

## PRIMARY CALIBRATION OF ACOUSTIC EMISSION SENSORS

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**Abstract** – The paper reviews the background of the primary calibration of acoustic emission (AE) sensors and the determination of uncertainty in the calibration. The main sources of uncertainty in practical usage of calibration results are discussed. The comparison of the results of the reciprocity primary calibration, step-force and reciprocity calibration with broadband-pulse excitation method is presented. The shape of calibration characteristics corresponds well up to 300 kHz. The calculation of the uncertainty in all the calibration methods is described. The problem of propagation of uncertainty in the fast Fourier algorithm was solved. Uncertainty of measurement by primary calibration is determined and the influence of selected sources of uncertainty for each used method of calibration is presented and practically measured results are discussed. Piezoelectric AE sensor PAC UT1000 was used as the sensor under test. The big influence on uncertainty in calibrations was the influence of remounting sensors and influence of precision of measuring device. This influence is possible to suppress by correct and precise mounting of the sensors and using of more accurate measuring device with high resolution.

**Keywords:** AE sensor calibration

### 1. AE SENSORS

Transducers used for AE 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 narrow frequency range, which must be carefully selected depending on the application. Resonant transducers in the range of 150 to 300 kHz are probably the most widely used. 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 the detection of AE signals. Piezoelectric devices offer the greatest sensitivity and thus they are the most widely used type of transducer in AE applications. Interferometers and capacitance transducers are often used as reference sensors in the calibration of piezoelectric AE transducers.

### 2. 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. The absolute value of input quantity and its shape has to be known for primary calibration. 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 aging, thermal cycling and so on.

#### 2.1. Step-function calibration

ASTM E1106 [1] and ISO 12713 [2] outline a step-force method for primary calibration of AE sensors. 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.



Fig. 1 Setup for step function calibration

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.

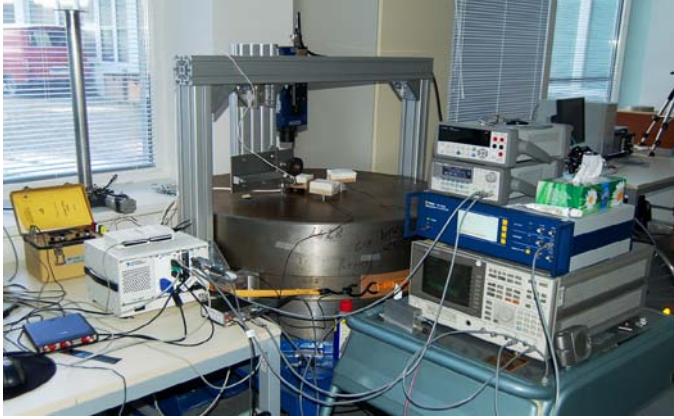


Fig. 2 Workspace for primary calibration

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

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

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

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 [3].

## 2.2. Reciprocity calibration

NDIS 2109 [4] outlines reciprocity calibration. Reciprocity calibration works on reciprocity theorem that is known from electrical circuits. This principal can be used 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 - they are purely electrostatic or purely electromagnetic in nature and 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 [3].

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.

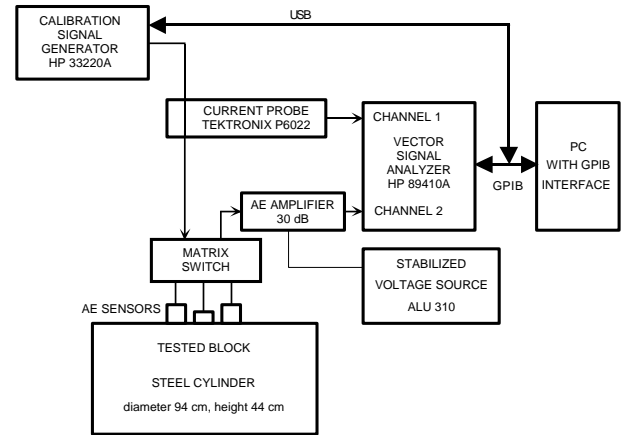


Fig. 3 Schema of workspace for reciprocity calibration with HP 89410A

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 [3]. Equation 2 shows the calculation of frequency response for sensor 2.

