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Progress in Primary Calibration of Acoustic Emission Sensors

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The paper reviews the background of the primary calibration of acoustic emission sensors and the determination of uncertainty by this calibration. There are discussed the aims and the purpose of the primary calibration and main sources of uncertainty in practical usage of calibration results. The comparison of the results of three methods is presented. The shape of calibration characteristics corresponds well up to 300 kHz. The calculations of the uncertainty of those methods are closely described. UT 1000 (PAC) was used as the reference sensor. The problem of propagation of uncertainty in the FFT was solved. Uncertainties of measurements by primary calibrations are determined and presented in the paper. The influence to the uncertainty of main sources was described and is presented. The big influence on uncertainty in reciprocity calibration was the influence of remounting reference sensor and pair sensors.

1 Introduction

Acoustic Emission (AE) is a passive non-destructive testing technique that has been used widely since the 1970s. AE has been defined as the spontaneous release of elastic energy by material when it undergoes deformation.

Good metrology of the AE calibration method is necessary to be able to compare the results of calibration made by other laboratories or to compare the effects of ageing, thermal cycling and so on. ASTM E1106 [1] outlines a method for primary calibration of AE sensors.

2 AE sensors

Transducers used for acoustic emission measurement are in general sensitive to motion normal to the surface to which they are attached. Typically, AE transducers are sensitive to frequencies above 100 kHz. Resonant transducers are highly sensitive to a very narrow frequency range, which must be carefully selected depending on the application. Resonant transducers in the range 150 kHz to 300 kHz are probably the most widely used in AE applications. The highest frequencies likely to be of interest to users of AE transducers are in the range from 800 kHz to 1 MHz.

There are several ways how this transduction can be achieved. The piezoelectric effect, capacitance methods and optical interferometry are common techniques used for detection of AE in industry and research. Piezoelectric devices offer the greatest sensitivity and thus they are the most widely used type of transducer in acoustic emission applications. Interferometers and capacitance transducers are often used as reference sensors by calibration of piezoelectric AE transducers.

3 AE sensor calibration

A main problem of the calibration is to find the characteristic of the transducer. A frequency response of a specific sensor in the mechanical input quantity (velocity, displacement) is the most common result of calibration. Output quantity of calibration is voltage relate to unit of mechanical input (velocity). The absolute value of input quantity and its shape has to be known for primary calibration.

3.1 Step function calibration

The basis for the step function force calibration is that known, well characterized displacements can be generated on a plane surface of a test block. A step function force applied to a point on one surface of the test block initiates an elastic disturbance that travels through the block. In general it is possible to use configuration of sensor for surface calibration and for through-pulse calibration. But through pulse calibration is used only for additional measurements.

It uses a standard reference capacitance transducer and the step-force is generated by the fracture of a glass capillary. The response of the sensor being calibrated to the step-force source is then compared with the reference transducer, which measures the surface displacement due to the elastic surface waves. The displacement at the position of the reference transducer can also be calculated using elastic theory – Pekeris's solution of Lamb's problem. The surface motion on the transfer block, determined using either technique, is the free motion of the surface and not the loaded surface displacement, under the transducer being calibrated. The loading effect of the sensor being calibrated, therefore, affects the measurement being made and thus becomes part of the calibration.

The measured data are used to calculate a fast Fourier transform to determine values of the spectra from unknown and reference sensor. The response of the transducer under test is as follows

$$D(f_m) = \frac{U(f_m)}{S(f_m)} \tag{1}$$

, where $U(f_m)$ is spectrum from unknown sensor and $S(f_m)$ is spectrum from standard sensor or from solution of Lamb problem.

The calibration is described in ASTM standard 1106 [1]. The NIST use follow calibration facility: a cylindrical steel test block 0.9 m in diameter 0.43 m long with optically polished end faces [4].

It is generally assumed that a transducer has only normal sensitivity because of its axial symmetry (an assumption that may not be justified). Calibration by the surface pulse technique for a transducer having significant sensitivity to tangential displacement will be in error, because the surface pulse from the step force contains a tangential component approximately as large as the normal component [4].

3.2 Reciprocity calibration

Reciprocity calibration works on reciprocity theorem that is known from electrical circuits:

“A voltage source U acting in one branch of a network causes a current I to flow in another branch of the network, then the same voltage source U acting in the second branch would cause an identical current I to flow in the first branch.”

This principal can be use for electromechanical system and makes relation between transition of the sensor acting as source and later as receiver.

