RESULTS OF A EUROPEAN COMPARISON IN LOW FREQUENCY DOMAIN

Claire BARTOLI

[1] LNE,29 avenue Roger Hennequin, 78190 TRAPPES, France, claire.bartoli@lne.fr

Abstract − A comparison in the area of vibration including 10 countries was conducted for the first time within the framework of the Euramet community in the low frequency domain DC – 200 Hz with a mandatory range of 1 – 80 Hz. The aim of this work is to compare primary interferometric measurements of complex voltage sensitivity for a standard accelerometer following standard ISO 16063-11 [1]. This comparison is registered in the BIPM database.

Keywords: interlaboratory comparison, calibration, accelerometer, vibration.

1. INTRODUCTION

This paper presents an overview of the results of the Euramet low frequency comparison registered in the BIPM database (Mutual Recognation Arrangement / Appendix B) as EURAMET.AUV.V-K3. It was organised and conducted in accordance with the guidelines for CIPM comparison [2]. It will be linked to the key comparison CCAUV.V-K3 as soon as the latter is completed. The aim is to link the weighted mean (WM) determined in this comparison to the future Key Comparison Reference Value that will be supplied by the CCAUV comparison.

Ten European countries participated through their national metrology institute, from January 2012 to September 2013, for the measurements. All participants used calibration performed calibration using method 3 Sine Approximation Method described in the international standard ISO 16063-11:1999 [1] and technical protocol which specifies in details the aim and the task of the comparison, the specifications of the device, and any requested information.

The ten participants were: CMI (Czech Republic), SP (Sweden), METAS (Switzerland), INRIM (Italy) GUM (Poland), CEM (Spain), PTB (Germany) and LNE (France).

2. ARTEFACT OF THE COMPARISON

2.1. Description

An accelerometer dedicated to low frequency working range was used: the Honeywell Q Flex sensor QA 700 with its conditioning module. Electric schemas were supplied in order to avoid any impedance input troubles.

Its current output and sensitivity, in mA/(m/s²) are conditioned to have voltage ones, in mV/(m/s²), which are less sensitive to external effects. Its nominal sensitivity is 500 mV/(m/s²).
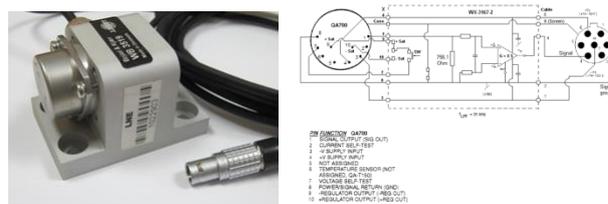

Fig. 1. Photo and schema of the device and its conditioning unit

The sensor can be powered well by an ICP input well using the power supply unit as presented below. It has to be connected to a +15 / 0 / -15V power supply unit (3 banana plugs) and from chassis/shield to ground or 0 V (1 banana plug) on the measurement instrument. The supply voltage shall be accurate within +/- 0.2 V.

Fig. 3. Photo of the power supply unit
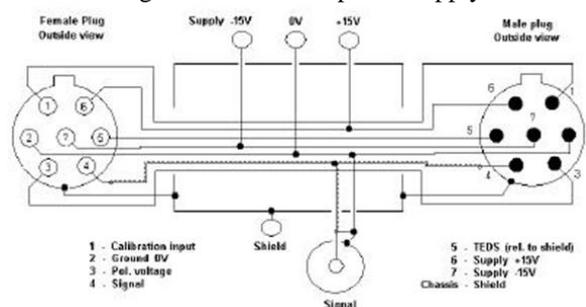
Fig. 3. Schema of the power supply unit

2.2. Circulation

The transducer was circulated in a star type fashion with a measurement period of two weeks, provided for each participant, and two weeks for the pilot laboratory. Between each measurement by a participant, a monitoring measurement of the accelerometer was performed. The monitoring could not be performed twice due to problems with the calibration system of the pilot laboratory. All the participants agreed to continue the measurements without monitoring.

2.3. Monitoring

The artefact was monitored by the pilot laboratory before and during the whole comparison.

As a representative of the overall change, the monitoring for the magnitude of the complex sensitivity is presented in figure 4 at several example frequencies. They depict the stability of the artefact over time for the duration of the comparison with the uncertainties of the pilot.

Same measurements were made for the phase of the complex sensitivity and it can be concluded that it did not drift over the comparison period.
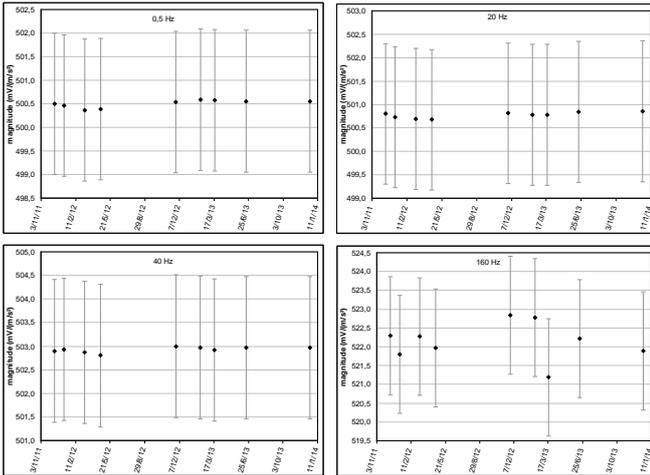

Fig. 4. Monitoring of the amplitude sensitivity over the comparison period

The visual inspection of the graphed results allows us to conclude that the device was sufficiently stable during the whole period of the comparison.

2.4 Calibration bench

The calibration bench where measurements have to be done is very specific to the frequency range. In the low frequency domain (below 10 Hz), dedicated exciters are used. They have specific characteristics such as a long stroke and air-borne moving part.

All laboratories involved used this kind of exciters.