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

$U$ : voltage [V],  $I$ : current [A],  $H$ : reciprocity parameter [ $\text{m}\cdot\text{s}^{-1}\cdot\text{N}^{-1}$ ] according to Hatano [5].

## 2.3. Reciprocity calibration with broadband impulses

This method is based on modified method of reciprocity calibration modification by Goujon and Baboux [6]. Their method was supplemented by using more than one excitation and final characteristics was calculated from more than one measured characteristics.

The experimental setup is similar to usual reciprocity calibration. 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, 200 kHz ... 1 MHz. The voltages and currents required for reciprocity calibration by Hatano [5] are then calculated from the fast Fourier transforms of the signals recorded with high sampling frequency. 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  $0.1 * 110 \text{ kHz}$  (200 kHz excitation) +  $0.9 * 110 \text{ kHz}$  (100 kHz excitation).

This broadband excitation allows a better discrimination between the direct signal and the echoes against the borders [6]. This method of the calibration is much faster than method according to standard reciprocity calibration and can be used to proof quality of sensor's mounting on the surface before usual standard reciprocity calibration measurement.

Comparison of the results for different calibration methods is shown on Fig. 4. This figure shows three measured characteristics for an AE sensor, PAC UT 1000, mounted on the surface of a steel block. The orange curve shows results from step-function calibration, the black from reciprocity calibration and the blue from reciprocity calibration with broadband-pulse excitation.

