NPL REPORT DQL-AC-003

EUROMET PROJECT 401

Harmonisation of Audiometry Measurements within Europe

Timothy Sherwood

June 2004

EUROMET PROJECT 401 - HARMONISATION OF AUDIOMETRY MEASUREMENTS WITHIN EUROPE

T R Sherwood
Quality of Life Division
National Physical Laboratory
Teddington, Middlesex, TW11 0LW, UK

ABSTRACT

NPL, in association with other national metrology institutes, including DPLA Denmark, PTB Germany, and OFMET Switzerland undertook a calibration intercomparison, the purpose of which was to ensure the harmonisation of measurement standards for bone-conduction audiometry within Europe. The project was split into two parts; Part A - a round robin investigation to measure the mechanical impedance and force sensitivity of a selected mechanical coupler and; Part B - a radial investigation to measure the output of a bone vibrator driven by a defined voltage with NPL acting as the central co-ordinator. The report concentrates on Part A and provides background discussion on the formulation of the project, describes the measurements made by all participating laboratories, collates and compares the measurement results, and offers discussion and conclusion on the findings. Documentation of Part B is limited to a presentation of the data submitted by the participants.

ISSN 1744-0599

National Physical Laboratory
Teddington, Middlesex, TW11 0LW, United Kingdom.

 We gratefully acknowledge the financial support of the UK Department of Trade and Industry (National Measurement System Policy Unit).

Approved on behalf of the Managing Director, National Physical Laboratory
by Dr. R. C. Preston, Authorised by Director, Quality of Life Division

CONTENTS

1. INTRODUCTION

The National Physical Laboratory (NPL), United Kingdom, was commissioned by the National Measurement System Directorate, under DTI contract, to participate in EUROMET Project 401 'Harmonisation of Audiometry measurements within Europe'. EUROMET is a cooperative organisation between the national metrology institutes in the EU and has the objective of promoting the coordination of metrological activities.

The principal objective of Project 401 was to compare measurement standards for bone-conduction audiometry at national measurement institutes throughout Europe.

Bone conduction audiometry permits measurement of hearing threshold level, and more particularly provides useful diagnostic information on the state of a person's hearing. There are a number of standardised devices used for calibration of measurement equipment in this area. This study has been concerned with the *mechanical coupler* which is essentially used as a transfer standard and is specified in IEC 60373 [1].

In striving to attain reliability in the accuracy of results obtained from using the devices, International Standards have been progressively developed for many years. IEC 60373 has been criticised by the audiometric community. One concern is that the mechanical impedance specified for the mechanical coupler was derived from a compromise between discordant scientific data, and consequently it can only be approximated in physical realisations of the device. As a result, the *de facto* standard has in practice become that of the primary manufacturer of mechanical couplers who has, meanwhile, changed the design of the product to slightly improve its stability, and make use of materials currently available. In response to this, NPL proposed this collaborative investigation with participation from experts throughout the audiometric community. The purpose of this report is to present the results of this investigation.

2. SCOPE & OBJECTIVES

The project was divided into two parts. NPL acted as pilot laboratory for both parts and provided the devices circulated as well as measurements to check stability.

The outline scope of Part A was:

- Measurement of the force sensitivity of the mechanical coupler at a range of frequencies;
- Measurement of the mechanical impedance of the mechanical coupler at a range of frequencies.

Initially five laboratories agreed to participate in Part A.

Part B was a simplified exercise involving:

- Measurement of the output of one type of bone vibrator, driven by a prescribed voltage, at a range of frequencies at a number of different national measurement institutes.

The main objective was to test the consistency of measurement standards for bone-conduction audiometer within Europe, to establish the cause of any anomalies, and if necessary, suggest ways of improving the device or measurement methods.

3. METHODOLGY

3.1. PART A

Part A involved a round robin investigation to measure the mechanical impedance and force sensitivity of a selected mechanical coupler. NPL, as the pilot laboratory, provided the test device, Brüel & Kjær Mechanical Coupler type 4930, serial number 1895330. The following laboratories participated in the intercomparison.

- United Kingdom NPL
- Germany PTB
- Switzerland OFMET
- Denmark DPLA

A fifth laboratory, SP Sweden was not able to perform the measurements during the timescale of the project.

The protocol required participants to measure the mechanical impedance and force sensitivity of the mechanical coupler at frequencies of 250 Hz, 500 Hz, 750 Hz, 1 kHz, 1.5 kHz, 2 kHz, 3 kHz and 4 kHz. Optionally, participants were free to make measurements at other third-octave frequencies between 125 Hz and 8 kHz. It was requested that the mechanical impedance be reported in Nsm^{-1} and the force response in N.

It was specified that a single result should be the mean of five repeated measurements, and a total of five such results were requested at each frequency, each being determined on a different day. Measurements had to be made in accordance with the requirements of ISO 389-3 [4], IEC 60373 and IEC 60645-1 [3].

All measurements had to be carried out with the mechanical coupler at a temperature of 23° C ± 1° C. In addition to monitoring the temperature of the device it was required that the air temperature and relative humidity be determined. The full measurement protocol can be found in Appendix A.

3.2. PART B

Part B involved a radial investigation to measure the output of a type of bone vibrator commonly used for audiometry in Europe. NPL provided the test devices, Radioear type B71 Bone vibrator. The following laboratories participated in the intercomparison.

- United Kingdom NPL
- Germany PTB
- Austria BEV
- Poland GUM

A further five laboratories planned to take part, but did not report their results within the timescale of the project.

The protocol required participants to measure the force levels produced by two of the bone vibrators driven with an r.m.s sinusoidal signal of 100 mV when applied to their own calibrated IEC 60373 type 4930 mechanical coupler at frequencies of 250 Hz, 500 Hz, 750 Hz, 1 kHz, 1.5 kHz, 2 kHz, 3 kHz and 4 kHz. Optionally participants were free to make measurements at other third-octave frequencies between 125 Hz and 8 kHz.

It was specified that a single result should be the mean of five repeated measurements, and a total of five results were requested at each frequency, each being determined on a different day. Measurements had to be made in accordance with the requirements of ISO 389-3, IEC 60373 and IEC 60645-1.

All measurements had to be carried out with the mechanical coupler at a temperature of 23° C ± 1° C, and the air temperature and relative humidity had to be recored. The full measurement protocol can be found in Appendix A.

3.3. REPORTING OF RESULTS

Participants were required to submit a report on the measurements to the pilot laboratory (NPL), with the following details.

- A brief description of the measurement method
- A list of equipment used (i.e. make, type, and serial number)
- A diagram of the apparatus with key items of equipment named
- A statement of results together with the environmental conditions during measurements
- A statement of the measurement uncertainty according to The ISO “Guide to the expression of uncertainty in measurement”, together with a description of the main contributing components
- Any difficulties or observations encountered while performing the measurements.

3.4. DISTRIBUTION OF INTERCOMPARISON DEVICES

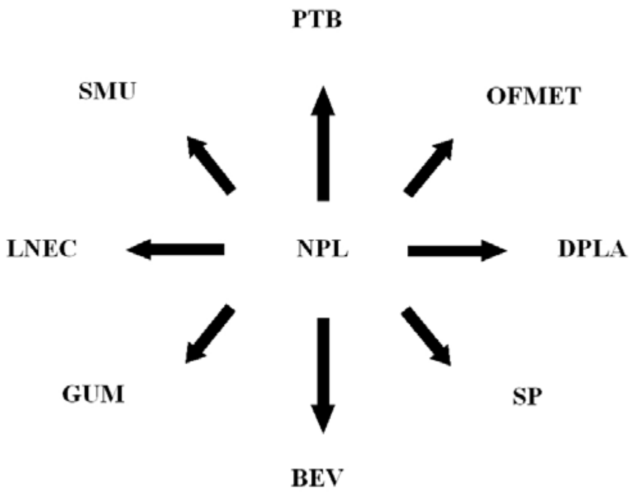
Following initial calibration at NPL in November 1996, the mechanical coupler used for part A was circulated in the following sequence

NPL –► PTB –► NPL –► OFMET –► DPLA –► NPL

PTB conducted measurements according to the specification. Based on prior experience they also agreed to investigate the effect of humidity on the calibration of the mechanical coupler. On its return from PTB, NPL performed monitoring measurements on the device to check its stability.

On receipt of the mechanical coupler, OFMET reported damage to the device packaging and the possibility that the device itself may have been affected. OFMET conducted measurements according to the specification and dispatched the device to DPLA. DPLA conducted measurements according to the specification and dispatched the device to NPL. NPL conducted a final calibration in May 2000 at the end of the circulation period.

