EURAMET Project 1142

A bilateral acceleration comparison between MIKES and SP

Final Report

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1. Introduction

This report presents the results of the bilateral EURAMET comparison between MIKES (Finland) and SP (Sweden) in the area of acceleration and vibration. This comparison was organised in order to confirm the measurement capabilities of MIKES. The comparison was registered as EURAMET project ref. 1142, title “Bilateral Comparison of Accelerometer Calibration”. MIKES acted as the pilot laboratory of the comparison.

MIKES has been building a vibration transducer calibration facility on a secondary level. Now, when the calibration facility is ready to be used, MIKES is motivated to carry out a bilateral comparison to validate it. The results of comparison will be used as an evidence for MIKES CMCs for secondary calibration of vibration transducers.

The participants agreed to use weighted mean to compute the degrees of equivalencies of the comparison. The results at 19 specified frequencies and the respective degrees of equivalencies are presented.

The technical protocol (Appendix 1) specifies in detail the aim and the task of the comparison, the conditions of measurement, the transfer standards used, measurement instructions and other items. A brief survey is given in the following sections.

The calibrations were performed from September 2010 to December 2010. After the measurements were done it was discovered that accelerometer A (single-ended type) has higher temperature sensitivity that was expected. This caused problems since the measurements protocol did not specify the method of measuring the temperatures of the accelerometers during calibrations clearly enough.

2. Task and purpose of the comparison

The task was to compare measurements of sinusoidal linear accelerations and piezoelectric accelerometer calibration in the frequency range from 10 Hz to 10 kHz. Two accelerometers, one provided by each laboratory, were used during the comparison. One of the accelerometers was a single-ended type and the other was a back-to-back-type. The calibration was accomplished by primary method according to ISO 16063-11 or by secondary method according to ISO 16063-21. The result of the calibration was the magnitude and phase shift of the complex charge sensitivity and the associated uncertainty. In this comparison SP accomplished its measurements by primary and MIKES by secondary method. The traceability of MIKES reference accelerometer comes from PTB (*The Physikalisch-Technische Bundesanstal).*

The main purpose of this comparison was to provide an objective evidence of the current measurement capabilities of MIKES against SP, which has taken part in the key comparison EUROMET.AUV.V- K1.

3. Conditions of measurement

The conditions of the measurement specified in the technical protocol were fulfilled to a large extent:

- Frequencies in Hz: 10, 12.5, 16, 20, 40, 80, 160, 315, 630, 800, 1250, 2000, 2500, 3150, 4000, 5000, 6300, 8000 and 10000 Hz

- Amplitudes: preferred value 10 m/s². A range of 5 m/s² to 200 m/s² should be complied with. *If needed, up to 300 m/s² will be accepted*.
- Ambient temperature and accelerometer temperature during the calibration: 23°C ± 1°C (actual values to be stated within tolerances of ±0.5°C).
- Relative humidity: max. 75%.
- Mounting torque of the accelerometer: (2 ± 0.1) Nm.

4. Transfer standards

As transfer standards, two types of piezoelectric accelerometers were used: standard accelerometer (single-ended), type 4366, manufacturer Brüel & Kjær (**Accelerometer A**), and standard accelerometer (back-to-back), type 2270, manufacturer Endevco (**Accelerometer B**).

Accelerometer A is provided by SP and accelerometer B by MIKES. Both accelerometers have been measured over a longer period for stability data.

In addition a dummy mass for calibrating accelerometer B by laser interferometry was provided by MIKES.

Specifications of Accelerometer A: Accelerometer (single ended) type 4366, serial number 716185, manufacturer Brüel & Kjær. Weight: 28 grams. Length: 19 mm. Width over flats of hexagonal faces: 16 mm. Mounting thread: 10-32 UNF. Electrical connector: coaxial 10-32 UNF. Accelerometer capacitance: ≈ 1.1 nF. Sensitivity:≈ 5 pC/(m/s²). Max. transverse sensitivity: ≤ 2%.

Specifications of Accelerometer B: Accelerometer (back-to-back) type 2270, serial number 0050, manufacturer Endevco. Weight: 40 grams. Length: 28 mm. Width over flats of hexagonal faces: 16 mm. Mounting thread: 1/4-28 UNF. Electrical connector: coaxial 10 – 32. Accelerometer capacitance: ≈ 1.6 nF. Sensitivity: ≈ 0.22 pC/(m/s²). Max. transverse sensitivity: ≤ 3%.

Specifications of Dummy mass: Dummy mass made of steel. Weight: 50 grams. Dummy mass has three equally spaced longitudinal holes on its circumference and one center hole for mounting it on top of an accelerometer.

5. Measurement instructions

The ***measurand*** is the magnitude and phase shift of the complex charge sensitivity.

- ***Calibration of Accelerometer A by laser interferometry:***

  The reference surface for acceleration measurement is by definition the base or mounting surface of the accelerometer. If this surface is covered during the calibration, the motion is to be sensed on the moving part close to the accelerometer. Alternatively, the motion can be sensed at the mounting surface of the accelerometer via longitudinal holes in the moving part of the vibration exciter. ISO 16063-11:1999 is to be observed.

- ***Calibration of Accelerometer B by laser interferometry:***

  A dummy mass provided by the pilot laboratory shall be mounted on the top surface of the accelerometer B. The reference surface for acceleration measurement is by definition the top surface of the back-to-back accelerometer B. The motion is to be sensed at the polished top surface of accelerometer B via longitudinal holes in the dummy mass. ISO 16063-11:1999 is to be observed.

    - In order to suppress the effect of any non-rectilinear motion in laser-interferometric calibrations, the displacement should be measured at a minimum of three different points. These points should be equally spaced on the mounting surface of the accelerometer.

  - ***Calibration of Accelerometer A by comparison:***

  The accelerometer is to be calibrated according to ISO 16063-21 by comparison to a reference accelerometer calibrated by laser interferometry in accordance with ISO 16063-11:1999. The reference accelerometer of the calibrating laboratory may be of the so-called back-to-back type meant for direct mounting of the transducer to be calibrated (i.e. accelerometer A) on top of it in a so-called back-to-back configuration. It may also be a reference accelerometer with normal mounting provisions used underneath a fixture in line with accelerometer A. It is not recommended to mount the two transducers side by side as rocking motion will often be present, causing large errors in many circumstances. For calibrators, the reference transducer may be an integral part of a moving element.

  - ***Calibration of Accelerometer B by comparison:***

  Accelerometer B is calibrated by using a single-ended transfer standard accelerometer mounted on top of it as a reference. The transfer standard accelerometer is to be calibrated according to ISO 16063-21 by comparison to a reference accelerometer calibrated by laser interferometry in accordance with ISO 16063-11:1999. The weight of the transfer standard accelerometer should be the same as the weight of the dummy mass.

- The ***charge amplifier*** used in the laboratory should be calibrated. The calibration of the charge amplifier should be carried out using values of the electrical quantities similar to those occurring in the accelerometer calibration.
- The mounting surfaces of the accelerometer and the moving part of the vibration exciter shall slightly be lubricated before mounting.
- For each of the two accelerometers, carry out the calibration in accordance with the usual procedure of your laboratory.

6. Communication of the results to the pilot laboratory

MIKES and SP calibrated both accelerometers without any information from the other participant. Both participants sent the calibration results to the TC-AUV SC Acceleration and vibration convenor Thomas Bruns independently. After both participants had performed their calibrations and Thomas Bruns had received both calibration results, he sent the calibration results to MIKES.

The calibration results had to be submitted to Thomas Bruns within 6 weeks after performing the calibration. The calibration report was asked to contain detailed descriptions of:

- the calibration equipment
- the calibration method(s) used
- the ambient conditions
- the mounting technique
- the calibration results
- the uncertainty budget(s)

In addition to the calibration report, the measurement results were asked to be submitted to the pilot laboratory by electronic mail, with the data in *Excel* or ASCII text format.

For reporting the calibration results, clause 10 of ISO 16063-11:1999 and clause 7 of ISO 16063-21, respectively, were asked to be taken into account. For uncertainty, the following instructions were given:

The list(s) of the principal components of the uncertainty budget shall be in accordance with ISO 16063-11:1999, Annex A for the primary calibration by laser interferometry according to method 1 ("fringe-counting method"), method 2 ("minimum-point method") and/or method 3 ("sine-approximation method"). For vibration calibration by comparison to a reference accelerometer, Annex A of ISO 16063-21 shall be taken into account. In each case, the uncertainties shall be determined in accordance with the Guide to the expression of uncertainty in measurement, which is adapted to the calibration of vibration and shock transducers in ISO 16063-1:1998, Annex A.

Clause 10 and Annex A of ISO 16063-11:1999 and Annex A of ISO 16063-21 are formal parts of clause 6 of the technical protocol.

7. Circulation type

Only one link between SP and MIKES existed.

SP sent the accelerometer A to MIKES. MIKES calibrated the accelerometer and sent it back to SP, which performed its own calibration of accelerometer A.

MIKES sent the accelerometer B to SP. SP calibrated the accelerometer and sent it back to MIKES, which performed its own calibration of accelerometer B.

8. Calculation of the degree of equivalence

The data reported by each laboratory *i* for accelerometers A and B were as follows:

- $x_{i,f}$: the best estimate of sensitivity at frequency *f*, and
- $u(x_{i,f})$: the associated standard uncertainty of sensitivity at frequency *f*.

The degree of equivalence between MIKES and SP was determined at each frequency by using equations:

$$D_{ij} = x_i - x_j \qquad (1a) \qquad\qquad D_{ij,rel} = \frac{x_i - x_j}{x_i} \cdot 100\%, \qquad (1b)$$

$$U_{ij} = k\sqrt{u_i^2 + u_j^2} \qquad (2a) \qquad\qquad U_{ij,rel} = k\frac{\sqrt{u_i^2 + u_j^2}}{x_i} \cdot 100\% \qquad (2b)$$

D_{ij} is the difference between the measurement results of laboratories *i* and *j* at each frequency for the magnitude and phase shift of the sensitivity and U_{ij} is the associated expanded uncertainty with a coverage factor *k*. $D_{\mathrm{ij,rel}}$ and $U_{i,rel}$ are the degree of equivalence and its associated expanded uncertainty in relative form (in percent, %).

9. Results

Calibration of accelerometer B (back-to-back type) shows an agreement within 0.3 % from 10 Hz to 4 kHz and within 0.8 % from 5 kHz to 10 kHz in sensitivity magnitude and better than 0.8° in phase shift in the whole frequency range. Results from calibration of accelerometer A (single-ended) show an agreement within 1 % from 10 Hz to 5 kHz and within 2.8 % from 6.3 kHz to 10 kHz in sensitivity magnitude and better than 0.8° in phase shift in the whole frequency range

As mentioned, accelerometer A had high temperature sensitivity (0.4 %/K relative to accelerometer B, in which it was less than 0.1 %/K). This was not taken into account in calculation of degrees of equivalencies and associated uncertainties.