Concerning the signals acquisition and their processing, different options can be made for the acquisition and analysis. Some companies supply systems that automatically perform the acquisition and the analysis in primary configuration which are used by national metrology institutes. Others can use home-made software in complement to acquisition system.

3. RESULTS OF THE PARTICIPANTS

The following sections report the results submitted by the participants of the comparison to the pilot laboratory using the mandatory report spreadsheet. The results presented are in [mV/(m/s²)] for the magnitude and in [°] for the phase. They were rounded up by the pilot when necessary.

actual frequency in Hz	LNE magnitude of voltage sensitivity mV/(m/s²)	LNE rel. exp. Unc. %	CMI magnitude of voltage sensitivity mV/(m/s²)	CMI rel. exp. Unc. %	SP magnitude of voltage sensitivity mV/(m/s²)	SP rel. exp. Unc. %	METAS magnitude of voltage sensitivity mV/(m/s²)	METAS rel. exp. Unc. %	INRIM magnitude of voltage sensitivity mV/(m/s²)	INRIM rel. exp. Unc. %
DC			500,2	0,2	500,1	0,2	500,06	0,01	500,0	0,4
0,1			509,0	1,7						
0,125			506,1	1,1						
0,16			504,5	0,8						
0,2			502,8	0,5			501,5	0,47		
0,25			501,8	0,4			499,8	0,38		
0,315			501,5	0,4	495,3	1,8	500,0	0,34		
0,4			501,3	0,4	497,0	1,1	500,3	0,32		
0,5	500,5	0,3	500,9	0,4	498,2	0,8	500,2	0,32	498,8	0,4
0,63	500,3	0,3	500,7	0,4	499,0	0,5	500,3	0,31		
0,8	500,0	0,3	500,6	0,4	499,4	0,4	500,2	0,31	498,3	0,4
1	500,1	0,3	500,6	0,4	499,6	0,3	500,3	0,30	497,9	0,4
1,25	500,1	0,3	500,8	0,4	499,7	0,3	500,3	0,30	498,4	0,4
1,60	500,1	0,3	500,8	0,4	499,8	0,3	500,4	0,30	498,9	0,4
2	500,2	0,3	500,6	0,4	499,9	0,3	500,2	0,30	499,2	0,4
2,50	500,0	0,3	500,7	0,4	500,1	0,3	500,3	0,29	499,2	0,4
3,15	500,1	0,3	500,6	0,4	500,0	0,3	500,3	0,29	499,2	0,4
4	500,1	0,3	500,6	0,4	500,1	0,3	500,3	0,29	499,0	0,4
5	500,1	0,3	500,6	0,4	500,1	0,3	500,4	0,24	499,1	0,4
6,3	500,1	0,3	500,7	0,4	500,2	0,3	500,5	0,24	499,1	0,4
8	500,2	0,3	500,9	0,4	500,2	0,3	500,5	0,24	499,2	0,4
10	500,2	0,3	500,8	0,4	500,3	0,3	500,6	0,37	499,2	0,4
12,5	500,3	0,3	500,9	0,4	500,5	0,3	500,6	0,37	499,3	0,4
16	500,5	0,3	501,1	0,4	500,6	0,3	500,8	0,37	499,7	0,4
20	500,8	0,3	501,5	0,4	500,9	0,3	501,0	0,37	500,1	0,4
25	501,2	0,3	502,1	0,4	501,3	0,3	501,4	0,36	500,4	0,4
31,5	501,9	0,3	502,9	0,4	502,0	0,3	502,1	0,36	501,2	0,4
40	502,9	0,3	503,6	0,4	502,8	0,3	503,2	0,36	502,3	0,4
50	504,4	0,3	504,8	0,4	502,9	0,3	504,9	0,36	504,1	0,4
63	506,7	0,3	507,2	0,4	505,8	0,4	507,0	0,70	506,3	0,4
80	509,9	0,3	509,7	0,4	509,7	0,4	510,2	0,70	508,7	0,4
100	513,7	0,3	513,8	0,4	513,8	0,4	514,1	0,70	513,7	0,4
125	518,0	0,3	518,1	0,4	519,0	0,4	518,6	0,70	517,9	0,4
160	522,3	0,3	522,7	0,4			522,7	0,70	522,0	0,4
200			519,0	0,4	522,1	1,1	525,3	0,70		

