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FINAL REPORT ON SUPPLEMENTARY COMPARISON SADCMET.AUV.V-S1

NML-04-0076
Pretoria, Monday, 5 July 2004

Abstract

A supplementary comparison (SADC.AUV.V-S1) was organized to compare measurements of sinusoidal linear accelerations in the frequency range from 10 Hz to 10 kHz. In this bi-lateral comparison between the CSIR National Metrology Laboratory (CSIR-NML), South Africa and the Physikalisch-Technische Bundesanstalt (PTB), Germany both NMIs applied laser interferometry in compliance with method 3 of the international standard ISO 16063-11:1999.

The complex charge sensitivity (magnitude and phase) of two different transfer standards (single-ended accelerometer) was measured at 37 frequencies. The results of the SADCMET.AUV.V-S1 are a set of comparison values and their uncertainties, and degrees of equivalence between these and between the two laboratories. From this complete set of results, six matrices of equivalence per accelerometer were selected and are demonstrated graphically.

The deviations between the PTB and NML results were smaller than 0.6° and 2° for the phase shift measurements for the Endevco and Brüel & Kjær accelerometer respectively (37 measurement points each).

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1 Introduction

This report presents the results of a supplementary comparison in the area of “vibration” (quantity of acceleration), SADCMET.AUV.V-S1. It has the status of a Final report.

The participants have reached consensus and considered the weighted mean as the most appropriate method for this particular comparison to compute the supplementary comparison reference values (SCRVs) and the degrees of equivalence. Detail analysis and application of the method for use in comparisons in the field of vibration is documented in the CCAUV.V-K1 report [1]. The calculation of the SCRVs is also in accordance with the Guidelines for CIPM key comparisons [2].

The Technical Protocol of July 2003 [3] 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 survey is given in the following sections.

2 Participants

Two national metrology institutes (NMIs) from the two regional metrology organizations, (RMOs) SADCMET and EUROMET, have participated in the supplementary comparison SADCMET.AUV.V-S1 (cf. Table 1).

Table 1: List of participating institutes

Participating laboratory	**Acronym**	**Country**	**Metrology Region**	**Calibration Period**
CSIR National Metrology Laboratory	CSIR-NML	South Africa RSA	SADCMET	September 2003
Physikalisch-Technische Bundesanstalt	PTB	Germany DE	EUROMET	August, October 2003

3 Task and purpose of the comparison

In the field of vibration and shock, this supplementary comparison (SADC.AUV.V-S1) was organized in order to compare measurements of sinusoidal linear accelerations in the frequency range from 10 Hz to 10 kHz. Moreover, the complex (magnitude and phase) calibration and measurement capabilities (CMCs) of the NMIs for accelerometer calibration were to be examined and compared.

During the circulation period from August 2003 to October 2003, two national metrology institutes (NMIs) from two regional metrology organizations (RMOs) calibrated two accelerometers as transfer standards.

It was the task of the comparison to measure the magnitude and phase shift of the complex charge sensitivity of two accelerometer standards (both of single ended in design) at different frequencies and acceleration amplitudes as specified in section 4. The charge sensitivity was calculated as the ratio of the amplitude of the accelerometer output charge to the amplitude of the acceleration at its reference surface.

The reference surface was defined as the mounting surface of the accelerometer. The magnitude of the complex charge sensitivity was given in pico coulomb per metre per second squared (pC/(m/s²)), while the phase shift was given in degrees (°) for the different measurement conditions specified in clause 4. A calibrated charge amplifier was used to measure the output charge and phase shift of the accelerometer standards, applying the electrical calibration method specified in the Technical Protocol [3].

For the calibration of the two accelerometers, both NMIs applied laser interferometry in compliance with method 3 of the international standard ISO 16063-11:1999 [4], in order to cover the entire frequency range chosen, within a specified range of the acceleration amplitude with specified uncertainties.

4 Conditions of measurement

The participating laboratories observed fully the conditions stated in the Technical Protocol, i.e.

- frequencies in hertz:
  10 Hz, 12.5 Hz, 16 Hz, 20 Hz, 25 Hz, 31.5 Hz, 40 Hz, 50 Hz, 63 Hz, 80 Hz, 100 Hz, 125 Hz, 160 Hz, 200 Hz, 250 Hz, 315 Hz, 400 Hz, 500 Hz, 630 Hz, 800 Hz, 1 000 Hz, 1 250 Hz, 1 600 Hz, 2 000 Hz, 2 500 Hz, 3 150 Hz, 4 000 Hz, 5 000 Hz, 5 500 Hz, 6 300 Hz, 7 000 Hz, 7 500 Hz, 8 000 Hz, 8 500 Hz, 9 000 Hz, 9 500 Hz, 10 000 Hz
  (160 Hz is reference frequency)
- amplitudes:
  A range of 10 m/s² to 200 m/s² was allowed.
- ambient temperature and accelerometer temperature during the calibration:
  (23 ± 2) °C (actual values were stated within tolerances of ± 0.3 °K).
- relative humidity: max. 75 %
- mounting torque of the accelerometer: (2 ± 0.1) N m

The comparison was performed in compliance with the “Guidelines for CIPM key comparisons” [2].

5 Transfer standards

During the preparatory stage, the PTB thoroughly investigated the characteristics (long-term stability, linearity, etc.) of various reference standard accelerometers (property of PTB) considered to be candidates for the transfer standards to be used in the supplementary comparison. The following two accelerometers were selected:

- Accelerometer A
  - A transfer standard accelerometer; Brüel & Kjær model 8305 WH 2335
  - serial number: 1610174
  - nominal charge sensitivity (magnitude): 0.3 pC/(m/s²)

- Accelerometer B:
  - A reference standard accelerometer; Endevco model 2207M8
  - serial number: AC08
  - nominal charge sensitivity (magnitude): 0.22 pC/(m/s²)

6 Circulation type and transportation

- The comparison was a bi-lateral comparison.
- The transfer standards were transported in a closed box hand-carried by a representative of PTB.

7 Measurement instructions

In accordance with the Technical Protocol [3], the participating laboratories observed the following instructions fully or to a large extent:

- The charge amplifier used in the laboratory was calibrated using a standard capacitor and standard voltmeter, both traceable to national standards. The calibration of the charge amplifier was to be carried out shortly before the calibration, using values of the electric quantities similar to those found in accelerometer calibration.
- In order to suppress the effect of any non-rectilinear of the motion, the displacement was measured at least at three different points. These points were to be equally spaced on the base surface of the single-ended accelerometer.
- The reference surface for acceleration measurement is, by definition, the basis surface (mounting surface) of the accelerometer. As this surface was covered during calibration, the motion had to be sensed on the moving part close to the accelerometer.
- The mounting surfaces of the accelerometer and the moving part of the vibration exciter were slightly lubricated before mounting.

Complete measurement series were carried out on different days under nominally the same conditions, except that the accelerometer was re-mounted and the cable re-fixed. The (mean) result of the all the measurement series were to be given as the final measurement result.

8 Communication of the results to the co-ordinating laboratory

The PTB submitted the calibration report to the NML including descriptions of:

- the calibration equipment
- the calibration methods used
- the ambient conditions
- the mounting technique
- the calibration results
- the uncertainty of measurement (k = 2) for each measurement result

In each case, the uncertainties were evaluated in accordance with the Guide to the expression of uncertainty in measurement (GUM), which had been adapted to the calibration of vibration and shock transducers as stated in ISO 16063-1:1998, Annex A.

9 Results of the measurements

In the bi-lateral comparison between NML and PTB of calibrations of the magnitude and phase shift of the complex sensitivity of two reference accelerometers, the sine-approximation method specified in ISO 16063-11 (method 3) was applied in three versions:

Version 1: Homodyne interferometer with two output signals in quadrature (i.e. phase-shifted by 90 degrees)

Version 2: Heterodyne interferometer with quadrature signals generated by digital data processing

Version 3: Heterodyne interferometer with time-interval analyzer

Both the NML and the PTB used Version 1 as specified in ISO 16063-11, with a modified Michelson interferometer as depictured in Fig. 4 of that international standard, as a sub-system of the calibration equipment.

The special techniques and procedures developed at the NML (standard measuring equipment with vibration exciter, interferometer, data acquisition and signal processing system etc.) are described in detail in [5].

For the calibrations performed at PTB, versions 2 and 3 were applied in addition. The standard measuring equipment developed at the PTB is equipped with a heterodyne Mach-Zehnder interferometer head in conjunction with sub-systems for frequency-conversion, data acquisition and digital signal processing. The standard measurement equipment is described in [6] [7] [8].

A number of tables and figures are given in the following sections to present the measurement results. The data will be presented in table as well as in graphical formats, subdivided into:

- Complex sensitivity measurement results per laboratory
- Calculated Supplementary Comparison Reference Values (SCRVs)
- Calculated degrees of equivalence

9.1 Supplementary Comparison Reference Value

The weighted mean was agreed upon by both laboratories to calculate the SCRVs for the SADCMET.AUV.V-S1 data. SCRVs are calculated separately at each frequency point measured (37 points per accelerometer).

Calculation of SCRVs using the weighted mean method

Tables 2 to *5* contain the data for the two accelerometers (A and B) reported by the participating laboratories. For each laboratory *i* these data are (1) $x_{i,f}$: best estimate of sensitivity at frequency *f*, and (2) $u(x_{i,f})$: associated standard uncertainty of sensitivity reported at frequency *f*.