The results presented in tables 1a and 1b are the final calibration results of complex charge sensitivity of accelerometer A (single-ended) submitted by the participating laboratories.

Accordingly in tables 2a and 2b are presented the final measurement results of accelerometer B (back-to-back).

These final results are calculated as the arithmetic mean of multiple measurements obtained on different days.

Tables 1a, 1b, 2a and 2b include:

- The complex charge sensitivity calibration results (magnitude and phase shift) from each laboratory
- The degrees of equivalences between laboratories D_{ij} with associated expanded uncertainties (k=2).

Figure 1 presents the magnitude and phase shift of complex charge sensitivity of accelerometers A and B of both laboratories.

Figure 2 presents the degrees of equivalence between the laboratories for accelerometers A and B.

10. Conclusions

The results from calibration of accelerometer B show that MIKES has good agreement with SP within the stated uncertainties. However the measurements with accelerometer A show much bigger deviation and at two frequencies the deviation of MIKES‘s calibration result from SP value exceeds the stated uncertainty.

A probable reason for the deviation is the fact that accelerometer A had bigger temperature sensitivity than was expected - 0.4 %/K - and that with high probability the temperature of the transducers may have deviated by as much as 2°C between laboratories. This is due to heating effect from the shaker and that the temperature of the accelerometer itself was not measured and reported carefully enough during the calibrations.

Figure 3 shows the relative difference between sensitivity magnitude of MIKES and SP results for accelerometer A and the relative difference in acceleration sensitivity with another B&K 4366-type accelerometer in two different temperatures. It was found that the relative differences match when the temperature is varied by 1.4 °C.

In conclusion, the degrees of equivalence calculated from the data submitted by the laboratories support well the measurement uncertainties reported by the laboratories for the calibration of complex acceleration sensitivity of accelerometer over frequencies from 10 Hz to 10 kHz in case of accelerometer B.

In case of accelerometer A the results support the claimed uncertainties up to 5 kHz. However, the previously described temperature effects caused deviations not accounted for in the uncertainty budget. Further measurements with more appropriate sensors will be performed in the future in order to get more support for MIKES’s measurement capabilities.

Table 1a: Accelerometer A; results of sensitivity magnitude reported by the laboratories and calculated degrees of equivalence. Uncertainties are reported for *k*=2.

	SP		**MIKES**		**Degrees of equivalence (Magnitude)**	
Frequency [Hz]	Sensitivity magnitude [pC/(m/s^2)]	U_c [%]	Sensitivity magnitude [(pC/(m/s^2)]	U_c [%]	$D_{SP\text{-}MIKES,\ rel}$ [%]	$U_{SP\text{-}MIKES,rel}$ [%]
10	4.790	0.50	4.747	1.00	0.903	1.11
12.5	4.783	0.50	4.736	1.00	0.992	1.11
16	4.778	0.50	4.729	1.00	1.018	1.11
20	4.770	0.50	4.724	1.00	0.961	1.11
40	4.746	0.51	4.710	1.00	0.751	1.12
80	4.722	0.51	4.695	1.00	0.581	1.12
160	4.697	0.51	4.660	1.00	0.793	1.12
315	4.674	0.51	4.651	1.00	0.482	1.12
630	4.655	0.52	4.633	1.00	0.470	1.12
800	4.648	0.52	4.628	1.00	0.431	1.12
1250	4.643	0.60	4.620	1.50	0.494	1.61
2000	4.653	0.60	4.639	1.50	0.299	1.61
2500	4.666	0.71	4.639	1.50	0.572	1.65
3150	4.686	0.70	4.674	1.50	0.259	1.65
4000	4.745	0.89	4.718	1.50	0.562	1.74
5000	4.840	0.87	4.824	2.00	0.323	2.18
6300	4.991	0.94	4.875	2.00	2.338	2.18
8000	5.318	1.30	5.218	2.00	1.888	2.37
10000	5.756	1.49	5.600	2.00	2.734	2.48

Table 1b: Accelerometer A; results of phase shift reported by the laboratories and calculated degrees of equivalence. Uncertainties are reported for *k*=2.

	SP		**MIKES**		**Degrees of equivalence (Phase shift)**	
Frequency [Hz]	Phase shift [°]	U_c [°]	Phase shift [°]	U_c [°]	$D_{SP-MIKES}$ [°]	$U_{SP-MIKES}$ [°]
10	-0.6	0.3	-0.5	1.2	-0.1	1.2
12.5	-0.6	0.3	-0.5	1.2	-0.1	1.2
16	-0.6	0.3	-0.5	1.2	-0.1	1.2
20	-0.6	0.3	-0.4	1.2	-0.2	1.2
40	-0.7	0.3	-0.5	1.2	-0.3	1.2
80	-0.7	0.3	-0.5	1.2	-0.2	1.2
160	-0.6	0.3	-0.6	1.2	0.0	1.2
315	-0.7	0.3	-0.7	1.2	0.0	1.2
630	-0.7	0.3	-0.7	1.2	0.0	1.2
800	-0.8	0.3	-0.7	1.2	-0.1	1.2
1250	-0.8	0.6	-0.8	1.8	0.0	1.9
2000	-0.6	0.6	-0.7	1.8	0.1	1.9
2500	-0.8	0.6	-1.1	1.8	0.3	1.9
3150	-0.9	0.6	-0.9	1.8	0.0	1.9
4000	-0.8	0.6	-1.1	1.8	0.3	1.9
5000	-0.9	0.6	-1.3	2.4	0.5	2.5
6300	-0.9	0.6	-1.7	2.4	0.8	2.5
8000	-1.3	0.6	-1.2	2.4	-0.1	2.5
10000	-1.5	0.6	-1.9	2.4	0.4	2.5

Table 2a: Accelerometer B; results of sensitivity magnitude reported by the laboratories and calculated degrees of equivalence. Uncertainties are reported for *k*=2.

	SP		**MIKES**		**Degrees of equivalence (Magnitude)**	
Frequency [Hz]	Sensitivity magnitude [pC/(m/s^2)]	U_c [%]	Sensitivity magnitude [(pC/(m/s^2)]	U_c [%]	$D_{SP-MIKES,rel}$ [%]	$U_{SP-MIKES,rel}$ [%]
10	0.2046	0.39	0.2051	1.2	-0.22	1.24
12.5	0.2045	0.39	0.2049	1.2	-0.20	1.25
16	0.2046	0.39	0.2049	1.2	-0.17	1.24
20	0.2045	0.39	0.2049	1.2	-0.20	1.25
40	0.2046	0.39	0.2048	1.2	-0.12	1.24
80	0.2044	0.39	0.2049	1.2	-0.23	1.25
160	0.2044	0.39	0.2047	1.2	-0.16	1.24
315	0.2044	0.39	0.2047	1.2	-0.15	1.24
630	0.2043	0.39	0.2046	1.2	-0.16	1.24
800	0.2043	0.39	0.2047	1.2	-0.18	1.25
1250	0.2043	0.49	0.2048	1.9	-0.23	1.97
2000	0.2045	0.49	0.2048	1.9	-0.13	1.96
2500	0.2046	0.49	0.2050	1.9	-0.21	1.97
3150	0.2049	0.49	0.2048	1.9	0.04	1.96
4000	0.2052	0.73	0.2052	1.9	0.01	2.04
5000	0.2059	0.73	0.2051	2.3	0.39	2.40
6300	0.2065	0.73	0.2065	2.3	0.01	2.41
8000	0.2077	0.96	0.2074	2.3	0.14	2.49
10000	0.2093	0.96	0.2077	2.3	0.75	2.48

Table 2b: Accelerometer B; results of phase shift reported by the laboratories and calculated degrees of equivalence. Uncertainties are reported for *k*=2.

	SP		**MIKES**		**Degrees of equivalence (Phase shift)**	
Frequency [Hz]	Phase shift [°]	U_c [°]	Phase shift [°]	U_c [°]	$D_{SP\text{-}MIKES}$ [°]	$U_{SP\text{-}MIKES}$ [°]
10	0.0	0.3	0.0	1.5	0.0	1.5
12.5	0.0	0.3	0.0	1.5	0.0	1.5
16	0.0	0.3	0.0	1.5	0.0	1.5
20	0.0	0.3	-0.1	1.5	0.1	1.5
40	0.0	0.3	-0.1	1.5	0.1	1.5
80	0.0	0.3	-0.1	1.5	0.1	1.5
160	0.0	0.3	-0.2	1.5	0.2	1.5
315	-0.1	0.3	-0.1	1.5	0.0	1.5
630	-0.1	0.3	-0.1	1.5	0.0	1.5
800	-0.1	0.3	-0.1	1.5	0.0	1.5
1250	-0.2	0.6	-0.2	2.2	0.0	2.3
2000	-0.2	0.6	-0.4	2.2	0.2	2.3
2500	-0.3	0.6	-0.4	2.2	0.1	2.3
3150	-0.3	0.6	-0.6	2.2	0.3	2.3
4000	-0.4	0.6	-0.6	2.2	0.2	2.3
5000	-0.3	0.6	-0.9	2.8	0.6	2.9
6300	-0.5	0.6	-1.0	2.8	0.5	2.9
8000	-1.0	0.6	-1.2	2.8	0.2	2.9
10000	-0.9	0.6	-1.7	2.8	0.8	2.9

