Development of uncertainty estimation procedure for measurement of nonlinear distortions

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Abstract. The article is devoted to the question of expediency of development of uncertainty estimation procedure for measurement of nonlinear distortions. The article deals with the sequence of uncertainty estimation in the measurement of nonlinear distortions. Using the reference calibration tool, the installation of the measuring sample K2C-57, calibration was carried out and the results of experimental studies were obtained, in assessing the uncertainty of measuring the harmonic distortion.

Key words. Measurement, calibration, means of measurement, uncertainty, harmonic distortion, measurement uncertainty budget

Introduction

It is now widely accepted that when all of the known or assumed error components have been calculated and the corresponding corrections applied, there is still uncertainty as to the correctness of the corrected result, i.e. doubt as to how well the measurement result represents the value of the physical quantity being measured [11-13].

Methods

During calibration devices are divided into standards and calibrated measuring instruments. According to the method of obtaining the values of the measured values are two main methods of measurement [1,4]:

- direct evaluation method;
- method of comparison with measure.

The method of direct evaluation is a method of measurement, in which the values of the quantities are determined directly by the reference device of the measuring device.

Measure comparison method – a measurement method in which the values of quantities are compared with the value specified by the measure[6-7].

A specific procedure for the evaluation of uncertainty depends on the method of measurements used during calibration. The following methods are used to transfer a unit of value in calibration schemes:

- direct measurement by the calibrated measuring instrument of the value formed by the reference measure;
- direct comparison of calibrated and reference measuring instruments;
- indirect formation by several reference measures of a value that is measured by a calibrated measuring instrument;
- direct measurement by reference measurement of the value formed by the calibrated measure;
- comparison of the values generated by the reference and calibrated measure using a comparator;
- indirect measurement of the value generated by the calibrated measure.

During the calibration of the measuring instrument, the value and uncertainty of the difference between the value of Xs, which is formed by the reference measure or measured by the reference measuring instrument, and the value of Xc, measured by the calibrated instrument, are estimated:

$$\Delta = X_c - X_s$$  \hspace{1cm} (1)

This difference is then used to correct the measurement result. Thus, the assessment of uncertainty in calibration is the estimation of the uncertainty of the \( \Delta \).

When calibrating measures, the magnitude and uncertainty of the actual value of the XC measure to be calibrated is usually estimated by measurement with a reference measurement tool or by comparison with a reference measure Xs. The correction in this case is the difference between the nominal XN and the actual Xc values of the measure:

$$\Delta = X_c - X_N$$  \hspace{1cm} (2)

Assessment of uncertainty in calibration is to estimate the uncertainty of the value of Xc.

Also, the measurements should take into account the values, the effect of which is not taken into account by the experimental data, but which are significant during calibration [5,15]. For example, environmental parameters, supply voltage, quantization errors, inaccuracy of value setting, mutual influence of measure and measuring instrument [14].

Extended calibration uncertainty is determined by the formula:

$$U = kU$$  \hspace{1cm} (3)

where U - is the standard uncertainty, 
k - is the coverage coefficient calculated in the General case as the student coefficient with the effective number of degrees of freedom veff defined by the Welch-Sattersweit formula.

Consider the procedure for estimating uncertainty in the measurement of the harmonic distortion. In our case, the uncertainty is determined by type A. For a more reliable estimate, the number of observations should be at least ten. The calibration results are recorded in a protocol [8-10].

In the process of calibration, the difference between the value of the harmonic distortion coefficient (Kg), set on the reference unit, and the value of the harmonic distortion coefficient (Kg), measured by the calibrated non-linear distortion meter, is determined (NDM).

The calibration scheme is shown in figure 1.

![Figure 1. Scheme of the calibration](image)

The measurement method is based on direct multiple measurement of the Kg sample unit, using a calibrated NDM.

The model equation in this case has the form:

$$\Delta = (X_c + \Delta_c) - X_s$$ \hspace{1cm} (4)

where \( \Delta \) – evaluation of the output value at the point of calibration;
\( X_c \) – the Kg value that was measured by the calibrated NDM;
\( \Delta_c \) – the quantization accuracy of the calibrated NDM;
\( X_s \) – nominal value Kg.

The following expression for the total standard measurement uncertainty will correspond to the
model equation (4):
\[ u(\Delta) = \sqrt{u(x_i)^2 + u_{(\Delta_c)}^2 + u_{(\Delta_s)}^2} \],

where \( u(x_i) \) - standard type A uncertainty determined by the formula (7);
\( u(\Delta_c) \) - quantization error of the measuring device, determined by the formula (8);
\( u(\Delta_s) \) - standard calibration uncertainty of the reference installation specified in the calibration certificate.