For each of the two transfer standards and at each frequency *f*, a key comparison reference value $x_{R,f}$ has been determined as the weighted mean of the results of n laboratories (for this comparison, n = 2) according to

$$x_{R,f} = \frac{\sum_{i=1}^{n} \frac{x_{i,f}}{u^2(x_{i,f})}}{\sum_{i=1}^{n} \frac{1}{u^2(x_{i,f})}} \tag{1}$$

$$u^2(x_{R,f}) = \frac{1}{\sum_{i=1}^{n} \frac{1}{u^2(x_{i,f})}} \tag{2}$$

The degree of equivalence, $D_{\mathrm{NMI\text{-}WM}}$, and $U_{\mathrm{NMI\text{-}WM}}$, was determined for the magnitude as well as the phase shift measurements for both accelerometers using

$$D_{\mathrm{NMI\text{-}WM}} = x_{\mathrm{NMI}} - x_{\mathrm{WM}} , \qquad U_{\mathrm{NMI\text{-}WM}} = \sqrt{U_{\mathrm{NMI}}^2 - U_{\mathrm{WM}}^2} \tag{3}$$

where x_{NMI} represents the measurement results obtained by the laboratory at each frequency point for the magnitude and the phase shift and x_{WM} represents the reference value (SCRV) calculated as the weighted mean using Eq. (1). $U_{\mathrm{NMI\text{-}WM}}$ is the uncertainty of measurement associated with the calculated $D_{\mathrm{NMI\text{-}WM}}$ for $k = 2$.

9.2 Results - Part 1: Laboratory individual measurements (stated results for standard frequency series)

The stated results given in Table 2 to Table 5 are in all cases the final measurement results submitted by the two participating laboratories for accelerometers A and B respectively.

PTB submitted the arithmetic mean values for measurements obtained using the three different versions of systems described (cf. clause 9) over the measurement period.

The NML submitted measurement results obtained using version 1 (cf. clause 9) of the systems described. Five measurements were performed, one per day per, for each accelerometer. The arithmetic mean of the five measurements was submitted as the comparison result.

Table 2: Accelerometer A; magnitude and phase shift results of the complex sensitivity reported by PTB

PTB					
Frequency (Hz)	Sensitivity magnitude ($pC/m/s^2$)	U_c		Phase shift (°)	U_c (°)
		(%)	($pC/m/s^2$)		
10	0.12896	0.2	0.00026	0.04	0.5
12.5	0.12889	0.2	0.00026	-0.02	0.5
16	0.12890	0.2	0.00026	-0.01	0.5
20	0.12899	0.2	0.00026	-0.01	0.5
25	0.12899	0.2	0.00026	-0.02	0.5
31.5	0.12902	0.2	0.00026	0.01	0.5
40	0.12901	0.2	0.00026	-0.01	0.5
50	0.12900	0.2	0.00026	0.00	0.5
63	0.12900	0.2	0.00026	-0.01	0.5
80	0.12901	0.2	0.00026	-0.01	0.5
100	0.12901	0.2	0.00026	0.00	0.5
125	0.12903	0.2	0.00026	-0.01	0.5
160	0.12904	0.2	0.00026	-0.04	0.5
200	0.12902	0.2	0.00026	0.11	0.5
250	0.12905	0.2	0.00026	-0.03	0.5
315	0.12911	0.2	0.00026	-0.05	0.5
400	0.12916	0.2	0.00026	-0.06	0.5
500	0.12914	0.2	0.00026	-0.06	0.5
630	0.12921	0.2	0.00026	-0.10	0.5
800	0.12930	0.2	0.00026	-0.12	0.5
1000	0.12935	0.2	0.00026	-0.15	0.5
1250	0.12940	0.3	0.00039	-0.21	1.0
1600	0.12960	0.3	0.00039	-0.23	1.0
2000	0.12991	0.3	0.00039	-0.23	1.0
2500	0.13026	0.3	0.00039	-0.39	1.0
3150	0.13078	0.3	0.00039	-0.36	1.0
4000	0.13178	0.3	0.00040	-0.50	1.0
5000	0.13331	0.4	0.00053	-0.30	1.0
5500	0.13370	0.4	0.00053	-0.69	1.0
6300	0.13580	0.4	0.00054	-0.71	1.0
7000	0.13700	0.4	0.00055	-0.46	1.0
7500	0.13860	0.4	0.00055	-0.46	1.0
8000	0.13990	0.4	0.00056	-0.60	1.0
8500	0.14120	0.4	0.00056	-0.61	1.0
9000	0.14300	0.4	0.00057	-0.78	1.0
9500	0.14444	0.4	0.00058	-0.28	1.0
10000	0.14580	0.4	0.00058	-1.09	1.0

Table 3: Accelerometer A; magnitude and phase shift results of the complex sensitivity reported by CSIR-NML

CSIR-NML					
Frequency (Hz)	Sensitivity magnitude (pC/m/s^2)	U_c (%)	U_c (pC/m/s^2)	Phase shift (°)	U_c (°)
10	0.12905	0.5	0.00065	0.02	0.5
12.5	0.12896	0.5	0.00064	0.04	0.5
16	0.12918	0.5	0.00065	-0.02	0.5
20	0.12929	0.5	0.00065	-0.01	0.5
25	0.12941	0.5	0.00065	0.01	0.5
31.5	0.12911	0.5	0.00065	-0.02	0.5
40	0.12912	0.5	0.00065	-0.03	0.5
50	0.12911	0.5	0.00065	-0.02	0.5
63	0.12913	0.5	0.00065	-0.03	0.5
80	0.12913	0.5	0.00065	-0.03	0.5
100	0.12905	0.5	0.00065	-0.05	0.5
125	0.12910	0.5	0.00065	-0.06	0.5
160	0.12912	0.5	0.00065	-0.07	0.5
200	0.12911	0.5	0.00065	-0.15	0.5
250	0.12929	0.5	0.00065	-0.13	0.5
315	0.12923	0.5	0.00065	-0.11	0.5
400	0.12925	0.5	0.00065	-0.13	0.5
500	0.12928	0.5	0.00065	-0.18	0.5
630	0.12928	0.5	0.00065	-0.21	0.5
800	0.12931	0.5	0.00065	-0.27	0.5
1000	0.12938	1.0	0.00129	-0.37	0.5
1250	0.12948	1.0	0.00129	-0.40	1.0
1600	0.12963	1.0	0.00130	-0.51	1.0
2000	0.12990	1.0	0.00130	-0.60	1.0
2500	0.13020	1.0	0.00130	-0.76	1.0
3150	0.13077	1.0	0.00131	-0.94	1.0
4000	0.13172	1.0	0.00132	-1.16	1.0
5000	0.13330	1.5	0.00200	-1.47	1.5
5500	0.13410	1.5	0.00201	-1.64	1.5
6300	0.13611	1.5	0.00204	-1.79	1.5
7000	0.13755	1.5	0.00206	-2.10	1.5
7500	0.13878	1.5	0.00208	-2.16	1.5
8000	0.14034	1.5	0.00211	-2.34	1.5
8500	0.14126	1.5	0.00212	-2.33	1.5
9000	0.14302	1.5	0.00215	-2.40	1.5
9500	0.14433	1.5	0.00217	-2.51	1.5
10000	0.14556	1.5	0.00218	-2.57	1.5

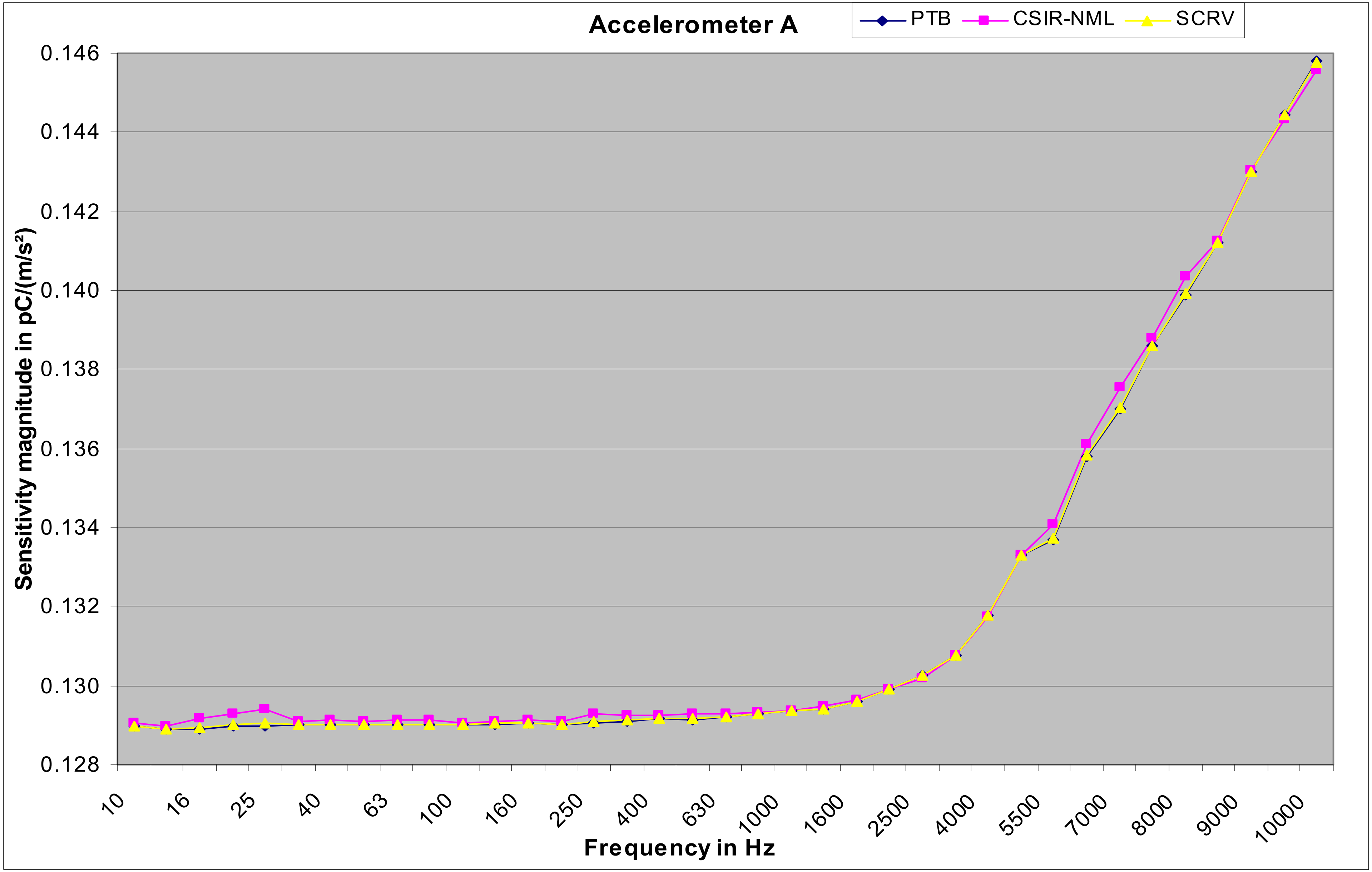


Figure 1: Sensitivity magnitude frequency response of accelerometer A as reported in tables 2 and 3