actual frequency in Hz	GUM magnitude of voltage sensitivity mV/(m/s²)	GUM rel. exp. Unc. %	CEM magnitude of voltage sensitivity mV/(m/s²)	CEM rel. exp. Unc. %	PTB magnitude of voltage sensitivity mV/(m/s²)	PTB rel. exp. Unc. %	DPLA magnitude of voltage sensitivity mV/(m/s²)	DPLA rel. exp. Unc. %	MIKES magnitude of voltage sensitivity mV/(m/s²)	MIKES rel. exp. Unc. %
DC					500,00	0,2	500,21	0,05		
0,1					497,72	0,5	500,4	0,5		
0,125					498,79	0,5	500,3	0,5		
0,16					498,83	0,5	500,4	0,5		
0,2					499,45	0,3	499,9	0,4		
0,25					499,25	0,3	499,9	0,4		
0,315					499,69	0,3	499,9	0,4		
0,4			499,9	0,5	499,62	0,2	499,9	0,4		
0,5			499,9	0,5	499,72	0,2	500,0	0,4		
0,63			499,9	0,5	499,70	0,2	499,9	0,4		
0,8			499,9	0,5	499,78	0,2	499,9	0,4		
1	500,40	0,7	499,9	0,5	499,82	0,2	499,9	0,4	499,6	0,5
1,25	500,41	0,7	499,9	0,5	499,81	0,2	499,9	0,4	499,7	0,5
1,60	500,32	0,7	499,9	0,5	499,82	0,2	499,9	0,4	499,7	0,5
2	500,18	0,7	499,9	0,5	499,87	0,2	499,9	0,4	499,6	0,5
2,50	500,24	0,7	499,9	0,5	499,75	0,2	499,9	0,4	499,7	0,5
3,15	500,18	0,7	499,9	0,5	499,75	0,2	499,9	0,4	500,0	0,5
4	500,22	0,7	499,9	0,5	499,81	0,2	500,0	0,4	499,9	0,5
5	500,32	0,7	500,0	0,5	499,72	0,2	500,0	0,4	500,0	0,5
6,3	500,34	0,7	500,0	0,5	499,75	0,2	500,0	0,4	500,1	0,5
8	500,32	0,7	500,1	0,5	499,76	0,2	500,0	0,4	500,1	0,5
10	500,42	0,6	500,1	0,5	499,78	0,1	500,1	0,4	500,1	0,5
12,5	500,48	0,6	500,1	0,5	499,90	0,1	500,2	0,4	500,1	0,5
16	500,70	0,6	500,4	0,5	500,12	0,1	500,4	0,4	500,3	0,5
20	500,97	0,5	500,7	0,5	500,44	0,1	500,8	0,4	500,5	0,5
25	501,41	0,5	501,1	0,5	500,86	0,1	501,2	0,5	501,0	0,5
31,5	502,04	0,5	501,8	0,5	501,57	0,1	501,7	0,5	501,6	0,5
40	503,03	0,5	502,8	0,5	502,64	0,1	502,5	0,5	502,4	0,5
50	506,07	0,5	504,3	0,5	504,15	0,1	504,5	0,5	504,3	0,6
63	506,74	0,5	506,4	0,5	506,41	0,1	505,9	0,5	506,3	0,6
80	510,04	0,6	510,3	0,5	509,67	0,1	515,8	1,5	509,0	1,0
100	513,96	0,6			513,71	0,1				
125	518,45	0,6			517,84	0,1				
160	522,14	0,7			522,45	0,1				
200					525,05	0,1				

Table 1. Reported participant's results for the magnitude of the accelerometer with relative expanded uncertainties (k=2)

actual frequency in Hz	LNE phase of voltage sensitivity in °	LNE abs. exp. Uno. in °	CMI phase of voltage sensitivity in °	CMI abs. exp. Uno. in °	SP phase of voltage sensitivity in °	SP abs. exp. Uno. in °	METAS phase of voltage sensitivity in °	METAS abs. exp. Uno. in °	INRIM phase of voltage sensitivity in °	INRIM abs. exp. Uno. in °
DC										
0,1			0,06	0,30						
0,125			-0,01	0,30						
0,16			-0,01	0,30						
0,2			0,02	0,30			-0,08	0,78		
0,25			0,01	0,30			0,09	0,78		
0,315			0,00	0,30	-0,02	0,30	0,07	0,78		
0,4			0,00	0,30	-0,02	0,30	0,03	0,78		
0,5			0,00	0,30	-0,01	0,30	0,03	0,78		
0,63			0,00	0,30	0,00	0,30	0,01	0,78		
0,8			0,01	0,30	-0,01	0,30	0,02	0,78		
1			-0,08	0,30	-0,01	0,30	0,01	0,46		
1,25			-0,12	0,30	-0,01	0,30	0,00	0,46		
1,6			-0,15	0,30	-0,01	0,30	0,00	0,46		
2,0			-0,20	0,30	-0,01	0,30	0,00	0,46		
2,50			-0,21	0,30	-0,01	0,30	-0,01	0,46		
3,15			-0,14	0,30	-0,02	0,30	-0,02	0,46		
4			-0,15	0,30	-0,02	0,30	-0,02	0,46		
5			-0,08	0,30	-0,03	0,30	-0,03	0,46		
6,3			-0,07	0,30	-0,04	0,30	-0,03	0,46		
8			-0,03	0,30	-0,05	0,30	-0,05	0,46		
10			-0,01	0,30	-0,06	0,30	-0,07	0,46		
12,5			0,03	0,30	-0,08	0,30	-0,10	0,40		
16			-0,06	0,30	-0,09	0,30	-0,11	0,40		
20			-0,10	0,30	-0,13	0,30	-0,14	0,40		
25,0			-0,14	0,30	-0,18	0,30	-0,17	0,41		
31,5			-0,19	0,30	-0,25	0,30	-0,24	0,41		
40			-0,34	0,30	-0,34	0,30	-0,33	0,41		
50			-0,44	0,50	-0,43	0,30	-0,47	0,41		
63			-0,68	0,50	-0,65	0,30	-0,71	0,72		
80			-1,08	0,50	-1,11	0,30	-1,08	0,72		
100			-1,67	0,50	-1,88	0,30	-1,73	0,72		
125			-2,57	0,50	-2,59	0,40	-2,66	0,72		
160			-4,04	0,50			-4,00	0,72		
200			-5,89	0,50			-5,89	0,72		