In reusable measurements, the value estimate is defined as the arithmetic mean of the observations:
\[ x_c = \frac{1}{n} \sum_{i=1}^{n} X_{ci} \]

Estimation of standard uncertainty by type A, \( u(x_i) \), is carried out by means of statistical analysis of a series of observations:
\[ u(x_i) = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (X_{ci} - x_c)^2} \]

where \( X_{ci} \) - i-th measurement result,
\( n \) - number of measurements.

For a more reliable estimate, the number of observations should be at least ten. Prior to the type A standard uncertainty assessment, omissions from the experimental data should be excluded.

The quantization error of the measuring device is determined by the following formula:
\[ u(\Delta_c) = \frac{q}{2 \cdot 2 \sqrt{3}} \]

where \( q \) - unit of scale division of the calibrated NDM.

The effective number of degrees of freedom for this case will be determined by the formula:
\[ \nu_{eff} = \left( n - 1 \right) \left[ \frac{u(\Delta)}{u(x_i)} \right]^4 \]

The expanded uncertainty of measurement during calibration of the NDM is determined from the expression:
\[ U(\Delta) = k \cdot u(\Delta) \]

where \( k \) - the coverage rate for the probability 0.95.

The budget of measurement uncertainty during calibration NDM is given in the table 1.

The measurement result is recorded in the following form:
\[ \Delta = [\Delta \pm U(\Delta)] \text{ B, } p = 0.95 \]

| Table 1. Measurement uncertainty budget for calibration NDM |
|-----------------------------------------------------------|
| **Input value** | **The evaluation of the input values** | **Standard uncertainty** | **Sensitivity coefficient** | **Contribution of uncertainty** |
|-----------------|---------------------------------------|--------------------------|----------------------------|-------------------------------|
| \( x_c \)      | \( x_c \)                              | (7)                      | 1                         | \( u(x_c) \)                 |
| \( \Delta_c \) | 0                                     | (8)                      | 1                         | \( u(\Delta_c) \)            |
| \( x_s \)      | \( x_s \)                              | \( \frac{U(\Delta)}{2} \) | -1                        | \( u(x_s) \)                 |
| **Output value** | **Evaluation of the output value** | **Total standard uncertainty** | **Enrolment rate** | **The expanded uncertainty** |
| \( \Delta \)   | (1)                                   | (5)                      | \( t_{0.05}(\nu_{eff}) \) | (10)                          |
Let's consider, on a concrete example, the proposed procedure of uncertainty estimation. In accordance with section 13 "Calibration of the device" of the technical description and operating instructions for the non-linear distortion meter automatic C6-11 [2], we determine the calibrated points (table 2).

**Table 2.** Calibrated points when measuring harmonic distortion NDM C6-11

| Kg   | Frequencies                                      |
|------|--------------------------------------------------|
| 0.03%| 200 Hz, 1.9 kHz, 2.2 kHz, 19.9 kHz              |
| 0.1% | 20 Hz, 198 Hz, 20 kHz, 100 kHz, 199.9 kHz        |
| 0.25%| 200 Hz, 1.9 kHz, 2.2 kHz, 19.9 kHz              |
| 0.6% | 20 Hz, 198 Hz, 200 Hz, 1.9 kHz, 2.2 kHz, 19.9 kHz, 20 kHz, 100 kHz, 199.9 kHz |
| 2.5% | 20 Hz, 198 Hz, 200 Hz, 1.9 kHz, 2.2 kHz, 19.9 kHz, 20 kHz, 100 kHz, 199.9 kHz |
| 9.0% | 20 Hz, 198 Hz, 200 Hz, 1.9 kHz, 2.2 kHz, 19.9 kHz, 20 kHz, 100 kHz, 199.9 kHz |
| 30.0%| 20 Hz, 198 Hz, 200 Hz, 1.9 kHz, 2.2 kHz, 19.9 kHz, 20 kHz, 100 kHz, 199.9 kHz |

Used reference calibration tool, measuring installation model K2C-57, has the following metrological characteristics:
- Kg = (0.003 – 100) %
- 10 Hz – 200 kHz
- U = (0.0005 ÷ 0.73) %

The accessories and other means used for calibration are presented in table 3.