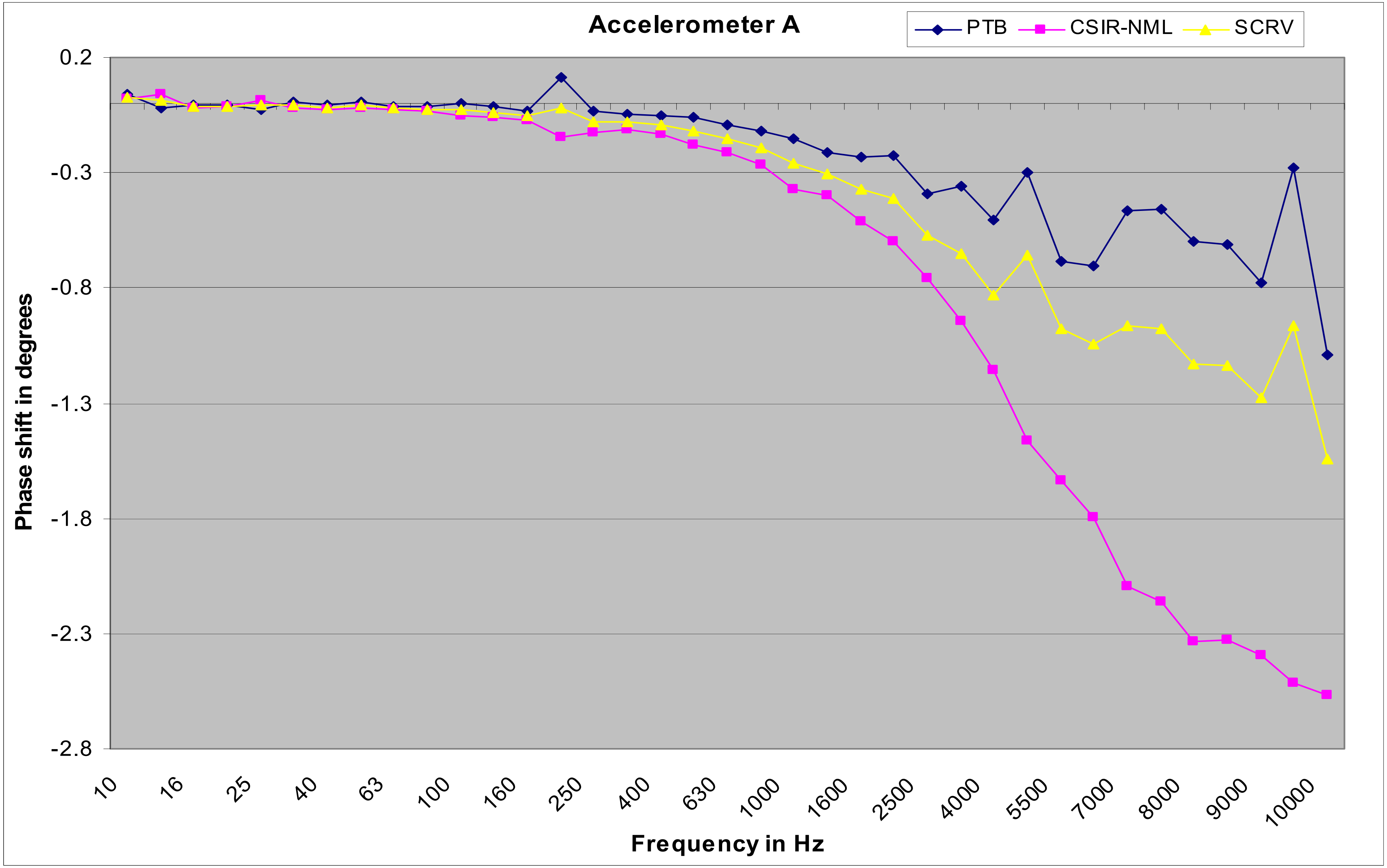


Figure 2: Phase shift response of accelerometer A as reported in tables 2 and 3

Table 4: Accelerometer B; magnitude and phase shift results of the complex sensitivity reported by PTB

PTB					
Frequency (Hz)	Sensitivity magnitude (pC/m/s^2)	U_c (%)	U_c (pC/m/s^2)	Phase shift (°)	U_c (°)
10	0.22057	0.2	0.00044	0.117	0.5
12.5	0.22015	0.2	0.00044	0.003	0.5
16	0.22016	0.2	0.00044	-0.012	0.5
20	0.22004	0.2	0.00044	0.089	0.5
25	0.22000	0.2	0.00044	0.005	0.5
31.5	0.22021	0.2	0.00044	-0.050	0.5
40	0.22010	0.2	0.00044	-0.021	0.5
50	0.22030	0.2	0.00044	-0.081	0.5
63	0.22009	0.2	0.00044	-0.057	0.5
80	0.21996	0.2	0.00044	-0.067	0.5
100	0.22003	0.2	0.00044	-0.004	0.5
125	0.22001	0.2	0.00044	0.005	0.5
160	0.22005	0.2	0.00044	0.035	0.5
200	0.22003	0.2	0.00044	0.016	0.5
250	0.21993	0.2	0.00044	0.002	0.5
315	0.22005	0.2	0.00044	0.023	0.5
400	0.21989	0.2	0.00044	0.008	0.5
500	0.21985	0.2	0.00044	-0.046	0.5
630	0.21999	0.2	0.00044	-0.066	0.5
800	0.21998	0.2	0.00044	-0.115	0.5
1000	0.22004	0.2	0.00044	-0.155	0.5
1250	0.22012	0.3	0.00066	-0.209	1.0
1600	0.22017	0.3	0.00066	-0.219	1.0
2000	0.22033	0.3	0.00066	-0.304	1.0
2500	0.22058	0.3	0.00066	-0.371	1.0
3150	0.22092	0.3	0.00066	-0.454	1.0
4000	0.22165	0.3	0.00066	-0.533	1.0
5000	0.22255	0.4	0.00089	-0.757	1.0
5500	0.22297	0.4	0.00089	-0.989	1.0
6300	0.22395	0.4	0.00090	-1.134	1.0
7000	0.22462	0.4	0.00090	-1.031	1.0
7500	0.22526	0.4	0.00090	-0.827	1.0
8000	0.22633	0.4	0.00091	-1.253	1.0
8500	0.22681	0.4	0.00091	-1.392	1.0
9000	0.22758	0.4	0.00091	-1.519	1.0
9500	0.22852	0.4	0.00091	-1.573	1.0
10000	0.22922	0.4	0.00092	-1.779	1.0

Table 5: Accelerometer B; magnitude and phase shift results of the complex sensitivity reported by CSIR-NML

CSIR-NML					
Frequency (Hz)	Sensitivity magnitude ($pC/m/s^2$)	U_c		Phase shift (°)	U_c (°)
		(%)	($pC/m/s^2$)		
10	0.22091	0.5	0.00110	0.042	0.5
12.5	0.22076	0.5	0.00110	0.063	0.5
16	0.22095	0.5	0.00110	0.078	0.5
20	0.22067	0.5	0.00110	0.064	0.5
25	0.22084	0.5	0.00110	0.057	0.5
31.5	0.22025	0.5	0.00110	0.027	0.5
40	0.22027	0.5	0.00110	0.025	0.5
50	0.22026	0.5	0.00110	-0.112	0.5
63	0.22027	0.5	0.00110	0.026	0.5
80	0.22024	0.5	0.00110	0.027	0.5
100	0.22013	0.5	0.00110	0.028	0.5
125	0.22018	0.5	0.00110	0.032	0.5
160	0.22023	0.5	0.00110	0.031	0.5
200	0.22022	0.5	0.00110	0.048	0.5
250	0.21987	0.5	0.00110	0.008	0.5
315	0.22004	0.5	0.00110	0.028	0.5
400	0.22002	0.5	0.00110	0.025	0.5
500	0.22001	0.5	0.00110	0.021	0.5
630	0.22001	0.5	0.00110	0.011	0.5
800	0.22000	0.5	0.00110	-0.003	0.5
1000	0.22012	0.5	0.00110	-0.151	0.5
1250	0.21999	1.0	0.00220	-0.336	1.0
1600	0.22010	1.0	0.00220	-0.481	1.0
2000	0.22019	1.0	0.00220	-0.586	1.0
2500	0.22019	1.0	0.00220	-0.711	1.0
3150	0.22051	1.0	0.00221	-0.667	1.0
4000	0.22114	1.0	0.00221	-0.457	1.0
5000	0.22202	1.5	0.00333	-0.555	1.5
5500	0.22232	1.5	0.00333	-0.618	1.5
6300	0.22367	1.5	0.00336	-0.644	1.5
7000	0.22438	1.5	0.00337	-0.720	1.5
7500	0.22499	1.5	0.00337	-0.816	1.5
8000	0.22527	1.5	0.00338	-0.991	1.5
8500	0.22581	1.5	0.00339	-1.078	1.5
9000	0.22621	1.5	0.00339	-1.010	1.5
9500	0.22685	1.5	0.00340	-1.066	1.5
10000	0.22979	1.5	0.00345	-1.188	1.5