actual frequency in Hz	GUM phase of voltage sensitivity in °	GUM abs. exp. Unc. in °	CEM phase of voltage sensitivity in °	CEM abs. exp. Unc. in °	PTB phase of voltage sensitivity in °	PTB abs. exp. Unc. in °	DPLA phase of voltage sensitivity in °	DPLA abs. exp. Unc. in °	MIKES phase of voltage sensitivity in °	MIKES abs. exp. Unc. in °
DC										
0,1					-0,05	0,20	-0,20	0,30		
0,125					-0,16	0,20	0,00	0,30		
0,16					-0,07	0,20	0,00	0,30		
0,2					-0,09	0,20	0,00	0,30		
0,25					-0,05	0,20	0,00	0,30		
0,315					-0,04	0,20	0,00	0,30		
0,4			-0,07	0,50	-0,06	0,20	0,00	0,30		
0,5			-0,06	0,50	-0,05	0,20	0,00	0,30		
0,63			-0,05	0,50	-0,04	0,20	0,00	0,30		
0,8			-0,04	0,50	-0,05	0,20	0,00	0,30		
1	-0,04	0,70	-0,04	0,50	-0,03	0,20	-0,01	0,30	-0,02	0,60
1,25	-0,03	0,70	-0,03	0,50	-0,05	0,20	-0,01	0,30	-0,03	0,60
1,6	-0,03	0,70	-0,03	0,50	-0,05	0,20	-0,01	0,30	0,00	0,60
2,0	-0,03	0,70	-0,03	0,50	-0,06	0,20	-0,01	0,30	-0,03	0,60
2,50	-0,03	0,70	-0,03	0,50	-0,04	0,20	-0,01	0,30	-0,05	0,60
3,15	-0,03	0,70	-0,03	0,50	-0,05	0,20	-0,02	0,30	-0,04	0,60
4	-0,03	0,70	-0,03	0,50	-0,07	0,20	-0,02	0,30	-0,05	0,60
5	-0,04	0,70	-0,04	0,50	-0,05	0,20	-0,03	0,30	-0,06	0,60
6,3	-0,04	0,70	-0,04	0,50	-0,07	0,20	-0,04	0,30	-0,06	0,60
8	-0,05	0,70	-0,05	0,50	-0,09	0,20	-0,05	0,30	-0,09	0,60
10	-0,06	0,70	-0,07	0,50	-0,09	0,20	-0,06	0,30	-0,10	0,60
12,5	-0,07	0,70	-0,10	0,50	-0,12	0,20	-0,08	0,30	-0,14	0,60
16	-0,09	0,70	-0,11	0,50	-0,15	0,20	-0,10	0,30	-0,18	0,60
20	-0,13	0,60	-0,13	0,50	-0,19	0,20	-0,14	0,30	-0,24	0,60
25,0	-0,17	0,60	-0,18	0,50	-0,24	0,20	-0,20	0,30	-0,29	0,60
31,5	-0,23	0,60	-0,24	0,50	-0,32	0,20	-0,23	0,50	-0,40	0,60
40	-0,32	0,60	-0,33	0,50	-0,43	0,20	-0,29	0,50	-0,52	0,60
50	-0,42	0,60	-0,47	0,50	-0,59	0,20	-0,44	0,50	-0,68	0,70
63	-0,72	0,70	-0,70	0,50	-0,85	0,20	-0,8	1,0	-1,11	0,70
80	-1,07	0,70	-0,91	0,50	-1,28	0,20	-0,8	1,0	-1,5	1,1
100	-1,70	0,70			-1,86	0,20				
125	-2,65	0,70			-2,87	0,20				
160	-4,09	0,80			-4,40	0,20				
200					-6,32	0,20				

Table 2. Reported participant's results for the phase shift of the accelerometer with absolute expanded uncertainties (k=2)

4. DEGREES OF EQUIVALENCE WITH RESPECT TO THE WEIGHTED MEAN

The evaluation of the results was performed using a weighted mean of the form:

$$x_{WM}(f) = \sum \frac{x_i(f)}{u_i^2(f)} \cdot \left(\sum \frac{1}{u_i^2(f)} \right)^{-1} \quad (1)$$

$$u_{WM}(f) = \left(\sum \frac{1}{u_i^2(f)} \right)^{-1/2} \quad (2)$$

Where the summation was performed over the largest consistent subset of the results of the participants according to (1). In the equations the following shortcuts were used:

$x_i(f)$ Result of participant i of the largest consistent subset at frequency f

$u_i(f)$ Absolute standard uncertainty of participant i of the largest consistent subset at frequency f

$x_{WM}(f)$ Best estimate of the weighted mean (WM) sensitivity at frequency f

$u_{WM}(f)$ Estimated absolute standard uncertainty for the weighted mean (WM) at frequency f

Consistency check was performed for phase and magnitude of the complex sensitivity. The consistency test defined by Cox in [3,4] was applied in order to determine the participants that are members of the largest consistent subset (MoCS).

Table 3 presents the results of the consistency test for both magnitude and phase results.

Cells in yellow are when $X^2_{obs} > X^2_{nu}$.

Frequency	number of participants	number of degrees of freedom	X^2_{obs}	$X^2(nu)$ with P<0,05	Frequency	number of participants	number of degrees of freedom	X^2_{obs}	$X^2(nu)$ with P<0,05
DC	6	5	1,56	11,07	DC				
0,1	3	2	7,38	5,991	0,1	3	2	1,49	5,991
0,125	3	2	5,77	5,991	0,125	3	2	1,13	5,991
0,16	3	2	5,71	5,991	0,16	3	2	0,21	5,991
0,2	4	3	6,37	7,815	0,2	4	3	0,46	7815
0,25	4	3	4,26	7,815	0,25	4	3	0,23	7,815
0,315	5	4	3,46	9,488	0,315	5	4	0,14	9,488
0,4	6	5	3,56	11,07	0,4	6	5	0,21	11,07
0,5	8	7	3,81	14,067	0,5	6	5	0,15	11,07
0,63	7	6	1,81	12,592	0,63	6	5	0,10	11,07
0,8	8	7	3,36	14,067	0,8	6	5	0,15	11,07
1	10	9	5,06	16,919	1	8	7	0,18	2,167
1,25	10	9	3,67	16,919	1,25	8	7	0,42	14,067
1,6	10	9	2,35	16,919	1,6	8	7	0,65	14,067
2	10	9	1,35	16,919	2	8	7	1,20	14,067
2,5	10	9	1,70	16,919	2,5	8	7	1,34	14,067
3,15	10	9	1,38	16,919	3,15	8	7	0,48	14,067
4	10	9	1,76	16,919	4	8	7	0,57	14,067
5	10	9	2,09	16,919	5	8	7	0,09	14,067
6,3	10	9	2,33	16,919	6,3	8	7	0,06	14,067
8	10	9	2,33	16,919	8	8	7	0,14	14,067
10	10	9	2,76	16,919	10	8	7	0,18	14,067
12,5	10	9	2,55	16,919	12,5	8	7	0,72	14,067
16	10	9	2,12	16,919	16	8	7	0,30	14,067
20	10	9	2,01	16,919	20	8	7	0,30	14,067
25	10	9	2,49	16,919	25	8	7	0,36	14,067
31,5	10	9	2,42	16,919	31,5	8	7	0,66	14,067
40	10	9	1,54	16,919	40	8	7	0,71	14,067
50	10	9	6,28	16,919	50	8	7	1,28	14,067
63	10	9	1,46	16,919	63	8	7	1,53	14,067
80	10	9	3,96	16,919	80	8	7	2,77	14,067
100	7	6	0,08	12,592	100	5	4	1,37	9,488
125	7	6	1,46	12,592	125	5	4	2,65	9,488
160	6	5	0,32	11,07	160	4	3	3,00	7,815
200	4	3	32,85	7,815	200	4	2	3,55	5,991

