Final Report of the Key Comparison

APMP.AUV.V-K2

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Abstract

A key comparison of vibration acceleration APMP.AUV.V-K2, which is upgraded from APMP.AUV.V-K1.1, has been made within the Asia Pacific Metrology Programme (APMP) to include three national laboratories; the CMS-ITRI (Chinese Taipei), the NIMT (Thailand) and the A*Star (Singapore). Only one pilot laboratory was the NMIJ (Japan) that participated to link the RMO APMP results to the CIPM CC key comparison (CCAUV.V-K2), according to the decision of CCAUV10/D7 in 10th CCAUV meeting. The admissible acceleration amplitude ranges from 10 m/s^2 to 200 m/s^2 over the frequency range from 40 Hz to 5 kHz. The RMO APMP results demonstrate the agreement with the key comparison reference value of CCAUV.V-K2 within the expanded uncertainties considering the armature effect of vibration exciter in high-frequency range.

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1. Introduction

This report presents the results of the APMP comparison in the area of 'vibration', which in this case means sinusoidal acceleration. It was organized to disseminate the key comparison reference values, which were established earlier in the CIPM key comparison CCAUV.V-K1 [1] and CCAUV.V-K2 [2] within the RMO APMP.

In this report the relationship between the results of the participants and the results of the CIPM comparison in the field of vibration CCAUV.V-K2 is calculated via a procedure of 'linking'. Only one pilot laboratory NMIJ, which participated in both the CIPM comparisons, acted as the linking laboratory for that process by the decision of CCAUV10/D7 [3] according to the resolution of 10th CCAUV meeting. In order to avoid an extra bias between NMIJ result and KCRV of CCAUV.V-K2, the linking factor is defined as a ratio of two NMIJ results in CCAUV.V-K2 and APMP.AUV.V-K2. Using the linking factor, the RMO APMP results of three participants were directly compared with the results of CCAUV.V-K2.

The Technical Protocol (c.f. App. 1) specifies in detail the aim and the task of the comparison, the conditions of measurement, the transfer standards used, measurement instructions, time schedule and other items. A brief summary is given in the following sections.

2. Participants

Four National Metrology Institutes (NMIs) in APMP participated in the RMO APMP.AUV.V-K2 comparison.

Table 1 Participants of the RMO APMP.AUV.V-K2 comparison

Participant (Laboratory name)	Acronym	Economy	Economy code
National Metrology Institute of Japan	NMIJ	Japan	JP
Center for Measurement Standards/Industrial Technology Research Institute	CMS/ITRI	Chinese Taipei	TW
National Institute of Metrology Thailand	NIMT	Thailand	TH
National Metrology Centre, Agency for Science, Technology and Research	NMC, A*Star	Singapore	SG

3. Task and Purpose of the comparison

The main purpose of this RMO-level comparison of the APMP in the field of vibration acceleration was to disseminate the key comparison reference to three NMIs namely CMS/ITRI, NIMT, NMC A*Star. It was also planned for CMS/ITRI to confirm their Calibration Measurement Capabilities (CMCs) of their improved primary calibration system since CMS/ITRI participated to the APMP.AUV.V-K1 [4].

In order to provide the necessary means for a linking of this RMO comparison APMP.AUV.V-K2 results to the CIPM CCAUV.V-K2 key comparison, NMIJ was requested to volunteer as the Pilot and Linking laboratory. The principal task of the comparison is to measure the charge sensitivity of two accelerometers (one of single-ended design and one of back-to-back design) at different frequencies and acceleration amplitudes specified in section 4.

The charge sensitivity is 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 charge sensitivity is given in pico coulombs per metres per second squared: pC/(m/s^2).

To calibrate the two accelerometers, each primary vibration calibration by laser interferometry in accordance with ISO 16063-11:1999 [5] was carried out.

4. Condition and Instruction of Measurement

All major conditions were specified in compliance with the relevant CC Key comparison CCAUV.V-K2 as follows;

- Frequencies (all values in Hz): 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, 5000 (160 Hz is reference frequency)
- Acceleration amplitudes: A range of 10 m/s^2 to 200 m/s^2 is admissible.
- Ambient temperature and accelerometer temperature during the calibration:
  (23 ± 2) ºC (actual values to be stated within tolerances of ± 0.3 ºC), relative humidity: max. 75 %
- Mounting torque of the accelerometer: (2.0 ± 0.1) N·m

The comparison was also consistent with the “Guidelines for CIPM key comparisons” [6].

5. Transfer Standards as Artifact

Two types of piezoelectric standard accelerometers were used as transfer standards.

• One transfer standard accelerometer (single-ended), type 8305-001, S/N 2644378 (manufacturer: Brüel & Kjær), subsequently named SE-transducer.

• One reference standard accelerometer (back-to-back) type 8305 S, S/N 2691032 (manufacturer: Brüel & Kjær), subsequently named BB-transducer.

The investigation of the long-term stability was continued throughout the circulation period. The results of the NMIJ stability measurements and other individual data of the transfer standards are given in Section 7.

6. Circulation of the Artifacts

The circulation Type of this comparison was a modified star type. During the comparison, an interim monitoring at the pilot laboratory was done to check the stability of the artifacts (c.f. section 7.1) and the state of the mounting surface. The artifacts were hand-carried in a closed box by a representative of the NMI.

Table 2 Circulation of the artifacts

Participant	Economy	Planed calibration period
NMIJ	Japan	August, 2011
CMS/ITRI	Chinese Taipei	September, 2011
Interim monitoring at NMIJ		
NMC, A*Star	Singapore	January, 2012
NIMT	Thailand	March, 2012
Final monitoring at NMIJ		

7. Results of the Measurements

7.1 Monitoring of stability

At the beginning of this comparison, it was planned to transport the artifacts by air parcel, starting in 2010. However, the pilot laboratory observed significant sensitivity drift on the back-to-back accelerometer after the comparison was completed. It was not obvious when and how the drift had occurred during the period of the comparison, but it was clear that the reported results from participants showed much larger deviation than the observed one at the pilot laboratory. We decided then to replace both the artifacts (single-ended and back-to-back) to restart the comparison. It was also decided to hand-carry the artifacts in a closed box by a representative to avoid any damage on the artifacts.

As shown in the table 2, we also adopted a modified star type circulation to monitor if any sensitivity drift or physical damage has occurred on the artifacts.

Table 3 shows the measurements results of the pilot laboratory at the reference frequency (160 Hz) for the time of beginning, interim and final monitoring.

Table 3 Charge sensitivities of the accelerometers at 160 Hz during the comparison measurements.

	Back-to-back		Single-ended	
Measurement period	Sq in pC/(m/s^2)	rel. exp. unc. in %	Sq in pC/(m/s^2)	rel. exp. unc. in %
Beginning	0.12773	0.24	0.12913	0.39
Interim	0.12749	0.24	0.12891	0.39
Final	0.12744	0.24	0.12882	0.39

These monitoring measurements can be summarized in the simplest way by the statistical properties given in table 4. This analysis indicates that the stability of the artifacts was acceptable considering the uncertainty claimed although the transportation did have some negative influence.

Table 4 Mean and its relative standard deviation of the charge sensitivity of the artifacts at 160 Hz calculated from the monitoring measurements

Back-to-back		Single-ended	
Long term mean in pC/(m/s^2)	rel. std. dev. in %	Long term mean in pC/(m/s^2)	rel. std. dev. in %
0.12755	0.12	0.12895	0.12

7.2 Results of the Participants

7.2.1 Results of the Back-to-Back Accelerometer

Table 7.2.1-1 Results of the Back-to-Back (BB) accelerometer

	NMIJ		CMS/ITRI		NIMT		A*STAR	
Frequency in Hz	Sq in pC/(m/s^2)	rel. exp. unc. in %	Sq in pC/(m/s^2)	rel. exp. unc. in %	Sq in pC/(m/s^2)	rel. exp. unc. in %	Sq in pC/(m/s^2)	rel. exp. unc. in %
40	0.12780	0.24	0.12794	0.31	0.12742	0.60	0.12740	0.46
50	0.12775	0.24	0.12788	0.28	0.12749	0.44		
63	0.12788	0.24	0.12793	0.25	0.12752	0.43		
80	0.12766	0.24	0.12791	0.24	0.12757	0.43	0.12753	0.48
100	0.12766	0.37	0.12792	0.27	0.12761	0.43		
125	0.12773	0.24	0.12787	0.25	0.12762	0.38		
160	0.12773	0.24	0.12793	0.27	0.12760	0.38	0.12760	0.49
200	0.12771	0.24	0.12791	0.27	0.12763	0.38		
250	0.12776	0.24	0.12785	0.28	0.12764	0.38		
315	0.12772	0.24	0.12794	0.31	0.12764	0.38	0.12748	0.48
400	0.12752	0.24	0.12791	0.29	0.12763	0.38		
500	0.12763	0.24	0.12795	0.33	0.12759	0.40		
630	0.12777	0.24	0.12795	0.30	0.12761	0.40	0.12763	0.48
800	0.12778	0.24	0.12790	0.35	0.12755	0.40		
1000	0.12785	0.24	0.12790	0.37	0.12764	0.76		
1250	0.12787	0.24	0.12785	0.39	0.12768	0.76	0.12755	0.48
1600	0.12803	0.24	0.12789	0.27	0.12777	0.76		
2000	0.12798	0.24	0.12787	0.32	0.12801	0.76		
2500	0.12836	0.24	0.12789	0.33	0.12814	0.76	0.12785	0.57
3150	0.12883	0.24	0.12819	0.46	0.12851	0.77		
4000	0.12917	0.25	0.12921	0.80	0.12903	0.77		
5000	0.13004	0.29	0.12948	0.87	0.12998	0.77	0.13128	3.1

7.2.2 Results of the Single-ended Accelerometer

Table 7.2.2-1 Results of the Single-ended (SE) accelerometer

	NMIJ		CMS/ITRI		NIMT		A*STAR	
Frequency in Hz	Sq in pC/(m/s^2)	rel. exp. unc. in %	Sq in pC/(m/s^2)	rel. exp. unc. in %	Sq in pC/(m/s^2)	rel. exp. unc. in %	Sq in pC/(m/s^2)	rel. exp. unc. in %
40	0.12914	0.39	0.12943	0.3	0.12866	0.61	0.12877	0.46
50	0.12915	0.47	0.12931	0.29	0.12875	0.44		
63	0.12919	0.40	0.12935	0.25	0.12878	0.43		
80	0.12911	0.39	0.12932	0.24	0.12884	0.43	0.1288	0.48
100	0.12913	0.42	0.12934	0.25	0.12888	0.43		
125	0.12913	0.39	0.12925	0.25	0.12893	0.38		
160	0.12913	0.39	0.12936	0.25	0.12893	0.38	0.12878	0.65
200	0.12911	0.40	0.12927	0.26	0.12892	0.38		
250	0.12909	0.39	0.12925	0.27	0.12888	0.38		
315	0.12918	0.39	0.12931	0.3	0.12893	0.38	0.1288	0.49
400	0.12916	0.39	0.12935	0.29	0.12895	0.38		
500	0.12920	0.39	0.12942	0.3	0.12890	0.40		
630	0.12921	0.39	0.12945	0.3	0.12898	0.40	0.12897	0.52
800	0.12923	0.39	0.12928	0.33	0.12893	0.40		
1000	0.12939	0.39	0.12941	0.43	0.12903	0.76		
1250	0.12945	0.39	0.12939	0.39	0.12902	0.76	0.12905	0.49
1600	0.12958	0.39	0.12942	0.29	0.12927	0.76		
2000	0.12976	0.39	0.12935	0.34	0.12938	0.77		
2500	0.13015	0.39	0.12940	0.32	0.12972	0.77	0.1301	0.56
3150	0.13085	0.39	0.13031	0.47	0.13021	0.77		
4000	0.13170	0.40	0.13149	0.8	0.13100	0.76		
5000	0.13274	0.41	0.13205	0.9	0.13235	0.77	0.13318	1.13

8. Analysis of the results

8.1 Unilateral degree of equivalence between the participants

In order to compare the individual results of the participating laboratories of this comparison with the linking laboratory (NMIJ), the unilateral degrees of equivalence (DoE) of pairs of results with respect to a certain frequency were calculated. For the purpose, we signify the measurand in this sequent KC as *Y*. The values $(y_1, u(y_1)), \ldots, (y_M, u(y_M))$ denote the charge sensitivities and associated standard uncertainties of the participants. These DoE are each a pair of values of the difference D_i between the respective participants *i* and NMIJ including the expanded uncertainty U_i of this difference. These values are calculated for each frequency according to:

$$D_i = y_i - y_{NMIJ} \tag{1}$$

$$U_i = k \cdot \sqrt{u^2(y_i) + u^2(y_{NMIJ})} \tag{2}$$

with a coverage factor of $k = 2$.

8.1.1 Unilateral DoE of the back-to-back accelerometer

Table 8.1.1-1 Unilateral Degrees of equivalence to NMIJ for the BB at 40 Hz

40 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_{ij}	U_i
	in $\mathrm{pC/(m/s^2)\cdot 10^{-4}}$		in $\mathrm{pC/(m/s^2)\cdot 10^{-4}}$		in $\mathrm{pC/(m/s^2)\cdot 10^{-4}}$	
NMIJ	1.4	5.0	-3.8	8.2	-4.0	6.6

Table 8.1.1-2 Degrees of equivalence to NMIJ for the BB at 50 Hz

50 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in $\mathrm{pC/(m/s^2)\cdot 10^{-4}}$		in $\mathrm{pC/(m/s^2)\cdot 10^{-4}}$		in $\mathrm{pC/(m/s^2)\cdot 10^{-4}}$	
NMIJ	1.3	4.7	-2.6	6.4		

Table 8.1.1-3 Degrees of equivalence to NMIJ for the BB at 63 Hz

63 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_{ij}	U_i	D_{ij}	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	0.5	4.4	-3.6	6.3		

Table 8.1.1-4 Degrees of equivalence to NMIJ for the BB at 80 Hz

80 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.5	4.3	-0.9	6.3	-1.3	6.8

Table 8.1.1-5 Degrees of equivalence to NMIJ for the BB at 100 Hz

100 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.6	5.8	-0.5	7.2		

Table 8.1.1-6 Degrees of equivalence to NMIJ for the BB at 125 Hz

125 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.4	4.4	-1.1	5.7		

Table 8.1.1-7 Degrees of equivalence to NMIJ for the BB at 160 Hz

160 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.0	4.6	-1.3	5.7	-1.3	6.9

Table 8.1.1-8 Degrees of equivalence to NMIJ for the BB at 200 Hz

200 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.0	4.6	-0.8	5.7		

Table 8.1.1-9 Degrees of equivalence to NMIJ for the BB at 250 Hz

250 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	0.9	4.7	-1.2	5.7		

Table 8.1.1-10 Degrees of equivalence to NMIJ for the BB at 315 Hz

315 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.2	5.0	-0.7	5.7	-2.4	6.8

Table 8.1.1-11 Degrees of equivalence to NMIJ for the BB at 400 Hz

400 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	3.9	4.8	1.0	5.7		

Table 8.1.1-12 Degrees of equivalence to NMIJ for the BB at 500 Hz

500 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	3.2	5.2	-0.4	5.9		

Table 8.1.1-13 Degrees of equivalence to NMIJ for the BB at 630 Hz

630 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.8	4.9	-1.6	5.9	-1.4	6.8

Table 8.1.1-14 Degrees of equivalence to NMIJ for the BB at 800 Hz

800 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.2	5.4	-2.2	5.9		

Table 8.1.1-15 Degrees of equivalence to NMIJ for the BB at 1000 Hz

1000 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	0.5	5.6	-2.1	10.2		

Table 8.1.1-16 Degrees of equivalence to NMIJ for the BB at 1250 Hz

1250 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-0.2	5.8	-2.0	10.2	-3.2	6.8

Table 8.1.1-17 Degrees of equivalence to NMIJ for the BB at 1600 Hz

1600 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-1.4	4.6	-2.6	10.2		

Table 8.1.1-18 Degrees of equivalence to NMIJ for the BB at 2000 Hz

2000 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-1.1	5.1	0.3	10.2		

Table 8.1.1-19 Degrees of equivalence to NMIJ for the BB at 2500 Hz

2500 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-4.6	5.2	-2.2	10.2	-5.1	7.9