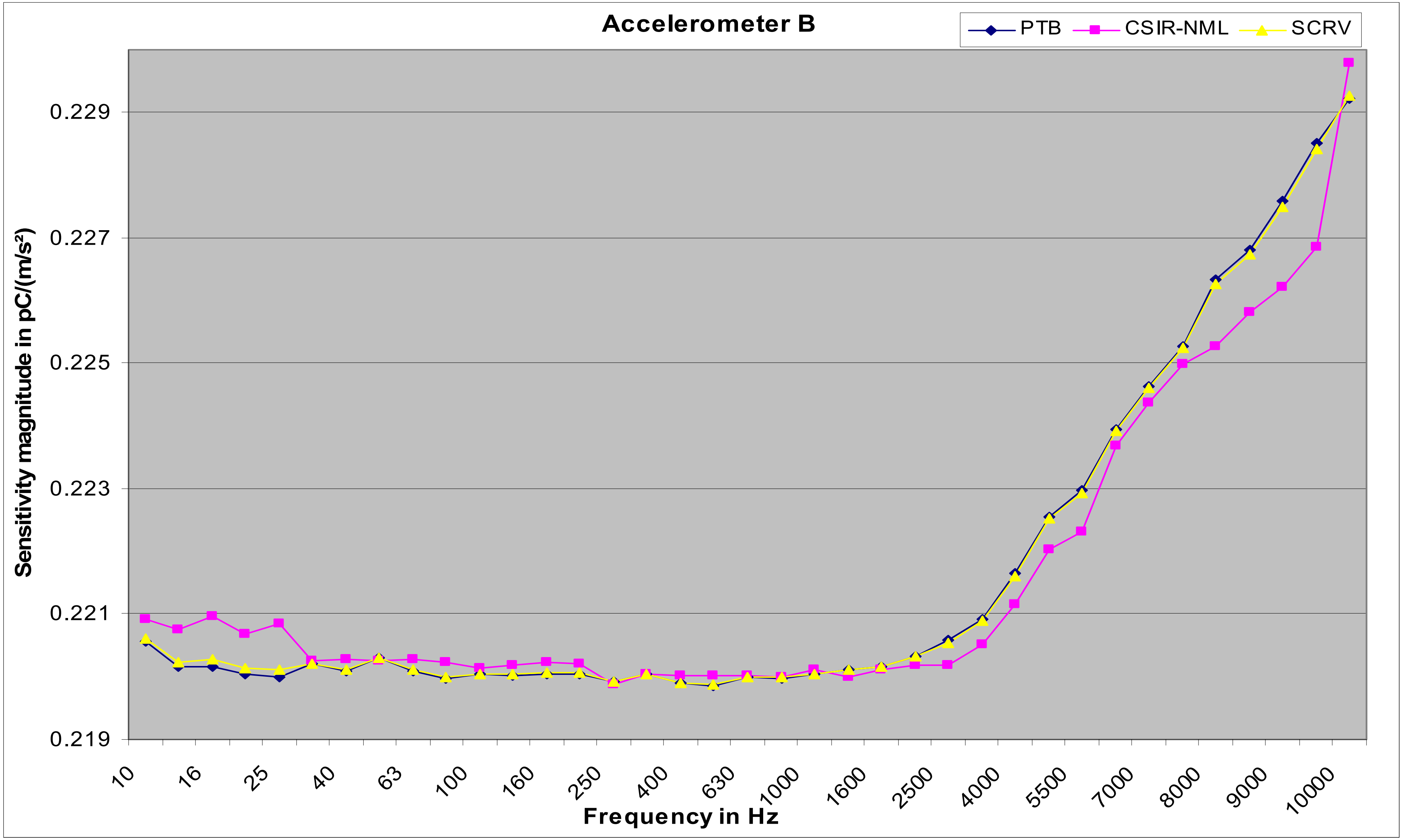


Figure 3: Magnitude sensitivity frequency response of accelerometer A as reported in tables 4 and 5

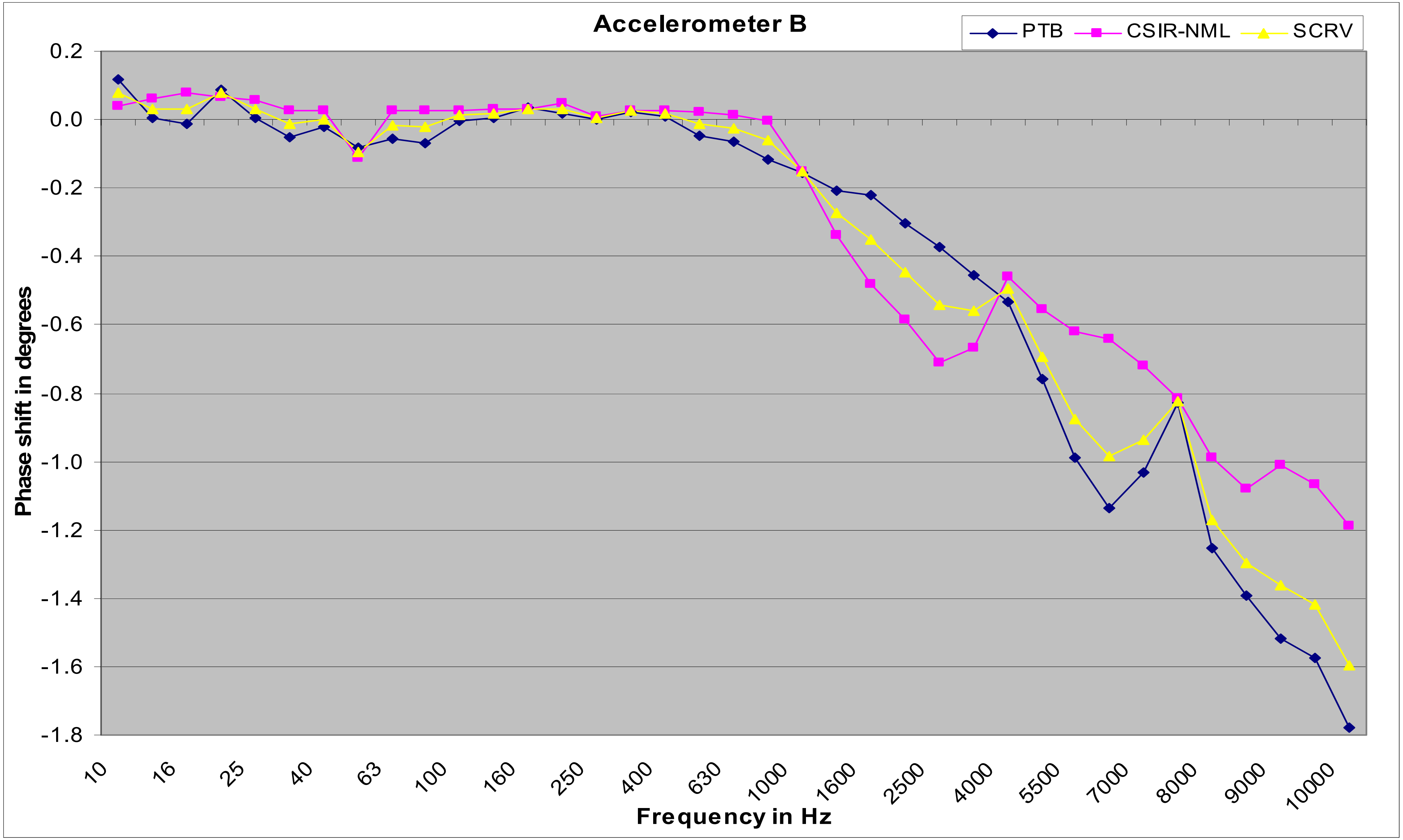


Figure 4: Phase shift response of accelerometer A as reported in tables 4 and 5

Table 6: Accelerometer A; weighted mean and degrees of equivalence for the sensitivity magnitude measurements

Weighted Mean		Degrees of equivalence (magnitude)					
WM (pC/m/s^2)	U_{WM} (%)	D_{PTB-WM} (pC/m/s^2)	U_{PTB-WM} (%)	D_{NML-WM} (pC/m/s^2)	U_{NML-WM} (%)	$D_{NML-PTB}$ (%)	$U_{NML-PTB}$ (%)
0.12897	0.19	-0.00001	0.07	0.00008	0.46	0.07	0.54
0.12890	0.19	-0.00001	0.07	0.00006	0.46	0.06	0.54
0.12894	0.19	-0.00004	0.07	0.00024	0.46	0.22	0.54
0.12903	0.19	-0.00004	0.07	0.00026	0.46	0.23	0.54
0.12905	0.19	-0.00006	0.07	0.00037	0.46	0.33	0.54
0.12903	0.19	-0.00001	0.07	0.00007	0.46	0.07	0.54
0.12902	0.19	-0.00001	0.07	0.00009	0.46	0.08	0.54
0.12901	0.19	-0.00001	0.07	0.00009	0.46	0.08	0.54
0.12902	0.19	-0.00002	0.07	0.00011	0.46	0.10	0.54
0.12903	0.19	-0.00002	0.07	0.00010	0.46	0.09	0.54
0.12902	0.19	-0.00001	0.07	0.00003	0.46	0.03	0.54
0.12904	0.19	-0.00001	0.07	0.00006	0.46	0.05	0.54
0.12905	0.19	-0.00001	0.07	0.00007	0.46	0.06	0.54
0.12903	0.19	-0.00001	0.07	0.00007	0.46	0.07	0.54
0.12908	0.19	-0.00003	0.07	0.00021	0.46	0.19	0.54
0.12913	0.19	-0.00002	0.07	0.00010	0.46	0.09	0.54
0.12917	0.19	-0.00001	0.07	0.00008	0.46	0.07	0.54
0.12916	0.19	-0.00002	0.07	0.00012	0.46	0.11	0.54
0.12922	0.19	-0.00001	0.07	0.00006	0.46	0.05	0.54
0.12930	0.19	0.00000	0.07	0.00000	0.46	0.00	0.54
0.12935	0.19	0.00000	0.07	0.00002	0.46	0.02	0.54
0.12941	0.29	-0.00001	0.09	0.00007	0.96	0.06	1.04
0.12960	0.29	0.00000	0.09	0.00003	0.96	0.02	1.04
0.12991	0.29	0.00000	0.09	-0.00001	0.96	-0.01	1.04
0.13025	0.29	0.00001	0.09	-0.00006	0.96	-0.05	1.04
0.13078	0.29	0.00000	0.09	-0.00001	0.96	0.00	1.04
0.13178	0.29	0.00000	0.09	-0.00005	0.96	-0.04	1.04
0.13331	0.39	0.00000	0.10	-0.00001	1.45	-0.01	1.55
0.13373	0.39	-0.00003	0.10	0.00037	1.45	0.30	1.55
0.13582	0.39	-0.00002	0.10	0.00028	1.45	0.22	1.55
0.13704	0.39	-0.00004	0.10	0.00052	1.45	0.40	1.55
0.13861	0.39	-0.00001	0.10	0.00017	1.45	0.13	1.55
0.13993	0.39	-0.00003	0.10	0.00041	1.45	0.32	1.55
0.14120	0.39	0.00000	0.10	0.00006	1.45	0.04	1.55
0.14300	0.39	0.00000	0.10	0.00002	1.45	0.02	1.55
0.14443	0.39	0.00001	0.10	-0.00010	1.45	-0.07	1.55
0.14578	0.39	0.00002	0.10	-0.00022	1.45	-0.16	1.55