Reciprocity applies to a category of passive electromechanical transducers that have two important characteristics according to [4]:

They are purely electrostatic or purely electromagnetic in nature.

They are reversible – can be used as either a source or a receiver of mechanical energy. This category includes all known commercial acoustic emission transducer without preamplifiers [4].

With nonidentical transducers three measurements using each of three possible pairs (Fig. 1) of transducer must be measured to obtain enough information to determine all of the response functions of the transducers absolutely.

The input current and reception signal voltage for tone bursts of varying frequency are established for each pair together with the reciprocity parameter, allowing each transducer to be calibrated by measuring electrical signals only. The transducer characteristics are defined as the transmission voltage response in the transmitter configuration and the free-field voltage sensitivity in the receiver configuration.

The primary advantage of the reciprocity calibration technique is that it avoids the necessity of measuring or producing a known mechanical displacement or force. All of the basic measurements made during the calibration are electrical. It is important to note, that the mechanical transfer function or Green function for the transmission of signals from the source location to receiver location must be known. This function is equivalent to the reciprocity parameter, that describes a transfer function of a Rayleigh-wave and it takes into account the frequency of the Rayleigh wave and the material properties of the propagating medium. It is the frequency domain representation of the elasticity theory solution [4]. Eq.(2) shows the calculation of frequency response for sensor 2.

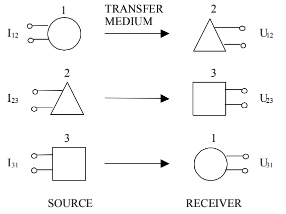

Fig.1 Reciprocity calibration for reversible transducers.

$$|F_2(f)| = \sqrt{\frac{1}{|H(f)|}\frac{|U_{12}(f)|}{|I_{12}(f)|}\frac{|U_{23}(f)|}{|I_{23}(f)|}\frac{|I_{31}(f)|}{|U_{31}(f)|}} \tag{2}$$

U … voltage [V], I … current [A], H … reciprocity parameter [m.s-1.N-1] according [3]

3.3 Reciprocity calibration with broadband pulse excitation

This method is based on modified method of reciprocity calibration modification by Goujon and Baboux [7]. Their method was supplement by using more then one excitation and final characteristics was calculated from more than one measured characteristics.

The experimental setup is similar to usual reciprocity calibration as in 3.2. When the sensors are working as transmitters, the transducers are driven with a short-pulse excitation (single-period sinusoid or single period gaussian). The excitation of sensor is provided for example at 100 kHz, 200kH … 1MHz. The voltages and currents required for reciprocity calibration by Hatano [3] are then calculated from the fast Fourier transforms of the signals, recorded with a sampling frequency of 25,6 MHz. Following calculations are the same as in 3.2 Sensitivities of the sensor are calculated for each excitation. The final characteristics for each sensor is calculated point to point by weighted mean of sensitivities of the two nearest excitation frequency to the calculated point. For example the final point of sensitivity at 110 kHz was calculated as 0.1 * 110 kHz (200 kHz excitation) + 0.9 * 110 kHz (100 kHz excitation).

This broadband excitation allows a better discrimination between the direct signal and the echoes against the borders [7]. This method of the calibration is much faster than method according to 3.2 and can be used to proof quality of sensor’s mounting on the surface before usual reciprocity calibration measurement. Comparison of the results is shown in Fig.5.

4 Analysis of uncertainty in AE sensor calibration

4.1 Analysis of uncertainty in reciprocity calibration

Calculations for the uncertainty of the reciprocity calibration are explained for sensor number 2. The equation Eq. (2) of shows calculation of frequency response for sensor 2.

The partial derivatives according all variable were calculated. For example for variable U_{12} Eq. (3) and I_{12} Eq.(4)

$$\frac{\partial F_2(f)}{\partial U_{12}(f)} = \sqrt{\frac{U_{23}(f)I_{31}(f)}{H(f)I_{12}(f)I_{23}(f)U_{31}(f)}} \bullet \frac{1}{2\sqrt{U_{12}(f)}} \tag{3}$$

$$\frac{\partial F_2(f)}{\partial I_{12}(f)} = \sqrt{\frac{U_{12}(f)U_{23}(f)I_{31}(f)}{H(f)I_{23}(f)U_{31}(f)}} \bullet -\frac{1}{2\sqrt{U_{12}(f)^3}} \tag{4}$$

Evaluation of the of uncertainty type A is based on a series at least of 10 measurements. Experimental standard deviation was used as an uncertainty of type A for measurements of voltage and current. Uncertainty of current probe was determined from measurements of probe characteristics and from manual.