**Table 3.** Accessories and other facilities used

| Name                              | Characteristics                      |
|-----------------------------------|--------------------------------------|
| Measuring parameters of the air «Atmosphere-1» | 650 – 1080 hPa, Δ = ± 1,0 hPa       |
|                                   | 5 – 40 ºC; Δ = ± 0,5 ºC              |
|                                   | 10 – 90 %; Δ = ± 3 %                 |
| Voltmeter AST                     | 150; 300 V                           |
| Digital panel meter ЕПВ-100       | Accuracy class 0,5                   |
|                                   | (10 – 100) Hz                       |
|                                   | Accuracy class 1,0                   |

During the calibration it is necessary to observe the conditions of the calibration (table 4).

**Table 4.** Calibration conditions

| Name                                | Norm      | Fact |
|-------------------------------------|-----------|------|
| air temperature, ºC                | 20 ± 5    | 21   |
| relative humidity, %               | 30…80     | 59   |
| atmospheric pressure, kPa          | 84…106    | 101,1|
| supply voltage, V                  | 220 ± 4,4 | 220,5|
| network frequency, Hz              | 50 ± 0,5  | 50,1 |
Table 5 Determination of metrological characteristics when measuring harmonic distortion

| Calibrated point | Measurement result (Kg), Xc, % | Price of measurements limit | Δ Kg, % |
|------------------|---------------------------------|----------------------------|---------|
| frequencies      | 1  2  3  4  5  6  7  8  9  10 | medium                      |         |
| 200 Hz           | 0.0295 0.0300 0.0305 0.0295 0.0295 0.030 0.0305 0.0290 0.0290 0.029 | 0.0005 | -0.00035 ± 0.0215 |
| 1.9 kHz          | 0.0290 0.0290 0.0295 0.0285 0.0285 0.0280 0.0280 0.0280 0.0280 0.0280 | 0.0005 | -0.00140 ± 0.0215 |
| 2.2 kHz          | 0.0280 0.0285 0.0280 0.0280 0.0280 0.0285 0.0285 0.0285 0.0285 0.0285 | 0.0005 | -0.00180 ± 0.0215 |
| 19.9 kHz         | 0.0285 0.0290 0.0290 0.0290 0.0290 0.0290 0.0290 0.0290 0.0290 0.0290 | 0.0005 | -0.00125 ± 0.0215 |
| 20 Hz            | 0.090 0.092 0.090 0.090 0.092 0.094 0.096 0.096 0.094 0.092 | 0.002 | -0.0074 ± 0.011 |
| 198 Hz           | 0.092 0.092 0.094 0.092 0.094 0.096 0.096 0.096 0.094 0.0942 | 0.002 | -0.0058 ± 0.011 |
| 20 kHz           | 0.105 0.105 0.100 0.105 0.105 0.110 0.105 0.105 0.105 0.105 | 0.005 | 0.0050 ± 0.070 |
| 100 kHz          | 0.100 0.105 0.105 0.105 0.105 0.110 0.105 0.105 0.105 0.105 | 0.005 | 0.0050 ± 0.070 |
| 199.9 kHz        | 0.130 0.125 0.125 0.125 0.125 0.130 0.135 0.125 0.125 0.1270 | 0.005 | 0.0270 ± 0.070 |
| 200 Hz           | 0.235 0.230 0.225 0.220 0.225 0.230 0.220 0.220 0.225 0.225 | 0.005 | -0.0250 ± 0.0325 |
| 1.9 kHz          | 0.220 0.225 0.220 0.220 0.230 0.235 0.225 0.225 0.225 0.2255 | 0.005 | -0.0245 ± 0.0325 |
| 2.2 kHz          | 0.220 0.230 0.225 0.220 0.225 0.230 0.225 0.225 0.225 0.2270 | 0.005 | -0.0230 ± 0.0325 |
| 19.9 kHz         | 0.225 0.230 0.225 0.220 0.225 0.225 0.220 0.225 0.225 0.2255 | 0.005 | -0.0265 ± 0.0325 |
| 20 Hz            | 0.52 0.54 0.52 0.56 0.52 0.52 0.52 0.54 0.52 0.528 | 0.02 | -0.072 ± 0.09 |
| 198 Hz           | 0.52 0.52 0.54 0.52 0.54 0.52 0.52 0.52 0.54 0.526 | 0.02 | -0.074 ± 0.09 |