Table 7: Accelerometer A; weighted mean and degrees of equivalence for the phase shift measurements

Weighted Mean		Degrees of equivalence (phase)					
WM (°)	U_{WM} (°)	D_{PTB-WM} (°)	U_{PTB-WM} (°)	D_{NML-WM} (°)	U_{NML-WM} (°)	$D_{NML-PTB}$ (°)	$U_{NML-PTB}$ (°)
0.03	0.35	0.01	0.35	-0.01	0.35	-0.02	0.71
0.01	0.35	-0.03	0.35	0.03	0.35	0.06	0.71
-0.01	0.35	0.01	0.35	-0.01	0.35	-0.01	0.71
-0.01	0.35	0.00	0.35	0.00	0.35	-0.01	0.71
-0.01	0.35	-0.02	0.35	0.02	0.35	0.03	0.71
-0.01	0.35	0.01	0.35	-0.01	0.35	-0.03	0.71
-0.02	0.35	0.01	0.35	-0.01	0.35	-0.02	0.71
-0.01	0.35	0.01	0.35	-0.01	0.35	-0.03	0.71
-0.02	0.35	0.01	0.35	-0.01	0.35	-0.01	0.71
-0.02	0.35	0.01	0.35	-0.01	0.35	-0.02	0.71
-0.03	0.35	0.03	0.35	-0.03	0.35	-0.05	0.71
-0.04	0.35	0.02	0.35	-0.02	0.35	-0.04	0.71
-0.05	0.35	0.02	0.35	-0.02	0.35	-0.04	0.71
-0.02	0.35	0.13	0.35	-0.13	0.35	-0.26	0.71
-0.08	0.35	0.05	0.35	-0.05	0.35	-0.10	0.71
-0.08	0.35	0.03	0.35	-0.03	0.35	-0.07	0.71
-0.09	0.35	0.04	0.35	-0.04	0.35	-0.08	0.71
-0.12	0.35	0.06	0.35	-0.06	0.35	-0.11	0.71
-0.15	0.35	0.06	0.35	-0.06	0.35	-0.12	0.71
-0.19	0.35	0.07	0.35	-0.07	0.35	-0.15	0.71
-0.26	0.35	0.11	0.35	-0.11	0.35	-0.22	0.71
-0.31	0.71	0.09	0.71	-0.09	0.71	-0.19	1.41
-0.37	0.71	0.14	0.71	-0.14	0.71	-0.28	1.41
-0.41	0.71	0.19	0.71	-0.19	0.71	-0.37	1.41
-0.57	0.71	0.18	0.71	-0.18	0.71	-0.37	1.41
-0.65	0.71	0.29	0.71	-0.29	0.71	-0.59	1.41
-0.83	0.71	0.33	0.71	-0.33	0.71	-0.66	1.41
-0.66	0.83	0.36	0.55	-0.81	1.25	-1.17	1.80
-0.98	0.83	0.29	0.55	-0.66	1.25	-0.95	1.80
-1.04	0.83	0.33	0.55	-0.75	1.25	-1.09	1.80
-0.97	0.83	0.50	0.55	-1.13	1.25	-1.63	1.80
-0.98	0.83	0.52	0.55	-1.18	1.25	-1.70	1.80
-1.13	0.83	0.53	0.55	-1.20	1.25	-1.74	1.80
-1.14	0.83	0.53	0.55	-1.19	1.25	-1.72	1.80
-1.28	0.83	0.50	0.55	-1.12	1.25	-1.62	1.80
-0.97	0.83	0.69	0.55	-1.55	1.25	-2.23	1.80
-1.54	0.83	0.45	0.55	-1.02	1.25	-1.48	1.80

Table 8: Accelerometer B; weighted mean and degrees of equivalence for the sensitivity magnitude measurements

Weighted Mean		Degrees of equivalence (magnitude)					
WM (pC/m/s^2)	U_{WM} (%)	D_{PTB-WM} (pC/m/s^2)	U_{PTB-WM} (%)	D_{NML-WM} (pC/m/s^2)	U_{NML-WM} (%)	$D_{NML-PTB}$ %	$U_{NML-PTB}$ (%)
0.22062	0.19	-0.00005	0.07	0.00030	0.46	0.16	0.54
0.22023	0.19	-0.00008	0.07	0.00053	0.46	0.28	0.54
0.22027	0.19	-0.00011	0.07	0.00068	0.46	0.36	0.54
0.22013	0.19	-0.00009	0.07	0.00055	0.46	0.29	0.54
0.22012	0.19	-0.00012	0.07	0.00072	0.46	0.38	0.54
0.22022	0.19	-0.00001	0.07	0.00004	0.46	0.02	0.54
0.22012	0.19	-0.00002	0.07	0.00014	0.46	0.08	0.54
0.22029	0.19	0.00001	0.07	-0.00003	0.46	-0.02	0.54
0.22011	0.19	-0.00002	0.07	0.00015	0.46	0.08	0.54
0.22000	0.19	-0.00004	0.07	0.00024	0.46	0.13	0.54
0.22004	0.19	-0.00001	0.07	0.00009	0.46	0.05	0.54
0.22003	0.19	-0.00002	0.07	0.00015	0.46	0.08	0.54
0.22007	0.19	-0.00002	0.07	0.00015	0.46	0.08	0.54
0.22006	0.19	-0.00003	0.07	0.00016	0.46	0.08	0.54
0.21992	0.19	0.00001	0.07	-0.00005	0.46	-0.03	0.54
0.22005	0.19	0.00000	0.07	0.00000	0.46	0.00	0.54
0.21991	0.19	-0.00002	0.07	0.00011	0.46	0.06	0.54
0.21987	0.19	-0.00002	0.07	0.00014	0.46	0.07	0.54
0.21999	0.19	0.00000	0.07	0.00002	0.46	0.01	0.54
0.21998	0.19	0.00000	0.07	0.00001	0.46	0.01	0.54
0.22005	0.19	-0.00001	0.07	0.00007	0.46	0.04	0.54
0.22011	0.29	0.00001	0.09	-0.00012	0.96	-0.06	1.04
0.22016	0.29	0.00001	0.09	-0.00006	0.96	-0.03	1.04
0.22032	0.29	0.00001	0.09	-0.00013	0.96	-0.06	1.04
0.22055	0.29	0.00003	0.09	-0.00036	0.96	-0.18	1.04
0.22089	0.29	0.00003	0.09	-0.00038	0.96	-0.19	1.04
0.22161	0.29	0.00004	0.09	-0.00047	0.96	-0.23	1.04
0.22251	0.39	0.00004	0.10	-0.00049	1.45	-0.24	1.55
0.22293	0.39	0.00004	0.10	-0.00061	1.45	-0.29	1.55
0.22393	0.39	0.00002	0.10	-0.00026	1.45	-0.12	1.55
0.22460	0.39	0.00002	0.10	-0.00023	1.45	-0.11	1.55
0.22524	0.39	0.00002	0.10	-0.00025	1.45	-0.12	1.55
0.22626	0.39	0.00007	0.10	-0.00099	1.45	-0.47	1.55
0.22674	0.39	0.00007	0.10	-0.00094	1.45	-0.44	1.55
0.22749	0.39	0.00009	0.10	-0.00128	1.45	-0.60	1.55
0.22841	0.39	0.00011	0.10	-0.00156	1.45	-0.73	1.55
0.22926	0.39	-0.00004	0.10	0.00054	1.45	0.25	1.55

Table 9: Accelerometer B; weighted mean and degrees of equivalence for the phase shift measurements