Main source of uncertainty of type B was vector signal analyzer HP 89410A. Its absolute amplitude full-scale accuracy is ±0.5 dB from full-scale [5].

Also the uncertainty of current probe was included and uncertainty of AE signal amplifier was included. For measuring devices PXI 5122 by National Instruments and Handy Scope 3 by TeePee the uncertainty of type B was determined according to manual of producer.

Because of simultaneous measurements of voltage and current for each pair it was assumed that at least two input quantities are interdependent. So the correlation for each combination of variables was calculated according to [9]. The assumption that the variables are correlated was not confirmed and from calculations followed, that the calculated covariance was negligible.

Expanded uncertainty was calculated with the value of coverage factor 2.

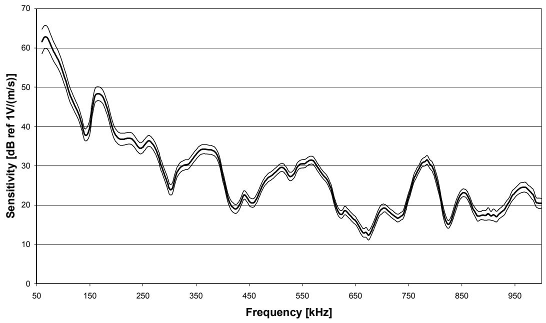

Fig. 2 Reciprocity calibration for UT 1000

In Fig.2 there are shown measured characteristics of reciprocity calibration for sensor UT 1000 (PAC) mounted on the surface of steel block.

4.2 Analysis of uncertainty in step function calibration

Calculations of determination of uncertainty for the step function calibration result from following basic equation for calculation of sensitivity of sensor

$$U = \frac{FFT(U_{cal})}{FFT(U_{ref})} \tag{5}$$

U_{cal} … voltage of calibrated sensor [V], U_{ref} … voltage on reference sensor [V], or determined by calculation.

Main problem was to determine the propagation of uncertainty in discrete fast Fourier transform algorithm (FFT). The calculations follow [6]. Equation for FFT

$$X(k) = \sum_{n=0}^{N-1} x(n) \cdot e^{-j\frac{2\pi}{N}nk} \tag{6}$$

General complex sequence $X(k)$ can be described as $X(k) = R(k) + j\,I(k)$. Spectrum modulus is calculated as

$$M(k) = |X(k)| = \sqrt{R^2(k) + I^2(k)} \tag{7}$$

Amplitude of first frequency point

$$V_0 = M(0)/N \tag{8}$$

And subsequent points

$$Vim = 2M(i)/N \tag{9}$$

Uncertainty of modulus M can be determined [6] as

$$U^2{}_{M(k)} = \begin{cases} N \cdot U_q^2 & for\ k = 0 \\ \frac{N}{2} \cdot U_q^2 & for\ k \neq 0 \end{cases} \tag{10}$$

The partial derivatives according all variable were calculated

$$\frac{\partial U}{\partial FFT(U_{nez})} = \frac{1}{FFT(U_{ref})} \tag{11}$$

$$\frac{\partial U}{\partial FFT(U_{ref})} = -\frac{FFT(U_{nez})}{FFT(U_{ref})^2} \tag{12}$$

The uncertainty of type A and B was calculated for calibrated sensor and following combined uncertainty

$$u_c^2(y) = \left(\frac{2}{N}u_{ref}^2\right) \bullet \left(\frac{1}{FFT(U_{ref})}\right)^2 + \left(\frac{2}{N}u_{nez}^2\right) \bullet \left(-\frac{FFT(U_{nez})}{FFT(U_{ref})^2}\right)^2 \tag{13}$$

Finally the expanded uncertainty with coverage factor 2 was calculated.