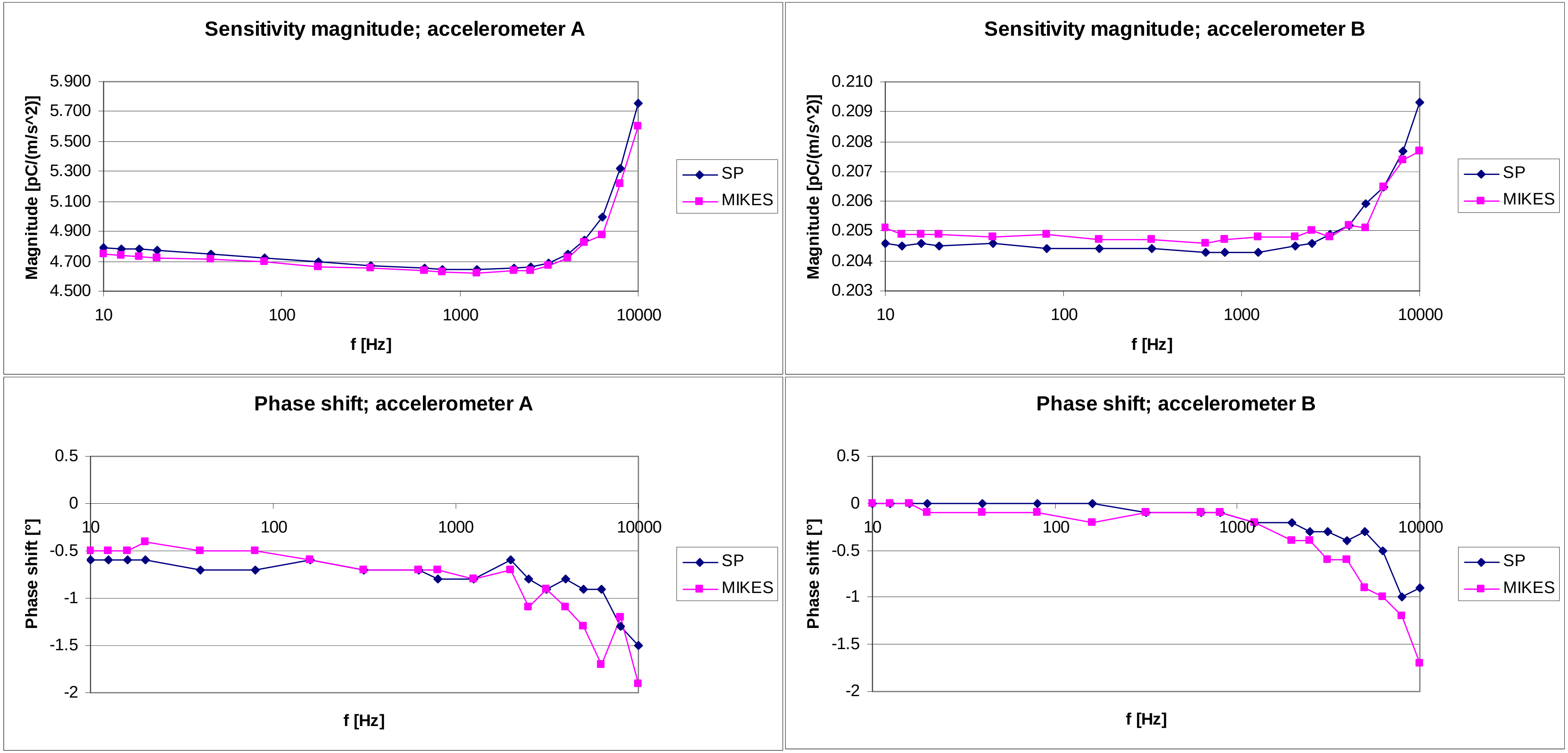
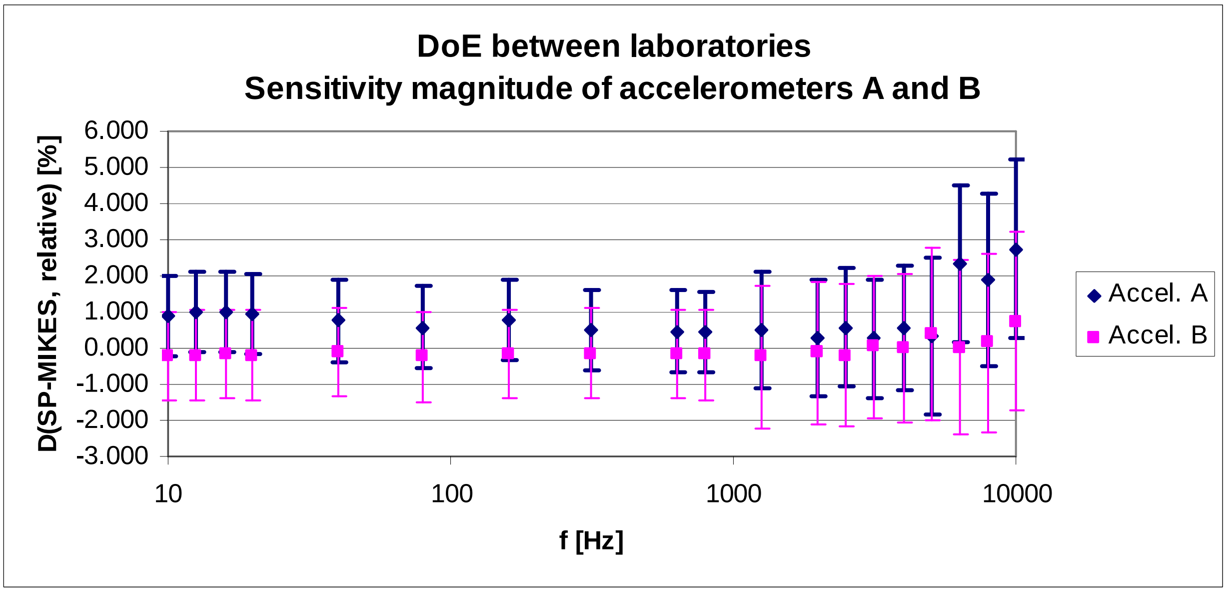
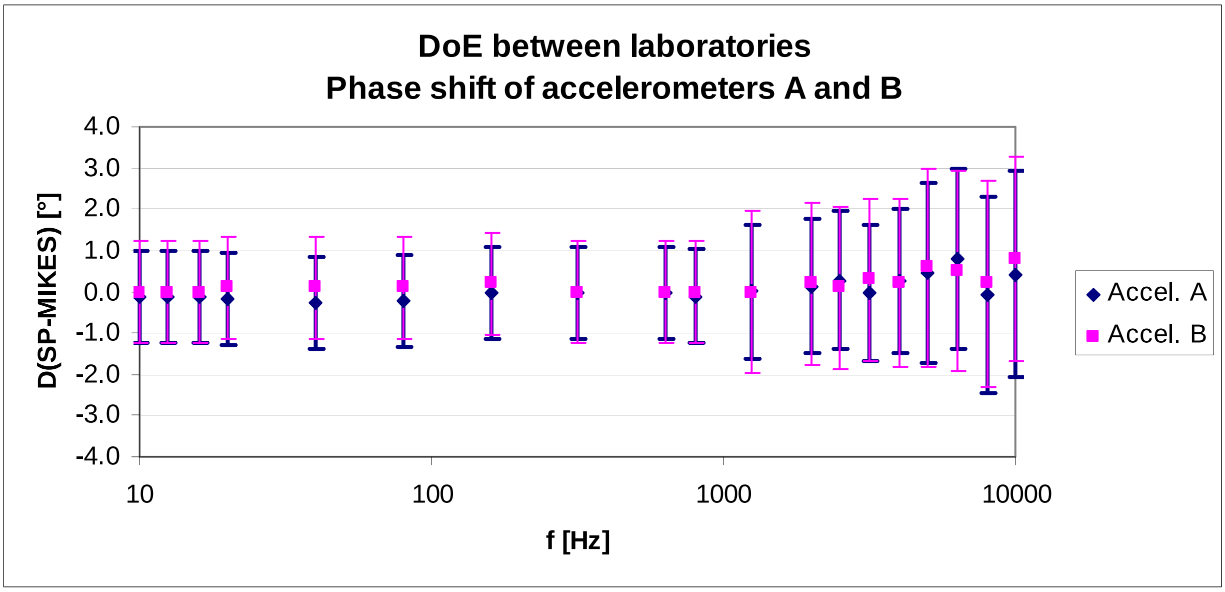


Figure 1: Results of the measured complex sensitivity values by the laboratories for accelerometers A and B



(a)



(b)

Figure 2: Degrees of equivalence and expanded uncertainties between the laboratories for accelerometers A and B for magnitude (figure 2a) and phase shift (figure 2b) of the measured complex sensitivity.

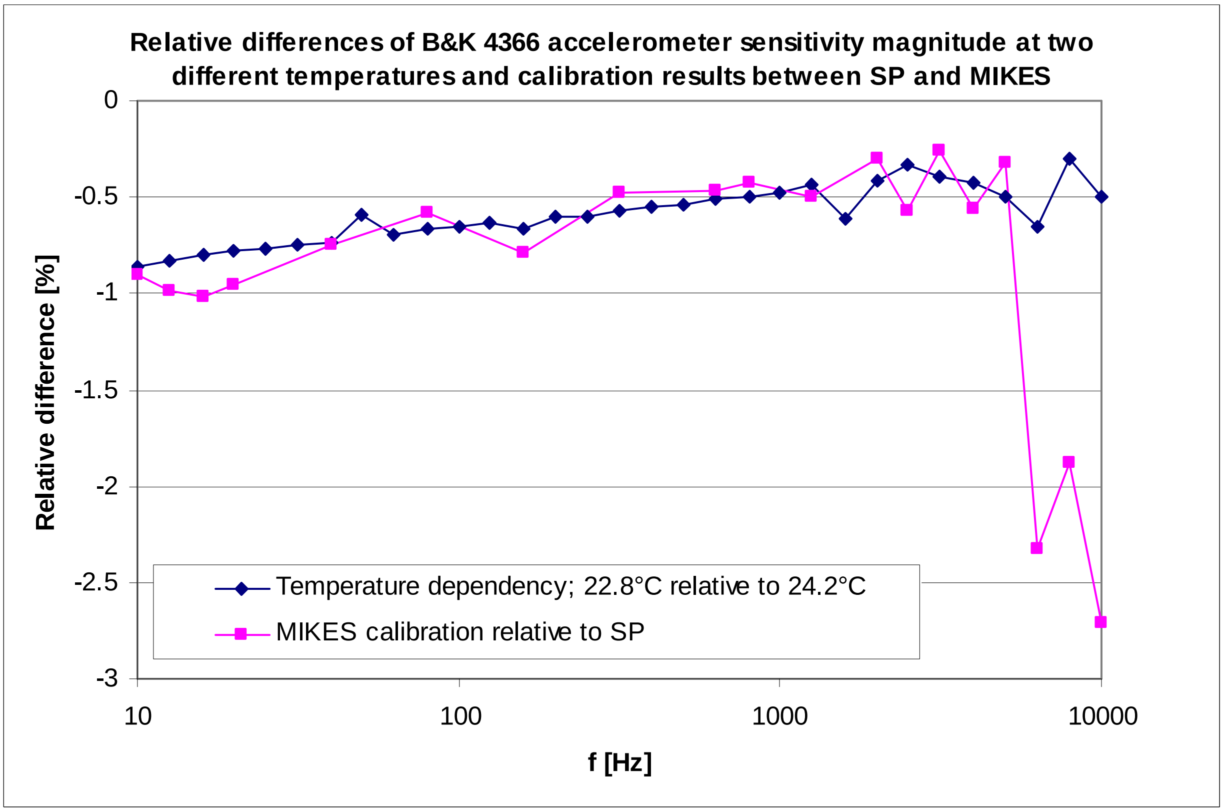


Figure 3: Relative difference of sensitivity magnitude of accelerometer A between MIKES and SP and between two different temperatures with identical type of accelerometer measured at MIKES.