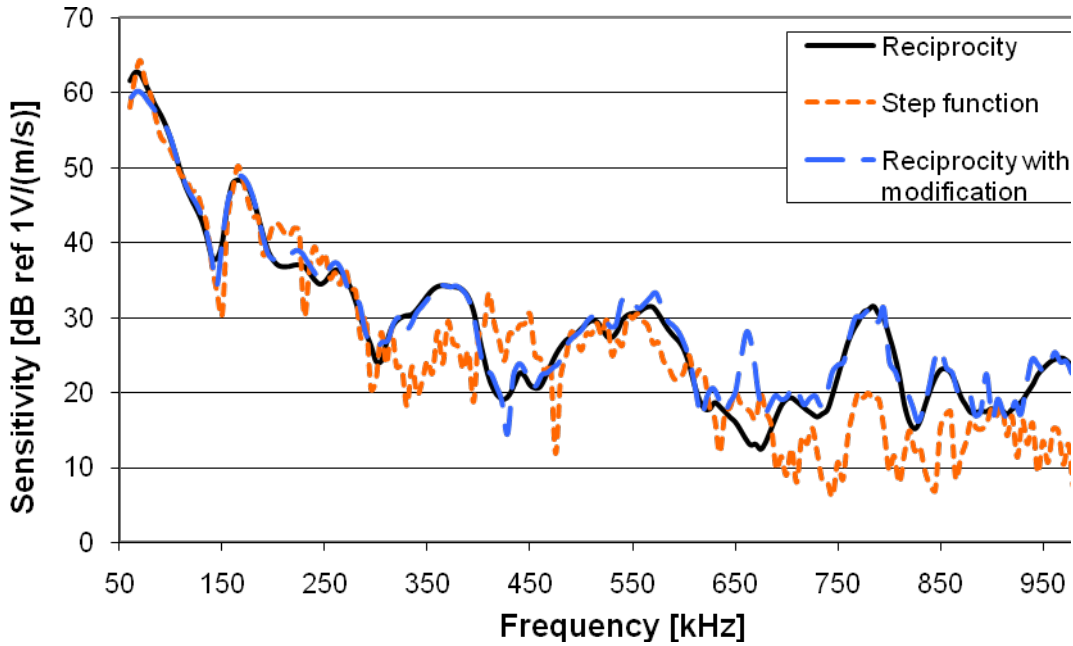


Fig. 4 Results of three methods of calibration of PAC UT 1000

### 3. ANALYSIS OF UNCERTAINTY IN AE SENSOR CALIBRATION

#### 3.1. 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

$$U = \frac{FFT(U_{cal})}{FFT(U_{ref})} \quad (3)$$

$U_{cal}$  is voltage of calibrated sensor [V],  $U_{ref}$  is 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 [7]. Equation for FFT is

$$X(k) = \sum_{n=0}^{N-1} x(n) \cdot e^{-j\frac{2\pi}{N}nk} \quad (4)$$

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

$$M(k) = |X(k)| = \sqrt{R^2(k) + I^2(k)} \quad (5)$$

Amplitude of first frequency point

$$V_0 = M(0)/N \quad (6)$$

And subsequent points

$$V_{im} = 2M(i)/N \quad (7)$$

Uncertainty of modulus M can be determined [7] as

$$U^2_{M(k)} = \begin{cases} N \cdot U_q^2 & \text{for } k = 0 \\ \frac{N}{2} \cdot U_q^2 & \text{for } k \neq 0 \end{cases} \quad (8)$$

The partial derivatives according all variable were calculated

$$\frac{\partial U}{\partial FFT(U_{cal})} = \frac{1}{FFT(U_{ref})} \quad (9)$$

$$\frac{\partial U}{\partial FFT(U_{ref})} = -\frac{FFT(U_{cal})}{FFT(U_{ref})^2} \quad (10)$$

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

$$u_c^2(y) = \left(\frac{2}{N} u_{ref}^2\right) \cdot \left(\frac{1}{FFT(U_{ref})}\right)^2 + \left(\frac{2}{N} u_{cal}^2\right) \cdot \left(-\frac{FFT(U_{cal})}{FFT(U_{ref})^2}\right)^2 \quad (11)$$

Finally the expanded uncertainty with coverage factor 2 was calculated.

### 3.2. Analysis of uncertainty in reciprocity calibration

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

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

$$\frac{\partial F_2(f)}{\partial I_{12}(f)} = \sqrt{\frac{U_{12}(f)U_{23}(f)I_{31}(f)}{H(f)I_{23}(f)U_{31}(f)}}} \cdot -\frac{1}{2\sqrt{U_{12}(f)}^3} \quad (13)$$

The partial derivatives according all variable were calculated. For example for variable  $U_{12}$  Eq. (12) and  $I_{12}$  Eq.(13)

Evaluation of the 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  $\pm 0.5$  dB from full-scale [8].

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.

### 3.3. Analysis of uncertainty in reciprocity calibration with broadband pulse excitation

The main problem was to determine uncertainty of calculated currents and voltages. Because these variables were calculated from FFT, so the determination of uncertainty of modulus was the same as in equation (8) according to [7]. These values were supplement to calculations as the uncertainties of voltages and currents and following calculations were the same as for standard reciprocity calibration

