y(t)* is shown in different distances from the excitation source.

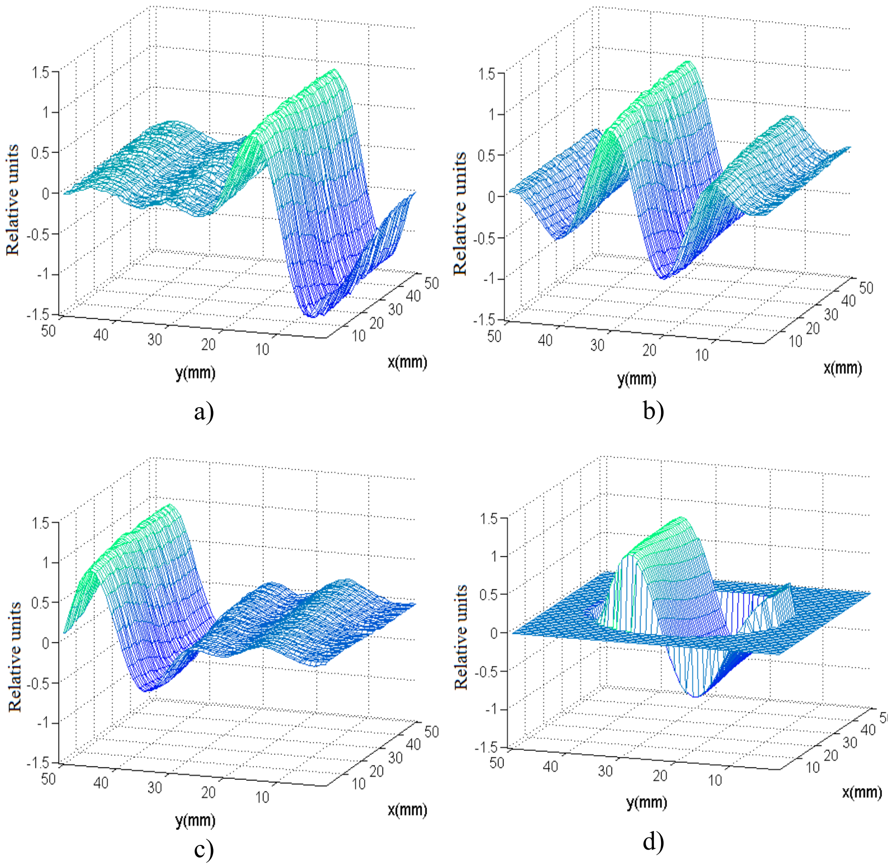
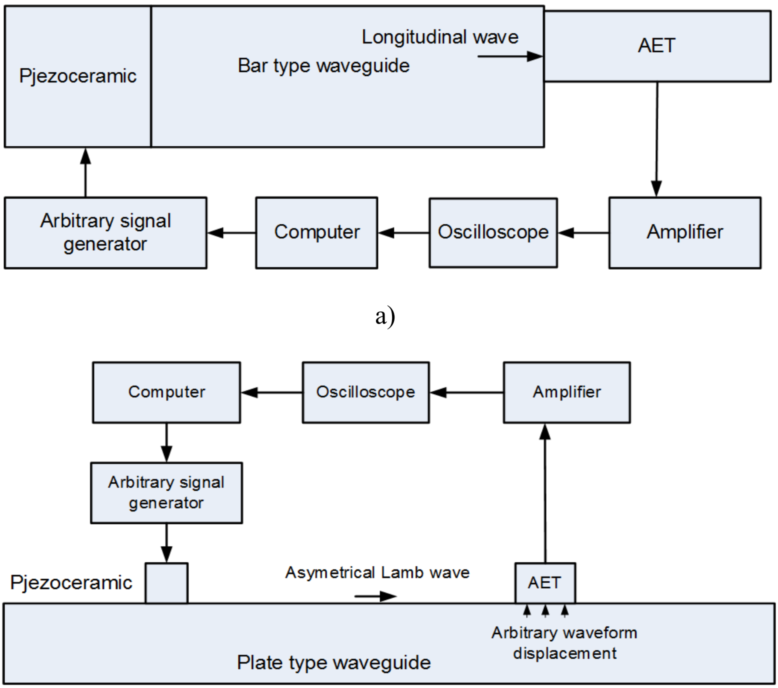