Weighted Mean		Degrees of equivalence (phase)					
WM (°)	U_{WM} (°)	D_{PTB-WM} (°)	U_{PTB-WM} (°)	D_{NML-WM} (°)	U_{NML-WM} (°)	$D_{NML-PTB}$ (°)	$U_{NML-PTB}$ (°)
0.08	0.35	0.04	0.35	-0.04	0.35	-0.07	0.71
0.03	0.35	-0.03	0.35	0.03	0.35	0.06	0.71
0.03	0.35	-0.05	0.35	0.05	0.35	0.09	0.71
0.08	0.35	0.01	0.35	-0.01	0.35	-0.02	0.71
0.03	0.35	-0.03	0.35	0.03	0.35	0.05	0.71
-0.01	0.35	-0.04	0.35	0.04	0.35	0.08	0.71
0.00	0.35	-0.02	0.35	0.02	0.35	0.05	0.71
-0.10	0.35	0.02	0.35	-0.02	0.35	-0.03	0.71
-0.02	0.35	-0.04	0.35	0.04	0.35	0.08	0.71
-0.02	0.35	-0.05	0.35	0.05	0.35	0.09	0.71
0.01	0.35	-0.02	0.35	0.02	0.35	0.03	0.71
0.02	0.35	-0.01	0.35	0.01	0.35	0.03	0.71
0.03	0.35	0.00	0.35	0.00	0.35	0.00	0.71
0.03	0.35	-0.02	0.35	0.02	0.35	0.03	0.71
0.01	0.35	0.00	0.35	0.00	0.35	0.01	0.71
0.03	0.35	0.00	0.35	0.00	0.35	0.01	0.71
0.02	0.35	-0.01	0.35	0.01	0.35	0.02	0.71
-0.01	0.35	-0.03	0.35	0.03	0.35	0.07	0.71
-0.03	0.35	-0.04	0.35	0.04	0.35	0.08	0.71
-0.06	0.35	-0.06	0.35	0.06	0.35	0.11	0.71
-0.15	0.35	0.00	0.35	0.00	0.35	0.00	0.71
-0.27	0.71	0.06	0.71	-0.06	0.71	-0.13	1.41
-0.35	0.71	0.13	0.71	-0.13	0.71	-0.26	1.41
-0.44	0.71	0.14	0.71	-0.14	0.71	-0.28	1.41
-0.54	0.71	0.17	0.71	-0.17	0.71	-0.34	1.41
-0.56	0.71	0.11	0.71	-0.11	0.71	-0.21	1.41
-0.50	0.71	-0.04	0.71	0.04	0.71	0.08	1.41
-0.69	0.83	-0.06	0.55	0.14	1.25	0.20	1.80
-0.87	0.83	-0.11	0.55	0.26	1.25	0.37	1.80
-0.98	0.83	-0.15	0.55	0.34	1.25	0.49	1.80
-0.93	0.83	-0.10	0.55	0.22	1.25	0.31	1.80
-0.82	0.83	0.00	0.55	0.01	1.25	0.01	1.80
-1.17	0.83	-0.08	0.55	0.18	1.25	0.26	1.80
-1.30	0.83	-0.10	0.55	0.22	1.25	0.31	1.80
-1.36	0.83	-0.16	0.55	0.35	1.25	0.51	1.80
-1.42	0.83	-0.16	0.55	0.35	1.25	0.51	1.80
-1.60	0.83	-0.18	0.55	0.41	1.25	0.59	1.80

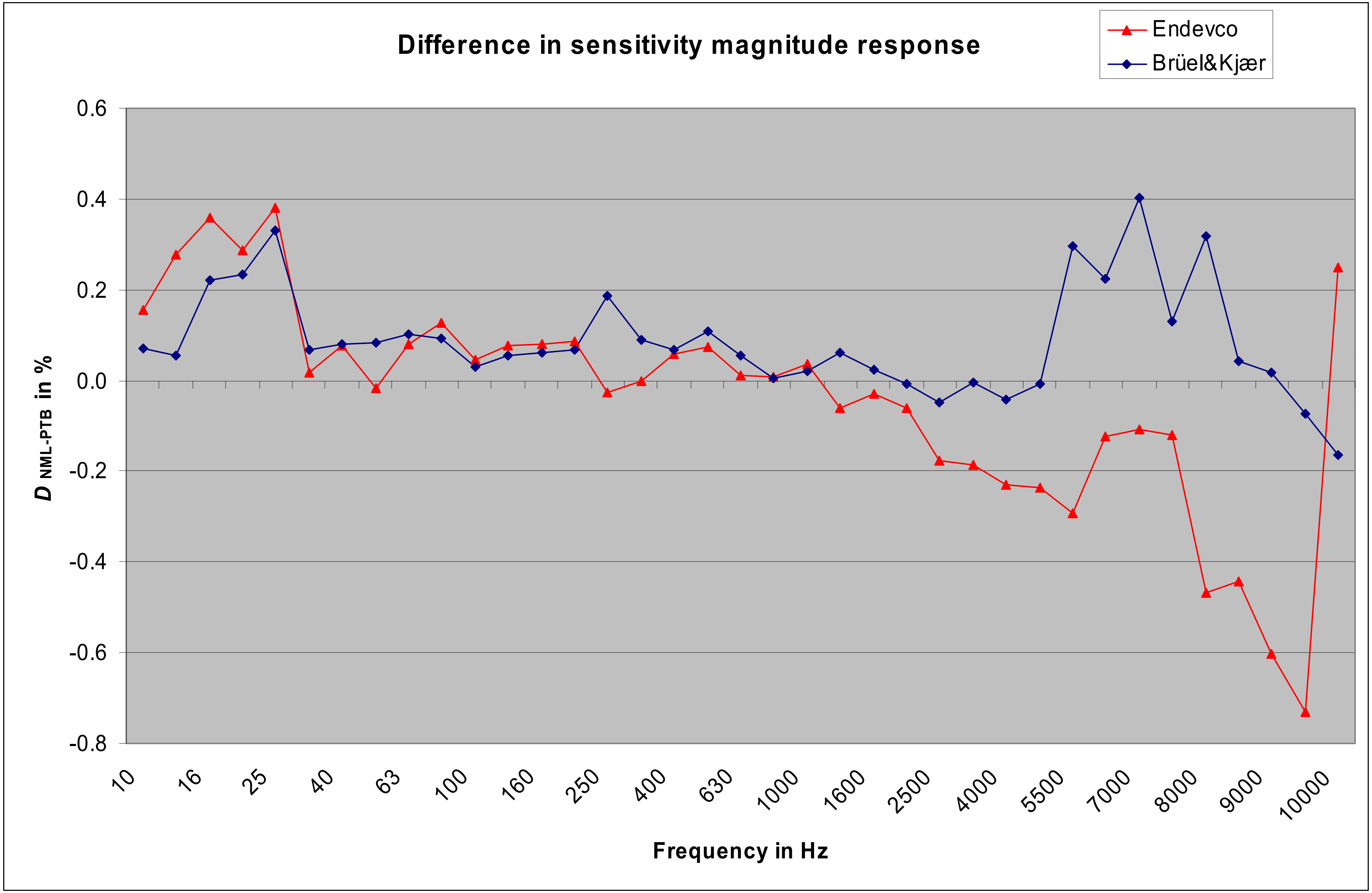


Figure 3: Degrees of equivalence (magnitude sensitivity) for accelerometers A & B