Initial measurements for Part B were made at NPL in November 1996. The bone vibrators were then circulated as follows



On return, final measurements were carried out on the bone vibrators by NPL.

Summaries of the reports from individual participants including descriptions of the measurement systems, raw data and uncertainties can be found in Appendices C to H.

4. RESULTS SUMMARY & DISCUSSION

4.1. MECHANICAL IMPEDANCE AND FORCE SENSITIVITY COMPARISONS (PART A)

Tables 1 and 2 summarise the main results included in the reports from the participants. These results are also plotted in Figures 1 to 6.

As mentioned earlier, OFMET reported that the mechanical coupler may have been damaged in transit. Although there were no visible signs of damage to the device itself, Figures 1 and 2 clearly show a distinction in the results up to 2 kHz, before and after transportation to OFMET. It was therefore assumed that the mechanical coupler suffered a change in sensitivity and the results were then analysed in a way that was, as far as possible, insensitive to this change.

Table 1. The mean mechanical impedance (dB re 1Nsm^{-1}) and associated standard deviations reported by each participant for the mechanical coupler (B&K Type 4930, Serial No. 1895330).

	Before reported damage				*After reported damage*					
	NPL		PTB		OFMET		DPLA		NPL	
Freq	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
100	-	-	-	-	**51.98**	0.13	**51.95**	0.12	-	-
125	-	-	**48.50**	0.11	**50.37**	0.12	**50.29**	0.10	-	-
160	-	-	-	-	**48.30**	0.11	**48.66**	0.09	-	-
200	-	-	-	-	**47.20**	0.09	**47.23**	0.09	-	-
250	**44.23**	0.15	**44.12**	0.13	**45.73**	0.08	**45.82**	0.10	**45.80**	0.04
315	-	-	-	-	**44.25**	0.15	**44.39**	0.10	-	-
400	-	-	-	-	**42.88**	0.12	**42.94**	0.10	-	-
500	**40.14**	0.18	**39.98**	0.17	**41.47**	0.12	**41.58**	0.10	**41.58**	0.03
630	-	-	-	-	**40.27**	0.12	**40.19**	0.10	-	-
750	**37.65**	0.20	**37.68**	0.17	-	-	**39.14**	0.10	**39.12**	0.03
800	-	-	-	-	**38.67**	0.12	**38.75**	0.10	-	-
1000	**35.79**	0.20	**35.96**	0.15	**37.42**	0.15	**37.36**	0.11	**37.32**	0.04
1250	-	-	-	-	**35.93**	0.16	**35.94**	0.11	-	-
1500	**32.97**	0.24	**33.18**	0.17	-	-	**34.69**	0.12	**34.68**	0.02
1600	-	-	-	-	**34.17**	0.18	**34.23**	0.13	-	-
2000	**30.94**	0.09	**31.06**	0.19	**32.53**	0.22	**32.57**	0.14	**32.54**	0.04
2500	-	-	-	-	**30.70**	0.28	**30.88**	0.15	-	-
3000	**28.67**	0.28	**28.50**	0.19	-	-	**29.68**	0.16	**29.63**	0.04
3150	-	-	-	-	**29.37**	0.23	**29.40**	0.13	-	-
4000	**29.61**	0.28	**29.54**	0.10	**29.73**	0.10	**30.08**	0.07	**29.92**	0.12
5000	**33.80**	0.10	-	-	**32.12**	0.20	**32.38**	0.05	**32.32**	0.05
6000	-	-	**33.90**	0.11	-	-	**34.52**	0.03	-	-
6300	-	-	-	-	**35.00**	0.19	**35.04**	0.05	-	-
8000	-	-	**35.00**	0.14	**36.82**	0.20	**36.76**	0.07	-	-
10000	-	-	-	-	**37.18**	0.31	-	-	-	-

Table 2. The mean force sensitivity (dB re 1 VN^{-1}) and associated standard deviations reported by each participant for the mechanical coupler (B&K Type 4930, Serial No. 1895330).

Freq	*Before reported damage*				*After reported damage*					
	NPL		**PTB**		**OFMET**		**DPLA**		**NPL**	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
	-	-	**-**	-	**-18.05**	0.14	**-18.13**	0.01	**-**	-
125	**-**	-	**-17.50**	0.00	**-17.88**	0.12	**-18.12**	0.01	**-**	-
160	**-**	-	**-**	-	**-17.70**	0.18	**-18.13**	0.01	**-**	-
200	**-**	-	**-**	-	**-17.92**	0.12	**-18.12**	0.01	**-**	-
250	**-17.42**	0.44	**-17.40**	0.00	**-17.82**	0.13	**-18.10**	0.01	**-18.04**	0.06
315	**-**	-	**-**	-	**-17.75**	0.10	**-18.05**	0.01	**-**	-
400	**-**	-	**-**	-	**-17.72**	0.12	**-18.00**	0.01	**-**	-
500	**-17.22**	0.14	**-17.20**	0.00	**-17.83**	0.12	**-17.91**	0.01	**-17.87**	0.05
630	**-**	-	**-**	-	**-17.82**	0.12	**-17.77**	0.02	**-**	-
750	**-17.27**	0.21	**-17.00**	0.00	**-**	-	**-17.67**	0.02	**-17.70**	0.03
800	**-**	-	**-**	-	**-17.62**	0.08	**-17.63**	0.02	**-**	-
1000	**-16.33**	0.10	**-16.70**	0.00	**-17.45**	0.12	**-17.42**	0.02	**-17.37**	0.04
1250	**-**	-	**-**	-	**-17.20**	0.11	**-17.17**	0.01	**-**	-
1500	**-16.49**	0.14	**-16.08**	0.04	**-**	-	**-16.88**	0.01	**-16.88**	0.04
1600	**-**	-	**-**	-	**-16.72**	0.16	**-16.76**	0.01	**-**	-
2000	**-15.53**	0.21	**-15.52**	0.04	**-16.38**	0.12	**-16.43**	0.02	**-16.34**	0.04
2500	**-**	-	**-**	-	**-16.08**	0.17	**-16.12**	0.03	**-**	-
3000	**-15.53**	0.46	**-15.90**	0.09	**-**	-	**-16.23**	0.07	**-16.15**	0.05
3150	**-**	-	**-**	-	**-16.47**	0.12	**-16.39**	0.04	**-**	-
4000	**-19.02**	0.05	**-18.98**	0.16	**-18.58**	0.17	**-18.98**	0.11	**-19.08**	0.08
5000	**-**	-	**-**	-	**-21.70**	0.15	**-22.12**	0.14	**-**	-
6000	**-**	-	**-23.56**	0.10	**-**	-	**-24.29**	0.23	**-**	-
6300	**-**	-	**-**	-	**-24.22**	0.19	**-25.14**	0.13	**-**	-
8000	**-**	-	**-23.52**	0.07	**-24.88**	0.46	**-25.69**	0.08	**-**	-
10000	**-**	-	**-**	-	**-23.88**	0.44	**-**	-	**-**	-

The two groups of results in Figures 1 and 2 demonstrate that there is generally good agreement between the measurement results especially given that overall the measurements were conducted over a four year period. However, the course scale of the vertical axis needs to be taken into account before making any specific judgements.

Results in Figure 1 show the measured values of mechanical impedance following the damage are higher than before the damage. This is evident across most of the frequency range. Similarly in Figure 2, a general trend can be seen where force sensitivity results returned after the damage are consistently lower than before. Given that the mechanical coupler changed in sensitivity during the project, the traditional comparison against the grand mean of all participating laboratories has been avoided. However, it was considered reasonable to divide the traditional comparison into two discrete groups, "*pre*-" and "*post-damage*".

Figure 1. Results of all participating laboratories showing mean mechanical impedance in dB re 1Nsm^{-1} of the mechanical coupler (B&K Type 4930, Serial No. 1895330).