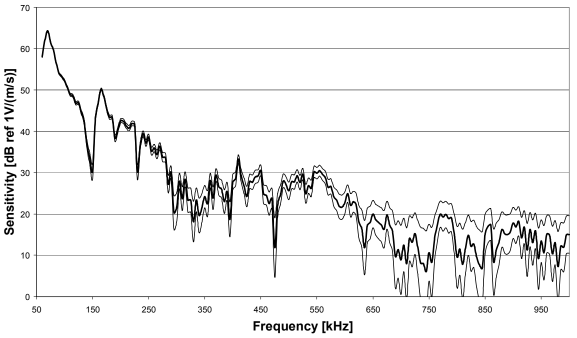

Fig. 3 Step function calibration for UT 1000

4.3 Analysis of uncertainty in reciprocity calibration with broadband pulse excitation

The main problem was to determine uncertainty of calculated currents and voltages according to 3.3. Because these variables were calculated from FFT, so the determination of uncertainty of modulus was the same as in 4.2 Eq.(10) according to [6]. These values were supplement to calculation in 4.1. as the uncertainties of voltages and currents and following calculation was the same as in 4.1. The results are presented in Fig. 4

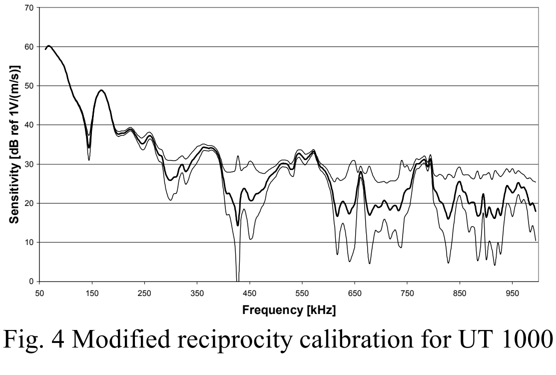

Fig. 4 Modified reciprocity calibration for UT 1000

5 Comparison of results of reciprocity, step function and modified reciprocity calibration

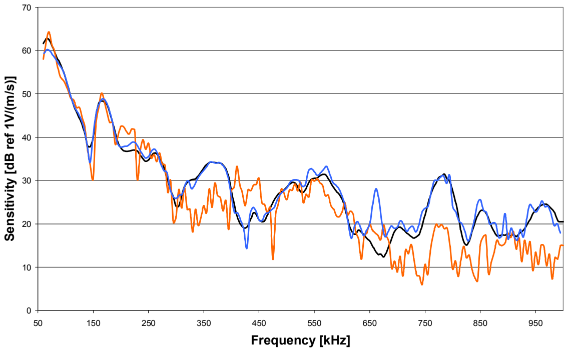

Fig. 5 Results of three methods of calibration UT 1000

In Fig.5. and Fig.6. there are measured characteristics for sensor UT 1000 (PAC) mounted on the surface of steel block. The orange characteristic shows results from step function calibration, the black from reciprocity calibration and the blue from reciprocity calibration with broadband pulse excitation.

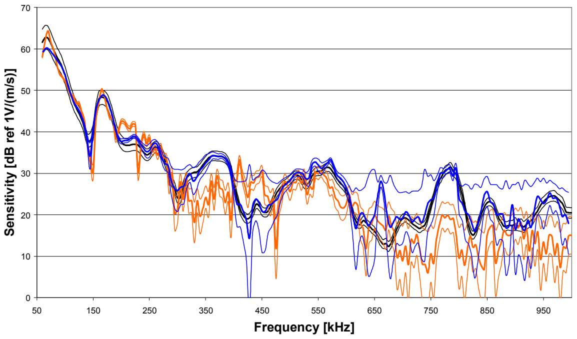

Fig. 6 Calibrations of UT 1000 with uncertainties

6 Analysis influence of sources of uncertainty on reciprocity calibration

The analysis of influence of sources of uncertainty on measured characteristics was done. To be able to compare the impact of the sources to the final characteristics the uncertainty type A was calculated from the experimental standard deviation of final calculated sensitivities. Calibration of UT 1000 (PAC) was measured many times on the same conditions and with the same equipment and only the one condition was change to determine uncertainty of this source. Because of limited capacity of this article, the results were summarized to following table 1.

	Source of uncertainty	Median uncer. type A (rn 1)	Median uncer. type A (rn 2)	Max uncer. type A
1	used channel on matrix switcher	0,032	0,029	0,060
2	with and without normal force	0,008	0,030	0,153
3	temperature	0,056	0,209	0,632
4	time stability of binding paste	0,009	0,018	0,126
5	mount of binding paste	1,795	0,982	2,567
6	remounting of UT 1000 sensor	0,484	0,489	1,135
7	remounting of pair sensors	0,802	1,079	1,878
8	slewing with sensor	0,145	0,438	0,986
9	moving with weight	0,274	0,311	0,996
10	incorrect position of pair sensors	0,586	0,830	0,193