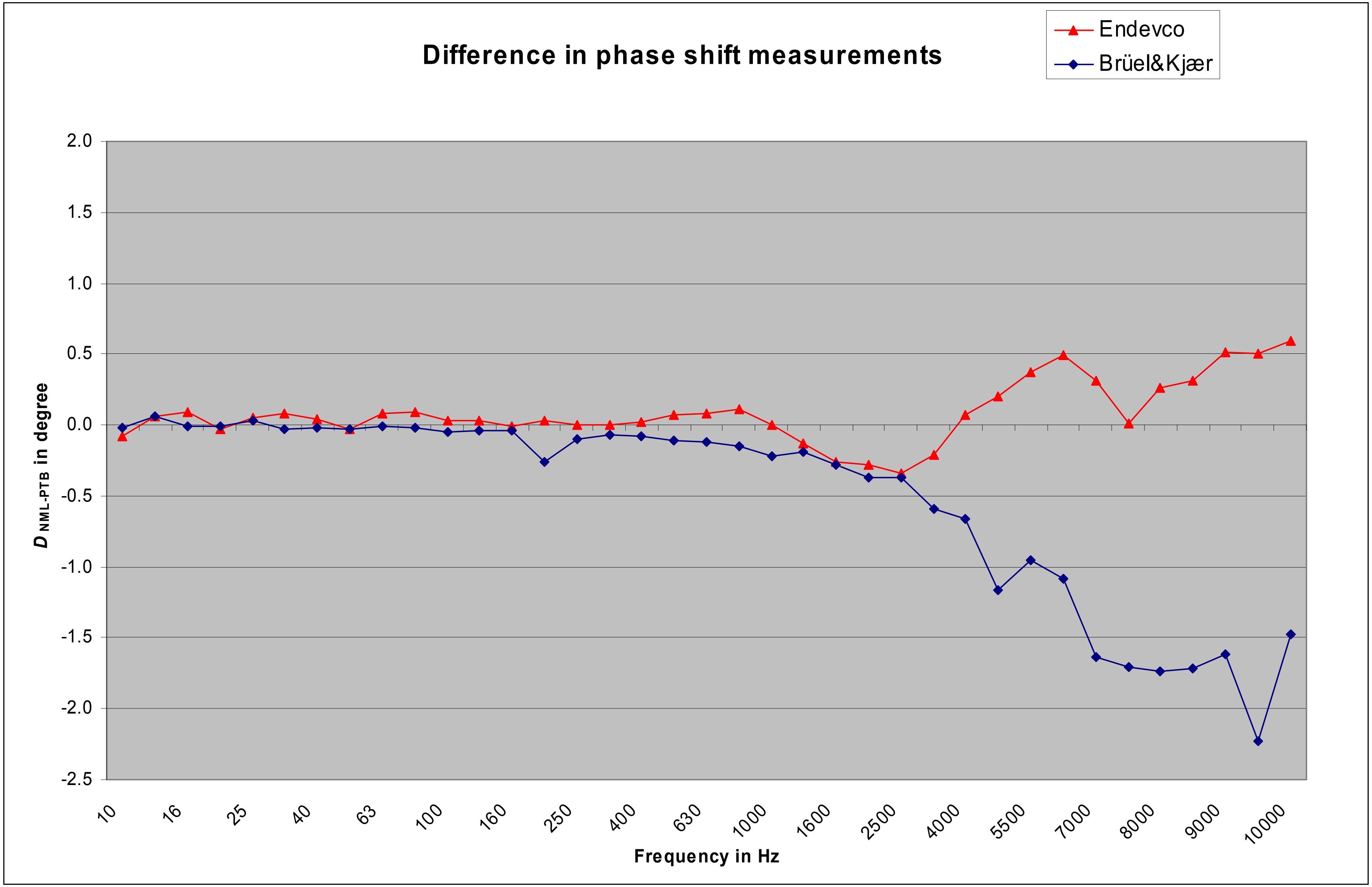
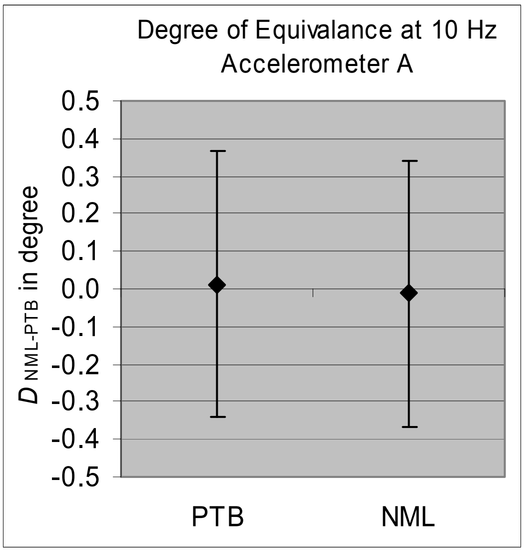
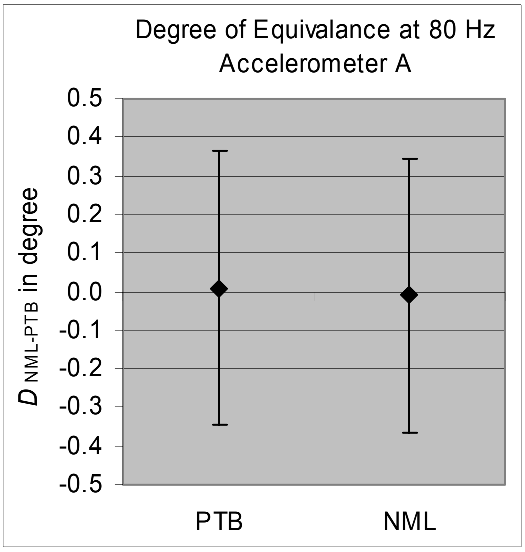
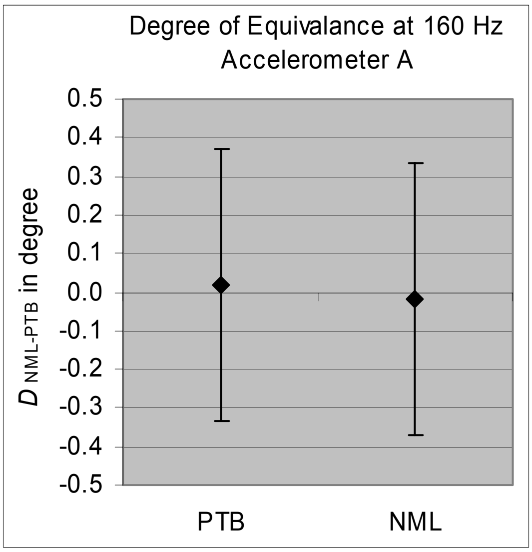
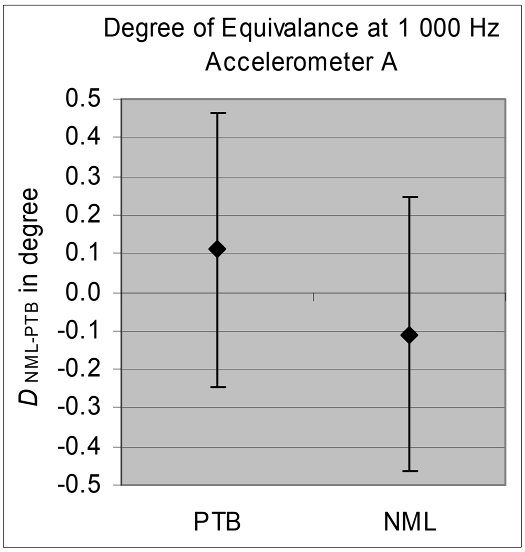


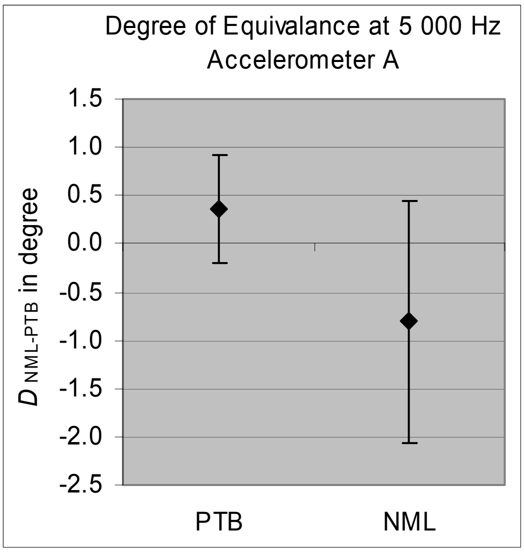
Figure 4: Degrees of equivalence for phase shift measurements for accelerometers A & B

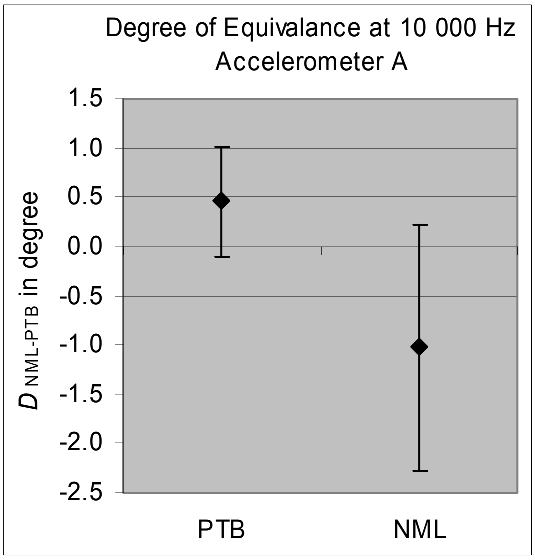

Degree of Equivalance at 10 Hz
Accelerometer A
D NML-PTB in degree
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
PTB
NML

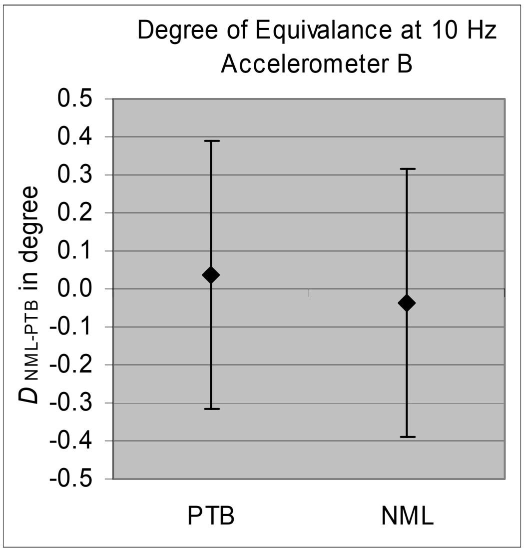

Degree of Equivalance at 80 Hz
Accelerometer A
D NML-PTB in degree
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
PTB
NML

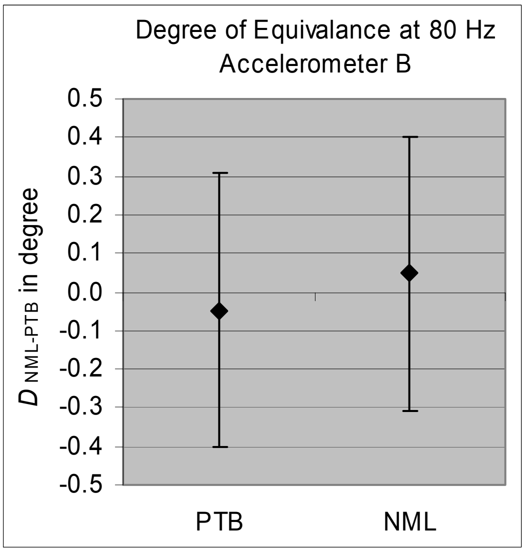

Degree of Equivalance at 160 Hz
Accelerometer A
D NML-PTB in degree
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
PTB
NML

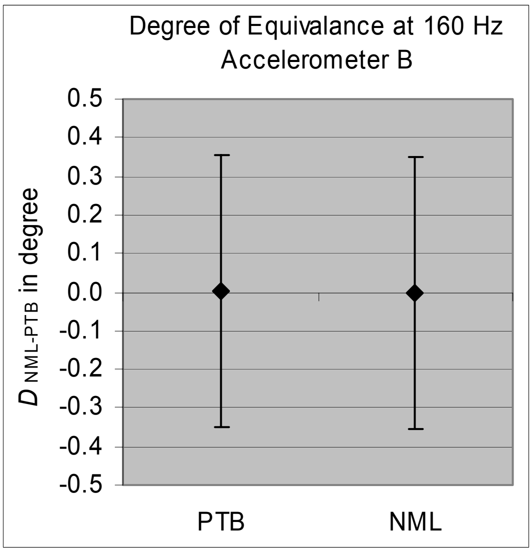

Degree of Equivalance at 1 000 Hz
Accelerometer A
D NML-PTB in degree
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
PTB
NML