Table 3. results of the consistency test respectively for amplitude (left) and phase (right)

4.1 Results for the magnitude of the complex sensitivity

In the following section, the results of the participants are given in a tabulated form and in a graphical representation with reference to the WM (zero line) for each frequency.

Results which were excluded from the largest consistent subset (non MoCS) and which therefore did not contribute to the WM are also marked by an asterisk (*).

For further evaluation of the comparison, the degrees of equivalence, with respect to the WM, are proposed to be calculated according to:

$$d_{i,WM}(f) = x_i(f) - x_{WM}(f)$$

$$u_{i,WM}^2(f) = \begin{cases} u_i^2(f) - u_{WM}^2(f) & \text{for MoCs} \quad (3) \\ u_i^2(f) + u_{WM}^2(f) & \text{for non MoCs} \quad (4) \end{cases}$$

The formulas are applicable for both phase and magnitude results. In the subsequent table results with $d_{i,WM}(f) > 2.u_{i,WM}(f)$ are marked by a yellow background.

actual frequency In Hz	WM X_WM mV/(m/s²)	WM u_WM	LNE d_i,WM mVl/(m/s²)	LNE u_i,WM	CMI d_i,WM mVl/(m/s²)	CMI u_i,WM	SP d_i,WM mVl/(m/s²)	SP u_i,WM	METAS d_i,WM mVl/(m/s²)	METAS u_i,WM	INRIM d_i,WM mVl/(m/s²)	INRIM u_i,WM
DC	500.06	0.02	/	/	0.15	0.50	0.04	0.50	-0.01	0.01	-0.02	1.00
0.1	499.05	0.88	/	/	9.95 (*)	4.42 (*)	/	/	/	/	/	/
0.125	500.14	0.84	/	/	5.98	2.65	/	/	/	/	/	/
0.16	500.40	0.81	/	/	4.10	1.85	/	/	/	/	/	/
0.2	500.43	0.49	/	/	2.37	1.16	/	/	1.07	1.07	/	/
0.25	500.03	0.45	/	/	1.77	0.90	/	/	-0.22	0.84	/	/
0.315	500.12	0.44	/	/	1.38	0.90	-4.82	4.44	-0.12	0.73	/	/
0.4	499.95	0.35	/	/	1.35	0.94	-2.95	2.71	0.30	0.73	/	/
0.5	499.93	0.30	0.57	0.69	0.97	0.96	-1.73	1.97	0.22	0.73	-1.13	0.95
0.63	499.97	0.31	0.33	0.69	0.73	0.95	-0.97	1.21	0.33	0.72	/	/
0.8	499.79	0.29	0.21	0.69	0.81	0.96	-0.39	0.96	0.36	0.72	-1.49	0.95
1	499.81	0.27	0.29	0.70	0.79	0.96	-0.21	0.70	0.46	0.70	-1.91	0.96
1.25	499.89	0.27	0.21	0.70	0.91	0.97	-0.19	0.70	0.43	0.70	-1.49	0.96
1.60	499.94	0.27	0.16	0.70	0.86	0.97	-0.14	0.70	0.41	0.70	-1.04	0.96
2	499.96	0.27	0.24	0.70	0.64	0.96	-0.06	0.70	0.26	0.70	-0.76	0.96
2.50	499.96	0.27	0.04	0.70	0.74	0.96	0.14	0.70	0.39	0.67	-0.76	0.96
3.15	499.95	0.27	0.15	0.70	0.65	0.97	0.05	0.70	0.30	0.67	-0.75	0.96
4	499.98	0.27	0.12	0.70	0.62	0.97	0.12	0.70	0.34	0.67	-0.98	0.96
5	500.02	0.26	0.08	0.70	0.58	0.97	0.08	0.70	0.42	0.54	-0.92	0.96
6.3	500.06	0.26	0.04	0.70	0.64	0.97	0.14	0.70	0.44	0.54	-0.96	0.96
8.0	500.09	0.26	0.11	0.70	0.81	0.97	0.11	0.70	0.37	0.54	-0.89	0.96
10	499.94	0.20	0.26	0.72	0.86	0.98	0.36	0.72	0.69	0.90	-0.74	0.98
12.5	500.05	0.20	0.25	0.72	0.85	0.98	0.45	0.72	0.53	0.90	-0.75	0.98
16	500.27	0.20	0.23	0.72	0.83	0.98	0.33	0.72	0.55	0.91	-0.57	0.98
20	500.58	0.20	0.22	0.72	0.92	0.98	0.32	0.72	0.41	0.91	-0.48	0.98
25	501.01	0.20	0.19	0.72	1.09	0.98	0.29	0.73	0.44	0.88	-0.61	0.98
31.5	501.71	0.20	0.19	0.73	1.19	0.98	0.29	0.73	0.36	0.88	-0.51	0.98
40	502.72	0.20	0.18	0.73	0.88	0.99	0.38	0.73	0.47	0.88	-0.42	0.98
50	504.20	0.20	0.21	0.73	0.60	0.99	-1.30	0.73	0.69	0.89	-0.10	0.99
63	506.44	0.21	0.26	0.73	0.76	0.99	-0.64	0.99	0.56	1.76	-0.14	0.99
80	509.69	0.22	0.21	0.73	0.01	1.00	0.01	1.00	0.51	1.77	-0.99	0.99
100	513.73	0.22	-0.03	0.74	0.07	1.00	0.07	1.00	0.37	1.79	-0.03	1.00
125	517.95	0.22	0.05	0.74	0.15	1.01	1.05	1.01	0.65	1.80	-0.05	1.01
160	522.43	0.23	-0.13	0.75	0.27	1.02	/	/	0.27	1.81	-0.43	1.02
200	525.03	0.26	/	/	-6.03	1.07	-2.93	2.86	0.27	1.82	/	/