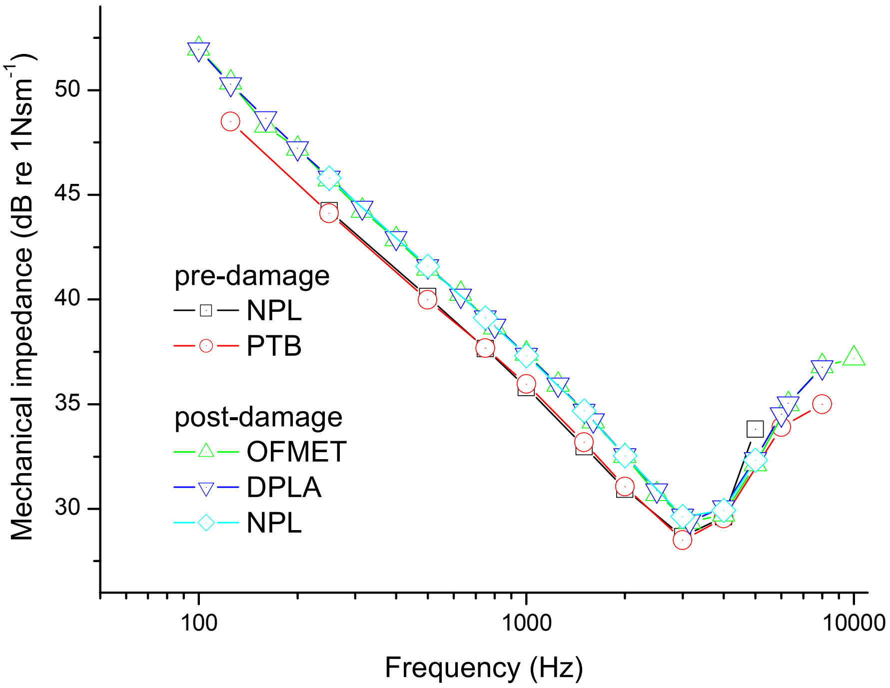


Figure 2. Results of all participating laboratories showing mean force sensitivity in dB re 1VN^{-1} of the mechanical coupler (B&K Type 4930, Serial No. 1895330).

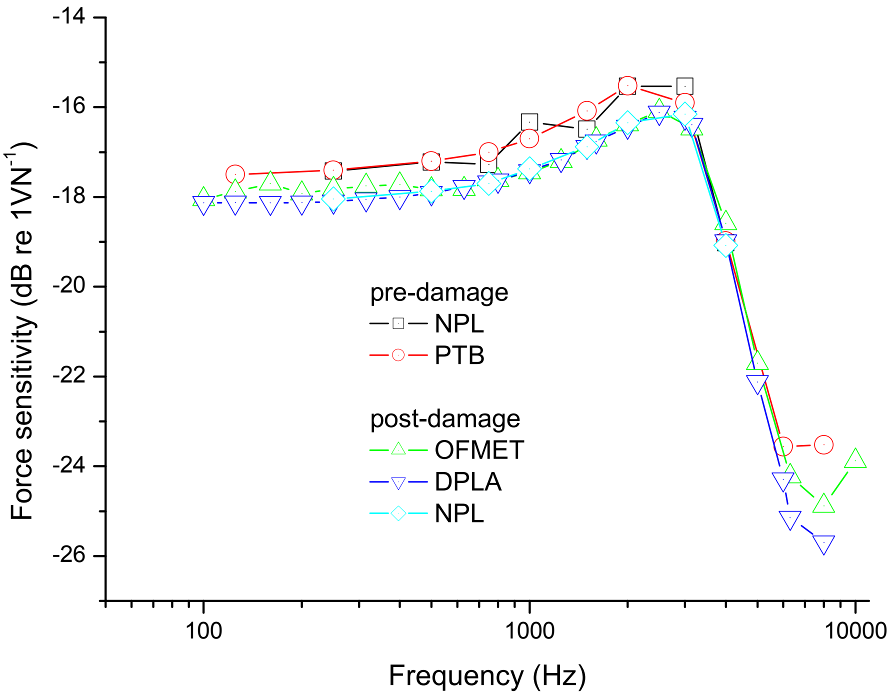


Figure 3. Difference between mechanical impedance of the mechanical coupler (B&K Type 4930, Serial No. 1895330) measured by NPL and PTB relative to the mean difference pre-damage.

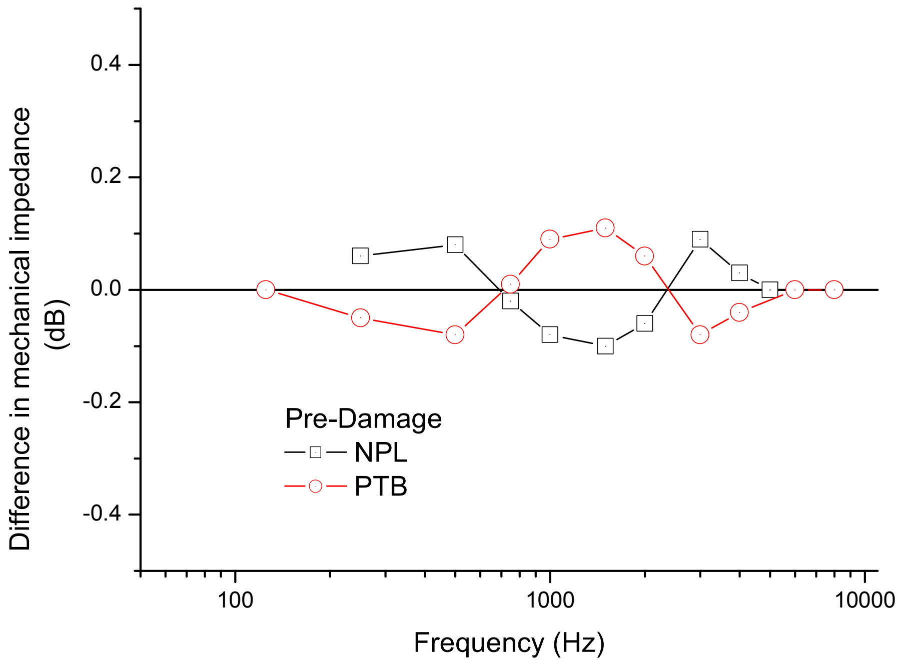


Figure 4. Difference between force sensitivity of the mechanical coupler (B&K Type 4930, Serial No. 1895330) measured by NPL and PTB relative to the mean difference pre-damage.

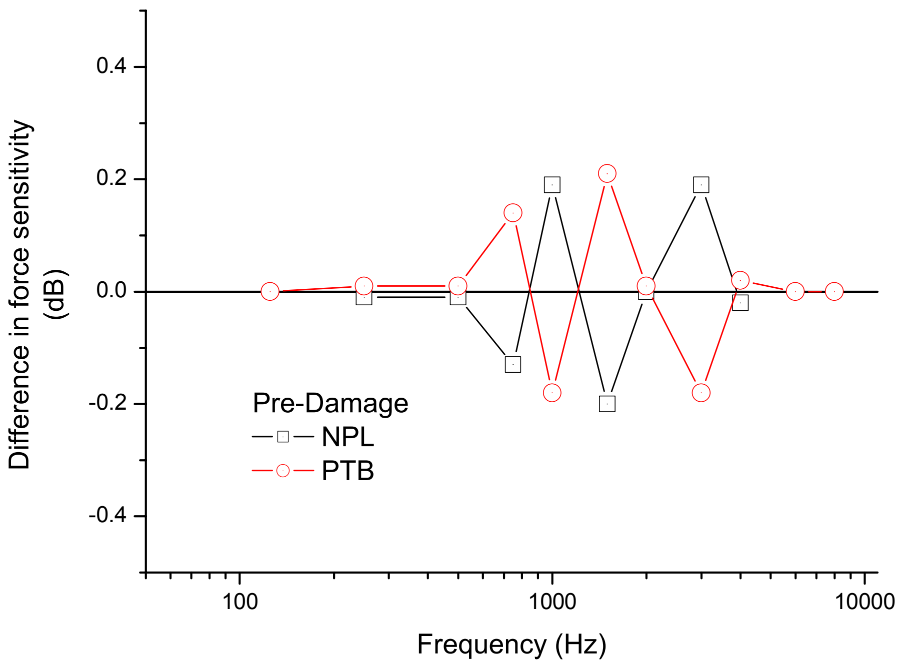


Figure 5. Difference between mechanical impedance of the mechanical coupler (B&K Type 4930, Serial No. 1895330) measured by participating laboratories relative to the mean difference post-damage.