Appendix 1. Technical protocol of the comparison

MIKES
10.2.2010
Jussi Hämäläinen

Technical protocol of the Bilateral EURAMET Comparison

(Vibration & acceleration**)**

EURAMET Project Ref. - 1142

1 Participants

The following two laboratories will participate in the project:

SP / Sweden	Andersson, Håkan: Tel: +46 10 516 5000 E-mail: hakan.andersson@sp.se
MIKES / Finland	Hämäläinen, Jussi: Tel: +358 10 605 4404 E-mail: jussi.hamalainen@mikes.fi

Contact details of pilot laboratory/coordinator:
MIKES
Jussi Hämäläinen
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02150 Espoo
Finland
Phone: + 358 10 6054 404
Fax: + 358 10 6054 299
E-mail: jussi.hamalainen@mikes.fi

2 Aim and task of the comparison

The principal task of the comparison is the measurement of the complex charge sensitivity of two accelerometer standards (one of single-ended design and one of back-to-back design) at different frequencies and acceleration amplitudes specified in clause 3. The charge sensitivity shall be calculated as the ratio of the amplitude of the output charge of the accelerometer to the amplitude of the acceleration at its reference surface. The reference surface is the base or mounting surface of the accelerometer of single-ended design, and the top surface of the accelerometer of back-to-back design. The magnitude of complex charge sensitivity shall be given in pico coulombs per metres per second squared: pC/(m/s^2) and the phase shift of complex charge sensitivity shall be given in degrees: °. Different measurement conditions specified below.

To calibrate two accelerometers, Primary vibration calibration by laser interferometry in accordance with ISO 16063-11:1999 or Secondary vibration calibration by the comparison method in accordance with ISO 16063-21 shall be used. The latter method shall only be applied if the participating laboratory is supplied with traceability by primary calibration of reference accelerometers. To measure the output charge of the accelerometer standards, a calibrated charge amplifier shall be used. For the calibration of the charge amplifier, see clause 5.

Recommendation: expanded uncertainty of measurement (coverage factor $k = 2$) determined by the participating laboratories should be in the approximate range of

- 0,5 % to 1 % or smaller for magnitude, if laser interferometry is used,
- 1 % to 3 % or smaller for magnitude, if the comparison method is used,
- 1 ° or smaller for phase shift.

Note: The participating laboratory shall report the measurement results of the complex charge sensitivity and the associated uncertainties individually as they were calculated for any specified measurement condition (in particular, for a given frequency), without applying any curve fitting procedure which is frequently used to suppress deviations from a "flat" frequency response.

3 Conditions of measurement

- frequencies in Hz: 10, 12.5, 16, 20, 40, 80, 160, 315, 630, 800, 1250, 2000, 2500, 3150, 4000, 5000, 6300, 8000 and 10000 Hz
- amplitudes: preferred value 10 m/s². A range of 5 m/s² to 200 m/s² should be complied with. *If needed, up to 300 m/s² will be accepted*.
- ambient temperature and accelerometer temperature during the calibration:

  23°C ± 1 K (actual values to be stated within tolerances of ±0,5 K).
- relative humidity: max. 75%.
- mounting torque of the accelerometer: (2 ± 0,1) N·m.

4 Transfer standards

As transfer standards, two types of piezoelectric accelerometers are used: standard accelerometer (single-ended), type 4366, manufacturer Brüel & Kjær (**Accelerometer A**), and standard accelerometer (back-to-back), type 2270, manufacturer Endevco (**Accelerometer B**).

Accelerometer A is provided by SP and accelerometer B by MIKES. Both accelerometers have been measured over a longer period for stability data.

In addition a dummy mass for calibrating accelerometer B by laser interferometry is provided by MIKES.

Specifications of Accelerometer A: Accelerometer (single ended) type 4366, manufacturer Brüel & Kjær. Weight: 28 grams. Length: 19 mm. Width over flats of hexagonal faces: 16 mm. Mounting thread: 10-32 UNF. Electrical connector: coaxial 10-32 UNF. Accelerometer capacitance: ≈ 1.1 nF. Sensitivity:≈ 5 pC/(m/s²). Max. transverse sensitivity: ≤ 2%.

Specifications of Accelerometer B: Accelerometer (back-to-back) type 2270 (manufacturer Endevco). Weight: 40 grams. Length: 28 mm. Width over flats of hexagonal faces: 16 mm. Mounting thread: 1/4-28 UNF. Electrical connector: coaxial 10 – 32. Accelerometer capacitance: ≈ 1.6 nF. Sensitivity: ≈ 0.22 pC/(m/s²). Max. transverse sensitivity: ≤ 3%.

Specifications of Dummy mass: Dummy mass made of steel. Weight: 50 grams. Dummy mass has three equally spaced longitudinal holes on its circumference and one center hole for mounting it on top of an accelerometer.

5 Measurement instructions

- The ***measurand*** is the magnitude and phase shift of the complex charge sensitivity.
    - ***Calibration of <u>Accelerometer A</u> by <u>laser interferometry</u>:***

      The reference surface for acceleration measurement is by definition the base or mounting surface of the accelerometer. If this surface is covered during the calibration, the motion is to be sensed on the moving part close to the accelerometer. Alternatively, the motion can be sensed at the mounting surface of the accelerometer via longitudinal holes in the moving part of the vibration exciter. ISO 16063-11:1999 is to be observed.
    - ***Calibration of <u>Accelerometer B</u> by <u>laser interferometry</u>:***

      A dummy mass provided by the pilot laboratory shall be mounted on the top surface of the accelerometer B. The reference surface for acceleration measurement is by definition the top surface of the back-to-back accelerometer B. The motion is to be sensed at the polished top surface of accelerometer B via longitudinal holes in the dummy mass. ISO 16063-11:1999 is to be observed.
    - In order to suppress the effect of any non-rectilinear motion in laser-interferometric calibrations, the displacement should be measured at a minimum of three different points. These points should be equally spaced on the mounting surface of the accelerometer.
    - ***Calibration of <u>Accelerometer A</u> by <u>comparison</u>:***

      The accelerometer is to be calibrated according to ISO 16063-21 by comparison to a reference accelerometer calibrated by laser interferometry in accordance with ISO 16063-11:1999. The reference accelerometer of the calibrating laboratory may be of the so-called back-to-back type meant for direct mounting of the transducer to be calibrated (i.e. accelerometer A) on top of it in a so-called back-to-back configuration. It may also be a reference accelerometer with normal mounting provisions used underneath a fixture in line with accelerometer A. It is not recommended to mount the two transducers side by side as rocking motion will often be present, causing large errors in many circumstances. For calibrators, the reference transducer may be an integral part of a moving element.

  - ***Calibration of <u>Accelerometer B</u> by <u>comparison</u>:***

    Accelerometer B is calibrated by using a single-ended transfer standard accelerometer mounted on top of it as a reference. The transfer standard accelerometer is to be calibrated according to ISO 16063-21 by comparison to a reference accelerometer calibrated by laser interferometry in accordance with ISO 16063-11:1999. The weight of the transfer standard accelerometer should be the same as the weight of the dummy mass.

- The ***charge amplifier*** used in the laboratory should be calibrated. The calibration of the charge amplifier should be carried out using values of the electrical quantities similar to those occurring in the accelerometer calibration.
- The mounting surfaces of the accelerometer and the moving part of the vibration exciter shall slightly be lubricated before mounting.
- For each of the two accelerometers, carry out the calibration in accordance with the usual procedure of your laboratory.

6 Communication of the results to the pilot laboratory

MIKES and SP will calibrate both accelerometers without any information from the other participant. Both participants will send the calibration results to the TC-AUV SC Acceleration and vibration convenor Thomas Bruns independently. After both participants have performed their calibrations and Thomas Bruns has received both calibration results, he will send the calibration results to MIKES.

The calibration results will be submitted to Thomas Bruns within 6 weeks after performing the calibration. The calibration report will contain detailed descriptions of:

- the calibration equipment
- the calibration method(s) used
- the ambient conditions
- the mounting technique
- the calibration results
- the uncertainty budget(s)

In addition to the calibration report, the measurement results should be submitted to the pilot laboratory by electronic mail, with the data in *Excel* or ASCII text format.

For reporting the calibration results, clause 10 of ISO 16063-11:1999 and clause 7 of ISO 16063-21, respectively, shall be taken into account. For uncertainty, the following instructions are given:

The list(s) of the principal components of the uncertainty budget shall be in accordance with ISO 16063-11:1999, Annex A for the primary calibration by laser interferometry according to method 1 ("fringe-counting method"), method 2 ("minimum-point method") and/or method 3 ("sine-approximation method"). For vibration calibration by comparison to a reference accelerometer, Annex A of ISO 16063-21 shall be taken into account. In each case, the uncertainties shall be determined in accordance with the Guide to the expression of uncertainty in measurement, which is adapted to the calibration of vibration and shock transducers in ISO 16063-1:1998, Annex A.

Clause 10 and Annex A of ISO 16063-11:1999 and Annex A of ISO 16063-21 are formal parts of clause 6 of the technical protocol.

7 Circulation type

Only one link between SP and MIKES exists.

SP will send the accelerometer A to MIKES. MIKES calibrates the accelerometer and sends it back to SP, which will perform its own calibration of accelerometer A.

MIKES will send the accelerometer B to SP. SP calibrates the accelerometer and sends it back to MIKES, which will perform its own calibration of accelerometer B.

8 Time schedule

- ***Calibration and transportation time period:***

A total time period of 6 weeks is allocated for each laboratory covering both calibration and transportation.

- ***Total circulation period*:**
  3 months
- ***Start of the circulation period*:**
  March 2010
- ***End of the circulation period*:**
  May 2010 (or earlier if possible)
- ***Draft report*:**
  July 2010 (or earlier if possible)
- ***Final report*:**
  2010

9 Transportation

The transfer standards will be transported in a closed box by an international transportation agency (e.g. UPS) or directly from one laboratory to another by a car.