actual frequency In Hz	WM X_WM mVl/(m/s²)	WM u_WM	GUM d_i,WM mVl/(m/s²)	GUM u_i,WM	CEM d_i,WM mVl/(m/s²)	CEM u_i,WM	PTB d_i,WM mVl/(m/s²)	PTB u_i,WM	DPLA d_i,WM mVl/(m/s²)	DPLA u_i,WM	MIKES d_i,WM mVl/(m/s²)	MIKES u_i,WM
DC	500.06	0.02	/	/	/	/	-0.06	0.50	0.15	0.12	/	/
0.1	499.05	0.88	/	/	/	/	-1.33	0.88	1.35	0.89	/	/
0.125	500.14	0.84	/	/	/	/	-1.35	0.92	0.16	0.93	/	/
0.16	500.40	0.81	/	/	/	/	-1.57	0.95	0.00	0.95	/	/
0.2	500.43	0.49	/	/	/	/	-0.98	0.57	-0.53	0.87	/	/
0.25	500.03	0.45	/	/	/	/	-0.78	0.60	-0.13	0.89	/	/
0.315	500.12	0.44	/	/	/	/	-0.43	0.61	-0.22	0.90	/	/
0.4	499.96	0.35	/	/	-0.05	1.20	-0.33	0.36	-0.05	0.94	/	/
0.5	499.93	0.30	/	/	-0.03	1.21	-0.21	0.40	0.07	0.95	/	/
0.63	499.97	0.31	/	/	-0.07	1.21	-0.27	0.40	-0.07	0.95	/	/
0.8	499.79	0.29	/	/	0.11	1.22	-0.01	0.41	0.11	0.96	/	/
1	499.81	0.27	0.59	1.73	0.09	1.22	0.01	0.42	0.09	0.96	-0.21	1.22
1.25	499.89	0.27	0.52	1.73	0.01	1.22	-0.08	0.42	0.01	0.96	-0.19	1.22
1.60	499.94	0.27	0.38	1.73	-0.04	1.22	-0.12	0.42	-0.04	0.96	-0.24	1.22
2	499.96	0.27	0.22	1.73	-0.06	1.22	-0.09	0.42	-0.06	0.96	-0.36	1.22
2.50	499.96	0.27	0.28	1.73	-0.06	1.22	-0.21	0.42	-0.06	0.96	-0.26	1.22
3.15	499.95	0.27	0.23	1.73	-0.05	1.22	-0.20	0.42	-0.05	0.96	0.05	1.22
4	499.98	0.27	0.24	1.73	-0.08	1.22	-0.17	0.42	0.02	0.96	-0.08	1.22
5	500.02	0.26	0.30	1.73	-0.02	1.22	-0.30	0.43	-0.02	0.97	-0.02	1.22
6.3	500.06	0.26	0.28	1.73	-0.06	1.22	-0.31	0.43	-0.06	0.97	0.04	1.22
8.0	500.09	0.26	0.23	1.73	0.01	1.22	-0.33	0.43	-0.09	0.97	0.01	1.22
10	499.94	0.20	0.48	1.49	0.16	1.23	-0.16	0.15	0.16	0.98	0.16	1.23
12.5	500.05	0.20	0.43	1.49	0.05	1.23	-0.15	0.15	0.15	0.98	0.05	1.23
16	500.27	0.20	0.43	1.49	0.13	1.24	-0.15	0.15	0.13	0.98	0.03	1.23
20	500.58	0.20	0.39	1.24	0.12	1.24	-0.14	0.15	0.22	0.98	0.04	1.24
25	501.01	0.20	0.40	1.24	0.09	1.24	-0.15	0.15	0.19	1.24	-0.01	1.24
31.5	501.71	0.20	0.33	1.24	0.09	1.24	-0.14	0.15	-0.01	1.24	-0.11	1.24
40	502.72	0.20	0.31	1.24	0.08	1.24	-0.08	0.15	-0.22	1.24	-0.32	1.24
50	504.20	0.20	1.87	1.25	0.10	1.24	-0.05	0.15	0.30	1.25	0.10	1.50
63	506.44	0.21	0.30	1.25	-0.04	1.25	-0.03	0.14	-0.54	1.25	-0.14	1.50
80	509.69	0.22	0.35	1.51	0.61	1.26	-0.02	0.14	6.11	3.86	-0.69	2.54
100	513.73	0.22	0.23	1.53	/	/	-0.02	0.13	/	/	/	/
125	517.95	0.22	0.50	1.54	/	/	-0.11	0.13	/	/	/	/
160	522.43	0.23	-0.29	1.81	/	/	0.02	0.12	/	/	/	/
200	525.03	0.26	/	/	/	/	0.019	0.044	/	/	/	/

Table 4: Unilateral degrees of equivalence for the magnitude of sensitivity with absolute standard uncertainties

The following figure gives a graphical representation of the results without including the uncertainties of the participants. To compare results, the expanded uncertainty of the weighted mean is represented around the value of 0 mV/(m/s²). Between 1 and 200 Hz, a very good consistency is observed between all the results. In very low and very high frequencies, discrepancies appear for participating laboratories.