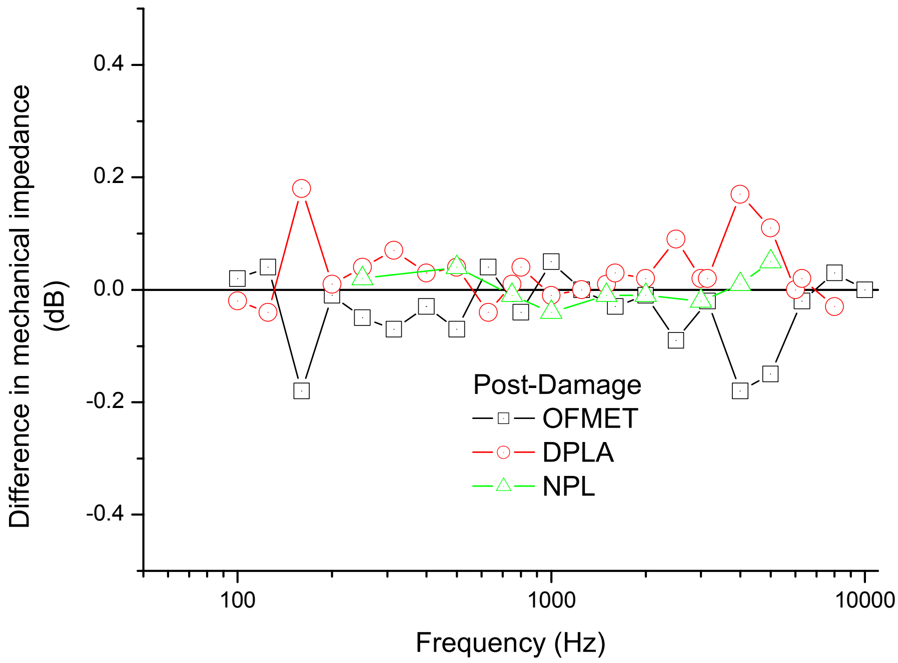
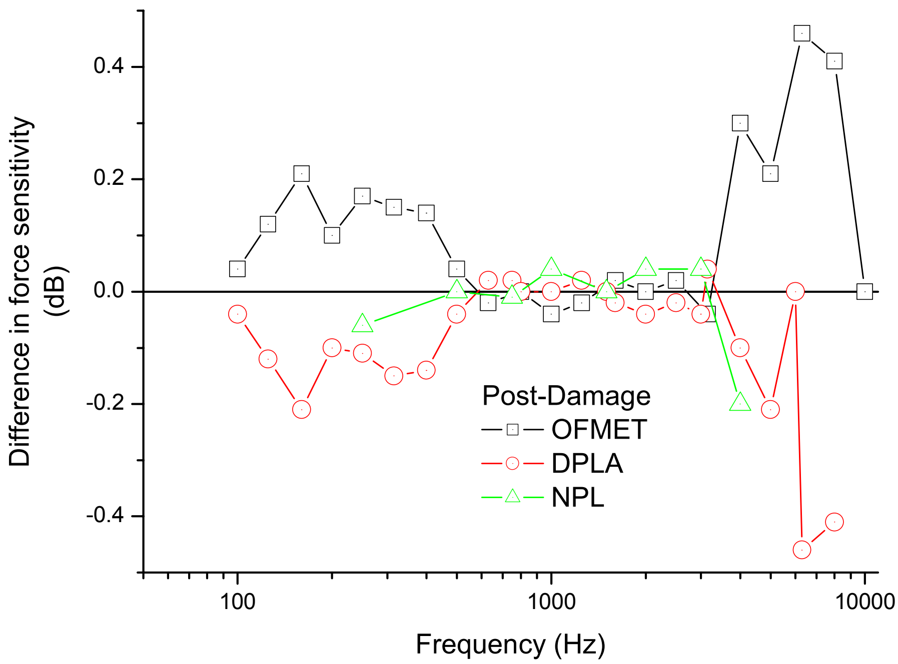


Figure 6. Difference between force sensitivity of the mechanical coupler (B&K Type 4930, Serial No. 1895330) measured by participating laboratories relative to the mean difference post-damage.



Figures 3 and 4 show the absolute difference between both the mechanical impedance and force sensitivity reported by NPL and PTB, respectively, before it was reported that the coupler had been damaged.

The absolute difference in mechanical impedance measured by the two laboratories is marginal. The greatest difference of 0.21 dB occurs at 1.5 kHz, while at all other frequencies the difference is less than 0.17 dB. The differences between the results of force sensitivity measurements given by the two laboratories are relatively more discernable, where a difference of up to 0.41dB occurs at 1.5 kHz. At 250 Hz, 500 Hz, and 2 kHz, the difference in results between laboratories is, however less than 0.02 dB.

Figures 5 and 6, show the differences in measurements results provided by laboratories after the damage, relative to the mean difference. The mean differences adopted as the baseline, was calculated by taking means of the differences between the results given by laboratories that made measurements after the damage.

Overall, it is apparent that deviation from the mean difference is relatively marginal. Figure 5 indicates that the mechanical impedance differences reported by the three laboratories are at most frequencies, around 0.1 dB or less. Only at 4 kHz, is this there a departure from this trend, where NPL report a difference of 0.34 dB. Similarly, the differences for force sensitivity, indicated in Figure 6, over the frequency range 500 Hz to 3 kHz, are less than 0.1 dB. At 250 Hz and 4 kHz greater differences were found. The most significant difference of 0.5 dB occurred at 4 kHz. DPLA reported that their measurements were conducted in such a way that the mass compensation element of the calibration was performed at each frequency. They note that a consequence of this may be that the measurement results above 3 kHz may be slightly different from the measurements results of calibration on the same device, performed at other laboratories.

Table 3. Reported measurement uncertainties for mechanical coupler calibration (dB).

Measurement uncertainty (*k*=2)								
Freq.(Hz)	calibration of mechanical impedance				calibration of force sensitivity			
	NPL	PTB	OFMET	DPLA	NPL	PTB	OFMET	DPLA
125 Hz – 2000 Hz	0.3	0.4	0.3	0.3	0.4.	0.5	0.3	0.1
3000 Hz	0.3	<0.5	0.3	0.4	0.4	<1	0.3	0.2
4000 Hz	0.3	<1	0.3	-	0.4	<1.5	0.3	-
4000 Hz – 8000 Hz	-	<1	0.3	0.2	-	<1.5	0.3	0.5
10000 Hz	-	-	0.3	-	-	-	0.3	-

Although all four laboratories reported data for the measurement uncertainty, each participant has determined this differently. One for example has based their estimate on the ISO GUM procedure. Others have used different processes or based their estimate on the nominal value used for routine calibration in their laboratory. This makes it difficult to make a rigorous comparison of uncertainties. However these calibrations are not particularly sensitive to the level of uncertainty and the approximations that have been provided are sufficient for justifying the level of agreement shown in the data.

Thus, in comparing the measurement results provided by all the participating laboratories, it has been found that there is relatively good agreement, where differences in measured mechanical impedance and force sensitivity values are, for the most, within 0.5 dB. This compares with a typical uncertainty of the order of 0.4 dB ~ 0.5 dB for force sensitivity and 0.3 dB ~ 0.4 dB for mechanical impedance.

4.2. ADDITIONAL TECHNICAL CONTRIBUTION

In addition to the requirements of the protocol for Part A of the project, a number of the participating laboratories contributed further associated information.

PTB conducted measurements to investigate the effect of humidity on the device. The results, presented in Appendix D indicate that the differences of coupler sensitivity level in dB at 40 % and 80 % relative humidity, ranged from 0 dB to 0.3 dB for frequencies 125 Hz to 4 kHz. The results also show that the output level of a type B-71 bone vibrator of type B-71 measured on the mechanical coupler is not significantly dependent on humidity.

DPLA also contributed additional information, including investigations on:

- methods for calibrating the impedance transducer element of the bone conduction system over the whole frequency range;
- dependency on level and frequency of the excitation signal.

On the first point it was noted by DPLA that determination of the force sensitivity requires only a number of known cylindrical masses loading the transducer, while a determination of the acceleration sensitivity requires a comparison with a calibrated reference accelerometer or force transducer. It was considered that the most suitable method is to calibrate the accelerometer unit of the impedance transducer by comparison with a small 2 g accelerometer mounted on top of the impedance transducer and then derive the force sensitivity.

On the second point, DPLA noted that if a range of excitation levels are used to determine the force sensitivity or the mechanical impedance then the results are found to depend on this excitation level. This effect is in addition to the well-known non-linear properties of the rubber dome caused by temperature variation and static compression.

The effect amounted to changes of around 0.5 dB in the measured mechanical impedance for moderate changes in the excitation signal. The changes were considered to be significant only in the stiffness-controlled frequency range of the artificial mastoid, i.e. below 3 kHz.