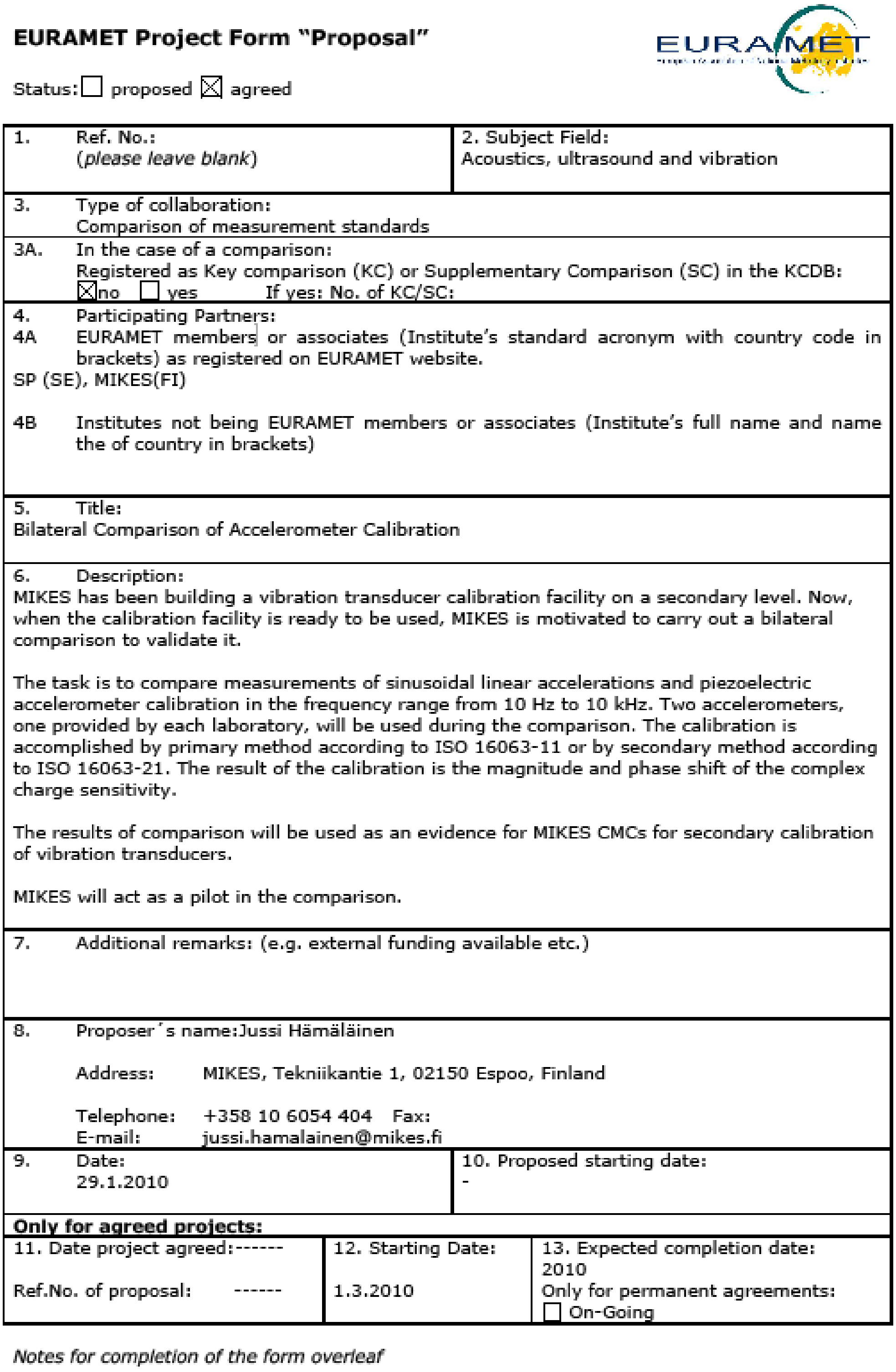
10 Financial aspects

Each participating laboratory is responsible for its own costs for the measurements as well as any damage that may occur within its country. Pilot laboratory is responsible for transportation, any customs charges and overall costs of the organization of the comparison.

11. Insurance of transfer devices

Insurance of transfer devices is decided by agreement among the participants taking account of the responsibility of each participant for any damage in its country.

ANNEX A: Agreed EUROMET Project Ref.-No 1142



EURAMET Project Form "Proposal"

Status: ☐ proposed ☒ agreed

1. Ref. No.: *(please leave blank)*	2. Subject Field: Acoustics, ultrasound and vibration

3. Type of collaboration:
Comparison of measurement standards

3A. In the case of a comparison:
Registered as Key comparison (KC) or Supplementary Comparison (SC) in the KCDB:
☒no ☐ yes If yes: No. of KC/SC:

4. Participating Partners:
4A EURAMET members or associates (Institute's standard acronym with country code in brackets) as registered on EURAMET website.
SP (SE), MIKES(FI)

4B Institutes not being EURAMET members or associates (Institute's full name and name the of country in brackets)

5. Title:
Bilateral Comparison of Accelerometer Calibration

6. Description:
MIKES has been building a vibration transducer calibration facility on a secondary level. Now, when the calibration facility is ready to be used, MIKES is motivated to carry out a bilateral comparison to validate it.

The task is to compare measurements of sinusoidal linear accelerations and piezoelectric accelerometer calibration in the frequency range from 10 Hz to 10 kHz. Two accelerometers, one provided by each laboratory, will be used during the comparison. The calibration is accomplished by primary method according to ISO 16063-11 or by secondary method according to ISO 16063-21. The result of the calibration is the magnitude and phase shift of the complex charge sensitivity.

The results of comparison will be used as an evidence for MIKES CMCs for secondary calibration of vibration transducers.

MIKES will act as a pilot in the comparison.

7. Additional remarks: (e.g. external funding available etc.)

8. Proposer´s name:Jussi Hämäläinen

Address: MIKES, Tekniikantie 1, 02150 Espoo, Finland

Telephone: +358 10 6054 404 Fax:
E-mail: jussi.hamalainen@mikes.fi

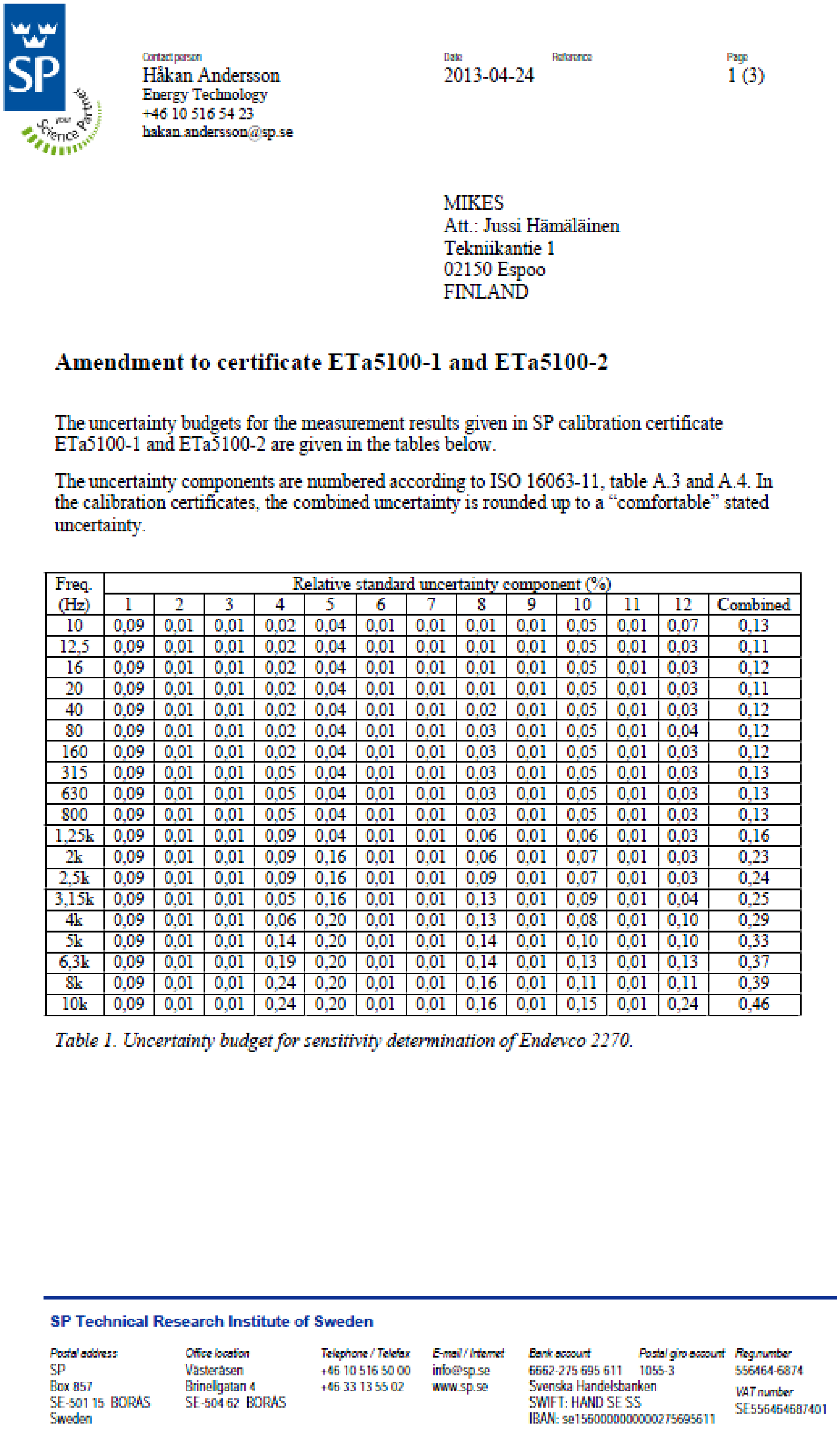
9. Date: 29.1.2010	10. Proposed starting date: -

Only for agreed projects:

11. Date project agreed:------ Ref.No. of proposal: ------	12. Starting Date: 1.3.2010	13. Expected completion date: 2010 Only for permanent agreements: ☐ On-Going

Notes for completion of the form overleaf

Appendix 2. Uncertainty budgets of SP



Contact person
Håkan Andersson
Energy Technology
+46 10 516 54 23
hakan.andersson@sp.se

Date
2013-04-24

Reference

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MIKES
Att.: Jussi Hämäläinen
Tekniikantie 1
02150 Espoo
FINLAND

Amendment to certificate ETa5100-1 and ETa5100-2

The uncertainty budgets for the measurement results given in SP calibration certificate ETa5100-1 and ETa5100-2 are given in the tables below.