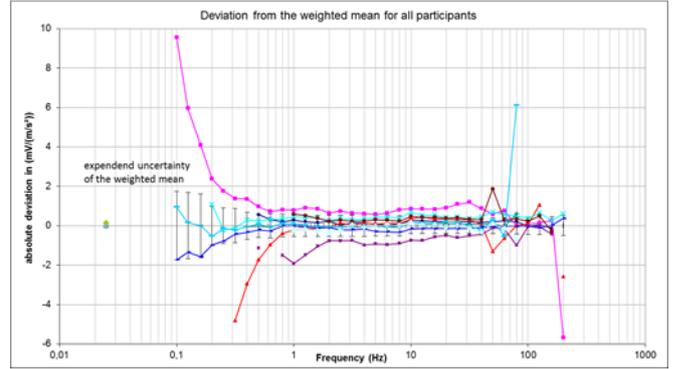These effects are also confirmed by non-participating laboratories that performed measurements below 1 Hz.

Fig. 5. Graphical representation of the deviation to the weighed mean for all participants.

4.2 Results for the phase of the complex sensitivity

In the following section, the results of the participants are given in a tabulated form and in a graphical representation with reference to the WM (zero line) for each frequency.

All the laboratories are contributing to the WM as all participants are MoCs for the whole frequency domain.

In the subsequently presented tables, all results meet the condition $d_{i,WM}(f) < 2.u_{i,WM}(f)$.

actual frequency In Hz	WM X_WM In°	WM u_WM	GUM d_i,WM In°	GUM u_i,WM	CEM d_i,WM In°	CEM u_i,WM	PTB d_i,WM In°	PTB u_i,WM	DPLA d_i,WM In°	DPLA u_i,WM	MIKES d_i,WM In°	MIKES u_i,WM
0.1	-0.06	0.07	/	/	/	/	0.01	0.07	-0.14	0.13	/	/
0.125	-0.09	0.07	/	/	/	/	-0.07	0.07	0.09	0.13	/	/
0.16	-0.04	0.07	/	/	/	/	-0.03	0.07	0.04	0.13	/	/
0.2	-0.05	0.07	/	/	/	/	-0.04	0.07	0.05	0.13	/	/
0.25	-0.02	0.07	/	/	/	/	-0.03	0.07	0.02	0.13	/	/
0.315	-0.02	0.06	/	/	/	/	-0.02	0.08	0.02	0.14	/	/
0.4	-0.03	0.06	/	/	-0.04	0.24	-0.03	0.08	0.03	0.14	/	/
0.5	-0.02	0.06	/	/	-0.04	0.24	-0.03	0.08	0.02	0.14	/	/
0.63	-0.02	0.06	/	/	-0.03	0.24	-0.02	0.08	0.02	0.14	/	/
0.8	-0.02	0.06	/	/	-0.02	0.24	-0.03	0.08	0.02	0.14	/	/
1	-0.03	0.06	-0.01	0.34	-0.01	0.24	0.00	0.08	0.02	0.14	0.01	0.29
1.25	-0.04	0.06	0.01	0.34	0.01	0.24	-0.01	0.08	0.03	0.14	0.01	0.29
1.6	-0.05	0.06	0.02	0.34	0.02	0.24	0.00	0.08	0.04	0.14	0.05	0.29
2.0	-0.06	0.06	0.03	0.34	0.03	0.24	0.00	0.08	0.05	0.14	0.03	0.29
2.50	-0.05	0.06	0.02	0.34	0.02	0.24	0.01	0.08	0.04	0.14	0.00	0.29
3.15	-0.05	0.06	0.02	0.34	0.02	0.24	0.00	0.08	0.03	0.14	0.01	0.29
4	-0.06	0.06	0.03	0.34	0.03	0.24	-0.01	0.08	0.04	0.14	0.01	0.29
5	-0.05	0.06	0.01	0.34	0.01	0.24	0.00	0.08	0.02	0.14	-0.01	0.29
6.3	-0.05	0.06	0.01	0.34	0.01	0.24	-0.02	0.08	0.01	0.14	-0.01	0.29
8	-0.06	0.06	0.01	0.34	0.01	0.24	-0.03	0.08	0.01	0.14	-0.03	0.29
10	-0.07	0.06	0.01	0.34	0.00	0.24	-0.02	0.08	0.01	0.14	-0.03	0.29
12.5	-0.08	0.06	0.01	0.35	-0.02	0.24	-0.04	0.08	0.00	0.14	-0.06	0.29
16	-0.11	0.06	0.02	0.35	0.00	0.24	-0.04	0.08	0.01	0.14	-0.07	0.29
20	-0.15	0.06	0.02	0.29	0.02	0.24	-0.04	0.08	0.01	0.14	-0.09	0.29
25.0	-0.20	0.06	0.03	0.29	0.02	0.24	-0.04	0.08	0.00	0.14	-0.09	0.29
31.5	-0.27	0.06	0.04	0.29	0.03	0.24	-0.05	0.08	0.04	0.24	-0.13	0.29
40	-0.38	0.06	0.06	0.29	0.05	0.24	-0.05	0.08	0.09	0.24	-0.14	0.29
50	-0.51	0.07	0.09	0.29	0.04	0.24	-0.08	0.08	0.07	0.24	-0.17	0.34
63	-0.78	0.07	0.06	0.34	0.08	0.24	-0.07	0.07	0.02	0.50	-0.33	0.34
80	-1.17	0.07	0.10	0.34	0.26	0.24	-0.11	0.07	0.34	0.49	-0.32	0.55
100	-1.78	0.08	0.08	0.34	/	/	-0.08	0.07	/	/	/	/
125	-2.77	0.08	0.12	0.34	/	/	-0.10	0.06	/	/	/	/
160	-4.32	0.09	0.23	0.39	/	/	-0.08	0.05	/	/	/	/
200	-6.24	0.09	/	/	/	/	-0.08	0.04	/	/	/	/