Fig. 10. Scanned plate surface, where the sinusoid period type mechanical displacement *y(t)*is obtained: a) sinusoid period type pulse *y(t)*at 320 mm distance from the excitation source; b) sinusoid period type pulse *y(t)*at 340 mm distance from the excitation source c) sinusoid period type pulse *y(t)*at 350 mm distance from the excitation sourced) pulse *y(t)* in the AET aperture area

3. ACOUSTIC EMISSION TRANSDUCER CALIBRATION AND UNCERTANTY EVALUATION

3.1 AET calibration stands with bar and plate type waveguides

Block diagrams of acoustic emission calibration stand with bar and plate type waveguides are presented in Fig. 11. In both cases the AET are calibrated using arbitrary mechanical displacements generated according to formula (6). Calibration stands waveguides measurements are selected according to formulas (14) - (16). Both calibration stands allow to measure AET impulse response, from which AET frequency response is calculated. Depending on the applied measurement methods, the suggested AET calibration stands allow to measure the AET pulse response with less than 10% uncertainty.



b)

Fig. 11. AET calibration stands block diagrams a) calibration stand with bar type waveguide b) calibration stand with plate type waveguide

3.1 AET calibration system with a grid consisting of *N* bar-type waveguides

For the purpose of AET calibration using surface and longitudinal waves, two types of waveguides were proposed: bars and plates. Experiments performed have indicated that it is possible to generate the displacements of arbitrary shapes as well as use them for the AET calibration in both types of waveguides.

A large number of different AET calibration stands is not convenient due to a series of reasons, and therefore the AET calibration system was suggested, spanning AET calibration functionalities using longitudinal and surface waves, allowing to perform measurements with 10% uncertainty depending on the measurement method used. One of the main elements of such a calibration system is the grid consisting of *N* bar type waveguides.

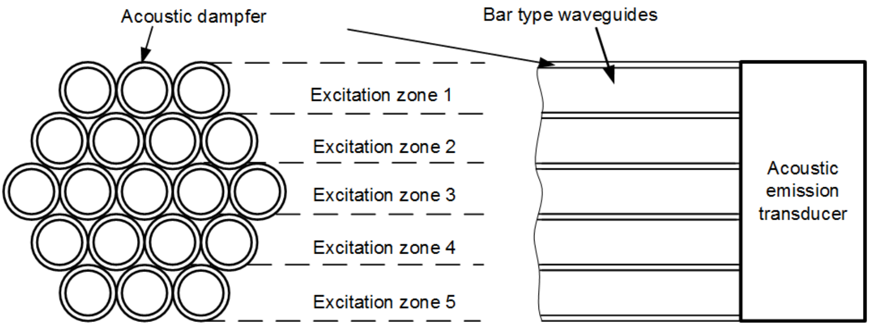


Fig. 12. Structural diagram of the grid consisting of *N* waveguides

The idea of the calibration system is the generation of surface impacts of a complex waveform using a grid consisting of *N* bar type waveguides. A complex, cumulative surface effect is obtained by summing up the effects of arbitrary waveforms generated by different waveguide grid excitation areas. Each of the waveguides is attached side by side, and in this way, forms a specific surface geometry. One of the possible variants of surface geometry is shown in Fig. 12. The AET which is being calibrated, is mounted on the ends of the waveguides. Waveguides are divided into *N* excitation zones. Each waveguide has a separate piezo ceramic which is excited using an individual signal generator dedicated to that specific zone.

Each of the waveguides excites the AET using a longitudinal wave, and in different time intervals. Time intervals must be maintained long enough to measure the AET impulse response. Evaluation of any AET impact is then possible after measuring the *N* impulse responses of AET.

The grid of waveguides cannot be used for AET excitation by surface wave, and therefore, a concept of virtual velocity has been introduced. Each of the measured impulse responses is delayed by a certain time interval. The total delay between the first and N–the excitation zones—is the sum of all delay times, or Δt. When the time interval Δt and the distance D between the first and the last zones of excitation are known, it can be assumed that an impact by a surface wave of a velocity v is available. Such virtual velocity is evaluated according to Fig. 13. If the virtual velocity is zero, then there is no delay between the individual measured impulse responses, and it can be assumed that the longitudinal wave effect on AET has been measured.