Table 8.1.1-20 Degrees of equivalence to NMIJ for the BB at 3150 Hz

3150 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-6.4	6.7	-3.2	10.4		

Table 8.1.1-21 Degrees of equivalence to NMIJ for the BB at 4000 Hz

4000 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	0.4	10.8	-1.4	10.5		

Table 8.1.1-22 Degrees of equivalence to NMIJ for the BB at 5000 Hz

5000 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-5.6	11.9	-0.6	10.7	12.4	40.9

8.1.2 Unilateral DoE of the single-ended (SE) accelerometer

Table 8.1.2-1 Unilateral Degrees of equivalence to NMIJ for the SE at 40 Hz

40 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.9	6.4	-4.8	9.4	-3.7	7.8

Table 8.1.2-2 Degrees of equivalence to NMIJ for the SE at 50 Hz

50 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.6	7.2	-4.0	8.3		

Table 8.1.2-3 Degrees of equivalence to NMIJ for the SE at 63 Hz

63 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.6	6.1	-4.0	7.6		

Table 8.1.2-4 Degrees of equivalence to NMIJ for the SE at 80 Hz

80 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in $pC/(m/s^2)\cdot 10^{-4}$		in $pC/(m/s^2)\cdot 10^{-4}$		in $pC/(m/s^2)\cdot 10^{-4}$	
NMIJ	2.1	5.9	-2.8	7.5	-3.1	8.0

Table 8.1.2-5 Degrees of equivalence to NMIJ for the SE at 100 Hz

100 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in $pC/(m/s^2)\cdot 10^{-4}$		in $pC/(m/s^2)\cdot 10^{-4}$		in $pC/(m/s^2)\cdot 10^{-4}$	
NMIJ	2.0	6.3	-2.5	7.7		

Table 8.1.2-6 Degrees of equivalence to NMIJ for the SE at 125 Hz

125 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in $pC/(m/s^2)\cdot 10^{-4}$		in $pC/(m/s^2)\cdot 10^{-4}$		in $pC/(m/s^2)\cdot 10^{-4}$	
NMIJ	1.2	6.0	-2.0	7.1		

Table 8.1.2-7 Degrees of equivalence to NMIJ for the SE at 160 Hz

160 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in $pC/(m/s^2)\cdot 10^{-4}$		in $pC/(m/s^2)\cdot 10^{-4}$		in $pC/(m/s^2)\cdot 10^{-4}$	
NMIJ	2.2	6.0	-2.0	7.1	-3.5	9.8

Table 8.1.2-8 Degrees of equivalence to NMIJ for the SE at 200 Hz

200 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in $pC/(m/s^2)\cdot 10^{-4}$		in $pC/(m/s^2)\cdot 10^{-4}$		in $pC/(m/s^2)\cdot 10^{-4}$	
NMIJ	1.6	6.2	-1.9	7.1		

Table 8.1.2-9 Degrees of equivalence to NMIJ for the SE at 250 Hz

250 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in $pC/(m/s^2)\cdot 10^{-4}$		in $pC/(m/s^2)\cdot 10^{-4}$		in $pC/(m/s^2)\cdot 10^{-4}$	
NMIJ	1.6	6.2	-2.1	7.1		

Table 8.1.2-10 Degrees of equivalence to NMIJ for the SE at 315 Hz

315 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.3	6.4	-2.5	7.0	-3.8	8.1

Table 8.1.2-11 Degrees of equivalence to NMIJ for the SE at 400 Hz

400 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.9	6.3	-2.1	7.0		

Table 8.1.2-12 Degrees of equivalence to NMIJ for the SE at 500 Hz

500 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.2	6.4	-2.9	7.2		

Table 8.1.2-13 Degrees of equivalence to NMIJ for the SE at 630 Hz

630 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.3	6.4	-2.4	7.2	-2.4	8.4

Table 8.1.2-14 Degrees of equivalence to NMIJ for the SE at 800 Hz

800 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	0.5	6.6	-3.0	7.2		

Table 8.1.2-15 Degrees of equivalence to NMIJ for the SE at 1000 Hz

1000 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	0.3	7.5	-3.5	11.0		

Table 8.1.2-16 Degrees of equivalence to NMIJ for the SE at 1250 Hz

1250 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-0.6	7.2	-4.2	11.0	-4.0	8.1

Table 8.1.2-17 Degrees of equivalence to NMIJ for the SE at 1600 Hz

1600 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-1.6	6.3	-3.1	11.1		

Table 8.1.2-18 Degrees of equivalence to NMIJ for the SE at 2000 Hz

2000 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-4.1	6.7	-3.8	11.2		

Table 8.1.2-19 Degrees of equivalence to NMIJ for the SE at 2500 Hz

2500 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-7.5	6.6	-4.3	11.2	-0.5	8.9

Table 8.1.2-20 Degrees of equivalence to NMIJ for the SE at 3150 Hz

3150 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-5.4	8.0	-6.4	11.3		

Table 8.1.2-21 Degrees of equivalence to NMIJ for the SE at 4000 Hz

4000 Hz	CMS/ITRI		NIMT		A*STAR	
i→	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-2.1	11.8	-7.0	11.3		

Table 8.1.2-22 Degrees of equivalence to NMIJ for the SE at 5000 Hz

5000 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_i	U_i	D_i	U_i	D_i	U_i
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-6.9	13.1	-3.9	11.6	4.4	16.0

8.2 Bilateral degree of equivalence between the participants

In order to bilaterally compare the individual results of the participating laboratories with one another, the bilateral degrees of equivalence (DoE) with respect to a certain frequency were calculated. Again, we signify the measurand in this sequent KC as *Y*. The values $(y_1, u(y_1)), \ldots, (y_M, u(y_M))$ denote the charge sensitivities and associated standard uncertainties of the participants. These DoE are each a pair of values of the difference D_{ij} between the respective participants *i* and *j* and the expanded uncertainty U_{ij} of this difference. These values are calculated for each frequency according to:

$$D_{ij} = y_i - y_j \tag{3}$$

$$U_{ij} = k \cdot \sqrt{u^2(y_i) + u^2(y_j)} \tag{4}$$

with a coverage factor of k = 2.

8.2.1 Bilateral DoE of the back-to-back accelerometer

Table 8.2.1-1 Degrees of equivalence between the participants for the BB at 40 Hz

40 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.4	5.0	-3.8	8.2	-4.0	6.6
CMS/ITRI			-5.2	8.6	-5.4	7.1
NIMT					-0.2	9.6

Table 8.2.1-2 Degrees of equivalence between the participants for the BB at 50 Hz

50 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.3	4.7	-2.6	6.4		
CMS/ITRI			-3.9	6.7		
NIMT						

Table 8.2.1-3 Degrees of equivalence between the participants for the BB at 63 Hz

63 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	0.5	4.4	-3.6	6.3		
CMS/ITRI			-4.1	6.3		
NIMT						

Table 8.2.1-4 Degrees of equivalence between the participants for the BB at 80 Hz

80 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.5	4.3	-0.9	6.3	-1.3	6.8
CMS/ITRI			-3.5	6.3	-3.8	6.8
NIMT					-0.4	8.2

Table 8.2.1-5 Degrees of equivalence between the participants for the BB at 100 Hz

100 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.6	5.8	-0.5	7.2		
CMS/ITRI			-3.1	6.5		
NIMT						

Table 8.2.1-6 Degrees of equivalence between the participants for the BB at 125 Hz

125 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j \downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.4	4.4	-1.1	5.7		
CMS/ITRI			-2.5	5.8		
NIMT						

Table 8.2.1-7 Degrees of equivalence between the participants for the BB at 160 Hz

160 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j \downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.0	4.6	-1.3	5.7	-1.3	6.9
CMS/ITRI			-3.3	6.0	-3.3	7.1
NIMT					0.0	7.9

Table 8.2.1-8 Degrees of equivalence between the participants for the BB at 200 Hz

200 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j \downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.0	4.6	-0.8	5.7		
CMS/ITRI			-2.8	6.0		
NIMT						

Table 8.2.1-9 Degrees of equivalence between the participants for the BB at 250 Hz

250 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j \downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	0.9	4.7	-1.2	5.7		
CMS/ITRI			-2.2	6.0		
NIMT						

Table 8.2.1-10 Degrees of equivalence between the participants for the BB at 315 Hz

315 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.2	5.0	-0.7	5.7	-2.4	6.8
CMS/ITRI			-2.9	6.3	-4.6	7.3
NIMT					-1.6	7.8

Table 8.2.1-11 Degrees of equivalence between the participants for the BB at 400 Hz

400 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	3.9	4.8	1.0	5.7		
CMS/ITRI			-2.9	6.1		
NIMT						

Table 8.2.1-12 Degrees of equivalence between the participants for the BB at 500 Hz

500 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	3.2	5.2	-0.4	5.9		
CMS/ITRI			-3.6	6.6		
NIMT						

Table 8.2.1-13 Degrees of equivalence between the participants for the BB at 630 Hz

630 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.8	4.9	-1.6	5.9	-1.4	6.8
CMS/ITRI			-3.3	6.4	-3.2	7.2
NIMT					0.2	8.0

Table 8.2.1-14 Degrees of equivalence between the participants for the BB at 800 Hz

800 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.2	5.4	-2.2	5.9		
CMS/ITRI			-3.5	6.8		
NIMT						

Table 8.2.1-15 Degrees of equivalence between the participants for the BB at 1000 Hz

1000 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	0.5	5.6	-2.1	10.2		
CMS/ITRI			-2.5	10.8		
NIMT						

Table 8.2.1-16 Degrees of equivalence between the participants for the BB at 1250 Hz

1250 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-0.2	5.8	-2.0	10.2	-3.2	6.8
CMS/ITRI			-1.8	10.9	-3.0	7.9
NIMT					-1.3	11.5

Table 8.2.1-17 Degrees of equivalence between the participants for the BB at 1600 Hz

1600 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-1.4	4.6	-2.6	10.2		
CMS/ITRI			-1.2	10.3		
NIMT						

Table 8.2.1-18 Degrees of equivalence between the participants for the BB at 2000 Hz

2000 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-1.1	5.1	0.3	10.2		
CMS/ITRI			1.4	10.6		
NIMT						

Table 8.2.1-19 Degrees of equivalence between the participants for the BB at 2500 Hz

2500 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-4.6	5.2	-2.2	10.2	-5.1	7.9
CMS/ITRI			2.5	10.6	-0.4	8.4
NIMT					-2.9	12.2

Table 8.2.1-20 Degrees of equivalence between the participants for the BB at 3150 Hz

3150 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-6.4	6.7	-3.2	10.4		
CMS/ITRI			3.2	11.5		
NIMT						

Table 8.2.1-21 Degrees of equivalence between the participants for the BB at 4000 Hz

4000 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	0.4	10.8	-1.4	10.5		
CMS/ITRI			-1.8	14.3		
NIMT						

Table 8.2.1-22 Degrees of equivalence between the participants for the BB at 5000 Hz

5000 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-5.6	11.9	-0.6	10.7	12.4	40.9
CMS/ITRI			5.0	15.1	18.0	42.2
NIMT					13.0	41.9

8.2.2 Bilateral DoE of the single-ended (SE) accelerometer

Table 8.2.2-1 Degrees of equivalence between the participants for the SE at 40 Hz

40 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.9	6.4	-4.8	9.4	-3.7	7.8
CMS/ITRI			-7.7	8.8	-6.6	7.1
NIMT					1.1	9.8

Table 8.2.2-2 Degrees of equivalence between the participants for the SE at 50 Hz

50 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.6	7.2	-4.0	8.3		
CMS/ITRI			-5.6	6.8		
NIMT						

Table 8.2.2-3 Degrees of equivalence between the participants for the SE at 63 Hz

63 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.6	6.1	-4.0	7.6		
CMS/ITRI			-5.6	6.4		
NIMT						

Table 8.2.2-4 Degrees of equivalence between the participants for the SE at 80 Hz

80 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j \downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.1	5.9	-2.8	7.5	-3.1	8.0
CMS/ITRI			-4.8	6.4	-5.2	6.9
NIMT					-0.4	8.3

Table 8.2.2-5 Degrees of equivalence between the participants for the SE at 100 Hz

100 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j \downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.0	6.3	-2.5	7.7		
CMS/ITRI			-4.5	6.4		
NIMT						

Table 8.2.2-6 Degrees of equivalence between the participants for the SE at 125 Hz

125 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j \downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.2	6.0	-2.0	7.1		
CMS/ITRI			-3.2	5.9		
NIMT						

Table 8.2.2-7 Degrees of equivalence between the participants for the SE at 160 Hz

160 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j \downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.2	6.0	-2.0	7.1	-3.5	9.8
CMS/ITRI			-4.2	5.9	-5.8	9.0
NIMT					-1.5	9.7

Table 8.2.2-8 Degrees of equivalence between the participants for the SE at 200 Hz

200 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.6	6.2	-1.9	7.1		
CMS/ITRI			-3.5	5.9		
NIMT						

Table 8.2.2-9 Degrees of equivalence between the participants for the SE at 250 Hz

250 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.6	6.2	-2.1	7.1		
CMS/ITRI			-3.7	6.0		
NIMT						

Table 8.2.2-10 Degrees of equivalence between the participants for the SE at 315 Hz

315 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.3	6.4	-2.5	7.0	-3.8	8.1
CMS/ITRI			-3.8	6.2	-5.1	7.4
NIMT					-1.3	8.0

Table 8.2.2-11 Degrees of equivalence between the participants for the SE at 400 Hz

400 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	1.9	6.3	-2.1	7.0		
CMS/ITRI			-4.0	6.2		
NIMT						

Table 8.2.2-12 Degrees of equivalence between the participants for the SE at 500 Hz

500 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j \downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.2	6.4	-2.9	7.2		
CMS/ITRI			-5.1	6.5		
NIMT						

Table 8.2.2-13 Degrees of equivalence between the participants for the SE at 630 Hz

630 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j \downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	2.3	6.4	-2.4	7.2	-2.4	8.4
CMS/ITRI			-4.7	6.5	-4.8	7.7
NIMT					-0.1	8.5

Table 8.2.2-14 Degrees of equivalence between the participants for the SE at 800 Hz

800 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j \downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	0.5	6.6	-3.0	7.2		
CMS/ITRI			-3.5	6.7		
NIMT						

Table 8.2.2-15 Degrees of equivalence between the participants for the SE at 1000 Hz

1000 Hz	CMS/ITRI		NIMT		A*STAR	
$i \rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j \downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	0.3	7.5	-3.5	11.0		
CMS/ITRI			-3.8	11.3		
NIMT						

Table 8.2.2-16 Degrees of equivalence between the participants for the SE at 1250 Hz

1250 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-0.6	7.2	-4.2	11.0	-4.0	8.1
CMS/ITRI			-3.6	11.0	-3.4	8.1
NIMT					0.3	11.7

Table 8.2.2-17 Degrees of equivalence between the participants for the SE at 1600 Hz

1600 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-1.6	6.3	-3.1	11.1		
CMS/ITRI			-1.5	10.5		
NIMT						

Table 8.2.2-18 Degrees of equivalence between the participants for the SE at 2000 Hz

2000 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-4.1	6.7	-3.8	11.2		
CMS/ITRI			0.3	10.9		
NIMT						

Table 8.2.2-19 Degrees of equivalence between the participants for the SE at 2500 Hz

2500 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-7.5	6.6	-4.3	11.2	-0.5	8.9
CMS/ITRI			3.2	10.8	7.0	8.4
NIMT					3.8	12.4

Table 8.2.2-20 Degrees of equivalence between the participants for the SE at 3150 Hz

3150 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-5.4	8.0	-6.4	11.3		
CMS/ITRI			-1.0	11.7		
NIMT						

Table 8.2.2-21 Degrees of equivalence between the participants for the SE at 4000 Hz

4000 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-2.1	11.8	-7.0	11.3		
CMS/ITRI			-4.9	14.5		
NIMT						

Table 8.2.2-22 Degrees of equivalence between the participants for the SE at 5000 Hz

5000 Hz	CMS/ITRI		NIMT		A*STAR	
$i\rightarrow$	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$j\downarrow$	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
NMIJ	-6.9	13.1	-3.9	11.6	4.4	16.0
CMS/ITRI			3.0	15.7	11.3	19.2
NIMT					8.3	18.2

8.3 Linking procedure and Degree of Equivalence with the KCRV

In this section, the linking procedure to the relevant CC comparison and calculation procedure of the KCRV are described. At the CCAUV-Key Comparison Working Group (KCWG) meeting in 2015, it was recommended to consider the influence of correlation of the results of the linking laboratory(ies) based on the procedure described in the previous publication by: Clemens Elster et al [7]. Here, we apply the methodology in principle.