Table 1 Comparison influences on uncertainty of various sources in reciprocity calibration

Third column shows the mean of uncertainties [V/(m/s)] in range from 60 kHz to 300 kHz and the fourth column for range 300 kHz to 1 MHz. Step of the measurement was 5 kHz. The duration of the driving signal was 100 µs according to the size of the testing block. The first row shows the influence of used channel on matrix switch. Second was measured with and without weight (normal force 1000N). Third shows influence of temperature. The case of sensor was tempered from 25 to 60 ˚C and the temperature was measured by PT 1000. Fourth shows the influence of time settlement of binding paste, the value is calculated from more than hundred measurements during two days. Fifth shows the influence of mount of binding paste from zero mount to big mount of paste.

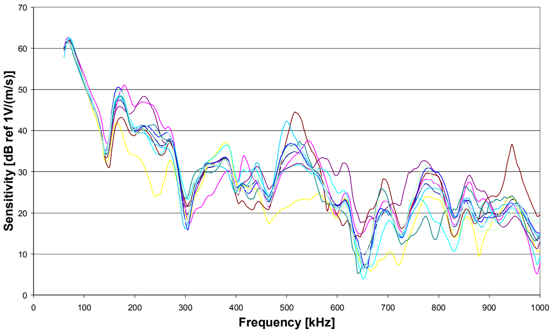

Fig. 7 Characteristics by remounting of pair sensors

The sixth row shows influence of remounting reference sensor UT 1000. The other sensor lies for a few days. Seventh shows the influence of remounting pair sensors (K2G and Aura). The reference sensor lies for a few days. Eighth shows the influence of slewing with reference sensor. Ninth shows the influence of moving with weight on the top of the mounted sensor. Tenth shows the influence of incorrect positioning on the surface. The reference sensor was positioned from 2 to 10 cm from the correct position to the direction opposite to direction to the centre of triangle of sensor and reciprocity parameter was calculated for correct position.

One of the biggest influences was the remounting of the pair sensor, so in the figure 7 are shown the measured characteristics for ten measurements.

7 Analysis of sources of uncertainty of step function calibration

Measuring device was driven by trigger 0,05 V and 200 µs of oncoming signal was sampled. Signal of the capillary break was calculated by Matlab with the same length and sampling parameters as real signal and validated by the noisy signal from interferometer. Signal generated from Matlab was recalculated from displacement to velocity. Final characteristic is calculated according to Eq.5.

	Source of uncertainty	Median uncer. type A (rg 1)	Median uncer. type A (rg 2)	Max uncer. type A
1	thickness of capillary	0,714	1,11	1,04
2	speed of capillary break	0,416	0,693	0,663
3	rotating with UT 1000	0,604	0,803	0,742

Table 2 Comparison influences on uncertainty of various sources in step function calibration

Third column shows the mean of uncertainties [V/(m/s)] in range from 60 kHz to 300 kHz and the fourth column for range 300 kHz to 1 MHz. The first row shows the influence of thickness of used capillary from 0,11mm to 0,32mm. Second shows the influence of speed of breaking capillary. It varies from slow to fast. Third shows the influence of slewing with reference sensor.

8 Conclusions

The paper reviews the background, the methodology and the standardization of the primary calibration of acoustic emission sensors. The reciprocity, reciprocity with broadband pulse excitation and step function method of absolute calibration were practically realized in laboratory of vibrodiagnostics at Brno University of Technology. The whole experiment was managed by PC with LabVIEW 8.5. The software and measuring apparatus enables primary calibration of acoustic emission sensors by reciprocity method according to NDIS 2109 [2] and by step function method according to ASTM 1106 [1] together.

The comparison of the results of all of the method is presented. The shape corresponds well up to 300 kHz. The uncertainty of all methods was determined and closely described. UT 1000 (PAC) was used as the reference sensor. The problem of the propagation of uncertainty in discrete fast Fourier transform algorithm was solved. For measurements were used more accurate measuring devices than HP 89410A – PXI 5122 by NI and Handy Scope 3 by Teepee. HP was used for measurements of reciprocity method with broadband pulse excitation due to its better dynamic range.

The main sources of the uncertainty were described and its influence to uncertainty is presented. The big influence on uncertainty in reciprocity calibration was the influence of remounting reference sensor and pair sensors. This influence is possible to suppress by correct and precise mounting of the sensors. The repeatability in the step function calibration is in general worse than in reciprocity calibration.

Acknowledgments

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