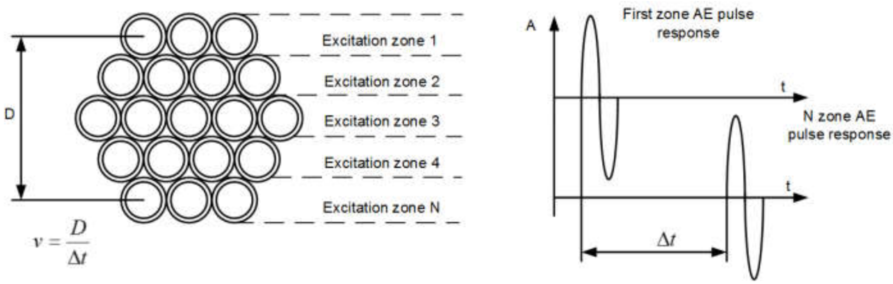


Fig. 13. Evaluation of the virtual velocity

The AET impulse response measured in such AET calibration system depends on the diameter of the transducer aperture and the virtual wave propagation velocity.

$$h(t)_\Sigma = f(S, v); \tag{17}$$

where $h(t)_\Sigma$ - AET impulse response, S – AET aperture area.

Assuming that the longitudinal wave is used for excitation, the AET impulse response is found as a sum of signals from all impact zones (18).

$$h(t)_\Sigma = \sum_{k=1}^{N} h(t)_k; \tag{18}$$

where N – number of excitation lines (zones), k–excitation zone index, $h(t)_k$ –impact zone signal, $h(t)_\Sigma$ – total signal that affects AET.

When assuming that AET is excited using a surface wave, it is necessary to assess the delay duration of each of the excitation zones. This time interval is selected, based on the virtual velocity which has to be obtained. The AET impulse response is then calculated using formula (19).

$$h(t)_{\Sigma} = \sum_{k=1}^{N} h(t + (k-1)t_{vel})_{k}; \tag{19}$$

where t_{vel}– interval of time delay of a single zone of excitation, among excitation signals of zones.

AET frequency response is then found according to formula (20).

$$K(j\omega)_{\Sigma} = \frac{Y_{\Sigma}(j\omega)}{H_{\Sigma}(j\omega)}; \tag{20}$$

where $K(j\omega)_{\Sigma}$ - AET frequency response, $H_{\Sigma}(j\omega)$–spectrum of the total AET impulse response, $Y_{\Sigma}(j\omega)$–total vibration spectrum of all grid excitation zones.

The total vibration spectrum of all grid excitation zones $Y_{\Sigma}(j\omega)$is found using formula (21).

$$Y_{\Sigma}(j\omega) = FFT(\sum_{k=1}^{n} y(t + (k-1)t_{v\grave{e}l})_{k}); \tag{21}$$

where *y(t)* - excitation zones.

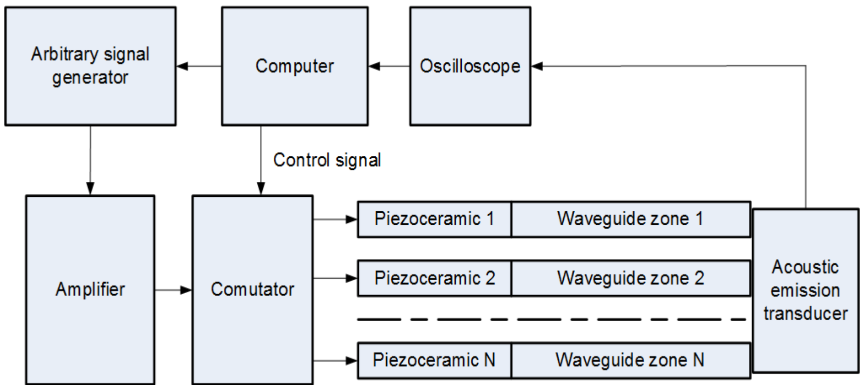


Fig. 14. Block diagram of the AET calibration system with *N* waveguides.

Each of the waveguides must not come into direct contact with another waveguide. In such a case, it becomes impossible to obtain displacements of the arbitrary form across the selected waveguide aperture area. In order to separate one waveguide from another, materials and constructional solutions providing poor acoustic contact between adjacent waveguides were used.

Acoustic wave attenuation between adjacent waveguides is shown Fig. 15. The measurements were performed according to the block diagram presented in Fig. 14. The wideband AET with a 2 mm aperture was used in the measurements. Piezo ceramics from one sector of waveguides were subjected to excitation using 1µs 10V signal, and the surface displacement in this and adjacent sectors was measured, and the acoustic wave attenuation level, when transiting from one waveguide sector to another, was evaluated.