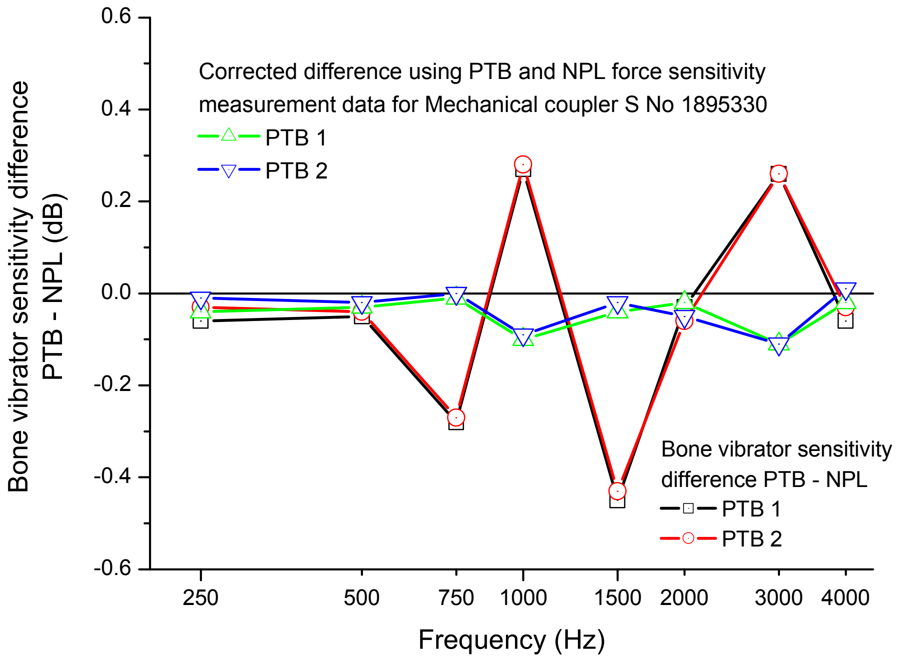
4.3. MEASUREMENTS OF THE OUTPUT SENSITIVITY OF BONE VIBRATORS (PART B)

Given the low number of participants submitting results for Part B of this project, the pilot lab has decided to not attempt any analysis of the data[†]. The results of the bone vibrator measurements together with the associated standard deviation or uncertainty, reported by each participant, is simply reproduced here as an acknowledgement of their efforts and contribution to the project.

Table 3. Output sensitivity (dB re 1 NV^{-1}) of bone vibrators measured by PTB and NPL.

	Bone vibrator PTB 1				Bone vibrator PTB 2			
	PTB		NPL		PTB		NPL	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
125	-21.95	0.03	-	-	-21.01	0.00	-	-
250	-8.57	0.04	-8.63	0.08	-7.47	0.06	-7.50	0.08
500	1.40	0.14	1.35	0.05	1.90	0.09	1.86	0.06
750	-4.85	0.07	-5.13	0.09	-4.22	0.07	-4.49	0.06
1000	-6.43	0.02	-6.16	0.10	-5.96	0.05	-5.68	0.09
1500	-3.22	0.05	-3.67	0.09	-2.94	0.08	-3.37	0.06
2000	-11.98	0.09	-12.01	0.08	-11.89	0.12	-11.95	0.07
3000	-18.36	0.11	-18.10	0.07	-18.03	0.08	-17.77	0.06
4000	-12.60	0.24	-12.66	0.08	-12.67	0.19	-12.70	0.06
6000	-33.78	0.16	-	-	-33.89	0.25	-	-

Figure 7 Mean output sensitivity difference (PTB – NPL) of bone vibrators measured by PTB and NPL

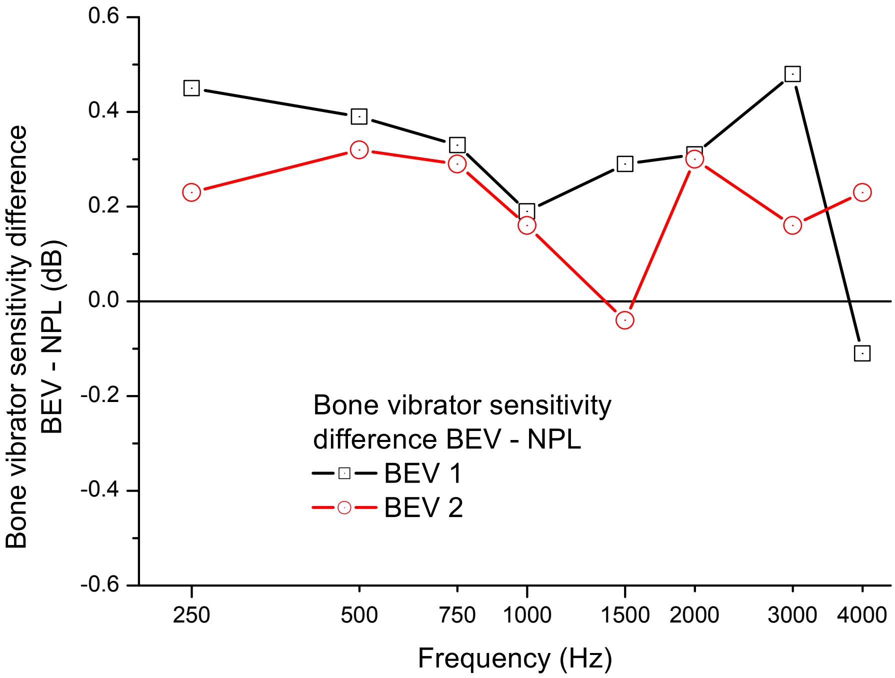


[†] The author will make the data available in electronic form if any reader wishes to perform their own analysis

Table 4. Output sensitivity (dB re 1 NV^{-1}) of bone vibrators measured by BEV and NPL.

	Bone vibrator BEV 1				Bone vibrator BEV 2			
	BEV		NPL		BEV		NPL	
	Mean	$U_{(k=2)}$	Mean	SD	Mean	$U_{(k=2)}$	Mean	SD
250	-6.72	0.45	-7.17	0.06	-7.96	0.37	-8.19	0.05
500	3.01	1.31	2.62	0.05	2.34	0.98	2.02	0.02
750	-3.24	0.60	-3.57	0.06	-3.92	0.46	-4.21	0.05
1000	-4.50	0.23	-4.69	0.04	-5.34	0.18	-5.5	0.06
1500	-3.21	0.28	-3.5	0.06	-3.84	0.34	-3.8	0.07
2000	-9.89	1.47	-10.2	0.04	-9.99	1.02	-10.29	0.05
3000	-17.42	1.11	-17.9	0.04	-18.12	0.77	-18.28	0.06
4000	-12.52	0.82	-12.41	0.07	-11.86	0.52	-12.09	0.08

Figure 8 Mean output sensitivity difference (BEV – NPL) of bone vibrators measured by BEV and NPL

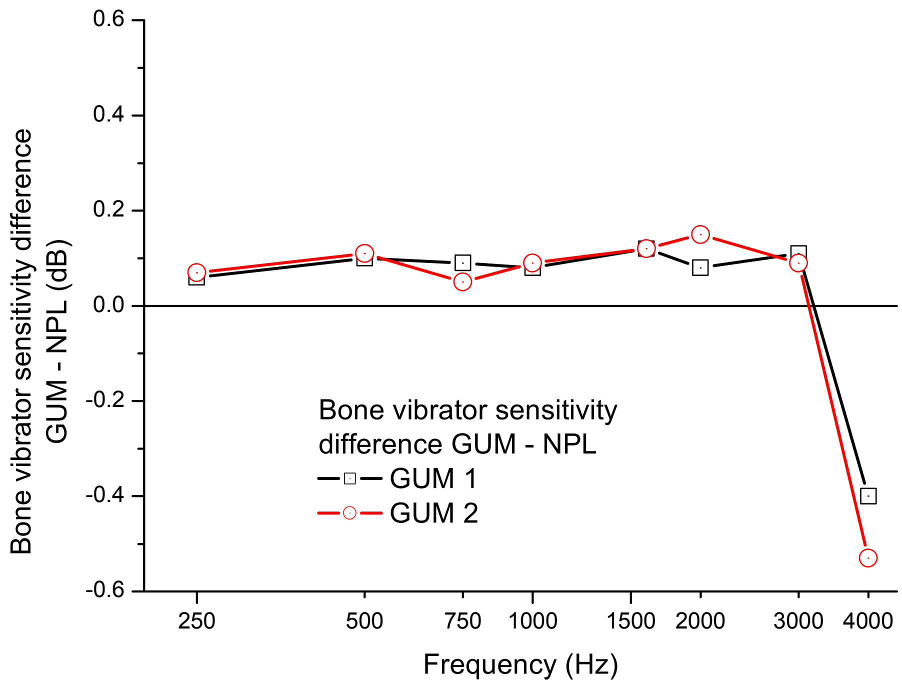


From Figures 7, 8 and 9 differences in measured output sensitivity of bone vibrators measured by NPL and the participating laboratories can to be seen to be less that 0.6 dB and in most cases better than 0.4 dB. For bone vibrators measured by PTB it was possible to correct for difference in force sensitivity measurement using results from Part A of the intercomparison. This then gave an agreement of better than 0.1 dB between laboratories.