The linking transforms the results (y_i , $u(y_i)$) of the participants of this comparison to scaled values z_i and their respective uncertainty $u(z_i)$, which are directly comparable to the relevant CC comparison results of CCAUV.V-K2. The scaling is done with the so called linking factor r. The values $(x_1, u(x_1)), \ldots, (x_N, u(x_N))$ denote the charge sensitivities and associated standard uncertainties of the participants in the CIPM comparison. Then, r is defined by two charge sensitivities (x_{NMIJ} and y_{NMIJ}) in the CIPM and RMO comparisons of NMIJ as follows.

$$r = \frac{x_{NMIJ}}{y_{NMIJ}} \tag{5}$$

where the uncertainty associated is described as

$$\begin{aligned} u^2(r) &= \left(\frac{\partial r}{\partial x_{NMIJ}}\right)^2 u^2(x_{NMIJ}) + \left(\frac{\partial r}{\partial y_{NMIJ}}\right)^2 u^2(y_{NMIJ}) \\ &\quad + 2\left(\frac{\partial r}{\partial x_{NMIJ}}\right)\left(\frac{\partial r}{\partial y_{NMIJ}}\right) u(x_{NMIJ}) u(y_{NMIJ}) r(x_{NMIJ}, y_{NMIJ}) \end{aligned} \tag{6}$$

Since CCAUV.V-K2 gives KCRV only in case of SE transducer, only the scaling of SE transducer results of APMP.AUV.V-K2 is linked to CCAUV.V-K2.

Considering the correlation coefficient of uncertainty in two comparisons $r(x_{NMIJ}, y_{NMIJ})$ is 1, equation (6) can be written as equation (7).

$$u^2(r) = \left(\frac{1}{y_{NMIJ}}\right)^2 u^2(x_{NMIJ}) + \left(\frac{x_{NMIJ}}{y_{NMIJ}^2}\right)^2 u^2(y_{NMIJ}) - 2\frac{x_{NMIJ}}{y_{NMIJ}^3} u(x_{NMIJ}) u(y_{NMIJ}) \tag{7}$$

RMO comparison participant result y_I can be transformed to the scaled value z_I of CC comparison employing r as follows

$$z_I = r y_I = \frac{x_{NMIJ}}{y_{NMIJ}} y_I \tag{8}$$

Thus, the degrees of equivalence are given as the differences between the scaled charge sensitivities in the RMO comparison and the KCRV of the CIPM comparison.

$$d_i = z_i - x_{KCRV} = \frac{x_{NMIJ}}{y_{NMIJ}} y_i - x_{KCRV}, \quad i = CMS/ITRI, NIMT,\ A*STAR \tag{9}$$

and the squared standard uncertainties associated with these differences are described as follows

$$\begin{aligned} u^2(d_i) &= \left(\frac{y_i}{y_{NMIJ}}\right)^2 u^2(x_{NMIJ}) + \left(-\frac{x_{NMIJ} y_i}{y_{NMIJ}^2}\right)^2 u^2(y_{NMIJ}) + \left(\frac{x_{NMIJ}}{y_{NMIJ}}\right)^2 u^2(y_i) \\ &\quad + u^2(x_{KCRV}) + 2\left(\frac{y_i}{y_{NMIJ}}\right)\left(-\frac{x_{NMIJ} y_i}{y_{NMIJ}^2}\right) u(x_{NMIJ}, y_{NMIJ}) \\ &\quad + 2\left(\frac{y_i}{y_{NMIJ}}\right)(-1) u(x_{NMIJ}, x_{KCRV}) + 2\left(-\frac{x_{NMIJ} y_i}{y_{NMIJ}^2}\right)(-1) u(y_{NMIJ}, x_{KCRV}) \end{aligned} \tag{10}$$

Here $u(x_{NMIJ}, y_{NMIJ})$ is transformed as $u(x_{NMIJ}) u(y_{NMIJ})$ as $r(x_{NMIJ}, y_{NMIJ}) = 1$. Next, the transformation of $u(x_{NMIJ}, x_{KCRV}) = u(x_{NMIJ}) u(x_{KCRV}) r(x_{NMIJ}, x_{KCRV})$ is carried out as follows.

$$r\left(x_{NMIJ},x_{KCRV}\right)=\frac{\frac{\partial x_{NMIJ}}{\partial x_{NMIJ}}\frac{\partial x_{KCRV}}{\partial x_{NMIJ}}u^2\left(x_{NMIJ}\right)}{u\left(x_{NMIJ}\right)u\left(x_{KCRV}\right)}=\frac{1\cdot\frac{1/u^2\left(x_{NMIJ}\right)}{1/u^2\left(x_{KCRV}\right)}u^2\left(x_{NMIJ}\right)}{u\left(x_{NMIJ}\right)u\left(x_{KCRV}\right)}=\frac{u\left(x_{KCRV}\right)}{u\left(x_{NMIJ}\right)} \qquad (11)$$

The value of eqation (11) at each frequency is shown in table 8.3.1 and lies from 0.15 to 0.47.

Table 8.3.1 Correlation coefficients of combined standard uncertainty between CCAUV.V-K2 and APMP.AUV.V-K2 international comparisons.

Frequency	$u(x_{KCRV})$	$u(x_{NMIJ})$	$r(x_{NMIJ}, x_{KCRV})$
Hz	pC/(m/s^2)	pC/(m/s^2)	
40	0.00004	0.00025	0.16
50		0.00031	
63	0.00004	0.00026	0.16
80	0.00004	0.00025	0.16
100	0.00004	0.00027	0.15
125	0.00004	0.00025	0.16
160	0.00004	0.00025	0.16
200	0.00004	0.00026	0.16
250	0.00004	0.00025	0.16
315	0.00004	0.00025	0.17
400	0.00004	0.00025	0.17
500	0.00004	0.00025	0.17
630	0.00004	0.00025	0.17
800	0.00004	0.00025	0.17
1000	0.00004	0.00025	0.17
1250	0.00005	0.00025	0.18
1600	0.00005	0.00025	0.18
2000	0.00005	0.00025	0.19
2500	0.00005	0.00026	0.21
3150	0.00007	0.00026	0.26
4000	0.00009	0.00026	0.33
5000	0.00013	0.00027	0.47

Also, the transformation of $u\left(y_{NMIJ},x_{KCRV}\right)=u\left(y_{NMIJ}\right)u\left(x_{KCRV}\right)r\left(y_{NMIJ},x_{KCRV}\right)$ can be given as equation (12) same as equation (11) because of $r\left(x_{NMIJ},y_{NMIJ}\right)=1$.

$$\begin{aligned} r\left(y_{NMIJ},x_{KCRV}\right)&=\frac{\frac{1/u^2\left(x_{NMIJ}\right)}{1/u^2\left(x_{KCRV}\right)}u\left(x_{NMIJ},y_{NMIJ}\right)}{u\left(y_{NMIJ}\right)u\left(x_{KCRV}\right)}=\frac{u\left(x_{KCRV}\right)}{u\left(y_{NMIJ}\right)u^2\left(x_{NMIJ}\right)}u\left(x_{NMIJ},y_{NMIJ}\right)\\ &=r\left(x_{NMIJ},y_{NMIJ}\right)\frac{u\left(x_{KCRV}\right)}{u\left(x_{NMIJ}\right)}=r\left(x_{NMIJ},x_{KCRV}\right)r\left(x_{NMIJ},y_{NMIJ}\right) \qquad (12)\\ &=r\left(x_{NMIJ},x_{KCRV}\right)\end{aligned}$$

This also lies from 0.15 to 0.47 as shown in table 8.3.1. These DoE of the SE transducer are each a pair of values of the difference d_i between the respective corresponding participants i and KCRV with the expanded uncertainty U_i of this difference. (See table 8.3.2.) These values are calculated for each frequency according to:

$$d_i = z_i - x_{KCRV} \tag{13}$$

$$U(d_i) = k \cdot \sqrt{u^2(d_i)} \tag{14}$$

with a coverage factor of $k = 2$. Figures 8.3.1-4 show each DoE at 40 Hz, 160 Hz, 1250 Hz and 5000 Hz. Since there is no KCRV regarding the BB transducer in CCAUV.V-K2, we provide the DoE of the BB transducer as reference information in Annex 3.

Table 8.3.2 DoE to the KCRV of CCAUV.V-K2 for the SE transducer

Frequency in Hz	CMS/ITRI		NIMT		A*STAR	
	d_i	$U(d_i)$	d_i	$U(d_i)$	d_i	$U(d_i)$
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
40	2.9	3.9	-4.7	7.8	-3.7	5.9
50						
63	1.9	3.3	-3.6	5.5		
80	2.0	3.2	-2.8	5.5	-3.2	6.2
100	2.2	3.3	-2.3	5.6		
125	1.1	3.3	-2.1	4.9		
160	1.8	3.3	-2.4	4.9	-3.9	8.3
200	1.4	3.4	-2.1	4.9		
250	0.8	3.6	-2.8	4.9		
315	1.7	3.9	-2.1	4.9	-3.4	6.3
400	0.9	3.8	-3.0	4.9		
500	2.6	3.9	-2.4	5.2		
630	2.5	3.9	-2.2	5.2	-2.2	6.7
800	0.8	4.3	-2.7	5.2		
1000	1.0	5.6	-2.8	9.7		
1250	1.6	5.1	-2.0	9.8	-1.7	6.3
1600	-0.8	3.8	-2.3	9.8		
2000	-0.8	4.5	-0.5	9.9		
2500	-4.8	4.2	-1.7	10.0	2.1	7.3
3150	-1.7	6.2	-2.7	10.0		
4000	4.3	10.6	-0.6	10.0		
5000	-2.8	12.1	0.2	10.4	8.4	15.2

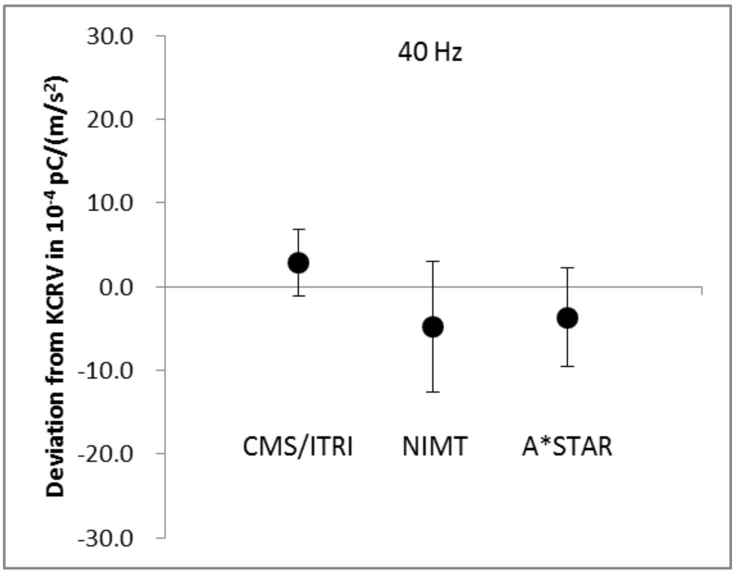

Figure 8.3.1 Deviations and expanded uncertainties of the magnitude from the KCRV at 40 Hz.

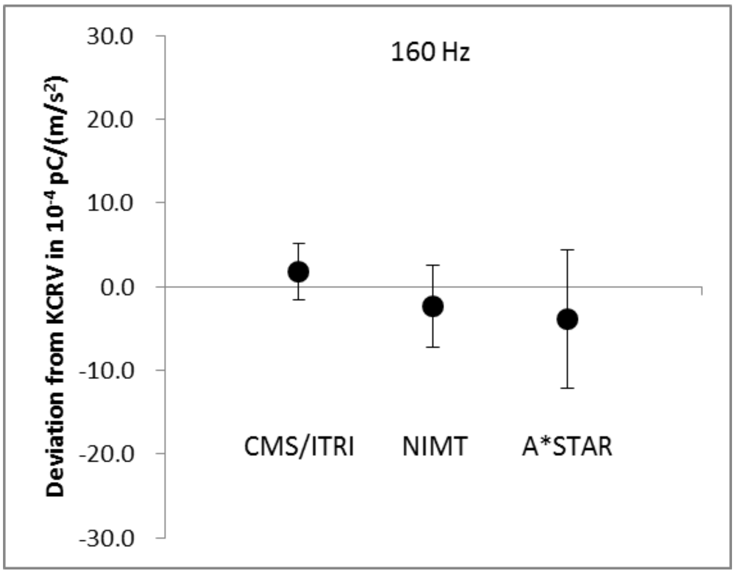

Figure 8.3.2 Deviations and expanded uncertainties of the magnitude from the KCRV at 160 Hz.

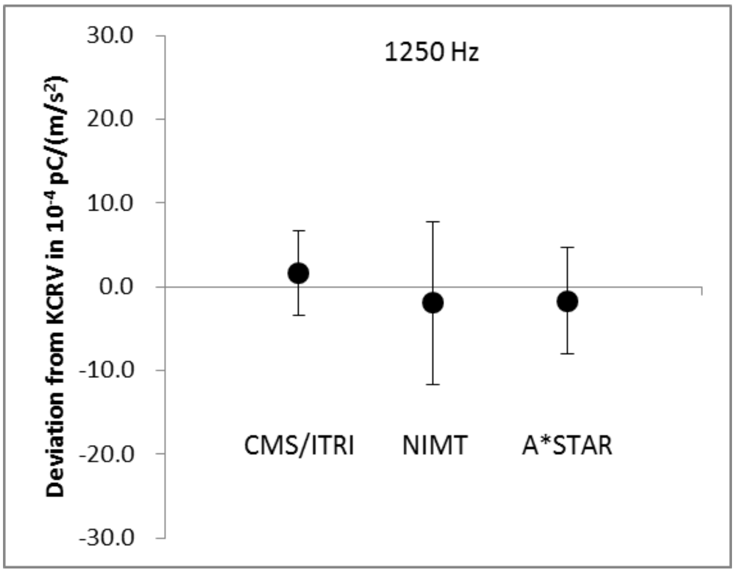

Figure 8.3.3 Deviations and expanded uncertainties of the magnitude from the KCRV at 1250 Hz.

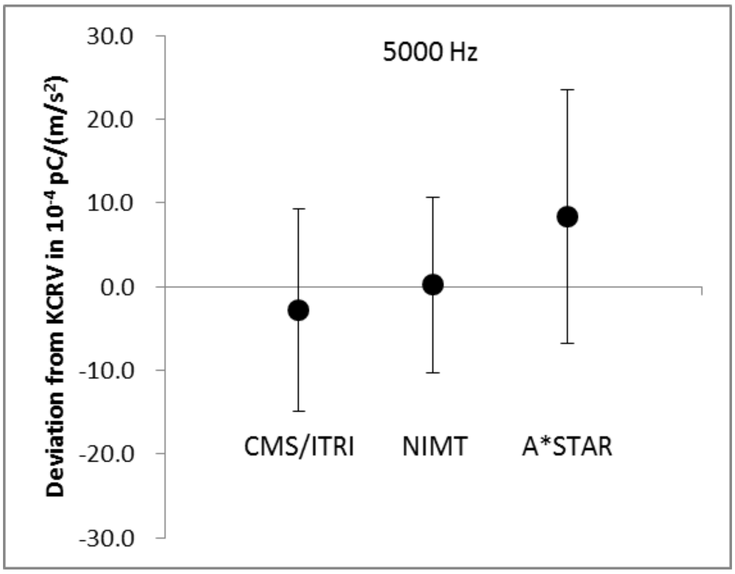

Figure 8.3.4 Deviations and expanded uncertainties of the magnitude from the KCRV at 5000 Hz.