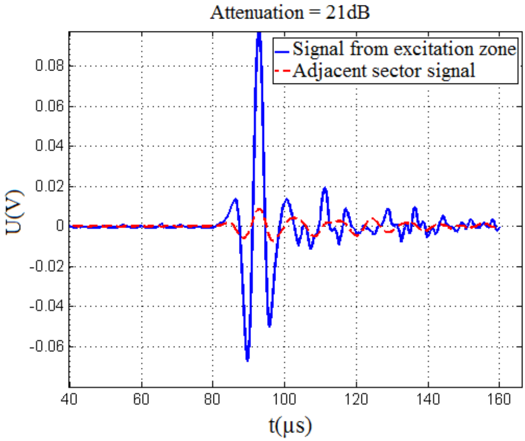


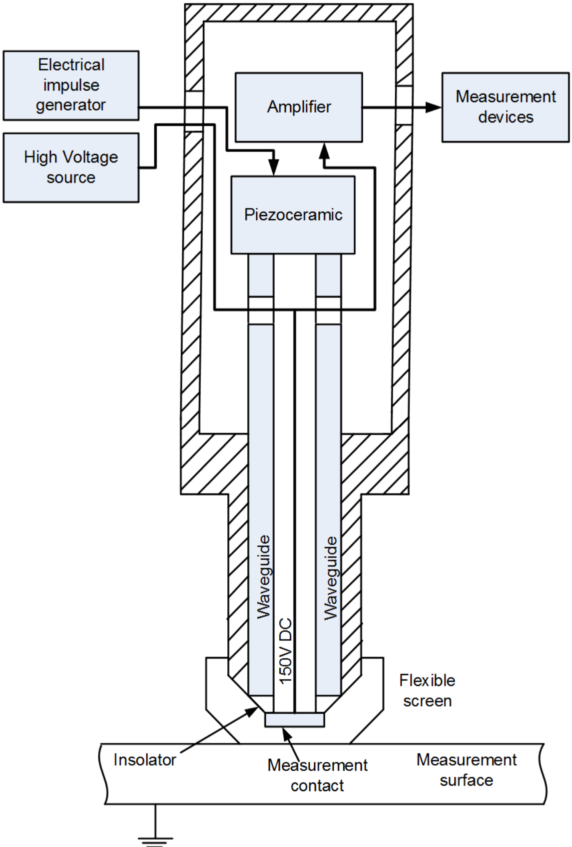
Fig. 15. Acoustic wave attenuation between adjacent waveguides

3.2 Smart capacitive displacement measurement transducer

The typical construction of capacitive transducer requires the calibration of such a transducer to be performed using an additional measurement tool, before carrying out other measurements. The use of additional measurement instruments in the process of each measurement is not viable. For this reason, a capacitive transducer construction of a new type has been proposed (Fig. 16a). The photograph of the manufactured transducer is provided in Fig. 16b.

The new type capacitive transducer construction contains a waveguide with the piezo ceramic attached to it. The waveguide is connected to the measurement electrode of the capacitive transducer. When an electrical pulse of several microseconds is transmitted to the piezo ceramic, the repetitive vibration of the measurement electrode is induced.

When calibrating the transducer of the new construction (smart capacitive transducer), the capacitive transducer electrode vibrations are measured using the interferometer. If the piezo ceramic excitation signal is not altered, the capacitive transducer electrode vibration is repetitive and known. Thus, by putting the capacitive transducer to the surface of the waveguide to be measured, the calibration of the capacitive transducer, without the use of any additional measurement tools, is possible during each instance of measurement.

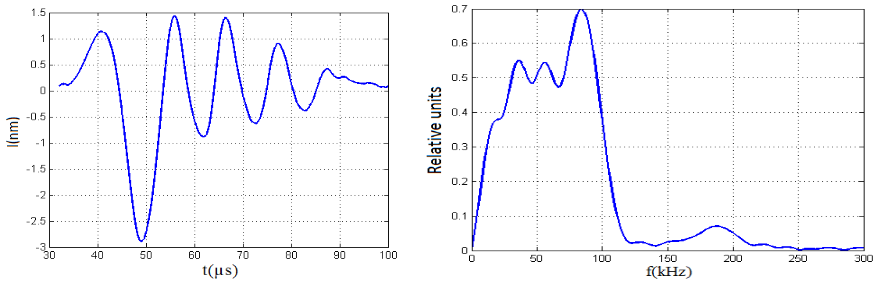


a)

b)

Fig. 16. The smart capacitive transducer: a) structural diagram; b) photograph of the manufactured transducer.