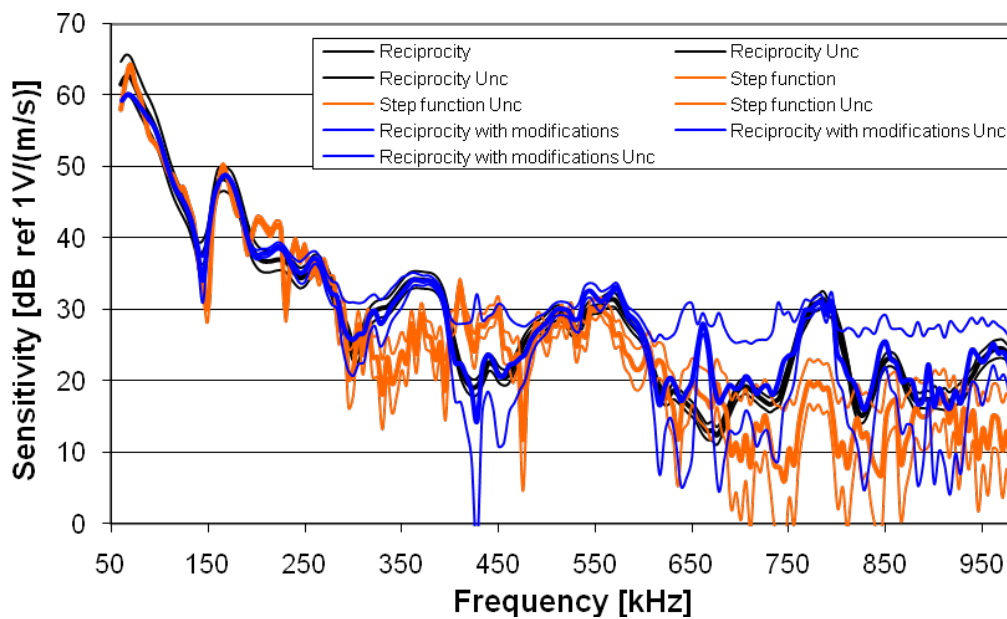


Fig. 5 Results of three methods of calibration of PAC UT 1000 with uncertainties

## 4. INFLUENCE OF SOURCES OF UNCERTAINTY

### 4.1. Influence of Sources of Uncertainty on Step-function Calibration

Measuring device was driven by trigger 0,05 V and 200  $\mu$ s 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 characteristics are calculated according to equation 1. Calculations of uncertainty for the step-function calibration result were determined. Main problem was to determine the propagation of uncertainty in discrete fast Fourier transform algorithm (FFT). The calculations follow [7].

Table 1. Comparison influences on uncertainty of various sources in step function calibration.

	Source of uncertainty	Median uncer. type A (reg. 1)	Median uncer. type A (reg. 2)	Max uncer. type A
1	thickness of capillary	6,7	10,3	17,0
2	speed of capill. break	4,2	7,1	11,0
3	rotating with UT 1000	5,1	8,0	25,2

Third column shows the mean of uncertainties [%] in range from 60 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 0.11 to 0.32 mm. The second row shows the influence of speed of breaking capillary. It varies from slow to fast and the third shows the influence of slewing with reference sensor.

### 4.2. 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. The results were summarized to following Table 2.

Evaluation of the 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 the vector signal analyzer, HP 89410A. Its absolute accuracy in amplitude is  $\pm 0.5$  dB at full-scale [8]. 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.

Third column of the following table 2 shows the mean of uncertainties [%] in region 1 (60 - 300 kHz) and the fourth column for region 2 (0.3 - 1 MHz). Step of the measurement was 5 kHz. The duration of the driving signal was 100  $\mu$ s 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 10 N). Third shows influence of temperature. The case of sensor was raised from 25 to 60°C and the temperature was measured by surface temperature sensor.

Table 2 Comparison influences on uncertainty of various sources in reciprocity calibration.

	Source of uncertainty	Median uncer. type A (region 1)	Median uncer. type A (region 2)	Max uncer. type A
1	used channel on matrix switcher	0,4	0,3	0,7
2	with and without normal force	0,1	0,3	1,7
3	temperature	0,7	2,4	8,1
4	time stability of couplant	0,1	0,2	1,6
5	amount of binding paste	13,8	9,3	16,7
6	remounting of UT 1000 sensor	5,1	5,4	17,1
7	remounting of pair sensors	8,3	13,7	31,0
8	slewing with sensor	1,6	4,9	11,2
9	moving with weight	2,9	3,5	11,9
10	incorrect position of pair sensors	6,1	9,2	21,7

Fourth shows the influence of setting time of couplant, the value being calculated from more than a hundred measurements during two days.