Table 5 Output sensitivity (dB re 1 NV^{-1}) of bone vibrators measured by GUM and NPL.

	Bone vibrator GUM 1				Bone vibrator GUM 2			
	GUM		NPL		GUM		NPL	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
125	-22.02	0.06	-	-	-22.56	0.04	-	-
160	-17.60	0.10	-	-	-18.05	0.03	-	-
200	-13.49	0.12	-	-	-13.81	0.06	-	-
250	-8.96	0.18	-9.02	0.04	-9.16	0.05	-9.23	0.06
315	-2.92	0.26	-	-	-2.91	0.06	-	-
400	4.65	0.37	-	-	5.04	0.13	-	-
500	3.03	0.48	2.93	0.07	2.07	0.07	1.96	0.06
630	-2.24	0.36	-	-	-2.63	0.03	-	-
750	-4.24	0.26	-4.33	0.05	-4.65	0.05	4.7	0.06
800	-4.81	0.22	-	-	-5.17	0.03	-	-
1000	-6.06	0.12	-5.05	0.06	-6.46	0.04	6.55	0.07
1250	-5.73	0.26	-	-	-6.02	0.03	-	-
1500	-4.90	0.13	-	-	-5.59	0.19	-	-
1600	-4.93	0.40	5.05	0.06	-5.81	0.20	5.93	0.08
2000	-10.82	0.43	-10.9	0.07	-11.85	0.08	-12	0.03
2500	-17.29	0.45	-	-	-17.82	0.08	-	-
3000	-18.12	0.49	-18.23	0.07	-18.45	0.08	-18.54	0.09
3150	-17.43	0.49	-	-	-17.63	0.09	-	-
4000	-13.09	0.50	-12.69	0.02	-15.00	0.16	14.47	0.05

Figure 9 Mean output sensitivity difference (GUM – NPL) of bone vibrators measured by GUM and NPL.



5. CONCLUSIONS

5.1. CALIBRATION OF MECHANICAL COUPLER

Four national measurement institutes have calibrated the same mechanical coupler. Although the transfer device exhibited a significant change during the course of the project (as a result of damage in transit), the analysis of the results was chosen to reduce the impact of this as far as possible. Consequently, it has been shown that:

- differences in the mechanical impedance are typically less than 0.1 dB, with a maximum difference of 0.2 dB being found at 160 Hz and 4 kHz
- differences in the force sensitivity are typically 0.3 dB, with a maximum difference of 0.5 dB being found at 6.3 kHz.

This compares with a typical measurement uncertainty of 0.5 dB for the mechanical impedance and 0.4 dB for force sensitivity.

In addition, the typical resolution of audiometric measuring equipment is around 5 dB, so the degree of agreement is considered to be acceptable.

5.2. MEASUREMENTS OF THE OUTPUT SENSITIVITY OF BONE VIBRATORS

Measurements with bone vibrators produced results that typically agreed to better than 0.4 dB and had a maximum difference of 0.6 dB at 4 kHz. However, it was also shown that if the same mechanical coupler is used with a given calibration, bone vibrator measurements can agree within 0.1 dB.

6. ACKNOWLEDGEMENTS

The authors acknowledges the financial support of the National Measurement System Policy Unit of the UK Department of Trade and Industry for the work carried out in this project by NPL. The author would also like to thank Hilary McNeill for her valuable contributions to the project and all the participants for their cooperation in this intercomparison.

7. REFERENCES

[1] INTERNATIONAL ELECTROTECHNICAL COMMISSION 1990. Mechanical coupler for measurements on bone vibrators IEC 60373:1990.

[2] INTERNATIONAL ELECTROTECHNICAL COMMISSION 1971. An IEC mechanical coupler for the calibration of bone vibrators having a specified contact area and being applied with a specified static force. IEC 60373:1971.

[3] INTERNATIONAL ELECTROTECHNICAL COMMISSION 1991. Audiometers Part 1: Pure-tone audiometers. IEC 60645-1:1991.

[4] INTERNATIONAL ORGANISATION FOR STANDARDIZATION 1994 Acoustics - Reference zero for the calibration of audiometric equipment - Part 3 .ISO 389-3:1994

[5] INTERNATIONAL ORGANISATION FOR STANDARDIZATION. 1987. Acoustics - Standard reference zero for the calibration of pure tone bone conduction audiometers. ISO 7566

[6] NATIONAL MEASUREMENT ACCREDITATION SERVICE 1995. The expression of uncertainty and confidence in measurements. NAMAS information sheet NIS 3003. Edition 8.

[7] DADSON R S, ROBINSON D W and GREIG R G P The mechanical impedance of the human mastoid British Journal of Applied Physics Vol 5 December 1954 435- 442

[8] HAWLEY M S Bell Lab. Record, 18, 1939 73

[9] GREIBICH E H Trans Amer. Inst. Elect. Engrs, 65, 1946 184

[10] CARLISLE R W and PEARSON H A J. Acoust. Soc. Amer. 23, 1951 300

[11] M E DELANY AND L S WHITTLE, 1966 A new artificial ear and mastoid. J. sci. Inst., 43, 519-520.

[12] DOWSON S.P. and McNEILL H.A. 1992. The effect of temperature on the performance of audiometric mechanical coupler systems. British Journal of Audiology, 26, 275-281.

[13] WHITTLE L S and ROBINSON D W Variations in the mechanical impedance of artificial mastoids and their effects on a reference bone conduction threshold NPL Acoustics Report Ac 51 1971

[14] B&K INSTRUCTION MANUAL Impedance heads type 8000 and 8001

APPENDIX A. PART A MEASUREMENT PROTOCOLS

EUROMET PROJECT 401 Harmonisation of audiometry measurements within Europe - Part A - Measurement of the mechanical impedance and force sensitivity of a mechanical coupler

A1. Introduction

The purpose of this part of the project is to compare measurements of the mechanical impedance and force sensitivity of an IEC 60373 mechanical coupler.

A2. Organisation and timescale

NPL (UK) will act as the pilot lab and the following laboratories will participate

- BEV (Austria)
- DPLA (Denmark)
- SP (Sweden)
- OFMET (Switzerland)
- PTB (Germany)

The test piece for the intercomparison is a mechanical coupler (Brüel & Kjær type 4930, serial number 1895330). NPL will determine the mechanical impedance and force sensitivity of the mechanical coupler and then each participating laboratory will in turn be sent the device.

The measurements at NPL will be completed before June 1999 and the bone vibrators distributed to the participants before July 1999. The devices must be returned to NPL and a report of the results obtained received by the end of November 1999. A final report on the measurements from part A and part B of this project will be completed by the end of January 2000.

A3. Specification of measurements to be made

Participants are required to measure the mechanical impedance and force sensitivity of a mechanical coupler (Brüel & Kjær type 4930, serial number 1895330) at frequencies of 250 Hz, 500 Hz, 750 Hz, 1.0 kHz, 1.5 kHz, 2.0 kHz, 3.0 kHz and 4.0 kHz. Optionally participant may make measurements at each of the 1/3-octave frequencies between 125 Hz and 8 kHz. The mechanical impedance of mechanical coupler shall be determined in Nsm^{-1} and the force response of mechanical coupler shall be determined in N.

A set of measurements shall consist of five repeated measurements at each frequency. A total of five sets of measurements shall be made each being determined on a different day, i.e. 5 sets of 5 measurements are required. Measurements shall be made in accordance with the requirements of ISO 389-3, IEC 60373 and IEC 60645.

All measurements shall be carried out with the mechanical coupler at a temperature of 23° C ±1° C

Both the air temperature and the mechanical coupler temperature and relative humidity shall be determined. Atmospheric pressure does not influence the results but can also be reported.