| 200 Hz           | 0.52 0.54 0.54 0.54 0.56 0.52 0.52 0.56 0.52 0.534 | 0.02 | -0.066 ± 0.05 |
| 1.9 kHz          | 0.62 0.64 0.64 0.64 0.62 0.64 0.64 0.64 0.64 0.634 | 0.02 | 0.034 ± 0.05 |
| 2.2 kHz          | 0.64 0.64 0.64 0.64 0.62 0.64 0.64 0.64 0.64 0.634 | 0.02 | 0.034 ± 0.05 |
| 19.9 kHz         | 0.52 0.54 0.56 0.52 0.52 0.52 0.54 0.52 0.54 0.530 | 0.02 | -0.070 ± 0.05 |
| 20 kHz           | 0.52 0.52 0.54 0.52 0.52 0.52 0.54 0.52 0.52 0.524 | 0.02 | -0.076 ± 0.12 |
| 100 kHz          | 0.56 0.62 0.64 0.66 0.66 0.68 0.68 0.68 0.68 0.656 | 0.02 | 0.056 ± 0.12 |
| 199.9 kHz        | 0.68 0.68 0.66 0.68 0.70 0.72 0.70 0.68 0.68 0.684 | 0.02 | 0.084 ± 0.12 |
| Calibrated point | Measurement result (Kg), Xc, % | Price of division of the scale measurements | Δ Kg, % limit |
|-----------------|---------------------------------|--------------------------------------------|----------------|
| frequencies     | Kg, %                           | medium | ± 0.090 | ± 0.120 |
| 20 Hz           | 2.45 2.40 2.40                  | 2.45   | 0.05    |         |
| 198 Hz          | 2.60 2.60 2.65                  | 2.60   | 0.05    | 0.180   |
| 200 Hz          | 2.60 2.65 2.65                  | 2.65   | 0.05    | 0.130   |
| 1.9 kHz         | 2.55 2.55 2.55                  | 2.55   | 0.05    | 0.130   |
| 2.2 kHz         | 2.60 2.60 2.60                  | 2.60   | 0.05    | 0.205   |
| 19.9 kHz        | 2.55 2.55 2.55                  | 2.55   | 0.05    | 0.205   |
| 20 kHz          | 2.65 2.70 2.75                  | 2.70   | 0.05    | 0.205   |
| 100 kHz         | 2.70 2.75 2.75                  | 2.75   | 0.05    | 0.205   |
| 199.9 kHz       | 2.70 2.75 2.75                  | 2.75   | 0.05    | 0.205   |
| 20 Hz           | 8.52 8.54 8.56                  | 8.56   | 0.05    | 0.205   |
| 198 Hz          | 8.54 8.52 8.54                  | 8.54   | 0.05    | 0.205   |
| 200 Hz          | 8.60 8.58 8.62                  | 8.62   | 0.05    | 0.205   |
| 1.9 kHz         | 9.26 9.30 9.28                  | 9.28   | 0.05    | 0.205   |
| 2.2 kHz         | 9.32 9.30 9.34                  | 9.34   | 0.05    | 0.205   |
| 19.9 kHz        | 9.36 9.38 9.40                  | 9.40   | 0.05    | 0.205   |
| 20 kHz          | 9.50 9.48 9.48                  | 9.48   | 0.05    | 0.205   |
| 100 kHz         | 9.62 9.64 9.66                  | 9.66   | 0.05    | 0.205   |
| 199.9 kHz       | 8.26 8.28 8.30                  | 8.30   | 0.05    | 0.205   |
| 20 Hz           | 29.5 29.0 28.5                  | 28.5   | 0.05    | -1.15   |
| 198 Hz          | 29.0 28.5 29.0                  | 29.0   | 0.05    | -1.15   |
| 200 Hz          | 30.5 31.0 30.5                  | 30.5   | 0.05    | -1.15   |
| 1.9 kHz         | 29.5 29.0 28.5                  | 28.5   | 0.05    | -1.15   |
| 2.2 kHz         | 29.5 30.0 28.5                  | 28.5   | 0.05    | -1.15   |
| 19.9 kHz        | 29.0 29.0 28.5                  | 28.5   | 0.05    | -1.15   |
| 20 kHz          | 28.0 27.5 27.5                  | 27.5   | 0.05    | -1.15   |
| 100 kHz         | 27.5 28.0 28.0                  | 28.0   | 0.05    | -1.15   |
| 199.9 kHz       | 27.5 28.0 28.5                  | 28.5   | 0.05    | -1.15   |
Table 6. Calculation of measurement uncertainty (Kg = 0.03 % in frequency range)