Fifth shows the influence of amount of couplant from none to excessive. 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 (sn. 58507-00797 by Krautkramer) and Aura (sn. SV416-416004 by Aura Milevsko). 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 center of triangle of sensor and reciprocity parameter was calculated for correct position. One of the largest influences was the remounting of the pair sensor.

### 4.3. Comparison of Uncertainties with Error Requirements in ASTM 1106

Figure 10 shows the results of combined uncertainties for all the methods of calibration related to final

characteristics of each method. So the results are presented in percent of final characteristics. The orange curve shows errors from step-function calibration, the black from reciprocity calibration and the blue from reciprocity calibration with broadband-pulse excitation.

The error for step-function measurement and reciprocity measurement with broadband-pulse excitation is low up to 300 kHz and then it grows. The main peaks in error are on defined frequencies caused by aperture effect of finite length of sensor surface of PAC UT 1000 having the radius of 0.775 cm. Zero points calculated according to [1] are 237, 433, 628 and 823 kHz for Rayleigh wave speed  $3006 \text{ m}\cdot\text{s}^{-1}$  for our testing block.

ASTM 1106 [1] and ISO 13713 [2] present that the error of measurements between 100 kHz and 1 MHz should be up to  $\pm 10\%$ . The data from repeated calibration with remounting sensor should be collected and the overall system should produce calibration with precision of  $\pm 15\%$ .

From figure 10 follows that previous assertion is valid for range 60 kHz to 300 kHz. On higher frequencies the sensitivity of the sensor is too low and uncertainty grows. For example, at 70 kHz the sensitivity is 62.5 dB ref. 1 V/(m/s) and at 300 kHz the sensitivity is 24.1 dB ref. 1 V/(m/s). So the difference is 38.4 dB ref. 1 V/(m/s). The final uncertainty of step-function calibration and reciprocity calibration with broadband-pulse excitation is in fact dependent on value of sensitivity of sensor on a certain frequency.

## 5. CONCLUSIONS

The paper reviews the background, the methodology and the standardization of the primary calibration of AE sensors. The reciprocity calibration, reciprocity calibration 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 AE sensors by reciprocity method according to NDIS 2109 [4] and by step-function method according to ASTM 1106 [1]. Approximately 1600 calibrations and 100 different sensors were measured.

The comparison of the results of all of the method is presented on figure 4 and 5. The shape corresponds well up to 300 kHz. The method of reciprocity calibration with broadband-pulse excitation was based on the modification of reciprocity calibration by Goujon and Baboux [6]. Their method was supplemented by using more than one excitation on different frequencies and final characteristics were calculated from more than one measured characteristics. The experimental setup is similar to usual reciprocity calibration. This method of the calibration is much faster than usual reciprocity method. The results correspond well with results from basic reciprocity calibration, but the uncertainty is worse especially on higher frequencies where the sensitivity of UT 1000 is lower. So the method can be used to verify the quality of sensor's

mounting on the surface before usual reciprocity calibration measurement.

The uncertainty of all methods was determined. PAC UT 1000 (s.n. 169) was used as the sensor-under-test. The problem of the propagation of uncertainty in discrete fast Fourier transform algorithm was solved. For measurements we used more accurate measuring devices than HP 89410A – PXI 5122 by NI and Handy Scope 3 by Teepee. PXI – 5122 by National Instruments was most cost-effective. It has the sampling frequency up to 100 MHz, good dynamic range and accuracy better than HP. Handy Scope 3 is unsuitable for measurements of reciprocity method with broadband-pulse excitation and step-function calibration due to its poor dynamic range and lower sampling frequency and resolution.

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. By correct and precise mounting of the sensors, this influence can be reduced. The repeatability of the step function calibration is in general worse than in reciprocity calibration for high frequency range up to 300 kHz. Noise is crucial, so we recommend using of digitizers with high resolution. For example NI 5922 with 24-bit flexible resolution.

## 6. ACKNOWLEDGMENT

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