A4. Reporting of results

A report on the measurements shall be submitted to the pilot laboratory (NPL) by the end of November 1999. This shall include:

- A brief description of the measurement method
- A list of equipment used (i.e. make type and serial number.)
- A diagram of the apparatus with key items of equipment named
- A statement of results together with the environmental conditions during measurements. The preferred format is shown below
- A statement of the measurement uncertainty according to The ISO Guide (GUM) together with a description of the main contributing components
- Any difficulties or observations encountered while performing the measurements

The results shall be reported in tabular form as shown below. Results submitted in a format compatible with Microsoft Excel 95 (Version 7) and text in MS Word format would also be appreciated.

	Measurement set 1 Date, air & coupler temperature						
Frequency	1	2	3	4	5	mean	standard deviation
250							
500							

APPENDIX B. PART B MEASUREMENT PROTOCOLS

EUROMET PROJECT 401 Harmonisation of audiometry measurements within Europe - Part B - Measurement of the output of bone vibrators

B1. Introduction

The purpose of this part of the project is to compare measurements of the output of the IEC 60373 mechanical coupler when driven by a specified model of bone vibrator.

B2. Organisation and timescale

NPL (UK) will act as the pilot lab and the following laboratories will participate

- BEV (Austria)
- DPLA (Denmark)
- GUM (Poland)
- LNEC (Portugal)
- SMU (Slovak Republic)
- SP (Sweden)
- OFMET (Switzerland)
- PTB (Germany)

The output from eight pairs of Radioear type B71 Bone vibrator will be determined at NPL. Each participating laboratory will then be sent one pair of bone vibrators and a 4-wire cable for driving them. The measurements at NPL will be completed before June 1999 and the bone vibrators distributed to the participants before July 1999. The devices must be returned to NPL and a report of the results obtained received by the end of November 1999. A final report on the measurements from part A and part B of this project will be completed by the end of January 2000.

B3. Specification of measurements to be made

Participants are required to measure the force levels produced by two Radioear B71 bone vibrators when applied to their own calibrated IEC 60373 type 4930 mechanical coupler. The bone vibrators will be supplied with a 4-wire cable allowing the driving voltage to be measured directly at the bone vibrator terminals. These cables will be fitted with 4mm plugs which can be adapted if necessary to suit the measuring instrumentation available. The signal should be applied to one pair of red and black connectors and measured on the other pair. Each bone vibrator shall be driven with an r.m.s sinusoidal signal of 100mV at frequencies of 250 Hz, 500 Hz, 750 Hz, 1.0 kHz, 1.5 kHz, 2.0 kHz, 3.0 kHz and 4.0 kHz. Optionally participant may make measurements at each of the 1/3-octave frequencies between 125 Hz and 8 kHz. Measurements of this voltage shall be made at the end of one pair of cables on the leads supplied.

The output of the mechanical coupler shall be determined in dB re 1N/V at each of the given frequencies. A set of measurements shall consist of five repeated measurements at each frequency. A total of five sets of measurements shall be made each being determined on a different day, i.e. 5 sets of 5 measurements are required.

The measurements shall be made with the bone vibrator positioned centrally on the dome of the mechanical coupler. Visual positioning should be used to achieve this. This position should result in the maximum output from the mechanical coupler at high frequencies.

ISO 389-3, IEC 60373 and IEC 60645 require that a static force of 5.4 N ± 0.5 N be applied to the bone vibrator. This is most easily achieved by using the loading arm of the mechanical coupler with its tension spring detached and a metal (e.g. brass) block of appropriate mass bolted to the arm immediately above the bone vibrator. To determine the correct mass it is necessary to consider both the effective mass of the loading arm (about 60 g) and the mass of the bone vibrator itself (approximately 20 g for a Radioear type B-71). Thus, the appropriate loading mass for calibration of a type B-71 bone vibrator would be:

$$550\ g - 60\ g - 20\ g = 470\ g.$$

All measurements shall be carried out with the mechanical coupler at a temperature of 23° C ±1° C

Both the air temperature and the mechanical coupler temperature and relative humidity shall be determined. Atmospheric pressure does not influence the results but can also be reported.

B4. Reporting of results

A report on the measurements shall be submitted to the pilot laboratory (NPL) by the end of November 1999. This shall include:

- A brief description of the measurement method
- A list of equipment used (i.e. make type and serial number.)
- A diagram of the apparatus with key items of equipment named
- A statement of results together with the environmental conditions during measurements. The preferred format is shown below
- A statement of the measurement uncertainty according to The ISO Guide (GUM) together with a description of the main contributing components
- Any difficulties or observations encountered while performing the measurements

The results shall be reported in tabular form as shown below. Results submitted in a format compatible with Microsoft Excel 95 (Version 7) and text in MS Word format would also be appreciated.

	Measurement set 1 Date, air & coupler temperature						
Frequency	1	2	3	4	5	mean	standard deviation
250							
500							

APPENDIX C. REPORT ON MEASUREMENTS MADE BY NPL

C1. Calibration Preparation

It is important that all parts of the measurement system used to calibrate a mechanical coupler are calibrated and that the environmental conditions are suitable. Calibration of a mechanical coupler system involves applying a known vibratory force to the coupler, under a static load of 5.4 N, at the reference temperature of 23 ºC and recording the response of the system. The required force level is delivered to the coupler using an impedance head, which is attached to an electromagnetic shaker. The impedance head contains two piezoelectric transducers, an accelerometer and a force transducer. The accelerometer of the impedance head was calibrated by a commercial accredited calibration laboratory, and provides traceability for the force measurement.

The calibrated accelerometer is then used to calibrate the force transducer. This is done internally by NPL. A small mass is attached to the driving platform of the impedance head using a smear of grease, and the assembly vibrated with the shaker freely in air. The force needed to impart a measured acceleration to the known mass can be calculated and thereby used to calibrate the force transducer.

Measurements were only performed when the ambient temperature was within the temperature range of 22.0 ºC to 24.0 ºC.

Prior to calibrating a device, NPL's procedure requires a reference device to be calibrated to check the measurement system. The calibration history of the reference device provides this check. In comparing the results with the previous four check runs of the calibration history, it is considered acceptable to proceed only where the mean value at each frequency does not differ from the historical mean by more than 0.5 dB.

C2. Set-Up & Calibration of mechanical coupler system

Having ensured that the laboratory measurement system operates to an acceptable degree of accuracy and the environmental conditions meet the appropriate requisite, the selected device can be set up for calibration. NPL, however, require a number of specific set-up checks to be made before measurements are taken.

The device temperature must be maintained at 23ºC ± 1ºC. It is monitored by attaching a thermocouple to the vertical side of the mechanical coupler. Where the temperature is found to be outside these limits the device will be allowed to acclimatise in an environment maintained at the reference temperature.

In the physical set-up, it is essential to ensure that the mechanical coupler base is horizontal, so as to achieve uniform contact between the impedance head and the mechanical coupler. Spacers, placed under the feet of the coupler are used to adjust the height, and a spirit level used to check the horizontal alignment.

A counterbalance system, which supports the mini-shaker and impedance head is used to apply the excitation force to the mechanical coupler. This counterbalance system is aligned by adjusting the counterbalancing weight so that the impedance head just touches the tip of the mechanical coupler's rubber dome then by applying a known mass directly above the dome of the mechanical coupler, a known force can be applied

It is also necessary, before making any measurements, to compensate for the seismic mass of the impedance head which would otherwise add to the impedance being measured. The impedance head is constructed in such a way that the phase of the acceleration and force outputs are 180º apart. A compensation voltage can be obtained by voltage division and the result of adding this to the force output is the cancellation of the force signal and therefore the mechanical impedance measured will be the true mechanical impedance. This is achieved using an electrical network referred to as a mass compensation unit [14]. Ensuring the impedance head is not in contact with the mechanical coupler the mini shaker is driven at a frequency of 3 kHz and the mass compensation unit is adjusted to give minimum output on an oscilloscope.

C3. Mechanical impedance measurement

This procedure measures the mechanical impedance of the test device and does not require anything to be attached to the output of the mechanical coupler.

The impedance head is mounted on the dome of the mechanical coupler and a 5.4 N force (using a known weight) applied centrally to mini-shaker. Using a spirit level to ensure the support arm is horizontal, the centre of the impedance head driving face is centrally positioned over the tip of the mechanical coupler's rubber dome.

The force and (integrated) acceleration outputs of the impedance head are now used to automatically measure the mechanical impedance over the specified frequency range. If there is noise or the signal is unstable, the results are rejected and the measurements repeated until a stable set of measurements has been obtained. For the intercomparison, three measurements were made, turning the mini-shaker and impedance head through an angle of approximately 120º between each measurement. The mean and standard deviation at each frequency was calculated and checked against the tolerances quoted for mechanical impedance in IEC 60373. The criteria for acceptance was that the standard deviation for the three measurements was less than 0.3 dB at each frequency.