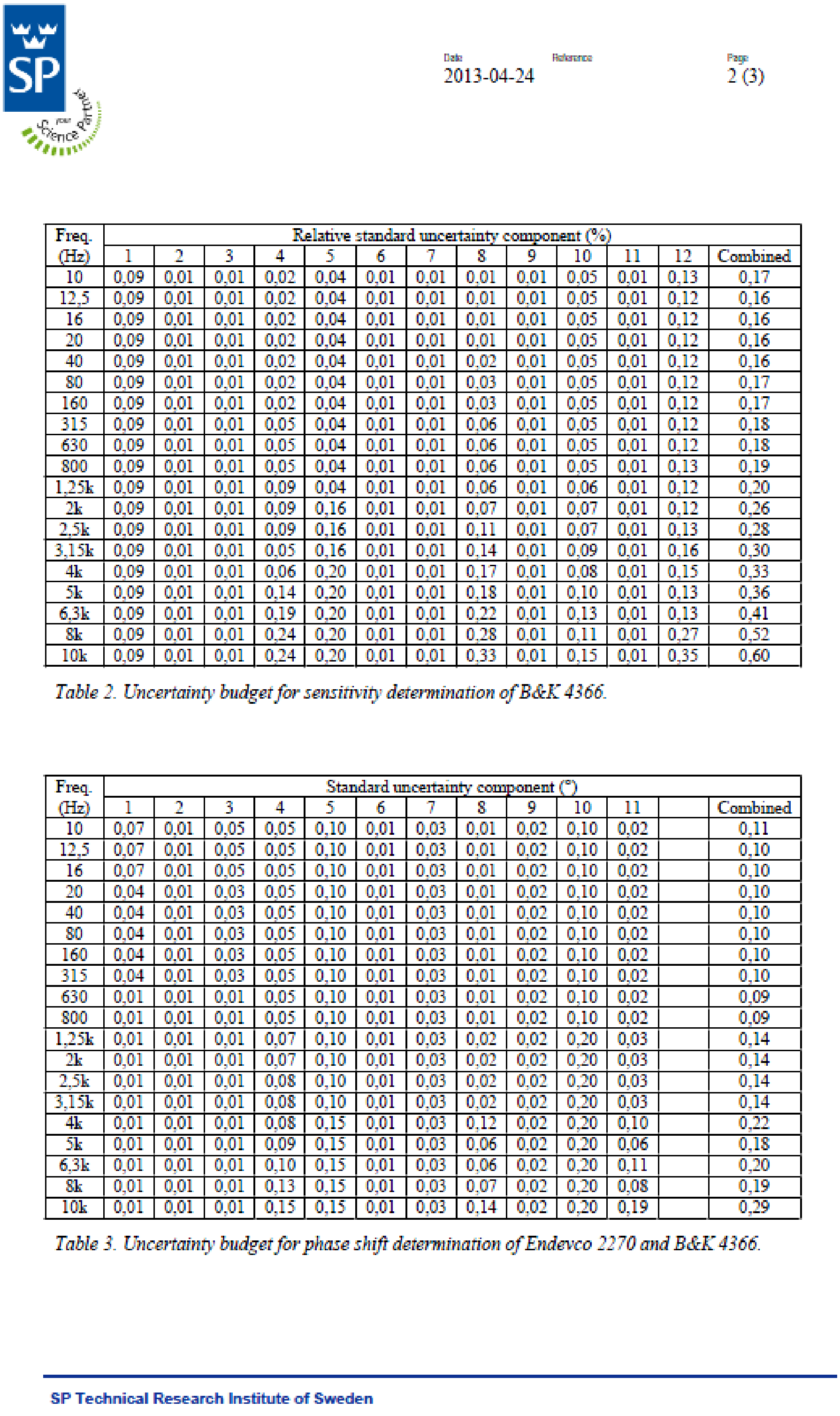
The uncertainty components are numbered according to ISO 16063-11, table A.3 and A.4. In the calibration certificates, the combined uncertainty is rounded up to a "comfortable" stated uncertainty.

Freq.	Relative standard uncertainty component (%)												
(Hz)	1	2	3	4	5	6	7	8	9	10	11	12	Combined
10	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,01	0,01	0,05	0,01	0,07	0,13
12,5	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,01	0,01	0,05	0,01	0,03	0,11
16	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,01	0,01	0,05	0,01	0,03	0,12
20	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,01	0,01	0,05	0,01	0,03	0,11
40	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,02	0,01	0,05	0,01	0,03	0,12
80	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,03	0,01	0,05	0,01	0,04	0,12
160	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,03	0,01	0,05	0,01	0,03	0,12
315	0,09	0,01	0,01	0,05	0,04	0,01	0,01	0,03	0,01	0,05	0,01	0,03	0,13
630	0,09	0,01	0,01	0,05	0,04	0,01	0,01	0,03	0,01	0,05	0,01	0,03	0,13
800	0,09	0,01	0,01	0,05	0,04	0,01	0,01	0,03	0,01	0,05	0,01	0,03	0,13
1,25k	0,09	0,01	0,01	0,09	0,04	0,01	0,01	0,06	0,01	0,06	0,01	0,03	0,16
2k	0,09	0,01	0,01	0,09	0,16	0,01	0,01	0,06	0,01	0,07	0,01	0,03	0,23
2,5k	0,09	0,01	0,01	0,09	0,16	0,01	0,01	0,09	0,01	0,07	0,01	0,03	0,24
3,15k	0,09	0,01	0,01	0,05	0,16	0,01	0,01	0,13	0,01	0,09	0,01	0,04	0,25
4k	0,09	0,01	0,01	0,06	0,20	0,01	0,01	0,13	0,01	0,08	0,01	0,10	0,29
5k	0,09	0,01	0,01	0,14	0,20	0,01	0,01	0,14	0,01	0,10	0,01	0,10	0,33
6,3k	0,09	0,01	0,01	0,19	0,20	0,01	0,01	0,14	0,01	0,13	0,01	0,13	0,37
8k	0,09	0,01	0,01	0,24	0,20	0,01	0,01	0,16	0,01	0,11	0,01	0,11	0,39
10k	0,09	0,01	0,01	0,24	0,20	0,01	0,01	0,16	0,01	0,15	0,01	0,24	0,46

Table 1. Uncertainty budget for sensitivity determination of Endevco 2270.

SP Technical Research Institute of Sweden

Postal address	Office location	Telephone / Telefax	E-mail / Internet	Bank account	Postal giro account	Reg.number
SP Box 857 SE-501 15 BORÅS Sweden	Västeråsen Brinellgatan 4 SE-504 62 BORÅS	+46 10 516 50 00 +46 33 13 55 02	info@sp.se www.sp.se	6662-275 695 611 Svenska Handelsbanken SWIFT: HAND SE SS IBAN: se1560000000000275695611	1055-3	556464-6874 VAT number SE556464687401



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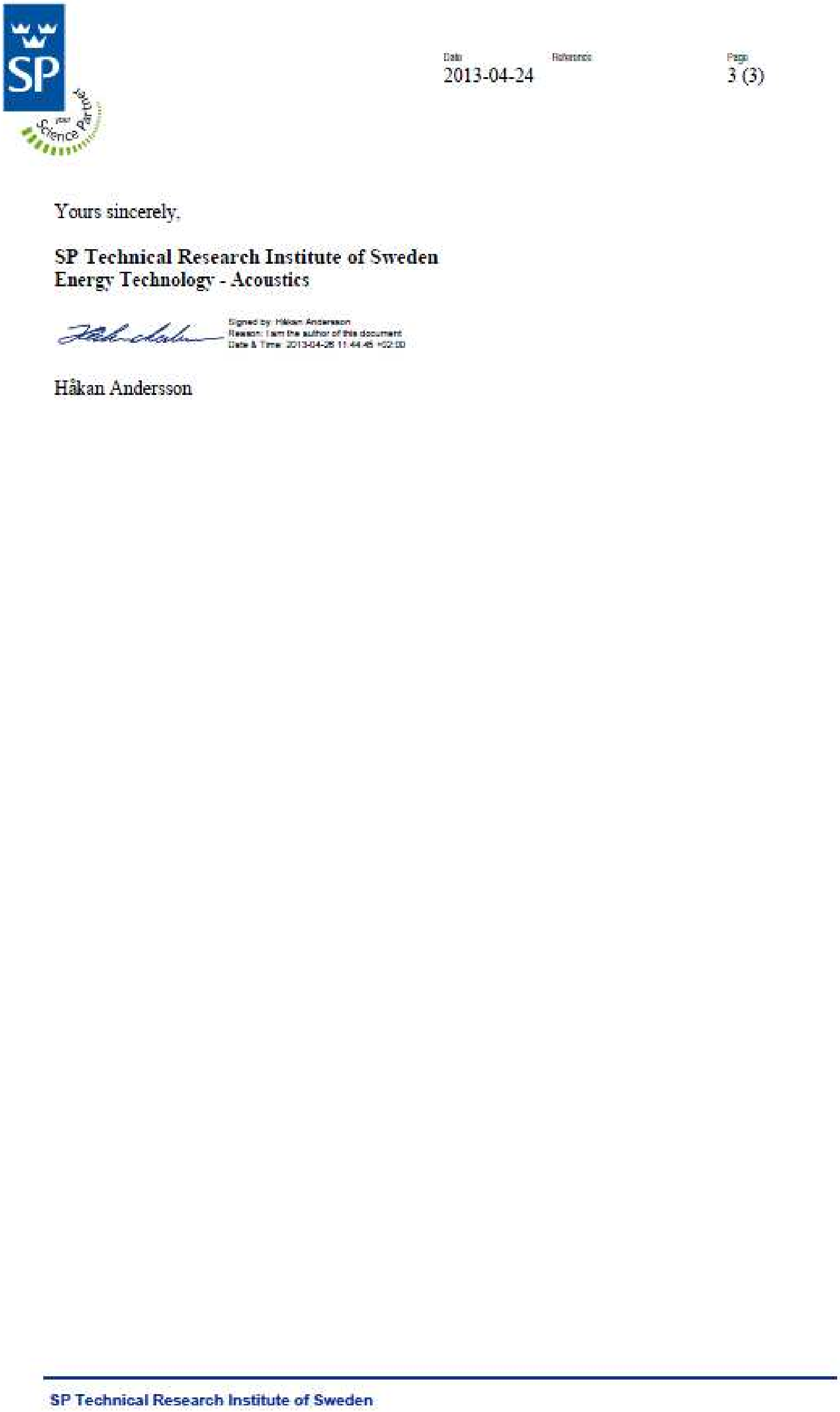
Freq.	Relative standard uncertainty component (%)												
(Hz)	1	2	3	4	5	6	7	8	9	10	11	12	Combined
10	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,01	0,01	0,05	0,01	0,13	0,17
12,5	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,01	0,01	0,05	0,01	0,12	0,16
16	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,01	0,01	0,05	0,01	0,12	0,16
20	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,01	0,01	0,05	0,01	0,12	0,16
40	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,02	0,01	0,05	0,01	0,12	0,16
80	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,03	0,01	0,05	0,01	0,12	0,17
160	0,09	0,01	0,01	0,02	0,04	0,01	0,01	0,03	0,01	0,05	0,01	0,12	0,17
315	0,09	0,01	0,01	0,05	0,04	0,01	0,01	0,06	0,01	0,05	0,01	0,12	0,18
630	0,09	0,01	0,01	0,05	0,04	0,01	0,01	0,06	0,01	0,05	0,01	0,12	0,18
800	0,09	0,01	0,01	0,05	0,04	0,01	0,01	0,06	0,01	0,05	0,01	0,13	0,19
1,25k	0,09	0,01	0,01	0,09	0,04	0,01	0,01	0,06	0,01	0,06	0,01	0,12	0,20
2k	0,09	0,01	0,01	0,09	0,16	0,01	0,01	0,07	0,01	0,07	0,01	0,12	0,26
2,5k	0,09	0,01	0,01	0,09	0,16	0,01	0,01	0,11	0,01	0,07	0,01	0,13	0,28
3,15k	0,09	0,01	0,01	0,05	0,16	0,01	0,01	0,14	0,01	0,09	0,01	0,16	0,30
4k	0,09	0,01	0,01	0,06	0,20	0,01	0,01	0,17	0,01	0,08	0,01	0,15	0,33
5k	0,09	0,01	0,01	0,14	0,20	0,01	0,01	0,18	0,01	0,10	0,01	0,13	0,36
6,3k	0,09	0,01	0,01	0,19	0,20	0,01	0,01	0,22	0,01	0,13	0,01	0,13	0,41
8k	0,09	0,01	0,01	0,24	0,20	0,01	0,01	0,28	0,01	0,11	0,01	0,27	0,52
10k	0,09	0,01	0,01	0,24	0,20	0,01	0,01	0,33	0,01	0,15	0,01	0,35	0,60