9. Conclusion

The RMO key comparison in vibration and acceleration APMP.AUV.V-K2 has been successfully finished. All participating laboratories had their results linked to the KCRV of the relevant CIPM level key comparison, namely CCAUV.V-K2, for the BB and SE transducers. The degrees of equivalence of the participants to the KCRV can be used to support their calibration and measurement capabilities.

10. References

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Annex 1 Technical Protocol of the APMP Key Comparison

APMP.AUV.V-K2

1. Task and purpose of the comparison

In the field of vibration and shock, this regional comparison is organized in order to compare measurements of sinusoidal linear accelerations in the frequency range from 40 Hz to 5 kHz. Moreover, the magnitude of the complex sensitivity calibration and measurement capabilities (CMCs) of the NMIs for accelerometer calibration are to be examined and compared and linked to the CIPM comparison. It is the task of the comparison to measure the magnitude of the complex sensitivity of two accelerometer standards (two piezoelectric accelerometers of back-to-back type and single ended type) at different frequencies with acceleration amplitudes as specified in section 4. The results of this APMP KC will, after approval for equivalence, be linked to CCAUV.V-K2 (only in case of the SE transducer) as the foundation for the registration of “calibration and measurement capabilities” (CMC) in the framework of the CIPM MRA.

The charge sensitivity is calculated as the ratio of the amplitude of the accelerometer output charge to the amplitude of the acceleration at its reference surface. The magnitude of the complex charge sensitivity shall be given in pico coulomb per metre per second squared ($pC/(m/s^2)$) for the different measurement conditions specified in section 4. A calibrated charge amplifier is to be used to measure the output charge of the accelerometer standards, applying appropriate electrical calibration methods.

For the calibration of the accelerometer standards, laser interferometry in compliance with any method from methods 1, 2, and 3 of the international standard ISO 16063-11:1999 has to be applied, in order to cover the entire frequency range.

The reported sensitivities and associated uncertainties will, after approval for equivalence, be used for the calculation of the “degrees of equivalence” (DoE) between the participating NMI and the key comparison reference value.

2. Pilot laboratory

Pilot laboratory for this Key Comparison, who had also participated in CCAUV.V-K2, is

Vibration and Hardness Section

Acoustics and Vibration Metrology Division

National Metrology Institute of Japan

National Institute of Advanced Industrial Science and Technology

AIST Tsukuba Central 3, 1-1-1 Umezono Tsukuba Ibaraki 305-8563 Japan

Contact Persons are

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3. Participants

Three National Metrology Institutes (NMIs) of APMP will participate in the comparison.

Participant number	Participant (laboratory name)	Acronym	Country	Country Code	
1	National Metrology Institute of Japan	NMIJ	Japan	JP	
2	Center for Measurement Standards/Industrial Technology Research Institute	CMS/ITRI	Chinese Taipei	TW	
	National Metrology Institute of Japan	NMIJ	Japan	JP	
3	National Institute of Metrology Thailand	NIMT	Thailand	TH	
4	National Metrology Centre, Agency for Science, Technology and Research	NMC, A*Star	Singapore	SG	

Circulation and Calibration Schedule

To prevent any drift/fluctuation of transducer characteristics, all transportations among the participants must be done by hand carry.

Date (tentative)	From	To	Carried by	Note
End of August 2011	NMIJ	CMS/ITRI	JP	Dr. Ota carries at the occasion of CMS/ITRI on-site visit
October 2011	CMS/ITRI	NMIJ	TW	
Interim monitoring and calibration at NMIJ				
December 2011	NMIJ	NMC, A*Star	SG	Delegate to APMP TCAUV carries to SG on the way back.
January 2012	NMC, A*Star	NIMT	SG	
March 2012	NIMT	NMIJ	TH	Dr. Hirunyapruk carries to JP.

Contact Person of each laboratory

CMS/ITRI, Mr. Yu-Chung Huang

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Vibration & Acoustics Measurement

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NIMT; Mr. Virat Plangsangmas

Head of Acoustics and Vibration Metrology Department

Tel; +66 2354 3700 ext.400

Fax; +66 2354 3692

E-mail; virat@nimt.or.th

NMC, A*Star; Ms Cui Shan

Mechanical Metrology Department

Tel; +65 6279 1963

Fax; +65 6279 1995

E-mail; cui_shan@nmc.a-star.edu.sg

4. Devices under Test and Measurement conditions

For the calibration task of this KC, a set of two piezoelectric accelerometers with connecting cable will be circulated among the participating laboratories. The individual transducers being a “single ended” (SE) type, namely a Brϋel & Kjær 8305-001 and a “back to back” (BB) type, namely a Brϋel & Kjær 8305. . No additional mass shall be attached to the top surface of BB type accelerometer

The accelerometers are to be calibrated for their complex charge sensitivity according to those procedures and conditions implemented by the NMI in conformance with ISO 16063-11 which provide magnitude information of the artefact. The sensitivities reported shall be for the accelerometers alone, excluding any effects from the charge amplifier.

The frequency range of the measurements was agreed to be from 40 Hz to 5 kHz. Specifically the laboratories are supposed to measure at the following frequencies (all values in Hz):

40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, 5000 (160 Hz is reference frequency).

The charge amplifier (CA) used for the calibration is not provided within the set of the artefacts, it must therefore be provided by the individual participant.

The measurement condition should be kept according to the laboratory's standard conditions for calibration of customer accelerometers for claiming their CMCs. This presumes that these conditions comply with those defined by the applicable ISO standards [references 1, 2 and 3], simultaneously.

Specific conditions for the measurements of this KC are:

- acceleration amplitudes: A range of 10 m/s^2 to 200 m/s^2 is admissible.
- ambient temperature and accelerometer temperature during the calibration: (23 ± 2) ºC (actual values to be stated within tolerances of ± 0.3 ºC).
- relative humidity: max. 75 %
- mounting torque of the accelerometer: (2.0 ± 0.1) N·m

5. Circulation and Transportation

The transducers will be circulated with a measurement period of four weeks for each participant. At the beginning and the end of the circulation, the transducers will be measured at the pilot laboratory in order to fix reference value and to monitor the stability of the transducers.

The cost of transportation to or from a participating laboratory shall be covered by the participating laboratory. The accelerometers have to be hand carried. 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.

6. Measurement and Analysis Instructions

The participating laboratories have to observe the following instructions:

- The charge amplifier used in the laboratory is to be calibrated using a standard capacitor and standard voltmeter, both traceable to national standards. The calibration of the charge amplifier has to be carried out shortly before the calibration, using values of the electric quantities similar to those expected in the accelerometer calibration.
- In order to suppress the effect of any non-rectilinear motion, the displacement has to be measured at least at four different points. These points should be equally spaced on the top surface of the back-to-back accelerometer or the basis surface of the single-ended accelerometer.
- Primary calibration of BB accelerometer by laser interferometry: The motion is to be sensed at the top surface of the transducer without any additional reflector or dummy mass.
- Primary calibration of SE accelerometer 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 is to be observed.

- The mounting surface of the accelerometer and the moving part of the vibration exciter must be slightly lubricated before mounting.
- It is advised that the measurement results should be compiled from complete measurement series (normally twice) carried out at different days under nominally the same conditions, except that the accelerometer is remounted and the cable reattached. The standard deviation of the subsequent measurements should be included in the report.

7. Communication of the Results to the Pilot laboratory

Each participating laboratory will submit one printed and signed calibration report for each accelerometer to the pilot laboratory including the following:

- a description of the calibration systems used for the comparison and the mounting techniques for the accelerometer
- a description of the calibration methods used
- documented record of the ambient conditions during measurements
- the calibration results, including the **relative expanded** measurement uncertainty, and the applied coverage factor for each value
- a detailed uncertainty budget for the system covering all components of measurement uncertainty (calculated according to GUM (references 4 and 5) and ISO (reference 2)). Including among others information on the type of uncertainty (A or B), assumed distribution function and repeatability component.

In addition each participating laboratory will receive two electronic spreadsheets prepared by the pilot laboratory, where the calibration results have to be filled in following the structure given in the files. The consistency between the results in electronic form and the printed and signed calibration report is the responsibility of the participating laboratory. The data submitted in the electronic spreadsheet shall be deemed to be the official results submitted for the comparison.

The results have to be submitted to the pilot laboratory within six weeks after the measurements.

The pilot laboratory will submit its set of results to the executive secretary of CCAUV prior to the first measurement of a participating laboratory.

8. Remarks on the post processing

- Presuming consistency of the results, the degrees of equivalence will be calculated according to the established methods agreed already for CCAUV.V-K2.

9. References

[1] ISO 16063-1:1998 “Methods for the calibration of vibration and shock transducers -- Part 1: Basic concepts

[2] ISO 16063-11:1999 “Methods for the calibration of vibration and shock transducers -- Part 11: Primary vibration calibration by laser interferometry”

[3] ISO/IEC 17025:2005 “General requirements for the competence of testing and calibration laboratories”

[4] ISO/IEC Guide 98-3:2008 “Uncertainty of measurement -- Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)

[5] ISO/IEC Guide 98-3:2008/Suppl 1:2008 “Propagation of distributions using a Monte Carlo method”

Annex 2 Measurement Uncertainty Budgets reported by the participants

A2-1: NMIJ

Table A2-1-1 Uncertainty budget for the BB transducer at 40 Hz to 80 Hz

Name of participant	NMIJ						
DUT	8305 sn2691032						
Acceleration amplitude	[m/s^2]			10	10	10	10
Vibration Frequency	[Hz]			40	50	63	80
Applied Calibration Method				sine-approximation	sine-approximation	sine-approximation	sine-approximation
Number of measurements				240	240	240	240
Charge Sensitivity	[pC/(m/s^2)]			0.12780	0.12775	0.12788	0.12766
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Capacitance standard uncertainty	B	1	∞	3.50E-03	3.50E-03	3.50E-03	3.50E-03
Voltage standard uncertainty	B	1	∞	5.00E-02	5.00E-02	5.00E-02	5.00E-02
Calibration uncertainty of charge amplifier	A	1	76	3.58E-03	2.19E-02	4.37E-03	4.43E-03
Accuracy of voltmeter resolution	B	√3	∞	2.89E-06	2.89E-06	2.89E-06	2.89E-06
Repeatability of sensitivity	A	1	237	3.50E-03	5.06E-03	5.65E-03	2.74E-03
Laser wavelength instability	B	1	∞	1.60E-03	1.60E-03	1.60E-03	1.60E-03
Vibration frequency instability	B	1	∞	6.00E-03	6.00E-03	6.00E-03	6.00E-03
Effect of phase disturbance on phase amplitude measurement	A	1	237	2.29E-04	1.73E-04	1.68E-04	2.12E-04
Attachment uncertainty of accelerometer	B	1	∞	7.19E-02	7.19E-02	7.19E-02	7.19E-02
Transverse sensitivity	B	1	∞	7.80E-02	7.80E-02	7.80E-02	7.80E-02
Effect of vibration distortion	B	1	∞	6.72E-04	6.72E-04	3.23E-04	2.84E-04
Relative combined uncertainty [%]				0.12	0.12	0.12	0.12
Relative expanded uncertainty (*k* =2) [%]				0.24	0.24	0.24	0.24

Table A2-1-2 Uncertainty budget for the BB transducer at 100 Hz to 200 Hz

Name of participant	NMIJ						
DUT	8305 sn2691032						
Acceleration amplitude	[m/s^2]			10	10	10	10
Vibration Frequency	[Hz]			100	125	160	200
Applied Calibration Method				sine-approximation	sine-approximation	sine-approximation	sine-approximation
Number of measurements				240	240	240	240
Charge Sensitivity	[pC/(m/s^2)]			0.12766	0.12773	0.12773	0.12771
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Capacitance standard uncertainty	B	1	∞	3.50E-03	3.50E-03	3.50E-03	3.50E-03
Voltage standard uncertainty	B	1	∞	5.00E-02	5.00E-02	5.00E-02	5.00E-02
Calibration uncertainty of charge amplifier	A	1	76	1.41E-01	1.34E-02	1.59E-02	3.58E-03
Accuracy of voltmeter resolution	B	√3	∞	2.89E-06	2.89E-06	2.89E-06	2.89E-06
Repeatability of sensitivity	A	1	237	2.15E-02	2.02E-03	2.81E-03	6.49E-03
Laser wavelength instability	B	1	∞	1.60E-03	1.60E-03	1.60E-03	1.60E-03
Vibration frequency instability	B	1	∞	6.00E-03	6.00E-03	6.00E-03	6.00E-03
Effect of phase disturbance on phase amplitude measurement	A	1	237	2.49E-04	3.78E-04	6.55E-04	1.33E-03
Attachment uncertainty of accelerometer	B	1	∞	7.19E-02	7.19E-02	7.19E-02	7.19E-02
Transverse sensitivity	B	1	∞	7.80E-02	7.80E-02	7.80E-02	7.80E-02
Effect of vibration distortion	B	1	∞				
Relative combined uncertainty [%]				0.18	0.12	0.12	0.12
Relative expanded uncertainty (*k* =2) [%]				0.37	0.24	0.24	0.24

Table A2-1-3 Uncertainty budget for the BB transducer at 250 Hz to 500 Hz

Name of participant	NMIJ						
DUT	8305 sn2691032						
Acceleration amplitude	[m/s^2]			10	50	50	50
Vibration Frequency	[Hz]			250	315	400	500
Applied Calibration Method				sine-approximation	sine-approximation	sine-approximation	sine-approximation
Number of measurements				240	240	240	240
Charge Sensitivity	[pC/(m/s^2)]			0.12776	0.12772	0.12752	0.12763
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Capacitance standard uncertainty	B	1	∞	3.50E-03	3.50E-03	3.50E-03	3.50E-03
Voltage standard uncertainty	B	1	∞	5.00E-02	5.00E-02	5.00E-02	5.00E-02
Calibration uncertainty of charge amplifier	A	1	76	2.19E-02	4.37E-03	4.43E-03	1.20E-02
Accuracy of voltmeter resolution	B	√3	∞	2.89E-06	5.77E-07	5.77E-07	5.77E-07
Repeatability of sensitivity	A	1	237	2.98E-03	1.46E-03	1.46E-03	1.77E-03
Laser wavelength instability	B	1	∞	1.60E-03	1.60E-03	1.60E-03	1.60E-03
Vibration frequency instability	B	1	∞	6.00E-03	6.00E-03	6.00E-03	6.00E-03
Effect of phase disturbance on phase amplitude measurement	A	1	237	1.79E-03	1.04E-03	1.19E-03	1.73E-03
Attachment uncertainty of accelerometer	B	1	∞	7.19E-02	7.19E-02	7.19E-02	7.19E-02
Transverse sensitivity	B	1	∞	7.80E-02	7.80E-02	7.80E-02	7.80E-02
Effect of vibration distortion	B	1	∞				
Relative combined uncertainty [%]				0.12	0.12	0.12	0.12
Relative expanded uncertainty (k =2) [%]				0.24	0.24	0.24	0.24

Table A2-1-4　Uncertainty budget for the BB transducer at 630 Hz to 1250 Hz

Name of participant	NMIJ						
DUT	8305 sn2691032						
Acceleration amplitude	[m/s^2]			50	50	100	100
Vibration Frequency	[Hz]			630	800	1000	1250
Applied Calibration Method				sine-approximation	sine-approximation	sine-approximation	sine-approximation
Number of measurements				240	240	240	240
Charge Sensitivity	[pC/(m/s^2)]			0.12777	0.12778	0.12785	0.12787
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Capacitance standard uncertainty	B	1	∞	3.50E-03	3.50E-03	3.50E-03	3.50E-03
Voltage standard uncertainty	B	1	∞	5.00E-02	5.00E-02	5.00E-02	5.00E-02
Calibration uncertainty of charge amplifier	A	1	76	4.99E-03	3.66E-03	4.54E-03	2.07E-03
Accuracy of voltmeter resolution	B	√3	∞	5.77E-07	5.77E-07	2.89E-07	2.89E-07
Repeatability of sensitivity	A	1	237	3.77E-04	5.08E-04	5.45E-03	4.89E-03
Laser wavelength instability	B	1	∞	1.60E-03	1.60E-03	1.60E-03	1.60E-03
Vibration frequency instability	B	1	∞	6.00E-03	6.00E-03	6.00E-03	6.00E-03
Effect of phase disturbance on phase amplitude measurement	A	1	237	2.37E-03	3.98E-03	3.43E-03	5.61E-03
Attachment uncertainty of accelerometer	B	1	∞	7.19E-02	7.19E-02	7.19E-02	7.19E-02
Transverse sensitivity	B	1	∞	7.80E-02	7.80E-02	7.80E-02	7.80E-02
Effect of vibration distortion	B	1	∞				
Relative combined uncertainty [%]				0.12	0.12	0.12	0.12
Relative expanded uncertainty (*k* =2) [%]				0.24	0.24	0.24	0.24