| The value of the range | Standard uncertainty of the measurement Kg (by type А) u(xc), % | The standard uncertainty of the quantization u(Δc), % | The standard uncertainty of the reference measures u(xs), % | Total standard uncertainty u(Δ), % | The expanded uncertainty in the measurement U(Δ), % |
|------------------------|---------------------------------------------------------------|---------------------------------------------------|------------------------------------------------|-------------------------------|---------------------------------------------|
| 200 Hz                 | 1,8·10^-4                                                     | 7,2·10^-5                                        | - 2·10^-4                                   | 2,8·10^-4                    | 5,6·10^-4 k = 2,01 |
| 1,9 kHz                | 1,6·10^-4                                                     | 7,2·10^-5                                        | - 2·10^-4                                   | 2,7·10^-4                    | 5,4·10^-4 k = 2,00 |
| 2,2 kHz                | 8,2·10^-5                                                     | 7,2·10^-5                                        | - 2·10^-4                                   | 2,3·10^-4                    | 4,5·10^-4 k = 1,96 |
| 19,9 kHz               | 1,1·10^-4                                                     | 7,2·10^-5                                        | - 2·10^-4                                   | 2,3·10^-4                    | 4,7·10^-4 k = 1,97 |

Table 7. Calculation of measurement uncertainty (Kg = 0.1 % in frequency range)

| The value of the range | Standard uncertainty of the measurement Kg (by type А) u(xc), % | The standard uncertainty of the quantization u(Δc), % | The standard uncertainty of the reference measures u(xs), % | Total standard uncertainty u(Δ), % | The expanded uncertainty in the measurement U(Δ), % |
|------------------------|---------------------------------------------------------------|---------------------------------------------------|------------------------------------------------|-------------------------------|---------------------------------------------|
| 20 Hz                  | 7,3·10^-4                                                     | 2,9·10^-4                                        | - 6,5·10^-4                                 | 1·10^-3                      | 2,1·10^-3 k = 2,03 |
| 1,98 Hz                | 5,5·10^-4                                                     | 2,9·10^-4                                        | - 6,5·10^-4                                 | 0,9·10^-3                    | 1,8·10^-3 k = 2,00 |
| 20 kHz                 | 7,5·10^-4                                                     | 7,2·10^-4                                        | - 1,8·10^-3                                 | 2·10^-3                      | 4·10^-3 k = 1,96 |
| 100 kHz                | 1,1·10^-3                                                     | 7,2·10^-4                                        | - 1,8·10^-3                                 | 2·10^-3                      | 4·10^-3 k = 1,97 |
| 199,9 kHz              | 1,1·10^-3                                                     | 7,2·10^-4                                        | - 1,8·10^-3                                 | 2·10^-3                      | 4·10^-3 k = 1,98 |

Table 8. Calculation of measurement uncertainty (Kg = 0.25 % in frequency range)

| The value of the range | Standard uncertainty of the measurement Kg (by type А) u(xc), % | The standard uncertainty of the quantization u(Δc), % | The standard uncertainty of the reference measures u(xs), % | Total standard uncertainty u(Δ), % | The expanded uncertainty in the measurement U(Δ), % |
|------------------------|---------------------------------------------------------------|---------------------------------------------------|------------------------------------------------|-------------------------------|---------------------------------------------|
| 200 Hz                 | 1,7·10^-3                                                     | 7,2·10^-4                                        | - 1·10^-3                                   | 2,1·10^-3                    | 4,3·10^-3 k = 2,08 |
| 1,9 kHz                | 1,6·10^-3                                                     | 7,2·10^-4                                        | - 0,5·10^-3                                 | 1,8·10^-3                    | 3,8·10^-3 k = 2,13 |
| 2,2 kHz                | 1,5·10^-3                                                     | 7,2·10^-4                                        | - 0,5·10^-3                                 | 1,8·10^-3                    | 3,8·10^-3 k = 2,13 |
| 19,9 kHz               | 1,1·10^-3                                                     | 7,2·10^-4                                        | - 0,5·10^-3                                 | 1,4·10^-3                    | 2,8·10^-3 k = 2,06 |

Conclusion
Using the proposed procedure of uncertainty estimation in the measurement of nonlinear distortions and the requirements used in the development of calibration techniques [3], established in GOST R 8.879-2014 "State system of ensuring the uniformity of measurements. Methods of calibration of measuring
instruments. General requirements for the content and presentation" it is advisable to develop a method of calibration of measuring instruments.

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