Table 2. Uncertainty budget for sensitivity determination of B&K 4366.

Freq.	Standard uncertainty component (°)												
(Hz)	1	2	3	4	5	6	7	8	9	10	11		Combined
10	0,07	0,01	0,05	0,05	0,10	0,01	0,03	0,01	0,02	0,10	0,02		0,11
12,5	0,07	0,01	0,05	0,05	0,10	0,01	0,03	0,01	0,02	0,10	0,02		0,10
16	0,07	0,01	0,05	0,05	0,10	0,01	0,03	0,01	0,02	0,10	0,02		0,10
20	0,04	0,01	0,03	0,05	0,10	0,01	0,03	0,01	0,02	0,10	0,02		0,10
40	0,04	0,01	0,03	0,05	0,10	0,01	0,03	0,01	0,02	0,10	0,02		0,10
80	0,04	0,01	0,03	0,05	0,10	0,01	0,03	0,01	0,02	0,10	0,02		0,10
160	0,04	0,01	0,03	0,05	0,10	0,01	0,03	0,01	0,02	0,10	0,02		0,10
315	0,04	0,01	0,03	0,05	0,10	0,01	0,03	0,01	0,02	0,10	0,02		0,10
630	0,01	0,01	0,01	0,05	0,10	0,01	0,03	0,01	0,02	0,10	0,02		0,09
800	0,01	0,01	0,01	0,05	0,10	0,01	0,03	0,01	0,02	0,10	0,02		0,09
1,25k	0,01	0,01	0,01	0,07	0,10	0,01	0,03	0,02	0,02	0,20	0,03		0,14
2k	0,01	0,01	0,01	0,07	0,10	0,01	0,03	0,02	0,02	0,20	0,03		0,14
2,5k	0,01	0,01	0,01	0,08	0,10	0,01	0,03	0,02	0,02	0,20	0,03		0,14
3,15k	0,01	0,01	0,01	0,08	0,10	0,01	0,03	0,02	0,02	0,20	0,03		0,14
4k	0,01	0,01	0,01	0,08	0,15	0,01	0,03	0,12	0,02	0,20	0,10		0,22
5k	0,01	0,01	0,01	0,09	0,15	0,01	0,03	0,06	0,02	0,20	0,06		0,18
6,3k	0,01	0,01	0,01	0,10	0,15	0,01	0,03	0,06	0,02	0,20	0,11		0,20
8k	0,01	0,01	0,01	0,13	0,15	0,01	0,03	0,07	0,02	0,20	0,08		0,19
10k	0,01	0,01	0,01	0,15	0,15	0,01	0,03	0,14	0,02	0,20	0,19		0,29

Table 3. Uncertainty budget for phase shift determination of Endevco 2270 and B&K 4366.

SP Technical Research Institute of Sweden



Date
2013-04-24

Reference

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Yours sincerely,

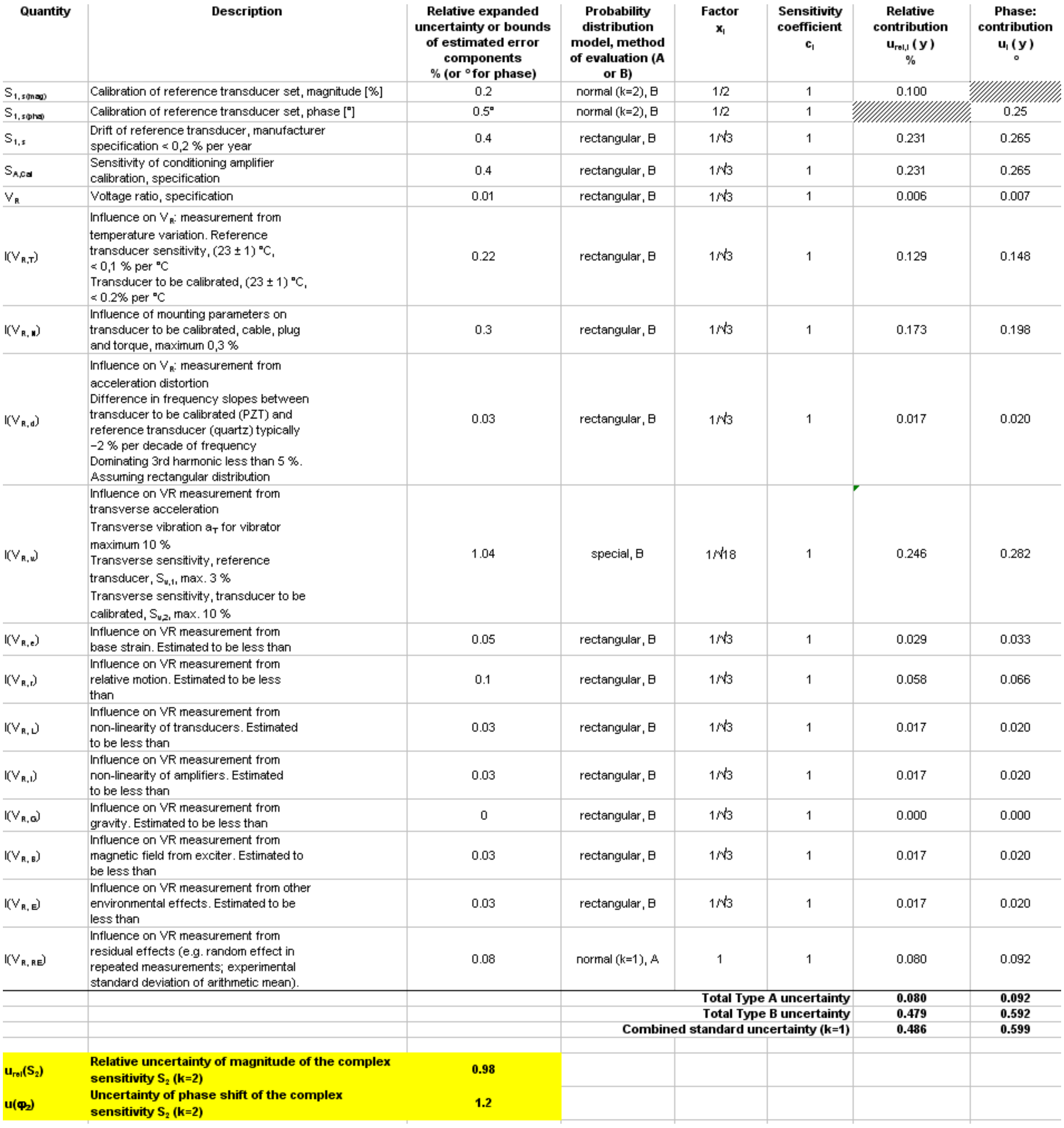
SP Technical Research Institute of Sweden
Energy Technology - Acoustics

Signed by: Håkan Andersson
Reason: I am the author of this document
Date & Time: 2013-04-26 11:44:46 +02:00