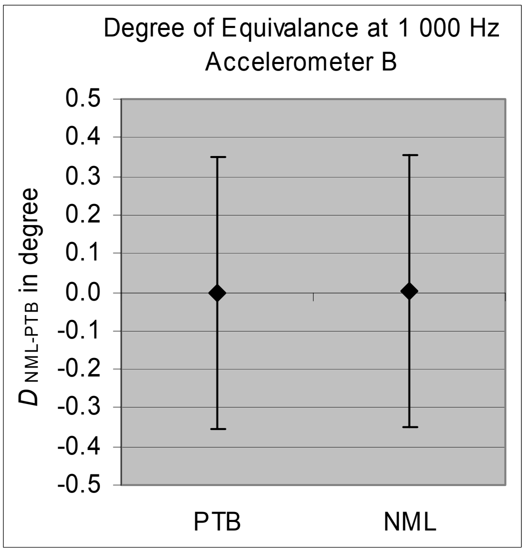

Degree of Equivalance at 5 000 Hz
Accelerometer A
D NML-PTB in degree
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
PTB
NML

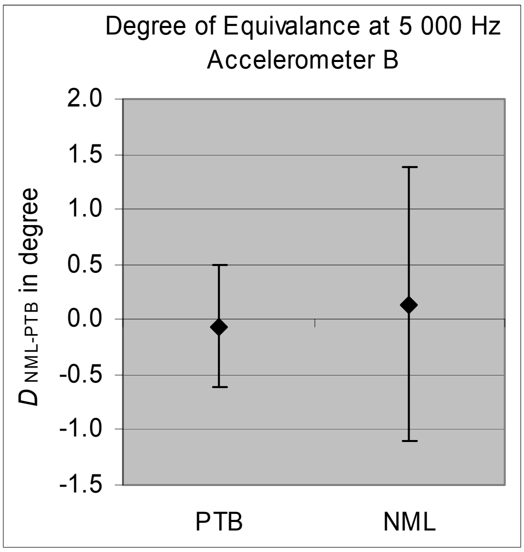

Degree of Equivalance at 10 000 Hz
Accelerometer A
D NML-PTB in degree
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
PTB
NML

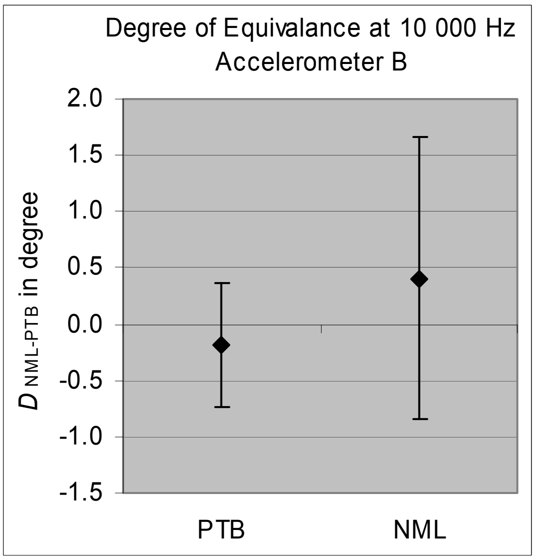

Degree of Equivalance at 10 Hz
Accelerometer B
D NML-PTB in degree
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
PTB
NML


Degree of Equivalance at 80 Hz
Accelerometer B
D NML-PTB in degree
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
PTB
NML


Degree of Equivalance at 160 Hz
Accelerometer B
D NML-PTB in degree
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
PTB
NML


Degree of Equivalance at 1 000 Hz
Accelerometer B
D NML-PTB in degree
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
PTB
NML


Degree of Equivalance at 5 000 Hz
Accelerometer B
D NML-PTB in degree
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
PTB
NML


Degree of Equivalance at 10 000 Hz
Accelerometer B
D NML-PTB in degree
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
PTB
NML

9.3 Results - Part 2: Comparison reference values and laboratory degrees of equivalence

The supplementary comparison reference values (SCRVs) for the complex sensitivity (magnitude and phase) for accelerometers A & B are listed in tables 6 to 9.

Table 6 and table 8 list the calculated magnitude SCRVs for accelerometer A & B respectively. These tables also lists the deviation of the reported sensitivities from the SCRVs by each individual laboratory ($D_{\text{NMI-WM}}$) as well as the difference in sensitivity magnitude values obtained between the two laboratories ($D_{\text{NML-PTB}}$). The calculated associated uncertainty for the sensitivity results, ($U_{\text{NMI-WM}}$) as well as ($U_{\text{NML-PTB}}$), for (k=2) are reported with the difference values are also listed in the tables.

Table 7 and table 9 list the calculated phase shift SCRVs for accelerometer A & B respectively. These tables also lists the deviation of reported phase shifts from the SCRVs by each individual laboratory ($D_{\text{NMI-WM}}$) as well as the difference in phase shift values obtained between the two laboratories ($D_{\text{NML-PTB}}$). The calculated associated uncertainty for the phase shift results, ($U_{\text{NMI-WM}}$) as well as ($U_{\text{NML-PTB}}$), for (k=2) are reported with the difference values.

10 Discussion of the measurement results

An appropriate method to compute SCRVs and degrees of equivalence is discussed in section 9.

Though the participants applied laser interferometry in accordance with ISO 16063-11 as required [4], this international standard also specifies that three different interferometric methods are applicable in various versions and techniques.

Although the same method was applied by the laboratories for SADCMET.AUV.V-S1 (i.e. ISO 16063-11 method 3), the systems implemented were largely different with respect to vibration exciters, laser interferometers, vibration isolation systems, hardware and signal processing configurations and measurement procedures. This explains the following observations.

Ratio between smallest and largest declared uncertainty:

- The uncertainties declared by the laboratories for the same frequency and for the same accelerometer differed from one another;
  - Magnitude - ratio 2.5 to ratio 3.75
  - Phase shift - ratio 1 to ratio 1.5

Frequency dependence of uncertainty:

- The declared uncertainties were frequency-dependent; the ratio of the highest (at 10 kHz) to lowest value (at 160 Hz or lower) by the same laboratory was between
  - Magnitude – 2 and 3 for PTB and NML respectively
  - Phase shift – 2 and 3 for PTB and NML respectively

Acceleration measurement capability:

- A comparison of the acceleration measurements is described by the calibration results for the accelerometers, assuming that there was no relative motion between the laser light spot sensing the motion close to the accelerometer and its reference surface. Both laboratories in this case demonstrated very good measurement capabilities (i.e. the relative deviations from the reference sensitivity values were clearly below 0.5% for accelerometer A and 0.8% for accelerometer B over the complete frequency range 10 Hz to 10 kHz).

Phase measurement capability:

- A comparison of the phase shift measurements is described by the calibration results for the accelerometers. Both laboratories in this case demonstrated very good measurement capabilities (i.e. the relative deviations from the reference phase shift values were clearly below 0.5 degrees for accelerometer B the complete frequency range 10 Hz to 10 kHz).

Credibility of uncertainty statements:

- ISO Standard 16063-11:1999 [4] provides well-established uncertainty budgets which were included as a formal part in the Technical Protocol. Accordingly, both laboratories submitted uncertainty budgets in compliance with the GUM.

11 Conclusions

Two NMIs measured the complex charge sensitivity of two different transfer standards (single-ended accelerometer at 37 frequencies from 10 Hz to 10 kHz). The results of the SADCMET.AUV.V-S1 are a set of SCRVs, their uncertainties and degrees of equivalence regarding the SCRV and regarding the laboratories with respect to one another. From this complete set of results, six matrices of equivalence per accelerometer were selected and demonstrated by graphs (figures 5 to 12).

In the calibration of the single-ended accelerometer, the reference surface (mounting surface) is not accessible to the laser light beam. Relative motion between the acceleration acting on and converted by the single-ended accelerometer and the acceleration sensed by the laser interferometer (close to the accelerometer) may have been present. In each case, the calibration results obtained for the SE accelerometer represent the current calibration capabilities of the participating laboratories for the complex charge sensitivity of single-ended accelerometers.

At the reference frequency of 160 Hz (specified in ISO 16063-11:1999), the participating laboratories calibrated both transfer standards with a relative expanded uncertainty (k = 2) smaller than 0.5%, i.e. the limit specified by the ISO standard [2], cf. also Technical Protocol [3].

In the most important frequency range of 40 Hz to 5 kHz covered by the key comparison CCAUV.V-K1 [1], the deviations between the corresponding PTB and NML results were smaller than 0.4° for the phase shift measured (22 measurement points) for the Endevco accelerometer. For the Brüel & Kjær accelerometer, the deviations between the corresponding PTB and NML results were smaller than 1.2° for the phase shift measurements (22 measurement points).

For the frequency range 10 Hz to 10 kHz, the deviations between the PTB and NML results were smaller than 0.6° for the phase shift measurements (37 measurement points) for the Endevco accelerometer. While with the Brüel & Kjær accelerometer for the frequency range 10 Hz to 10 kHz, the deviations between the PTB and NML results were smaller than 2° for the phase shift measurements (37 measurement points).

The uncertainties calculated for the phase shift difference values of PTB ranged from 0.4° to 0.7°. The corresponding uncertainties calculated for the phase shift difference values of the NML ranged from 0.4° to 1.2°.

In conclusion, the degrees of equivalence calculated from the data submitted by the two laboratories, support the uncertainty of measurement reported by the two laboratories for the calibration of the complex sensitivities of accelerometers over the frequency range 10 Hz to 10 kHz.

12 Acknowledgements

The authors would like to acknowledge the management of the CSIR-NML and PTB for their continued support for scientific research in metrology in the field of vibration.

The authors are grateful to the staff of the Acoustics, Ultrasound and Vibration Laboratory of the NML, responsible for Vibration, Me Katrina Davis, as well as to the staff of the Acceleration Working Group of PTB, Me. Angelika Täubner, Wolfgang Wabinski, Uwe Göbel and Dr. Alfred Link.
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