Table A2-1-5 Uncertainty budget for the BB transducer at 1600 Hz to 3150 Hz

Name of participant	NMIJ						
DUT	8305 sn2691032						
Acceleration amplitude	[m/s^2]			100	100	100	100
Vibration Frequency	[Hz]			1600	2000	2500	3150
Applied Calibration Method				sine-approximation	sine-approximation	sine-approximation	sine-approximation
Number of measurements				240	240	240	240
Charge Sensitivity	[pC/(m/s^2)]			0.12803	0.12798	0.12836	0.12883
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Capacitance standard uncertainty	B	1	∞	3.50E-03	3.50E-03	3.50E-03	3.50E-03
Voltage standard uncertainty	B	1	∞	5.00E-02	5.00E-02	5.00E-02	5.00E-02
Calibration uncertainty of charge amplifier	A	1	76	4.37E-04	5.65E-04	3.22E-04	3.65E-04
Accuracy of voltmeter resolution	B	√3	∞	2.89E-07	2.89E-07	2.89E-07	2.89E-07
Repeatability of sensitivity	A	1	237	1.56E-03	2.16E-03	2.16E-03	4.83E-03
Laser wavelength instability	B	1	∞	1.60E-03	1.60E-03	1.60E-03	1.60E-03
Vibration frequency instability	B	1	∞	6.00E-03	6.00E-03	6.00E-03	6.00E-03
Effect of phase disturbance on phase amplitude measurement	A	1	237	7.65E-03	1.24E-02	2.06E-02	3.01E-02
Attachment uncertainty of accelerometer	B	1	∞	7.19E-02	7.19E-02	7.19E-02	7.19E-02
Transverse sensitivity	B	1	∞	7.80E-02	7.80E-02	7.80E-02	7.80E-02
Effect of vibration distortion	B	1	∞				
Relative combined uncertainty [%]				0.12	0.12	0.12	0.12
Relative expanded uncertainty (k =2) [%]				0.24	0.24	0.24	0.24

Table A2-1-6 Uncertainty budget for the BB transducer at 4000 Hz to 5000 Hz

Name of participant	NMIJ						
DUT	8305 sn2691032						
Acceleration amplitude	[m/s^2]			100	100		
Vibration Frequency	[Hz]			4000	5000		
Applied Calibration Method				sine-approximation	sine-approximation		
Number of measurements				240	240		
Charge Sensitivity	[pC/(m/s^2)]			0.12917	0.13004		
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Capacitance standard uncertainty	B	1	∞	3.50E-03	3.50E-03		
Voltage standard uncertainty	B	1	∞	5.00E-02	5.00E-02		
Calibration uncertainty of charge amplifier	A	1	76	7.56E-04	1.34E-04		
Accuracy of voltmeter resolution	B	√3	∞	2.89E-07	2.89E-07		
Repeatability of sensitivity	A	1	237	1.29E-03	6.46E-04		
Laser wavelength instability	B	1	∞	1.60E-03	1.60E-03		
Vibration frequency instability	B	1	∞	6.00E-03	6.00E-03		
Effect of phase disturbance on phase amplitude measurement	A	1	237	4.89E-02	8.12E-02		
Attachment uncertainty of accelerometer	B	1	∞	7.19E-02	7.19E-02		
Transverse sensitivity	B	1	∞	7.80E-02	7.80E-02		
Effect of vibration distortion	B	1	∞				
Relative combined uncertainty [%]				0.13	0.14		
Relative expanded uncertainty (*k* =2) [%]				0.25	0.29		

Table A2-1-7 Uncertainty budget for the SE transducer at 40 Hz to 80 Hz

Name of participant	NMIJ						
DUT	8305-001 sn2644378						
Acceleration amplitude	[m/s^2]			10	10	10	10
Vibration Frequency	[Hz]			40	50	63	80
Applied Calibration Method				sine-approximation	sine-approximation	sine-approximation	sine-approximation
Number of measurements				240	240	240	240
Charge Sensitivity	[pC/(m/s^2)]			0.12914	0.12915	0.12919	0.12911
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Capacitance standard uncertainty	B	1	∞	3.50E-03	3.50E-03	3.50E-03	3.50E-03
Voltage standard uncertainty	B	1	∞	5.00E-02	5.00E-02	5.00E-02	5.00E-02
Calibration uncertainty of charge amplifier	A	1	76	2.60E-02	1.34E-01	4.11E-02	1.90E-02
Accuracy of voltmeter resolution	B	√3	∞	2.89E-06	2.89E-06	2.89E-06	2.89E-06
Repeatability of sensitivity	A	1	237	3.19E-03	5.93E-03	6.14E-03	2.85E-03
Laser wavelength instability	B	1	∞	1.60E-03	1.60E-03	1.60E-03	1.60E-03
Vibration frequency instability	B	1	∞	6.00E-03	6.00E-03	6.00E-03	6.00E-03
Effect of phase disturbance on phase amplitude measurement	A	1	237	1.33E-04	1.36E-04	1.29E-04	1.64E-04
Attachment uncertainty of accelerometer	B	1	∞	1.72E-01	1.72E-01	1.72E-01	1.72E-01
Transverse sensitivity	B	1	∞	7.80E-02	7.80E-02	7.80E-02	7.80E-02
Effect of vibration distortion	B	1	∞	6.72E-04	6.72E-04	3.23E-04	2.84E-04
Relative combined uncertainty [%]				0.20	0.24	0.20	0.20
Relative expanded uncertainty (*k* =2) [%]				0.39	0.47	0.40	0.39

Table A2-1-8　Uncertainty budget for the SE transducer at 100 Hz to 200 Hz

Name of participant	NMIJ						
DUT	8305-001 sn2644378						
Acceleration amplitude	[m/s²]			10	10	10	10
Vibration Frequency	[Hz]			100	125	160	200
Applied Calibration Method				sine-approximation	sine-approximation	sine-approximation	sine-approximation
Number of measurements				240	240	240	240
Charge Sensitivity	[pC/(m/s²)]			0.12913	0.12913	0.12913	0.12911
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Capacitance standard uncertainty	B	1	∞	3.50E-03	3.50E-03	3.50E-03	3.50E-03
Voltage standard uncertainty	B	1	∞	5.00E-02	5.00E-02	5.00E-02	5.00E-02
Calibration uncertainty of charge amplifier	A	1	76	6.82E-02	2.12E-02	1.99E-02	4.12E-02
Accuracy of voltmeter resolution	B	√3	∞	2.89E-06	2.89E-06	2.89E-06	2.89E-06
Repeatability of sensitivity	A	1	237	1.91E-02	2.41E-03	3.55E-03	9.95E-03
Laser wavelength instability	B	1	∞	1.60E-03	1.60E-03	1.60E-03	1.60E-03
Vibration frequency instability	B	1	∞	6.00E-03	6.00E-03	6.00E-03	6.00E-03
Effect of phase disturbance on phase amplitude measurement	A	1	237	2.03E-04	3.08E-04	5.08E-04	8.41E-04
Attachment uncertainty of accelerometer	B	1	∞	1.72E-01	1.72E-01	1.72E-01	1.72E-01
Transverse sensitivity	B	1	∞	7.80E-02	7.80E-02	7.80E-02	7.80E-02
Effect of vibration distortion	B	1	∞				
Relative combined uncertainty [%]				0.21	0.20	0.20	0.20
Relative expanded uncertainty (*k* =2) [%]				0.42	0.39	0.39	0.40

Table A2-1-9 Uncertainty budget for the SE transducer at 250 Hz to 500 Hz

Name of participant	NMIJ						
DUT	8305-001 sn2644378						
Acceleration amplitude	[m/s^2]			10	50	50	50
Vibration Frequency	[Hz]			250	315	400	500
Applied Calibration Method				sine-approximation	sine-approximation	sine-approximation	sine-approximation
Number of measurements				240	240	240	240
Charge Sensitivity	[pC/(m/s^2)]			0.12909	0.12918	0.12916	0.12920
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Capacitance standard uncertainty	B	1	∞	3.50E-03	3.50E-03	3.50E-03	3.50E-03
Voltage standard uncertainty	B	1	∞	5.00E-02	5.00E-02	5.00E-02	5.00E-02
Calibration uncertainty of charge amplifier	A	1	76	2.38E-02	8.86E-03	9.51E-03	9.62E-03
Accuracy of voltmeter resolution	B	√3	∞	2.89E-06	5.77E-07	5.77E-07	5.77E-07
Repeatability of sensitivity	A	1	237	4.73E-03	4.75E-03	3.52E-03	3.63E-03
Laser wavelength instability	B	1	∞	1.60E-03	1.60E-03	1.60E-03	1.60E-03
Vibration frequency instability	B	1	∞	6.00E-03	6.00E-03	6.00E-03	6.00E-03
Effect of phase disturbance on phase amplitude measurement	A	1	237	1.56E-03	6.09E-04	8.41E-04	1.35E-03
Attachment uncertainty of accelerometer	B	1	∞	1.72E-01	1.72E-01	1.72E-01	1.72E-01
Transverse sensitivity	B	1	∞	7.80E-02	7.80E-02	7.80E-02	7.80E-02
Effect of vibration distortion	B	1	∞				
Relative combined uncertainty [%]				0.20	0.20	0.20	0.20
Relative expanded uncertainty (*k* =2) [%]				0.39	0.39	0.39	0.39

Table A2-1-10 Uncertainty budget for the SE transducer at 630 Hz to 1250 Hz

Name of participant	NMIJ						
DUT	8305-001 sn2644378						
Acceleration amplitude	[m/s^2]			50	50	100	100
Vibration Frequency	[Hz]			630	800	1000	1250
Applied Calibration Method				sine-approximation	sine-approximation	sine-approximation	sine-approximation
Number of measurements				240	240	240	240
Charge Sensitivity	[pC/(m/s^2)]			0.12921	0.12923	0.12939	0.12945
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Capacitance standard uncertainty	B	1	∞	3.50E-03	3.50E-03	3.50E-03	3.50E-03
Voltage standard uncertainty	B	1	∞	5.00E-02	5.00E-02	5.00E-02	5.00E-02
Calibration uncertainty of charge amplifier	A	1	76	1.01E-02	1.10E-02	5.66E-03	4.25E-03
Accuracy of voltmeter resolution	B	√3	∞	5.77E-07	5.77E-07	2.89E-07	2.89E-07
Repeatability of sensitivity	A	1	237	1.05E-03	1.37E-03	1.48E-02	1.03E-02
Laser wavelength instability	B	1	∞	1.60E-03	1.60E-03	1.60E-03	1.60E-03
Vibration frequency instability	B	1	∞	6.00E-03	6.00E-03	6.00E-03	6.00E-03
Effect of phase disturbance on phase amplitude measurement	A	1	237	1.83E-03	3.04E-03	2.68E-03	4.37E-03
Attachment uncertainty of accelerometer	B	1	∞	1.72E-01	1.72E-01	1.72E-01	1.72E-01
Transverse sensitivity	B	1	∞	7.80E-02	7.80E-02	7.80E-02	7.80E-02
Effect of vibration distortion	B	1	∞				
Relative combined uncertainty [%]				0.20	0.20	0.20	0.20
Relative expanded uncertainty (*k* =2) [%]				0.39	0.39	0.39	0.39

Table A2-1-11 Uncertainty budget for the SE transducer at 1600 Hz to 3150 Hz

Name of participant	NMIJ						
DUT	8305-001 sn2644378						
Acceleration amplitude	$[m/s^2]$			100	100	100	100
Vibration Frequency	[Hz]			1600	2000	2500	3150
Applied Calibration Method				sine-approximation	sine-approximation	sine-approximation	sine-approximation
Number of measurements				240	240	240	240
Charge Sensitivity	$[pC/(m/s^2)]$			0.12958	0.12976	0.13015	0.13085
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Capacitance standard uncertainty	B	1	∞	3.50E-03	3.50E-03	3.50E-03	3.50E-03
Voltage standard uncertainty	B	1	∞	5.00E-02	5.00E-02	5.00E-02	5.00E-02
Calibration uncertainty of charge amplifier	A	1	76	4.50E-03	4.99E-03	4.98E-03	4.76E-03
Accuracy of voltmeter resolution	B	√3	∞	2.89E-07	2.89E-07	2.89E-07	2.89E-07
Repeatability of sensitivity	A	1	237	6.10E-03	6.84E-03	5.93E-03	1.43E-02
Laser wavelength instability	B	1	∞	1.60E-03	1.60E-03	1.60E-03	1.60E-03
Vibration frequency instability	B	1	∞	6.00E-03	6.00E-03	6.00E-03	6.00E-03
Effect of phase disturbance on phase amplitude measurement	A	1	237	5.93E-03	9.55E-03	1.57E-02	2.35E-02
Attachment uncertainty of accelerometer	B	1	∞	1.72E-01	1.72E-01	1.72E-01	1.72E-01
Transverse sensitivity	B	1	∞	7.80E-02	7.80E-02	7.80E-02	7.80E-02
Effect of vibration distortion	B	1	∞				
Relative combined uncertainty [%]				0.20	0.20	0.20	0.20
Relative expanded uncertainty (*k* =2) [%]				0.39	0.39	0.39	0.39

Table A2-1-12 Uncertainty budget for the SE transducer at 4000 Hz to 5000 Hz

Name of participant	NMIJ						
DUT	8305-001 sn2644378						
Acceleration amplitude	[m/s²]			100	100		
Vibration Frequency	[Hz]			4000	5000		
Applied Calibration Method				sine-approximation	sine-approximation		
Number of measurements				240	240		
Charge Sensitivity	[pC/(m/s²)]			0.13170	0.13274		
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Capacitance standard uncertainty	B	1	∞	3.50E-03	3.50E-03		
Voltage standard uncertainty	B	1	∞	5.00E-02	5.00E-02		
Calibration uncertainty of charge amplifier	A	1	76	3.46E-03	3.87E-03		
Accuracy of voltmeter resolution	B	√3	∞	2.89E-07	2.89E-07		
Repeatability of sensitivity	A	1	237	4.10E-03	2.98E-03		
Laser wavelength instability	B	1	∞	1.60E-03	1.60E-03		
Vibration frequency instability	B	1	∞	6.00E-03	6.00E-03		
Effect of phase disturbance on phase amplitude measurement	A	1	237	3.72E-02	6.06E-02		
Attachment uncertainty of accelerometer	B	1	∞	1.72E-01	1.72E-01		
Transverse sensitivity	B	1	∞	7.80E-02	7.80E-02		
Effect of vibration distortion	B	1	∞				
Relative combined uncertainty [%]				0.20	0.20		
Relative expanded uncertainty (*k* =2) [%]				0.40	0.41		

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Table A2-2-1 Uncertainty budget for the BB transducer at 40 Hz to 100 Hz