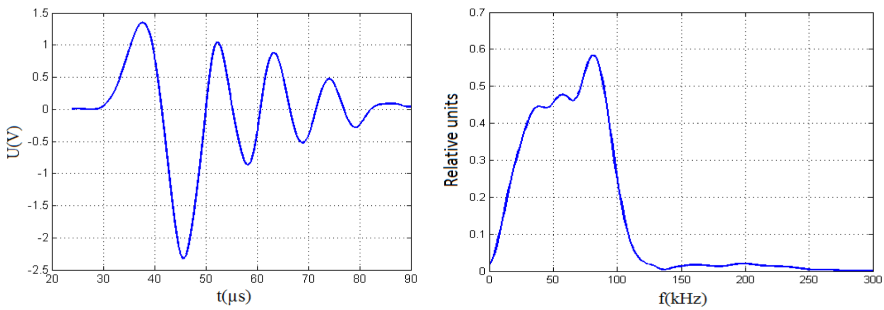
The measurement electrode vibrations of the manufactured smart capacitive transducer have been measured using the interferometer. The 12V pulse signal of 2 μs was used for the excitation, as shown in Fig. 17. The obtained measurement results allow the surface vibration to be evaluated in absolute units.



a) b)

Fig. 17. The capacitive transducer electrode vibration measurement: a) signal proportional to the vibration displacement, measured by the interferometer; b) calculated spectrum

The sensitivity of the capacitive transducer is evaluated without changing the excitation signal, and by measuring the vibrations of its measurement electrode using the capacitive sensor (measurement results are presented in Fig. 18). The capacitive transducer sensitivity value of 1.17 nm/V was acquired from the results obtained under former measurement conditions. When having the sensitivity of the capacitive transducer, it is possible to measure displacements of the waveguide surface onto which the transducer is positioned, as well as to evaluate these displacements in absolute units.



a) b)

Fig. 18. Measurement of the capacitive transducer electrode vibration: a) signal proportional to the capacitive electrode displacement, measured by the capacitive sensor; b) calculated spectrum

4. AET calibration uncertainty evaluation

End result of AET calibration is pulse and frequency response, obtained in suggested calibration stands. These results require calibration uncertainty evaluation which must be performed according to the block diagram presented in Fig. 19.

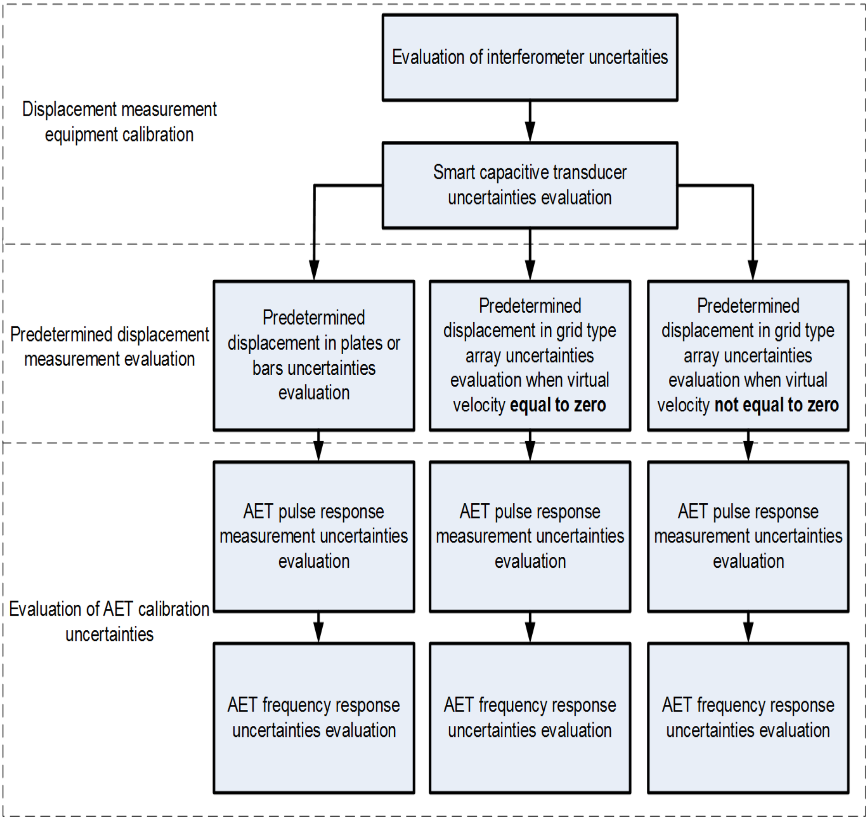


Fig. 19. AET calibration uncertainties evaluation block diagram

AET calibration is performed in three stages:

1. Evaluation of displacement measurement equipment uncertainties.
2. Predetermined displacement measurement uncertainties evaluation.
3. AET calibration uncertainties evaluation.

AET uncertainty evaluation is performed according to methods presented in literature. Evaluation results are presented in table 1.

Table 1. Proposed stands AET calibration uncertainty evaluation

Waveguide type	Impulse response measurement uncertainty	Frequency response uncertainty
Bar or plate	5.37 %	6.44 %
Grid array when virtual velocity is **equal to zero**	7.34 %	8.15 %
Grid array when virtual velocity is **not equal to zero**	7.68 %	8.47 %

4.1 Calibration stands preparation for work

Before AET calibration can be started, the stands must be prepared for measurement. Preparation is performed according to the block diagram presented in Fig. 20.

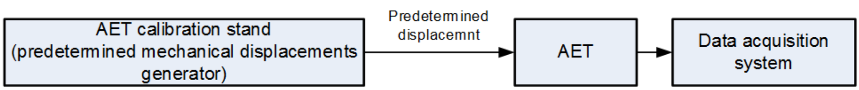


Fig. 20. AET calibration stands' preparation for work block diagram

Stands suitability for AET calibration is evaluated by comparing reference AET characteristics with last calibration data. In case the results are not in the range of a stand's uncertainties, the stand must be examined for the source of the errors. Further, AET calibration can be performed after errors are eliminated and the stand is calibrated according to the presented block diagram in Fig. 19.

GENERAL CONCLUSIONS

1. Two new arbitrary waveform mechanical displacement generation methods are proposed with limit coefficients and modified deconvolution methods. Measurement results demonstrate the proposed methods' application possibilities for the generation of arbitrary type displacements in waveguides with dispersive properties. Advantages of new methods were shown in a comparative analysis between the existing and the proposed methods. Arbitrary waveform signal evaluation criterion allowed for comparison between the different waveguides constructions and excitation signal calculation methods.
2. AET calibration stand constructions of a new type were proposed in the dissertation, offering calibration with different types of waves opportunities and reduced size, compared to existing solutions. These constructions use bar and plate type waveguides, waveguide arrays, and structures with acoustic fiber dampers. Until now, these constructions haven't been used for AET calibration, because of limited possibilities to generate arbitrary waveform displacements. Offered construction application possibilities for AET calibration are presented by the measurement results in dissertation.
3. Calibration of AET involves the measurement of arbitrary waveform displacements using absolute units. An analysis of different measurement transducers was performed and revealed capacitive displacements measurement transducer application advantages for the AET calibration. The problem of frequent transducer calibration was solved by introducing a new type of construction with self-calibration possibilities. Transducers' advantages were proved by the measurement results presented in the work.
4. Measurement uncertainty analysis revealed possibilities to perform AET impulse response measurement in bar and plate type waveguides with 5.37% and frequency response with 6.44% uncertainties. Stands in which grid type arrays were used had bigger uncertainties. Impulse response measurement was 7.34% and frequency response 8.15%, when virtual velocity not equal to zero 7.68% and 8.47%, respectively. Higher grid type array uncertainties can be considered as proposed stands disadvantage. However, these uncertainties can be lowered by improving used equipment and stands construction.

List of scientific publications

ARTICLES
INDEXED in the Web of Science with Impact Factor

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2. Vygantas, Augutis; Darius, Gailius; Edgaras, Vaštakas; Pranas, Kuzas. Evaluation of arbitrary waveform acoustic signal generation techniques in dispersive waveguides// Journal of Vibroengineering / Vibromechanika, Lithuanian Academy of Sciences, Kaunas University of Technology, Vilnius Gediminas Technical University. Vilnius : Vibromechanika. ISSN 1392-8716. 2015, Vol. 17, no. 7, p. 4047-4056.