actual frequency in Hz	WM xWM	WM uWM	GUM di,WM	GUM ui,WM	CEM di,WM	CEM ui,WM	PTB di,WM	PTB ui,WM	DPLA di,WM	DPLA ui,WM	MIKES di,WM	MIKES ui,WM
	in °		in °		in °		in °		in °		in °	
0,1	-0,06	0,07	/	/	/	/	0,01	0,07	-0,14	0,13	/	/
0,125	-0,09	0,07	/	/	/	/	-0,07	0,07	0,09	0,13	/	/
0,16	-0,04	0,07	/	/	/	/	-0,03	0,07	0,04	0,13	/	/
0,2	-0,05	0,07	/	/	/	/	-0,04	0,07	0,05	0,13	/	/
0,25	-0,02	0,07	/	/	/	/	-0,03	0,07	0,02	0,13	/	/
0,315	-0,02	0,06	/	/	/	/	-0,02	0,08	0,02	0,14	/	/
0,4	-0,03	0,06	/	/	-0,04	0,24	-0,03	0,08	0,03	0,14	/	/
0,5	-0,02	0,06	/	/	-0,04	0,24	-0,03	0,08	0,02	0,14	/	/
0,63	-0,02	0,06	/	/	-0,03	0,24	-0,02	0,08	0,02	0,14	/	/
0,8	-0,02	0,06	/	/	-0,02	0,24	-0,03	0,08	0,02	0,14	/	/
1	-0,03	0,06	-0,01	0,34	-0,01	0,24	0,00	0,08	0,02	0,14	0,01	0,29
1,25	-0,04	0,06	0,01	0,34	0,01	0,24	-0,01	0,08	0,03	0,14	0,01	0,29
1,6	-0,05	0,06	0,02	0,34	0,02	0,24	0,00	0,08	0,04	0,14	0,05	0,29
2,0	-0,06	0,06	0,03	0,34	0,03	0,24	0,00	0,08	0,05	0,14	0,03	0,29
2,50	-0,05	0,06	0,02	0,34	0,02	0,24	0,01	0,08	0,04	0,14	0,00	0,29
3,15	-0,05	0,06	0,02	0,34	0,02	0,24	0,00	0,08	0,03	0,14	0,01	0,29
4	-0,06	0,06	0,03	0,34	0,03	0,24	-0,01	0,08	0,04	0,14	0,01	0,29
5	-0,05	0,06	0,01	0,34	0,01	0,24	0,00	0,08	0,02	0,14	-0,01	0,29
6,3	-0,05	0,06	0,01	0,34	0,01	0,24	-0,02	0,08	0,01	0,14	-0,01	0,29
8	-0,06	0,06	0,01	0,34	0,01	0,24	-0,03	0,08	0,01	0,14	-0,03	0,29
10	-0,07	0,06	0,01	0,34	0,00	0,24	-0,02	0,08	0,01	0,14	-0,03	0,29
12,5	-0,08	0,06	0,01	0,35	-0,02	0,24	-0,04	0,08	0,00	0,14	-0,06	0,29
16	-0,11	0,06	0,02	0,35	0,00	0,24	-0,04	0,08	0,01	0,14	-0,07	0,29
20	-0,15	0,06	0,02	0,29	0,02	0,24	-0,04	0,08	0,01	0,14	-0,09	0,29
25,0	-0,20	0,06	0,03	0,29	0,02	0,24	-0,04	0,08	0,00	0,14	-0,09	0,29
31,5	-0,27	0,06	0,04	0,29	0,03	0,24	-0,05	0,08	0,04	0,24	-0,13	0,29
40	-0,38	0,06	0,06	0,29	0,05	0,24	-0,05	0,08	0,09	0,24	-0,14	0,29
50	-0,51	0,07	0,09	0,29	0,04	0,24	-0,08	0,08	0,07	0,24	-0,17	0,34
63	-0,78	0,07	0,06	0,34	0,08	0,24	-0,07	0,07	0,02	0,50	-0,33	0,34
80	-1,17	0,07	0,10	0,34	0,26	0,24	-0,11	0,07	0,34	0,49	-0,32	0,55
100	-1,78	0,08	0,08	0,34	/	/	-0,08	0,07	/	/	/	/
125	-2,77	0,08	0,12	0,34	/	/	-0,10	0,06	/	/	/	/
160	-4,32	0,09	0,23	0,39	/	/	-0,08	0,05	/	/	/	/
200	-6,24	0,09	/	/	/	/	-0,08	0,04	/	/	/	/

Table 5. Deviation of the phase from the WM for all frequencies of the comparison (excepted DC)

4. CONCLUSIONS

Results from the participants for this first comparison in low frequency domain in Europe are mostly consistent within their declared expanded uncertainties for magnitude results. Concerning phase results, all laboratories contributed to the weighted mean and all degrees of equivalence were lower than the expanded uncertainties. For magnitude results, difficulties appear, as one can expect, in very low and very high frequencies in relation to the considered domain.

It makes NMIs very confident for primary calibration in low frequency domain.

After discussion of the results during the Technical Committee Acoustic Ultrason and Vibration of Euramet, it was decided to investigate further on calibration in the very low frequency range 0.1 to 1 Hz about several causes that can be considered :
- Radius of bending of the bar
- Position of the shaker
- Behaviour during the other comparisons.

This comparison will be linked in the future to the low frequency CIPM key comparison CCAUV.V-K3 at the overlapping frequencies from 0,1 to 40 Hz.

ACKNOWLEDGMENTS

REFERENCES

[1] ISO 16063-11:1999 "Methods for the calibration of vibration and shock transducers – Part 11: Primary vibration calibration by laser interferometry"

[2] Guidelines for the CIPM key comparisons www.bipm.org/utils/en/pdf/guidelines.pdf

[3] M.G. Cox, The evaluation of key comparison data, Metrologia, 2002, volume 39, p 5989-595

[4] M.G. Cox, The evaluation of key comparison data: determining a largest consistent subset., Metrologia, 2007, 44, 187-200