Acceleration amplitude	[m/s^2]				10	15	15	15	20
Vibration Frequency	[Hz]				40	50	63	80	100
Applied Calibration Method					Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation
Number of measurements					90	90	90	90	90
Charge Sensitivity	[pC/(m/s^2)]				0.127941	0.127880	0.127929	0.127912	0.127920
Parameter of Measurement Function	Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
V (Acceleromter Output Voltage Measurement)	Voltage Measurement Repeatability	A	1	87	0.0366%	0.0189%	0.0098%	0.0055%	0.0347%
	Voltage Traceabilty	B	2	∞	0.08000%	0.03500%	0.03500%	0.03500%	0.03500%
	Voltage Measurement Resolution	B	$\sqrt{3}$	∞	0.0003%	0.0003%	0.0003%	0.0003%	0.0003%
	Effect of transervese, rocking and bending acceleration on acceleromter output voltage measurement	B	$\sqrt{3}$	200	0.0020%	0.0023%	0.0027%	0.0029%	0.0043%
	Distortion on Voltage Measurement	B	$\sqrt{3}$	200	0.0548%	0.0751%	0.0543%	0.0419%	0.0563%
	Effect of long-term data distribution	A	1	24	0.0354%	0.0370%	0.0421%	0.0377%	0.0388%
	Effect of Charge Amplifier (with the fixed [illegible]	B	2.57	∞	0.0973%	0.0973%	0.0973%	0.0973%	0.0973%
f (Vibration Frequency Measurement)	Frequency Measurement	A	1	87	0.0217011%	0.0161377%	0.0093735%	0.0078710%	0.0105945%
	Frequency Traceabilty	B	2	∞	0.000025%	0.000025%	0.000025%	0.000025%	0.000025%
	Frequency Measurement [illegible]	B	$\sqrt{3}$	∞	0.000289%	0.002887%	0.002887%	0.002887%	0.002887%
D (Vibration Displacement Measurement)	Amplitude measurement Errors from Sine Approximation Method, **Evaluated by Least-Square Method**	A	1	59955	0.0040%	0.0045%	0.0040%	0.0004%	0.0005%
	Amplitude Measurement Repeatability	A	1	87	0.0427%	0.0205%	0.0060%	0.0070%	0.0369%
	Amplitude Traceabilty (Laser Tube)	B	1.96	∞	0.00000434%	0.00000434%	0.00000434%	0.00000434%	0.00000434%
	Amplitude Measurement Resolution	B	$\sqrt{3}$	∞	0.0141%	0.0141%	0.0141%	0.0141%	0.0141%
coverage factor, *k* =	(Ref. Calculation for CMS)				1.96	1.96	1.96	1.96	1.96
effective degrees of freedom, ν_{eff}					3419	1530	1453	2043	1852
Relative combined (Standard) uncertainty [%]					0.16%	0.14%	0.13%	0.12%	0.14%
Relative expanded uncertainty (*k* =1.96) [%]					0.31%	0.28%	0.25%	0.24%	0.27%

Table A2-2-2　Uncertainty budget for the BB transducer at 125 Hz to 315 Hz

Acceleration amplitude	[m/s^2]				20	30	50	50	50
Vibration Frequency	[Hz]				125	160	200	250	315
Applied Calibration Method					Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation
Number of measurements					90	90	90	90	90
Charge Sensitivity	[pC/(m/s^2)]				0.127870	0.127928	0.127909	0.127853	0.127937
Parameter of Measurement Function	Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
V (Acceleromter Output Voltage Measurement)	Voltage Measurement Repeatability	A	1	87	0.0159%	0.0242%	0.0176%	0.0096%	0.0246%
	Voltage Traceabilty	B	2	∞	0.03500%	0.03500%	0.03500%	0.03500%	0.03500%
	Voltage Measurement Resolution	B	$\sqrt{3}$	∞	0.0003%	0.0003%	0.0003%	0.0003%	0.0003%
	Effect of transervese, rocking and bending acceleration on accelerometer output voltage measurement (transeverse sensitivity)	B	$\sqrt{3}$	200	0.0068%	0.0136%	0.0214%	0.0229%	0.0190%
	Distortion on Voltage Measurement	B	$\sqrt{3}$	200	0.0502%	0.0566%	0.0629%	0.0635%	0.0924%
	Effect of long-term data distribution	A	1	24	0.0388%	0.0380%	0.0387%	0.0507%	0.0348%
	Effect of Charge Amplifier (with the fixed setting)	B	2.57	∞	0.0973%	0.0973%	0.0973%	0.0973%	0.0973%
f (Vibration Frequency Measurement)	Frequency Measurement Repeatability	A	1	87	0.0077252%	0.0064974%	0.0017178%	0.0025829%	0.0029180%
	Frequency Traceabilty	B	2	∞	0.000025%	0.000025%	0.000025%	0.000025%	0.000025%
	Frequency Measurement Resolution	B	$\sqrt{3}$	∞	0.002887%	0.002887%	0.002887%	0.002887%	0.002887%
D (Vibration Displacement Measurement)	Amplitude measurement Errors from Sine Approximation Method, **Evaluated by Least-Square Method**	A	1	59955	0.0010%	0.0007%	0.0233%	0.0240%	0.0238%
	Amplitude Measurement Repeatability	A	1	87	0.0167%	0.0415%	0.0200%	0.0316%	0.0437%
	Amplitude Traceabilty (Laser Tube)	B	1.96	∞	0.00000434%	0.00000434%	0.00000434%	0.00000434%	0.00000434%
	Amplitude Measurement Resolution	B	$\sqrt{3}$	∞	0.0141%	0.0141%	0.0141%	0.0141%	0.0141%
coverage factor, *k* =	(Ref. Calculation for CMS)				1.96	1.96	1.96	1.96	1.96
effective degrees of freedom, ν_{eff}					1905	1863	1866	1056	1234
Relative combined (Standard) uncertainty [%]					0.13%	0.13%	0.13%	0.14%	0.16%
Relative expanded uncertainty (*k* =1.96) [%]					0.25%	0.27%	0.27%	0.28%	0.31%

Table A2-2-3　Uncertainty budget for the BB transducer at 400 Hz to 1000 Hz

Acceleration amplitude	[m/s^2]				50	50	50	50	50
Vibration Frequency	[Hz]				400	500	630	800	1000
Applied Calibration Method					Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation
Number of measurements					90	90	90	90	90
Charge Sensitivity	[pC/(m/s^2)]				0.127911	0.127946	0.127946	0.127899	0.127898
Parameter of Measurement Function	Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
V (Acceleromter Output Voltage Measurement)	Voltage Measurement Repeatability	A	1	87	0.0034%	0.0099%	0.0127%	0.0465%	0.0221%
	Voltage Traceabilty	B	2	∞	0.03500%	0.03500%	0.03500%	0.03500%	0.03500%
	Voltage Measurement Resolution	B	$\sqrt{3}$	∞	0.0003%	0.0003%	0.0003%	0.0003%	0.0003%
	Effect of transervese, rocking and bending acceleration on acceleromter output voltage measurement (transeverse sensitivity)	B	$\sqrt{3}$	200	0.0194%	0.0128%	0.0237%	0.0637%	0.0493%
	Distortion on Voltage Measurement	B	$\sqrt{3}$	200	0.0924%	0.0837%	0.0722%	0.0606%	0.0456%
	Effect of long-term data distribution	A	1	24	0.0401%	0.0635%	0.0719%	0.0932%	0.1306%
	Effect of Charge Amplifier (with the fixed setting)	B	2.57	∞	0.0973%	0.0973%	0.0973%	0.0973%	0.0973%
f (Vibration Frequency Measurement)	Frequency Measurement Repeatability	A	1	87	0.0024302%	0.0041280%	0.0029188%	0.0025093%	0.0244664%
	Frequency Traceabilty	B	2	∞	0.000025%	0.000025%	0.000025%	0.000025%	0.000025%
	Frequency Measurement Resolution	B	$\sqrt{3}$	∞	0.002887%	0.002887%	0.002887%	0.002887%	0.002887%
D (Vibration Displacement Measurement)	Amplitude measurement Errors from Sine Approximation Method, **Evaluated by Least-Square Method**	A	1	59955	0.0067%	0.0042%	0.0069%	0.0109%	0.0196%
	Amplitude Measurement Repeatability	A	1	87	0.0158%	0.0717%	0.0117%	0.0421%	0.0200%
	Amplitude Traceabilty (Laser Tube)	B	1.96	∞	0.00000434%	0.00000434%	0.00000434%	0.00000434%	0.00000434%
	Amplitude Measurement Resolution	B	$\sqrt{3}$	∞	0.0141%	0.0141%	0.0141%	0.0141%	0.0141%
coverage factor, k =	(Ref. Calculation for CMS)				1.96	1.96	1.96	1.96	1.96
effective degrees of freedom, ν_{eff}					1000	612	394	298	100
Relative combined (Standard) uncertainty [%]					0.15%	0.17%	0.15%	0.18%	0.19%
Relative expanded uncertainty (k =1.96) [%]					0.29%	0.33%	0.30%	0.35%	0.37%

Table A2-2-4 Uncertainty budget for the BB transducer at 1.25 kHz to 5 kHz

Acceleration amplitude	[m/s^2]				50	50	50	50	70	70	70
Vibration Frequency	[Hz]				1250	1600	2000	2500	3150	4000	5000
Applied Calibration Method					Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation
Number of measurements					90	90	90	90	90	90	90
Charge Sensitivity	[pC/(m/s^2)]				0.127852	0.127888	0.127870	0.127893	0.128189	0.129207	0.129481
Parameter of Measurement Function	Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
V (Accelerometer Output Voltage Measurement)	Voltage Measurement Repeatability	A	1	87	0.0192%	0.0049%	0.0032%	0.0036%	0.0038%	0.0067%	0.0044%
	Voltage Traceabilty	B	2	∞	0.03500%	0.03500%	0.03500%	0.03500%	0.03500%	0.03500%	0.03500%
	Voltage Measurement Resolution	B	$\sqrt{3}$	∞	0.0003%	0.0003%	0.0003%	0.0003%	0.0003%	0.0003%	0.0003%
	Effect of transervese, rocking and bending acceleration on accelerometer output voltage measurement (transeverse sensitivity)	B	$\sqrt{3}$	200	0.0609%	0.0389%	0.0223%	0.0308%	0.0899%	0.2920%	0.2346%
	Distortion on Voltage Measurement	B	$\sqrt{3}$	200	0.0404%	0.0260%	0.0289%	0.0289%	0.0346%	0.0387%	0.0346%
	Effect of long-term data distribution	A	1	24	0.1389%	0.0567%	0.0766%	0.0523%	0.0880%	0.0918%	0.1430%
	Effect of Charge Amplifier (with the fixed setting)	B	2.57	∞	0.0973%	0.0973%	0.0973%	0.0973%	0.0973%	0.0973%	0.0973%
f (Vibration Frequency Measurement)	Frequency Measurement Repeatability	A	1	87	0.0105345%	0.0060821%	0.0060821%	0.0060821%	0.0060821%	0.0105345%	0.0060821%
	Frequency Traceabilty	B	2	∞	0.000025%	0.000025%	0.000025%	0.000025%	0.000025%	0.000025%	0.000025%
	Frequency Measurement Resolution	B	$\sqrt{3}$	∞	0.002887%	0.002887%	0.002887%	0.002887%	0.002887%	0.002887%	0.002887%
D (Vibration Displacement Measurement)	Amplitude measurement Errors from Sine Approximation Method, **Evaluated by Least-Square Method**	A	1	59955	0.03050%	0.0452%	0.0617%	0.1015%	0.1553%	0.2356%	0.3201%
	Amplitude Measurement Repeatability	A	1	87	0.0333%	0.0222%	0.0550%	0.0470%	0.0320%	0.0604%	0.0702%
	Amplitude Traceabilty (Laser Tube)	B	1.96	∞	0.00000434%	0.00000434%	0.00000434%	0.00000434%	0.00000434%	0.00000434%	0.00000434%
	Amplitude Measurement Resolution	B	$\sqrt{3}$	∞	0.0141%	0.0141%	0.0141%	0.0141%	0.0141%	0.0141%	0.0141%
coverage factor, k =	(Ref. Calculation for CMS)				1.96	1.96	1.96	1.96	1.96	1.96	1.96
effective degrees of freedom, ν_{eff}					94	825	405	2102	1116	8619	2126
Relative combined (Standard) uncertainty [%]					0.20%	0.14%	0.16%	0.17%	0.23%	0.41%	0.44%
Relative expanded uncertainty (k =1.96) [%]					0.39%	0.27%	0.32%	0.33%	0.46%	0.80%	0.87%

Table A2-2-5 Uncertainty budget for the SE transducer at 40 Hz to 100 Hz

Acceleration amplitude	[m/s^2]				10	15	15	15	20
Vibration Frequency	[Hz]				40	50	63	80	100
Applied Calibration Method					Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation
Number of measurements					90	90	90	90	90
Charge Sensitivity	[pC/(m/s^2)]				0.129433647	0.129311	0.129349	0.129320	0.129335
Parameter of Measurement Function	Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
V (Accelerometer Output Voltage Measurement)	Voltage Measurement Repeatability	A	1	87	0.0202%	0.0382%	0.0126%	0.0060%	0.0070%
	Voltage Traceabilty	B	2	∞	0.08000%	0.03500%	0.03500%	0.03500%	0.03500%
	Voltage Measurement Resolution	B	$\sqrt{3}$	∞	0.0003%	0.0003%	0.0003%	0.0003%	0.0003%
	Effect of transervese, rocking and bending acceleration on acceleromter output voltage measurement (transeverse sensitivity)	B	$\sqrt{3}$	200	0.0020%	0.0023%	0.0027%	0.0029%	0.0043%
	Distortion on Voltage Measurement	B	$\sqrt{3}$	200	0.0548%	0.0751%	0.0543%	0.0419%	0.0563%
	Effect of long-term data distribution	A	1	24	0.0354%	0.0370%	0.0421%	0.0377%	0.0388%
	Effect of Charge Amplifier (with the fixed setting)	B	2.57	∞	0.0973%	0.0973%	0.0973%	0.0973%	0.0973%
f (Vibration Frequency Measurement)	Frequency Measurement Repeatability	A	1	87	0.0217011%	0.0161377%	0.0093735%	0.0078710%	0.0105945%
	Frequency Traceabilty	B	2	∞	0.000025%	0.000025%	0.000025%	0.000025%	0.000025%
	Frequency Measurement Resolution	B	$\sqrt{3}$	∞	0.000289%	0.002887%	0.002887%	0.002887%	0.002887%
D (Vibration Displacement Measurement)	Amplitude measurement Errors from Sine Approximation Method, Evaluated by Least-Square Method	A	1	59955	0.0040%	0.0045%	0.0040%	0.0004%	0.0005%
	Amplitude Measurement Repeatability	A	1	87	0.0242%	0.0391%	0.0099%	0.0059%	0.0074%
	Amplitude Traceabilty (Laser Tube)	B	1.96	∞	0.00000434%	0.00000434%	0.00000434%	0.00000434%	0.00000434%
	Amplitude Measurement Resolution	B	$\sqrt{3}$	∞	0.0141%	0.0141%	0.0141%	0.0141%	0.0141%
coverage factor, k =	(Ref. Calculation for CMS)				1.96	1.96	1.96	1.96	1.96
effective degrees of freedom, ν_{eff}					4072	1588	1474	2041	1753
Relative combined (Standard) uncertainty [%]					0.15%	0.15%	0.13%	0.12%	0.13%
Relative expanded uncertainty (k =1.96) [%]					0.30%	0.29%	0.25%	0.24%	0.25%

Table A2-2-6 Uncertainty budget for the SE transducer at 125 Hz to 315 Hz

Acceleration amplitude	[m/s²]				20	30	50	50	50
Vibration Frequency	[Hz]				125	160	200	250	315
Applied Calibration Method					Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation
Number of measurements					90	90	90	90	90
Charge Sensitivity	[pC/(m/s²)]				0.129253	0.129355	0.129274	0.129251	0.129310
Parameter of Measurement Function	Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
V (Accelerometer Output Voltage Measurement)	Voltage Measurement Repeatability	A	1	87	0.0073%	0.0098%	0.0115%	0.0132%	0.0178%
	Voltage Traceabilty	B	2	∞	0.03500%	0.03500%	0.03500%	0.03500%	0.03500%
	Voltage Measurement Resolution	B	$\sqrt{3}$	∞	0.0003%	0.0003%	0.0003%	0.0003%	0.0003%
	Effect of transervese, rocking and bending acceleration on acceleromter output voltage measurement (transeverse sensitivity)	B	$\sqrt{3}$	200	0.0068%	0.0136%	0.0214%	0.0229%	0.0190%
	Distortion on Voltage Measurement	B	$\sqrt{3}$	200	0.0502%	0.0566%	0.0629%	0.0635%	0.0924%
	Effect of long-term data distribution	A	1	24	0.0388%	0.0380%	0.0387%	0.0507%	0.0348%
	Effect of Charge Amplifier (with the fixed setting)	B	2.57	∞	0.0973%	0.0973%	0.0973%	0.0973%	0.0973%
f (Vibration Frequency Measurement)	Frequency Measurement Repeatability	A	1	87	0.0077252%	0.0064974%	0.0017178%	0.0025829%	0.0029180%
	Frequency Traceabilty	B	2	∞	0.000025%	0.000025%	0.000025%	0.000025%	0.000025%
	Frequency Measurement Resolution	B	$\sqrt{3}$	∞	0.002887%	0.002887%	0.002887%	0.002887%	0.002887%
D (Vibration Displacement Measurement)	Amplitude measurement Errors from Sine Approximation Method, Evaluated by Least-Square Method	A	1	59955	0.0010%	0.0007%	0.0233%	0.0240%	0.0238%
	Amplitude Measurement Repeatability	A	1	87	0.0085%	0.0119%	0.0077%	0.0092%	0.0249%
	Amplitude Traceabilty (Laser Tube)	B	1.96	∞	0.00000434%	0.00000434%	0.00000434%	0.00000434%	0.00000434%
	Amplitude Measurement Resolution	B	$\sqrt{3}$	∞	0.0141%	0.0141%	0.0141%	0.0141%	0.0141%
coverage factor, *k* =	(Ref. Calculation for CMS)				1.96	1.96	1.96	1.96	1.96
effective degrees of freedom, ν_{eff}					1829	1858	1788	998	1179
Relative combined (Standard) uncertainty [%]					0.13%	0.13%	0.14%	0.14%	0.16%
Relative expanded uncertainty (*k* =1.96) [%]					0.25%	0.25%	0.26%	0.27%	0.30%