In publications from other international databases

1. Edgaras, Vaštakas; Darius, Gailius; Vygantas, Augutis. Acoustic wave synthesis in dispersive media // Vibroengineering procedia : international conference Vibroengineering - 2014, Katowice, Poland, 13-15 October, 2014. Kaunas: JVE International. ISSN 2345-0533. 2014, vol. 3, p. 124-127.

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REZIUMĖ

Disertacijos struktūra ir apimtis

Daktaro disertaciją sudaro įvadas, 4 skyriai, išvados ir literatūros sąrašas. Bendra apimtis – 102 psl., kuriuose pateikiami 68 paveikslai, 13 lentelių, 63 matematinės išraiškos, yra 7 priedai ir 61 pozicijų literatūros sąrašas.

Pirmame skyriuje pateikiami AEK kalibravimo pavyzdžiai, kurie leidžia spręsti apie būtinybę pateikti išsamesnius kalibravimo duomenis. Išnagrinėti AEK kalibravimo metodai, aptarti jų privalumai ir trūkumai.

Antrame skyriuje atskleidžiamos problemos, atsirandančios siekiant gauti norimos formos poslinkius strypuose ir plokštėse, taip pat dispersijos įtaka sužadintiems poslinkiams. Pasiūlyti sprendimai, leidžiantys kompensuoti dispersijos įtaką ir gauti norimos formos poslinkius strypuose ir plokštėse. Pasiūlyti determinuotų poslinkių vertinimo kriterijai ir atlikta poslinkių vizualizacija.

Trečiame skyriuje siūlomos AEK charakteristikų matavimo išilgine ir paviršine bangomis sistemos. Nagrinėjamos esamos ir siūlomos matavimo priemonės, kurios leidžia matuoti generuojamus norimos formos mechaninius poveikius.

Ketvirtame skyriuje atliekama siūlomų kalibravimo sistemų ir matavimo priemonių neapibrėžčių analizė.

Kiekvieno skyriaus pabaigoje pateikiamos išvados, darbo pabaigoje – galutinės atliktų tyrimų išvados.

Darbo tikslas ir uždaviniai

Darbo tikslas – sukurti išplėstų galimybių naujo tipo žemojo dažnio AEK kalibravimo priemones ir ištirti jų metrologines charakteristikas.

Darbo tikslui pasiekti suformuluoti šie uždaviniai:

1. Pasiūlyti norimos formos mechaninių poslinkių gavimo metodus ir priemones, taikomus dispersiniams bangolaidžiams.
2. Pasiūlyti bangolaidžių konstrukcijas ir įvertinti jų naudojimo galimybes AEK kalibruoti.
3. Pasiūlyti ir ištirti galimas matavimo priemones, skirtas mechaniniams poslinkiams matuoti. Įvertinti siūlomų matavimo priemonių nulemtas neapibrėžtis AEK kalibruoti.

Mokslinis naujumas

1. Parodytos norimos formos mechaninių poveikių generavimo galimybės strypo ir plokštės tipo struktūrose.
2. Pasiūlyti nauji norimos formos mechaninių poveikių gavimo metodai. Atlikta pasiūlytų ir žinomų metodų lyginamoji analizė.

Praktinė vertė

Darbo rezultatai panaudoti „Smart accoustic emission transducers" projekte. Remiantis darbe gautais rezultatais, buvo sukalibruoti pagamintieji AEK.

Gynimui pateikiami teiginiai

1. Siūlomi bangolaidžių žadinimo metodai leidžia gauti norimos formos mechaninius poveikius dispersiniuose bangolaidžiuose. Todėl AEK kalibruoti gali būti naudojamos naujo tipo konstrukcijos su strypo ar plokštės tipo bangolaidžiais ir bangolaidžių gardelėmis.
2. Siūlomi naujo tipo AEK kalibravimo stendai praplečia AEK charakteristikų matavimo galimybes. Išsprendžiamos kalibravimo vieno tipo banga, matavimo greitaveikos, kalibravimo sistemos matmenų ir matavimo vieno tipo aplinkoje problemos.
3. Mechaninių poveikių įvertinimo absoliučiaisiais vienetais problema siūlomuose kalibravimo stenduose išsprendžiama naudojant naujo tipo talpinį poslinkių matavimo keitiklį su kalibravimosi galimybe.

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