Håkan Andersson

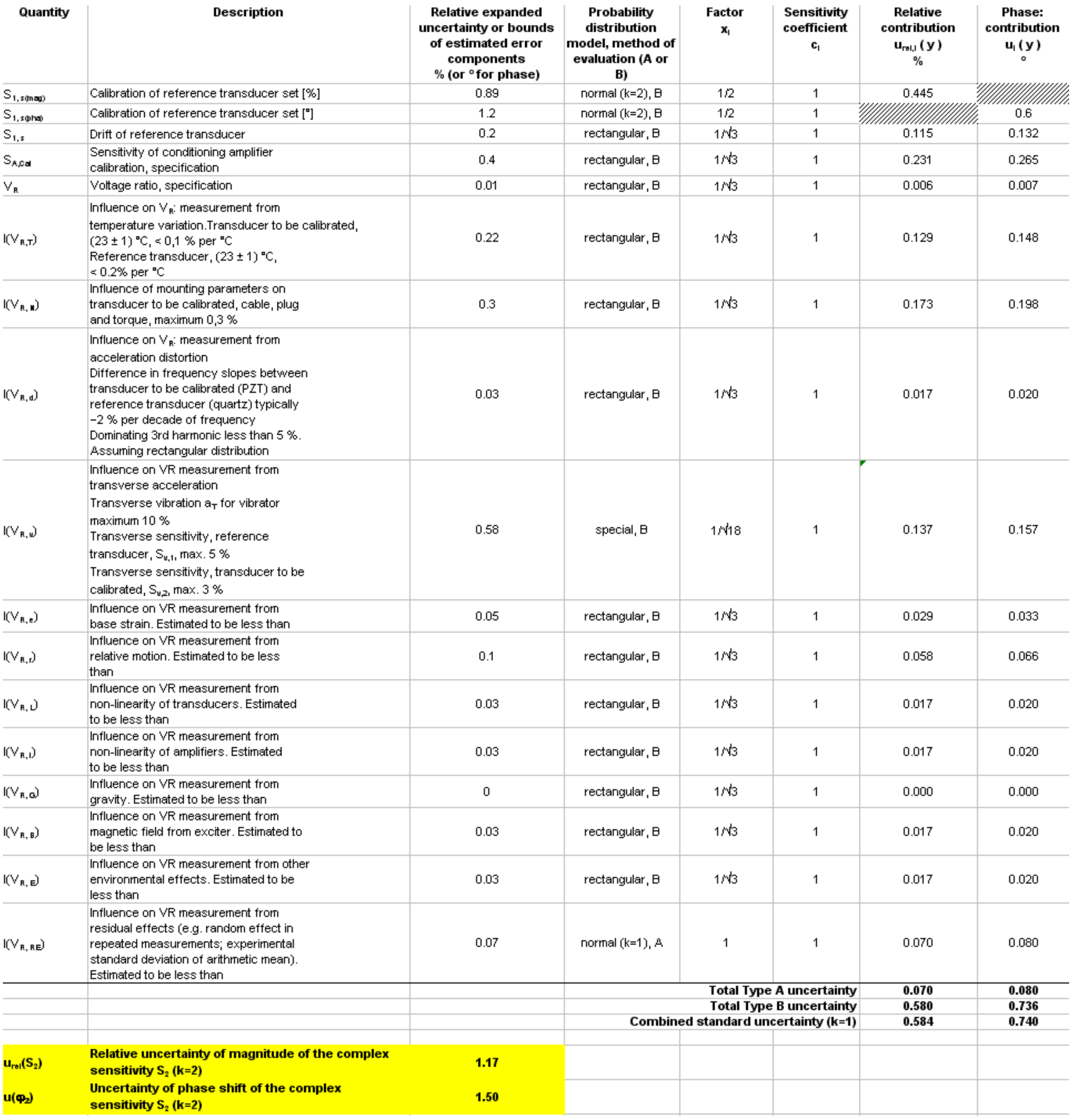
Appendix 3. Uncertainty budgets of MIKES

In this appendix are shown the uncertainty budgets of calibration of accelerometers A and B at 10 Hz frequency. All other frequencies included in the comparison have same kind of tables with different values in frequency depended uncertainty components.



Quantity	Description	Relative expanded uncertainty or bounds of estimated error components % (or ° for phase)	Probability distribution model, method of evaluation (A or B)	Factor x_i	Sensitivity coefficient c_i	Relative contribution $u_{rel,i}(y)$ %	Phase: contribution $u_i(y)$ °
$S_{1,s(mag)}$	Calibration of reference transducer set, magnitude [%]	0.2	normal (k=2), B	1/2	1	0.100	▨
$S_{1,s(pha)}$	Calibration of reference transducer set, phase [°]	0.5°	normal (k=2), B	1/2	1	▨	0.25
$S_{1,s}$	Drift of reference transducer, manufacturer specification < 0,2 % per year	0.4	rectangular, B	$1/\sqrt{3}$	1	0.231	0.265
$S_{A,Cal}$	Sensitivity of conditioning amplifier calibration, specification	0.4	rectangular, B	$1/\sqrt{3}$	1	0.231	0.265
V_R	Voltage ratio, specification	0.01	rectangular, B	$1/\sqrt{3}$	1	0.006	0.007
$I(V_{R,T})$	Influence on V_R: measurement from temperature variation. Reference transducer sensitivity, (23 ± 1) °C, < 0,1 % per °C Transducer to be calibrated, (23 ± 1) °C, < 0.2% per °C	0.22	rectangular, B	$1/\sqrt{3}$	1	0.129	0.148
$I(V_{R,M})$	Influence of mounting parameters on transducer to be calibrated, cable, plug and torque, maximum 0,3 %	0.3	rectangular, B	$1/\sqrt{3}$	1	0.173	0.198
$I(V_{R,d})$	Influence on V_R: measurement from acceleration distortion Difference in frequency slopes between transducer to be calibrated (PZT) and reference transducer (quartz) typically −2 % per decade of frequency Dominating 3rd harmonic less than 5 %. Assuming rectangular distribution	0.03	rectangular, B	$1/\sqrt{3}$	1	0.017	0.020
$I(V_{R,u})$	Influence on VR measurement from transverse acceleration Transverse vibration a_T for vibrator maximum 10 % Transverse sensitivity, reference transducer, $S_{u,1}$, max. 3 % Transverse sensitivity, transducer to be calibrated, $S_{u,2}$, max. 10 %	1.04	special, B	$1/\sqrt{18}$	1	0.246	0.282
$I(V_{R,e})$	Influence on VR measurement from base strain. Estimated to be less than	0.05	rectangular, B	$1/\sqrt{3}$	1	0.029	0.033
$I(V_{R,r})$	Influence on VR measurement from relative motion. Estimated to be less than	0.1	rectangular, B	$1/\sqrt{3}$	1	0.058	0.066
$I(V_{R,L})$	Influence on VR measurement from non-linearity of transducers. Estimated to be less than	0.03	rectangular, B	$1/\sqrt{3}$	1	0.017	0.020
$I(V_{R,l})$	Influence on VR measurement from non-linearity of amplifiers. Estimated to be less than	0.03	rectangular, B	$1/\sqrt{3}$	1	0.017	0.020
$I(V_{R,G})$	Influence on VR measurement from gravity. Estimated to be less than	0	rectangular, B	$1/\sqrt{3}$	1	0.000	0.000
$I(V_{R,B})$	Influence on VR measurement from magnetic field from exciter. Estimated to be less than	0.03	rectangular, B	$1/\sqrt{3}$	1	0.017	0.020
$I(V_{R,E})$	Influence on VR measurement from other environmental effects. Estimated to be less than	0.03	rectangular, B	$1/\sqrt{3}$	1	0.017	0.020
$I(V_{R,RE})$	Influence on VR measurement from residual effects (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean).	0.08	normal (k=1), A	1	1	0.080	0.092
					Total Type A uncertainty	**0.080**	**0.092**
					Total Type B uncertainty	**0.479**	**0.592**
					Combined standard uncertainty (k=1)	**0.486**	**0.599**
$u_{rel}(S_2)$	**Relative uncertainty of magnitude of the complex sensitivity S_2 (k=2)**	**0.98**					
$u(\varphi_2)$	**Uncertainty of phase shift of the complex sensitivity S_2 (k=2)**	**1.2**					

Figure 1. The uncertainty budget of calibration of accelerometer A at 10 Hz frequency. Calibration certificate M-11E026.



Quantity	Description	Relative expanded uncertainty or bounds of estimated error components % (or ° for phase)	Probability distribution model, method of evaluation (A or B)	Factor x_i	Sensitivity coefficient c_i	Relative contribution $u_{rel,i}(y)$ %	Phase: contribution $u_i(y)$ °
$S_{1,s(mag)}$	Calibration of reference transducer set [%]	0.89	normal (k=2), B	1/2	1	0.445	▨
$S_{1,s(pha)}$	Calibration of reference transducer set [°]	1.2	normal (k=2), B	1/2	1	▨	0.6
$S_{1,s}$	Drift of reference transducer	0.2	rectangular, B	$1/\sqrt{3}$	1	0.115	0.132
$S_{A,Cal}$	Sensitivity of conditioning amplifier calibration, specification	0.4	rectangular, B	$1/\sqrt{3}$	1	0.231	0.265
V_R	Voltage ratio, specification	0.01	rectangular, B	$1/\sqrt{3}$	1	0.006	0.007
$I(V_{R,T})$	Influence on V_R: measurement from temperature variation.Transducer to be calibrated, (23 ± 1) °C, < 0,1 % per °C Reference transducer, (23 ± 1) °C, < 0.2% per °C	0.22	rectangular, B	$1/\sqrt{3}$	1	0.129	0.148
$I(V_{R,M})$	Influence of mounting parameters on transducer to be calibrated, cable, plug and torque, maximum 0,3 %	0.3	rectangular, B	$1/\sqrt{3}$	1	0.173	0.198
$I(V_{R,d})$	Influence on V_R: measurement from acceleration distortion Difference in frequency slopes between transducer to be calibrated (PZT) and reference transducer (quartz) typically −2 % per decade of frequency Dominating 3rd harmonic less than 5 %. Assuming rectangular distribution	0.03	rectangular, B	$1/\sqrt{3}$	1	0.017	0.020
$I(V_{R,u})$	Influence on VR measurement from transverse acceleration Transverse vibration a_T for vibrator maximum 10 % Transverse sensitivity, reference transducer, $S_{u,1}$, max. 5 % Transverse sensitivity, transducer to be calibrated, $S_{u,2}$, max. 3 %	0.58	special, B	$1/\sqrt{18}$	1	0.137	0.157
$I(V_{R,e})$	Influence on VR measurement from base strain. Estimated to be less than	0.05	rectangular, B	$1/\sqrt{3}$	1	0.029	0.033
$I(V_{R,r})$	Influence on VR measurement from relative motion. Estimated to be less than	0.1	rectangular, B	$1/\sqrt{3}$	1	0.058	0.066
$I(V_{R,L})$	Influence on VR measurement from non-linearity of transducers. Estimated to be less than	0.03	rectangular, B	$1/\sqrt{3}$	1	0.017	0.020
$I(V_{R,l})$	Influence on VR measurement from non-linearity of amplifiers. Estimated to be less than	0.03	rectangular, B	$1/\sqrt{3}$	1	0.017	0.020
$I(V_{R,G})$	Influence on VR measurement from gravity. Estimated to be less than	0	rectangular, B	$1/\sqrt{3}$	1	0.000	0.000
$I(V_{R,B})$	Influence on VR measurement from magnetic field from exciter. Estimated to be less than	0.03	rectangular, B	$1/\sqrt{3}$	1	0.017	0.020
$I(V_{R,E})$	Influence on VR measurement from other environmental effects. Estimated to be less than	0.03	rectangular, B	$1/\sqrt{3}$	1	0.017	0.020
$I(V_{R,RE})$	Influence on VR measurement from residual effects (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean). Estimated to be less than	0.07	normal (k=1), A	1	1	0.070	0.080
			Total Type A uncertainty			**0.070**	**0.080**
			Total Type B uncertainty			**0.580**	**0.736**
			Combined standard uncertainty (k=1)			**0.584**	**0.740**
$u_{rel}(S_2)$	**Relative uncertainty of magnitude of the complex sensitivity S_2 (k=2)**	**1.17**					
$u(\varphi_2)$	**Uncertainty of phase shift of the complex sensitivity S_2 (k=2)**	**1.50**					

Figure 2. The uncertainty budget of calibration of accelerometer B at 10 Hz frequency. Calibration certificate M-11E040.