Table A2-2-7　Uncertainty budget for the SE transducer at 400 Hz to 1000 Hz

Acceleration amplitude	[m/s^2]				50	50	50	50	50
Vibration Frequency	[Hz]				400	500	630	800	1000
Applied Calibration Method					Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation
Number of measurements					90	90	90	90	90
Charge Sensitivity	[pC/(m/s^2)]				0.129347	0.129415	0.129446	0.129282	0.129413
Parameter of Measurement Function	Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
V (Accelerometer Output Voltage Measurement)	Voltage Measurement Repeatability	A	1	87	0.0139%	0.0073%	0.0057%	0.0153%	0.0668%
	Voltage Traceabilty	B	2	∞	0.03500%	0.03500%	0.03500%	0.03500%	0.03500%
	Voltage Measurement Resolution	B	$\sqrt{3}$	∞	0.0003%	0.0003%	0.0003%	0.0003%	0.0003%
	Effect of transervese, rocking and bending acceleration on acceleromter output voltage measurement (transeverse sensitivity)	B	$\sqrt{3}$	200	0.0194%	0.0128%	0.0237%	0.0637%	0.0493%
	Distortion on Voltage Measurement	B	$\sqrt{3}$	200	0.0924%	0.0837%	0.0722%	0.0606%	0.0456%
	Effect of long-term data distribution	A	1	24	0.0401%	0.0635%	0.0719%	0.0932%	0.1306%
	Effect of Charge Amplifier (with the fixed setting)	B	2.57	∞	0.0973%	0.0973%	0.0973%	0.0973%	0.0973%
f (Vibration Frequency Measurement)	Frequency Measurement Repeatability	A	1	87	0.0024302%	0.0041280%	0.0029188%	0.0025093%	0.0244664%
	Frequency Traceabilty	B	2	∞	0.000025%	0.000025%	0.000025%	0.000025%	0.000025%
	Frequency Measurement Resolution	B	$\sqrt{3}$	∞	0.002887%	0.002887%	0.002887%	0.002887%	0.002887%
D (Vibration Displacement Measurement)	Amplitude measurement Errors from Sine Approximation Method, Evaluated by Least-Square Method	A	1	59955	0.0067%	0.0042%	0.0069%	0.0109%	0.0196%
	Amplitude Measurement Repeatability	A	1	87	0.0145%	0.0125%	0.0152%	0.0248%	0.0974%
	Amplitude Traceabilty (Laser Tube)	B	1.96	∞	0.00000434%	0.00000434%	0.00000434%	0.00000434%	0.00000434%
	Amplitude Measurement Resolution	B	$\sqrt{3}$	∞	0.0141%	0.0141%	0.0141%	0.0141%	0.0141%
coverage factor, *k* =	(Ref. Calculation for CMS)				1.96	1.96	1.96	1.96	1.96
effective degrees of freedom, ν_{eff}					1013	542	393	249	172
Relative combined (Standard) uncertainty [%]					0.15%	0.15%	0.15%	0.17%	0.22%
Relative expanded uncertainty (*k* =1.96) [%]					0.29%	0.30%	0.30%	0.33%	0.43%

Table A2-2-8 Uncertainty budget for the SE transducer at 1.25 kHz to 5 kHz

Acceleration amplitude	[m/s^2]				50	50	50	50	70	70	70
Vibration Frequency	[Hz]				1250	1600	2000	2500	3150	4000	5000
Applied Calibration Method					Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation	Sine Approximation
Number of measurements					90	90	90	90	90	90	90
Charge Sensitivity	[pC/(m/s^2)]				0.129386	0.129415	0.129349	0.129402	0.130313	0.131491	0.132050
Parameter of Measurement Function	Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
V (Accelerometer Output Voltage Measurement)	Voltage Measurement Repeatability	A	1	87	0.0231%	0.0126%	0.0049%	0.0111%	0.0068%	0.0039%	0.0056%
	Voltage Traceabilty	B	2	∞	0.03500%	0.03500%	0.03500%	0.03500%	0.03500%	0.03500%	0.03500%
	Voltage Measurement Resolution	B	$\sqrt{3}$	∞	0.0003%	0.0003%	0.0003%	0.0003%	0.0003%	0.0003%	0.0003%
	Effect of transervese, rocking and bending acceleration on acceleromter output voltage measurement (transeverse sensitivity)	B	$\sqrt{3}$	200	0.0609%	0.0389%	0.0223%	0.0308%	0.0899%	0.2920%	0.2346%
	Distortion on Voltage Measurement	B	$\sqrt{3}$	200	0.0404%	0.0260%	0.0289%	0.0289%	0.0346%	0.0387%	0.0346%
	Effect of long-term data distribution	A	1	24	0.1389%	0.0567%	0.0766%	0.0523%	0.0880%	0.0918%	0.1430%
	Effect of Charge Amplifier (with the fixed setting)	B	2.57	∞	0.0973%	0.0973%	0.0973%	0.0973%	0.0973%	0.0973%	0.0973%
f (Vibration Frequency Measurement)	Frequency Measurement Repeatability	A	1	87	0.0105345%	0.0060821%	0.0060821%	0.0060821%	0.0060821%	0.0105345%	0.0060821%
	Frequency Traceabilty	B	2	∞	0.000025%	0.000025%	0.000025%	0.000025%	0.000025%	0.000025%	0.000025%
	Frequency Measurement Resolution	B	$\sqrt{3}$	∞	0.002887%	0.002887%	0.002887%	0.002887%	0.002887%	0.002887%	0.002887%
D (Vibration Displacement Measurement)	Amplitude measurement Errors from Sine Approximation Method, Evaluated by Least-Square Method	A	1	59955	0.0305%	0.0452%	0.0617%	0.1015%	0.1553%	0.2356%	0.3201%
	Amplitude Measurement Repeatability	A	1	87	0.0204%	0.0443%	0.0800%	0.0168%	0.0550%	0.0399%	0.1375%
	Amplitude Traceabilty (Laser Tube)	B	1.96	∞	0.00000434%	0.00000434%	0.00000434%	0.00000434%	0.00000434%	0.00000434%	0.00000434%
	Amplitude Measurement Resolution	B	$\sqrt{3}$	∞	0.0141%	0.0141%	0.0141%	0.0141%	0.0141%	0.0141%	0.0141%
coverage factor, k =	(Ref. Calculation for CMS)				1.96	1.96	1.96	1.96	1.96	1.96	1.96
effective degrees of freedom, ν_{eff}					91	885	423	2156	1160	8743	2011
Relative combined (Standard) uncertainty [%]					0.20%	0.15%	0.17%	0.17%	0.24%	0.41%	0.46%
Relative expanded uncertainty (k =1.96) [%]					0.39%	0.29%	0.34%	0.32%	0.47%	0.80%	0.90%

A2-3: NIMT

Table A2-3-1 Uncertainty budget for the BB transducer at 40 Hz to 100 Hz

Acceleration amplitude	[m/s²]			10	25	25	50	50
Vibration Frequency	[Hz]			40	50	63	80	100
Applied Calibration Method				Fringe-counting method	Fringe-counting method	Fringe-counting method	Fringe-counting method	Fringe-counting method
Number of measurements				4	4	4	4	4
Charge Sensitivity	[pC/(m/s²)]			0.12742	0.12749	0.12752	0.12757	0.12761
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Accuracy of ratio counter	B	0.577	∞	0.00020	0.00025	0.00032	0.00020	0.00025
Repeatability of ratio counter	A	1	19	0.019	0.004	0.002	0.002	0.004
Specification of Wavelength	B	0.577	∞	0.000046	0.000046	0.000046	0.000046	0.000046
Accuracy of Sine Generator	B	0.577	∞	0.0023	0.0023	0.0023	0.0023	0.0023
Repeatability of voltage output	A	1	19	0.019	0.020	0.003	0.002	0.004
Accuracy of voltmeter	B	0.577	∞	0.1228	0.053	0.053	0.044	0.044
Uncertainty of Charge Amplifier	A	2	∞	0.255	0.185	0.185	0.185	0.185
Drift of Charge Amplifier	B	0.577	∞	0.058	0.058	0.058	0.058	0.058
Effect of Geometric Location	B	0.577	∞	0.058	0.058	0.058	0.058	0.058
Effect of distortion	B	0.577	∞	0.0018	0.0018	0.0018	0.0018	0.0018
Effect of transverse	B	0.236	∞	0.047	0.047	0.047	0.047	0.047
Repeatability of Sensitivity	A	1	3	0.015	0.020	0.013	0.019	0.016
Resolution of Sensitivity	B	0.577	∞	0.0023	0.0023	0.0023	0.0023	0.0023
Effect of quantiztion error	B	0.577	∞	0.00010	0.00013	0.00016	0.00010	0.00013
Relative combined uncertainty [%]				0.300	0.216	0.215	0.213	0.213
Relative expanded uncertainty (*k* =2) [%]				0.60	0.44	0.43	0.43	0.43

Table A2-3-2 Uncertainty budget for the BB transducer at 125 Hz to 315 Hz

Acceleration amplitude	[m/s²]			50	50	50	50	50
Vibration Frequency	[Hz]			125	160	200	250	315
Applied Calibration Method				Fringe-counting method	Fringe-counting method	Fringe-counting method	Fringe-counting method	Fringe-counting method
Number of measurements				4	4	4	4	4
Charge Sensitivity	[pC/(m/s²)]			0.12762	0.12760	0.12763	0.12764	0.12764
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Accuracy of ratio counter	B	0.577	∞	0.00064	0.00082	0.00102	0.00127	0.00160
Repeatability of ratio counter	A	1	19	0.004	0.008	0.003	0.006	0.008
Specification of Wavelength	B	0.577	∞	0.000046	0.000046	0.000046	0.000046	0.000046
Accuracy of Sine Generator	B	0.577	∞	0.0023	0.0023	0.0023	0.0023	0.0023
Repeatability of voltage output	A	1	19	0.004	0.009	0.002	0.008	0.005
Accuracy of voltmeter	B	0.577	∞	0.021	0.021	0.021	0.021	0.021
Uncertainty of Charge Amplifier	A	2	∞	0.160	0.160	0.160	0.160	0.160
Drift of Charge Amplifier	B	0.577	∞	0.058	0.058	0.058	0.058	0.058
Effect of Geometric Location	B	0.577	∞	0.058	0.058	0.058	0.058	0.058
Effect of distortion	B	0.577	∞	0.0018	0.0018	0.0018	0.0018	0.0018
Effect of transverse	B	0.236	∞	0.047	0.047	0.047	0.047	0.047
Repeatability of Sensitivity	A	1	3	0.016	0.017	0.010	0.007	0.011
Resolution of Sensitivity	B	0.577	∞	0.0023	0.0023	0.0023	0.0023	0.0023
Effect of quantiztion error	B	0.577	∞	0.00032	0.00041	0.00051	0.00064	0.00080

Table A2-3-3 Uncertainty budget for the BB transducer at 400 Hz to 800 Hz

Acceleration amplitude	[m/s^2]			50	100	100	100
Vibration Frequency	[Hz]			400	500	630	800
Applied Calibration Method				Fringe-counting method	Fringe-counting method	Fringe-counting method	Fringe-counting method
Number of measurements				4	4	4	4
Charge Sensitivity	[pC/(m/s^2)]			0.12763	0.12759	0.12761	0.12755
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Accuracy of ratio counter	B	0.577	∞	0.00204	0.00637	0.00803	0.01019
Repeatability of ratio counter	A	1	19	0.011	0.017	0.019	0.035
Specification of Wavelength	B	0.577	∞	0.000046	0.000046	0.000046	0.000046
Accuracy of Sine Generator	B	0.577	∞	0.0023	0.0023	0.0023	0.0023
Repeatability of voltage output	A	1	19	0.001	0.008	0.005	0.006
Accuracy of voltmeter	B	0.577	∞	0.021	0.057	0.057	0.057
Uncertainty of Charge Amplifier	A	2	∞	0.160	0.160	0.160	0.160
Drift of Charge Amplifier	B	0.577	∞	0.058	0.058	0.058	0.058
Effect of Geometric Location	B	0.577	∞	0.058	0.058	0.058	0.058
Effect of distortion	B	0.577	∞	0.0018	0.0018	0.0018	0.0018
Effect of transverse	B	0.236	∞	0.047	0.047	0.047	0.047
Repeatability of Sensitivity	A	1	3	0.012	0.012	0.016	0.014
Resolution of Sensitivity	B	0.577	∞	0.0023	0.0023	0.0023	0.0023
Effect of quantiztion error	B	0.577	∞	0.00102	0.00319	0.00401	0.00510
Relative combined uncertainty [%]				0.188	0.196	0.196	0.198
Relative expanded uncertainty (*k* =2) [%]				0.38	0.40	0.40	0.40

Table A2-3-4 Uncertainty budget for the BB transducer at 1 kHz to 2.5 kHz

Acceleration amplitude	[m/s²]			50	50	59	57	62
Vibration Frequency	[Hz]			1000	1250	1600	2000	2500
Applied Calibration Method				minimum point method	minimum point method	minimum point method	minimum point method	minimum point method
Number of measurements				4	4	4	4	4
Charge Sensitivity	[pC/(m/s²)]			0.12764	0.12768	0.12777	0.12801	0.12814
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Specification of Wavelength	B	0.577	∞	0.000046	0.000046	0.000046	0.000046	0.000046
Accuracy of Sine Generator	B	0.577	∞	0.0023	0.0023	0.0023	0.0023	0.0023
Repeatability of voltage output	A	1	4	0.0043	0.0039	0.0043	0.0066	0.0034
Accuracy of voltmeter	B	0.577	∞	0.021	0.021	0.019	0.019	0.019
Uncertainty of Charge Amplifier	A	2	∞	0.160	0.160	0.160	0.160	0.160
Drift of Charge Amplifier	B	0.577	∞	0.058	0.058	0.058	0.058	0.058
Effect of Geometric Location	B	0.577	∞	0.058	0.058	0.058	0.058	0.058
Effect of distortion	B	0.577	∞	0.0018	0.0018	0.0018	0.0018	0.0018
Effect of transverse	B	0.236	∞	0.047	0.048	0.048	0.048	0.049
Repeatability of Sensitivity	A	1	3	0.013	0.014	0.013	0.012	0.018
Resolution of FFT Analyzer	B	0.577	∞	0.33	0.33	0.33	0.33	0.33
Resolution of Sensitivity report	B	0.577	∞	0.0023	0.0023	0.0023	0.0023	0.0023
Relative combined uncertainty [%]				0.380	0.380	0.380	0.380	0.380
Relative expanded uncertainty (k =2) [%]				0.76	0.76	0.76	0.76	0.76

Table A2-3-5 Uncertainty budget for the BB transducer at 3.15 kHz to 5 kHz

Acceleration amplitude	[m/s²]			53	86	135
Vibration Frequency	[Hz]			3150	4000	5000
Applied Calibration Method				minimum point method	minimum point method	minimum point method
Number of measurements				4	4	4
Charge Sensitivity	[pC/(m/s²)]			0.12851	0.12903	0.12998
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Specification of Wavelength	B	0.577	∞	0.000046	0.000046	0.000046
Accuracy of Sine Generator	B	0.577	∞	0.0023	0.0023	0.0023
Repeatability of voltage output	A	1	4	0.0055	0.0050	0.0056
Accuracy of voltmeter	B	0.577	∞	0.020	0.017	0.044
Uncertainty of Charge Amplifier	A	2	∞	0.160	0.160	0.160
Drift of Charge Amplifier	B	0.577	∞	0.058	0.058	0.058
Effect of Geometric Location	B	0.577	∞	0.058	0.058	0.058
Effect of distortion	B	0.577	∞	0.0018	0.0018	0.0018
Effect of transverse	B	0.236	∞	0.050	0.052	0.056
Repeatability of Sensitivity	A	1	3	0.022	0.026	0.004
Resolution of FFT Analyzer	B	0.577	∞	0.33	0.33	0.33
Resolution of Sensitivity report	B	0.577	∞	0.0022	0.0022	0.0022
Relative combined uncertainty [%]				0.380	0.381	0.382
Relative expanded uncertainty (k =2) [%]				0.77	0.77	0.77

Table A2-3-6 Uncertainty budget for the SE transducer at 40 Hz to 100 Hz

Acceleration amplitude	[m/s²]			25	25	25	50	50
Vibration Frequency	[Hz]			40	50	63	80	100
Applied Calibration Method				Fringe-counting method	Fringe-counting method	Fringe-counting method	Fringe-counting method	Fringe-counting method
Number of measurements				5	5	5	5	5
Charge Sensitivity	[pC/(m/s²)]			0.12866	0.12875	0.12878	0.12884	0.12888
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Accuracy of ratio counter	B	0.577	∞	0.00020	0.00025	0.00032	0.00020	0.00025
Repeatability of ratio counter	A	1	19	0.029	0.0078	0.0032	0.0020	0.0071
Specification of Wavelength	B	0.577	∞	0.000046	0.000046	0.000046	0.000046	0.000046
Accuracy of Sine Generator	B	0.577	∞	0.0023	0.0023	0.0023	0.0023	0.0023
Repeatability of voltage output	A	1	19	0.030	0.019	0.0034	0.0023	0.0074
Accuracy of voltmeter	B	0.577	∞	0.122	0.053	0.053	0.044	0.044
Uncertainty of Charge Amplifier	A	2	∞	0.255	0.185	0.185	0.185	0.185
Drift of Charge Amplifier	B	0.577	∞	0.058	0.058	0.058	0.058	0.058
Effect of Geometric Location	B	0.577	∞	0.058	0.058	0.058	0.058	0.058
Effect of distortion	B	0.577	∞	0.0018	0.0018	0.0018	0.0018	0.0018
Effect of transverse	B	0.236	∞	0.047	0.047	0.047	0.047	0.047
Repeatability of Sensitivity	A	1	4	0.0057	0.0092	0.004	0.0042	0.0046
Resolution of Sensitivity	B	0.577	∞	0.0022	0.0022	0.0022	0.0022	0.0022
Effect of quantiztion error	B	0.577	∞	0.00010	0.00013	0.00016	0.00010	0.00013
Relative combined uncertainty [%]				0.30	0.22	0.21	0.21	0.21
Relative expanded uncertainty (k =2) [%]				0.61	0.44	0.43	0.43	0.43

Table A2-3-7 Uncertainty budget for the SE transducer at 125 Hz to 315 Hz

Acceleration amplitude	[m/s^2]			50	50	50	50	50
Vibration Frequency	[Hz]			125	160	200	250	315
Applied Calibration Method				Fringe-counting method	Fringe-counting method	Fringe-counting method	Fringe-counting method	Fringe-counting method
Number of measurements				5	5	5	5	5
Charge Sensitivity	[pC/(m/s^2)]			0.12893	0.12893	0.12892	0.12888	0.12893
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Accuracy of ratio counter	B	0.577	∞	0.00064	0.00082	0.0010	0.0013	0.0016
Repeatability of ratio counter	A	1	19	0.0087	0.0045	0.011	0.0071	0.0094
Specification of Wavelength	B	0.577	∞	0.000046	0.000046	0.000046	0.000046	0.000046
Accuracy of Sine Generator	B	0.577	∞	0.0023	0.0023	0.0023	0.0023	0.0023
Repeatability of voltage output	A	1	19	0.0085	0.0041	0.010	0.0080	0.0025
Accuracy of voltmeter	B	0.577	∞	0.020	0.020	0.020	0.020	0.020
Uncertainty of Charge Amplifier	A	2	∞	0.160	0.160	0.160	0.160	0.160
Drift of Charge Amplifier	B	0.577	∞	0.058	0.058	0.058	0.058	0.058
Effect of Geometric Location	B	0.577	∞	0.058	0.058	0.058	0.058	0.058
Effect of distortion	B	0.577	∞	0.0018	0.0018	0.0018	0.0018	0.0018
Effect of transverse	B	0.236	∞	0.047	0.047	0.047	0.047	0.047
Repeatability of Sensitivity	A	1	4	0.0055	0.0042	0.0042	0.006	0.013
Resolution of Sensitivity	B	0.577	∞	0.0022	0.0022	0.0022	0.0022	0.0022
Effect of quantiztion error	B	0.577	∞	0.00032	0.00041	0.00051	0.00064	0.00080
Relative combined uncertainty [%]				0.19	0.19	0.19	0.19	0.19
Relative expanded uncertainty (k =2) [%]				0.38	0.38	0.38	0.38	0.38

Table A2-3-8 Uncertainty budget for the SE transducer at 400 Hz to 800 Hz

Acceleration amplitude	[m/s^2]			50	100	100	100
Vibration Frequency	[Hz]			400	500	630	800
Applied Calibration Method				Fringe-counting method	Fringe-counting method	Fringe-counting method	Fringe-counting method
Number of measurements				5	5	5	5
Charge Sensitivity	[pC/(m/s^2)]			0.12895	0.12890	0.12898	0.12893
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Accuracy of ratio counter	B	0.577	∞	0.0020	0.0064	0.0080	0.010
Repeatability of ratio counter	A	1	19	0.012	0.014	0.017	0.044
Specification of Wavelength	B	0.577	∞	0.000046	0.000046	0.000046	0.000046
Accuracy of Sine Generator	B	0.577	∞	0.0023	0.0023	0.0023	0.0023
Repeatability of voltage output	A	1	19	0.0043	0.0086	0.0059	0.0066
Accuracy of voltmeter	B	0.577	∞	0.020	0.056	0.056	0.056
Uncertainty of Charge Amplifier	A	2	∞	0.160	0.160	0.160	0.160
Drift of Charge Amplifier	B	0.577	∞	0.058	0.058	0.058	0.058
Effect of Geometric Location	B	0.577	∞	0.058	0.058	0.058	0.058
Effect of distortion	B	0.577	∞	0.0018	0.0018	0.0018	0.0018
Effect of transverse	B	0.236	∞	0.047	0.047	0.047	0.047
Repeatability of Sensitivity	A	1	4	0.012	0.016	0.019	0.016
Resolution of Sensitivity	B	0.577	∞	0.0022	0.0022	0.0022	0.0022
Effect of quantiztion error	B	0.577	∞	0.0010	0.0032	0.0040	0.0051
Relative combined uncertainty [%]				0.19	0.20	0.20	0.20
Relative expanded uncertainty (k =2) [%]				0.38	0.40	0.40	0.40

Table A2-3-9 Uncertainty budget for the SE transducer at 1 kHz to 2.5 kHz

Acceleration amplitude	[m/s^2]			50	50	59	57	62
Vibration Frequency	[Hz]			1000	1250	1600	2000	2500
Applied Calibration Method				minimum point method	minimum point method	minimum point method	minimum point method	minimum point method
Number of measurements				5	5	5	5	5
Charge Sensitivity	[pC/(m/s^2)]			0.12903	0.12902	0.12927	0.12938	0.12972
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Specification of Wavelength	B	0.577	∞	0.000046	0.000046	0.000046	0.000046	0.000046
Accuracy of Sine Generator	B	0.577	∞	0.0023	0.0023	0.0023	0.0023	0.0023
Repeatability of voltage output	A	1	4	0.010	0.0034	0.0062	0.016	0.0068
Accuracy of voltmeter	B	0.577	∞	0.021	0.020	0.019	0.019	0.019
Uncertainty of Charge Amplifier	A	2.000	∞	0.160	0.160	0.160	0.160	0.160
Drift of Charge Amplifier	B	0.577	∞	0.058	0.058	0.058	0.058	0.058
Effect of Geometric location	B	0.577	∞	0.058	0.058	0.058	0.058	0.058
Effect of distortion	B	0.577	∞	0.0018	0.0018	0.0018	0.0018	0.0018
Effect of transverse	B	0.236	∞	0.047	0.048	0.048	0.048	0.049
Repeatability of Sensitivity	A	1	4	0.017	0.022	0.018	0.031	0.024
Resolution of FFT Analyzer	B	0.577	∞	0.33	0.33	0.33	0.33	0.33
Resolution of Sensitivity report	B	0.577	∞	0.0022	0.0022	0.0022	0.0022	0.0022
Relative combined uncertainty [%]				0.38	0.38	0.38	0.38	0.38
Relative expanded uncertainty (k =2) [%]				0.76	0.76	0.76	0.77	0.77

Table A2-3-10 Uncertainty budget for the SE transducer at 3.15 kHz to 5 kHz

Acceleration amplitude	[m/s^2]			53	86	135
Vibration Frequency	[Hz]			3150	4000	5000
Applied Calibration Method				minimum point method	minimum point method	minimum point method
Number of measurements				5	5	5
Charge Sensitivity	[pC/(m/s^2)]			0.13021	0.13100	0.13235
Uncertainty Component	type (A or B)	factor	effective degree of freedom	Relative standard uncertainty [%]	Relative standard uncertainty [%]	Relative standard uncertainty [%]
Specification of Wavelength	B	0.577	∞	0.000046	0.000046	0.000046
Accuracy of Sine Generator	B	0.577	∞	0.0023	0.0023	0.0023
Repeatability of voltage output	A	1	4	0.0058	0.0085	0.021
Accuracy of voltmeter	B	0.577	∞	0.020	0.017	0.043
Uncertainty of Charge Amplifier	A	2.000	∞	0.160	0.160	0.160
Drift of Charge Amplifier	B	0.577	∞	0.058	0.058	0.058
Effect of Geometric location	B	0.577	∞	0.058	0.058	0.058
Effect of distortion	B	0.577	∞	0.0018	0.0018	0.0018
Effect of transverse	B	0.236	∞	0.050	0.052	0.056
Repeatability of Sensitivity	A	1	4	0.025	0.008	0.020
Resolution of FFT Analyzer	B	0.577	∞	0.33	0.33	0.33
Resolution of Sensitivity report	B	0.577	∞	0.0022	0.0022	0.0022
Relative combined uncertainty [%]				0.38	0.38	0.38
Relative expanded uncertainty (k =2) [%]				0.77	0.76	0.77

A2-4: A@Star

Table A2-4-1 Uncertainty budget for the BB transducer

Uncertainty Calculation:	Probability distribution model	20 Hz	40 Hz	80 Hz	160 Hz	315 Hz	630 Hz	1250 Hz	2500 Hz	5000 Hz
Output voltage measurement										
Output voltage	Normal	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062
Filtering effect	Rectangular	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Hum & noise	Rectangular	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Transverse sensitivity	Special	0.024	0.024	0.071	0.071	0.071	0.071	0.071	0.118	0.236
Displacement determination										
Phase amplitude measurement	Rectangular	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.058	0.058
Motion disturbance	Rectangular	0.024	0.071	0.071	0.071	0.071	0.071	0.071	0.118	0.118
Vibration Frequency										
Frequency generator & indicator	Rectangular	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Reference conditioning amplifier										
Charge sensitivity	Normal	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
Residual effect										
Gravity	Rectangular	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Non-linearity	Rectangular	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Exciter magnetic field	Rectangular	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Temperature variation	Rectangular	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
Other environmental effects	Rectangular	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Type B total		0.22	0.23	0.24	0.24	0.24	0.24	0.24	0.28	0.34
Type A										
Number of measurement		40	40	40	40	40	40	40	40	40
Standard uncertainty		0.03	0.02	0.03	0.07	0.02	0.04	0.04	0.06	1.47
Combined uncertainty		0.22	0.23	0.24	0.25	0.24	0.24	0.24	0.28	1.51
Effective degree of freedom		7.8E+04	7.1E+05	2.0E+05	8.0E+03	4.6E+05	3.8E+04	8.7E+04	2.4E+04	4.3E+01
Coverage factor		2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.06
Expended uncertainty [%]		0.44	0.46	0.48	0.49	0.48	0.48	0.48	0.57	3.10

Table A2-4-2 Uncertainty budget for the SE transducer

Uncertainty components	Probability distribution model	20 Hz	40 Hz	80 Hz	160 Hz	315 Hz	630 Hz	1250 Hz	2500 Hz	5000 Hz
Output voltage measurement										
Output voltage	Normal	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062
Filtering effect	Rectangular	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Hum & noise	Rectangular	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Transverse sensitivity	Special	0.024	0.024	0.071	0.071	0.071	0.071	0.071	0.118	0.236
Displacement determination										
Phase amplitude measurement	Rectangular	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.058	0.058
Motion disturbance	Rectangular	0.024	0.071	0.071	0.071	0.071	0.071	0.071	0.118	0.118
Vibration Frequency measurement										
Frequency generator & indicator	Rectangular	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Reference conditioning amplifier										
Charge sensitivity	Normal	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
Residual effect										
Gravity	Rectangular	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Non-linearity	Rectangular	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Exciter magnetic field	Rectangular	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Temperature variation	Rectangular	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
Other environmental effects	Rectangular	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Type B Total		0.22	0.23	0.24	0.24	0.24	0.24	0.24	0.28	0.34
Type A										
Number of measurement		60	60	60	60	60	60	60	60	60
Standard uncertainty		0.02	0.02	0.04	0.22	0.05	0.10	0.06	0.04	0.44
Combined uncertainty		0.22	0.23	0.24	0.33	0.24	0.26	0.25	0.28	0.56
Effective degree of freedom		6.0E+05	5.2E+05	1.2E+05	2.8E+02	3.6E+04	2.5E+03	1.9E+04	1.0E+05	1.5E+02
Coverage factor		2.00	2.00	2.00	2.01	2.00	2.00	2.00	2.00	2.02
Expended uncertainty [%]		0.44	0.46	0.48	0.65	0.49	0.52	0.49	0.56	1.13

Annex 3 DoE to the KCRV of CCAUV.V-K2 for the BB transducer

Frequency in Hz	CMS/ITRI		NIMT		A*STAR	
	d_i	$U(d_i)$	d_i	$U(d_i)$	d_i	$U(d_i)$
	in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}		in pC/(m/s^2)·10^{-4}	
40	1.4	4.4	-3.8	7.9	-4.0	6.2
50						
63	0.9	3.7	-3.3	5.8		
80	2.5	3.6	-1.0	5.8	-1.4	6.4
100	2.8	3.6	-0.3	5.5		
125	1.3	3.7	-1.2	5.2		
160	1.6	3.9	-1.7	5.2	-1.7	6.5
200	1.7	4.0	-1.0	5.2		
250	0.2	4.0	-2.0	5.2		
315	2.6	4.4	-0.3	5.2	-2.0	6.4
400	2.9	4.2	0.1	5.2		
500	3.6	4.6	0.0	5.5		
630	2.0	4.3	-1.4	5.5	-1.2	6.4
800	1.5	4.9	-1.9	5.5		
1000	1.2	5.1	-1.3	9.9		
1250	2.0	5.4	0.3	9.9	-1.0	6.4
1600	-0.6	4.0	-1.8	9.9		
2000	2.2	4.6	3.5	10.0		
2500	-2.0	4.7	0.4	10.0	-2.5	7.6
3150	-2.9	6.2	0.4	10.1		
4000	6.8	10.6	4.9	10.2		
5000	-1.7	11.6	3.4	10.3	16.6	41.3