C4. Force measurement

Essentially, the procedure requires that the impedance head be mounted centrally on the dome of the mechanical coupler and the applied signal level adjusted so that the mechanical coupler was driven at 30 dB re RETFL. With the test filters in, the reading is recorded. This is then repeated for each of the test frequencies in the range 250 Hz to 4 kHz. The mini-shaker and impedance head are then turned through an angle of approximately 120º and the measurements repeated a further five times. The criteria for acceptance was that the standard deviation for each set of measurements should be less than 0.2 dB at each frequency.

C5. Acceleration measurement

In addition to the force sensitivity, NPL historically measures the acceleration sensitivity. Although these results are not shown they are useful for checking other results (see 10.2.4). As with the force measurement, the procedure for acceleration sensitivity requires that the impedance head be mounted centrally on the dome of the mechanical coupler, and the applied signal level adjusted so that the mechanical coupler was driven at 10 dB re RETAL. With the test filters in, the reading is recorded. This is then repeated for each of the test frequencies in the range 250 Hz to 4 kHz. The mini-shaker and impedance head are then turned through an angle of approximately 120º and the measurements repeated a further five times. The criteria for acceptance was that the standard deviation for each set of measurements should be less than 0.2 dB at each frequency.

C6. Closing the loop

Having measured the force sensitivity, acceleration sensitivity and mechanical impedance independently a final consistency check is made referred to as "closing the loop". Essentially, the force sensitivity is calculated from the mean measured values of acceleration and mechanical impedance for each frequency and compared with the measured force sensitivity at each frequency. The acceptance criterion is that the difference between the measured and the calculated force sensitivity shall not exceed 0.6 dB at any frequency with an overall mean difference aggregated across all frequencies not exceeding 0.2 dB.

C7. Results

The measurement results obtained by NPL for both mechanical impedance (dB re $1Nsm^{-1}$) and force sensitivity (dB re 1 VN^{-1}) of the mechanical coupler are given in table 2 and 3, over.

Table 2. Mechanical impedance (dB re 1Nsm^{-1}) for the mechanical coupler

	14/11/96		14/11/96		27/11/96		27/02/98		27/02/98		02/03/99		28/07/99		03/02/00		16/07/00	
	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
250	44.28	0.18	44.33	0.11	44.07	0.17	44.10	0.09	44.45	0.17	44.14	0.08	45.76	0.10	45.8	0.05	45.84	0.10
500	40.07	0.19	40.14	0.08	39.83	0.18	40.39	0.06	40.22	0.14	40.17	0.04	41.61	0.07	41.58	0.03	41.55	0.11
750	37.60	0.21	37.66	0.08	37.33	0.19	37.94	0.06	37.75	0.15	37.64	0.03	39.14	0.01	39.13	0.03	39.09	0.07
1000	35.73	0.20	35.80	0.06	35.46	0.21	36.07	0.05	35.91	0.10	35.76	0.04	37.34	0.02	37.28	0.04	37.35	0.10
1500	32.87	0.25	32.94	0.08	32.58	0.26	33.30	0.06	33.13	0.12	32.99	0.00	34.69	0.05	34.66	0.05	34.68	0.05
2000	30.80	0.25	30.88	0.05	30.94	0.36	31.01	0.07	31.06	0.10	30.95	0.01	32.55	0.05	32.49	0.06	32.56	0.37
3000	28.49	0.18	28.57	0.03	28.86	0.39	28.33	0.05	28.65	0.11	29.10	0.01	29.59	0.09	29.67	0.04	29.63	0.05
4000	29.73	0.15	29.70	0.04	29.85	0.23	29.52	0.05	29.78	0.07	29.08	0.01	30.00	0.15	29.98	0.16	29.78	0.12
5000	33.84	0.06	33.8 3	0.11	33.75	0.09	33.69	0.02	33.7 5	0.05	33.93	0.01	32.38	0.06	32.28	0.13	32.3	0.09

Table 3. Force sensitivity (dB re 1 VN^{-1}) for the mechanical coupler

	14/11/96		27/02/98		02/03/99		28/07/99		03/02/00		17/07/00	
	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
250	-17.20	0.11	-17.13	0.13	-17.93	0.12	-18.10	0.11	-17.98	0.13	-18.05	0.12
500	-17.38	0.12	-17.18	0.15	-17.10	0.14	-17.90	0.12	-17.89	0.15	-17.81	0.14
750	-17.28	0.10	-17.06	0.07	-17.48	0.10	-17.70	0.10	-17.73	0.07	-17.67	0.10
1000	-16.32	0.10	-16.24	0.12	-16.43	0.14	-17.40	0.10	-17.33	0.12	-17.37	0.14
1500	-16.58	0.28	-16.57	0.25	-16.33	0.29	-16.84	0.28	-16.91	0.25	-16.88	0.29
2000	-15.77	0.17	-15.37	0.30	-15.46	0.21	-16.36	0.17	-16.30	0.30	-16.37	0.21
3000	-16.03	0.18	-15.44	0.20	-15.12	0.19	-16.15	0.18	-16.20	0.20	-16.10	0.19
4000	-19.07	0.26	-19.00	0.17	-18.98	0.27	-19.00	0.26	-19.15	0.17	-19.10	0.27

C8. Uncertainties

The two types of uncertainty component listed here are combined in accordance with the recommendations of NAMAS publication NIS 3003 Edition 8 1995 [6] to give the overall uncertainty based on a standard uncertainty multiplied by a coverage factor *k*=2, providing a confidence probability of approximately 95%. A single uncertainty value is used for all frequencies, it is calculated using the worst value over the measurement frequency range unless otherwise stated. The typical uncertainty is shown, but in practice the total uncertainty was calculated individually for each test system.

Table 1a. Uncertainty budget for measurement of mechanical impedance

Symbol	Sourse of uncertainty	Value +/- dB	Probability distribution	Divisor	C_i	u_i (dB) +/- dB	V_i or V_{eff}
I_{mc}	Effect of load impedance of coupler on force transducer	0.050	*rectangular*	1.732	1	0.029	*infinity*
A_{ca}	Gain of charge amplifier and filters	0.050	*rectangular*	1.732	1	0.029	*infinity*
A_{mcu}	Gain of mass compensation unit	0.043	*normal*	2.000	1	0.022	*infinity*
A_{dca}	Gain of digitally controlled amplifier	0.043	*normal*	2.000	1	0.022	*infinity*
U_v	Accuracy of standard voltmeter	0.010	*normal*	2.000	1	0.005	*infinity*
R	Rounding of final result	0.050	*rectangular*	1.732	1	0.029	*infinity*
U_{sft}	Sensitivity of standard force transducer	0.161	*normal*	2.000	1	0.081	*infinity*
T_{TF}	Component for temperature variation of force transducer	0.020	*rectangular*	1.732	1	0.012	*infinity*
T_{CA}	Component for temperature variation for charge amplifier	0.020	*rectangular*	1.732	1	0.012	*infinity*
M	Component for variation in masses	0.020	*rectangular*	1.732	1	0.012	*infinity*
L_x	Typical repeatability	0.050	*normal*	1.000	1	0.050	5
$U_c(L_x)$	Combined uncertainty		*normal*			0.113	*infinity*
U_T	Expanded uncertainty		*normal(k=2)*			0.227	*infinity*

Table 1b. Uncertainty budget for force sensitivity measurement

Symbol	Sourse of uncertainty	Value +/- dB	Probability distribution	Divisor	C_i	u_i (dB) +/- dB	V_i or V_{eff}
I_{mc}	Effect of load impedance of coupler on force transducer	0.050	*Rectangular*	1.732	1	0.029	*infinity*
R_{slm}	Setting up of sound level meter	0.100	*rectangular*	1.732	1	0.058	*infinity*
A_{ca}	Gain of charge amplifier and filters	0.050	*rectangular*	1.732	1	0.029	*infinity*
A_{mcu}	Gain of mass compensation unit	0.043	*normal*	2.000	1	0.022	*infinity*
A_{dca}	Gain of digitally controlled amplifier	0.043	*normal*	2.000	1	0.022	*infinity*
U_v	Accuracy of standard voltmeter	0.010	*normal*	2.000	1	0.005	*infinity*
R	Rounding of final result	0.050	*rectangular*	1.732	1	0.029	*infinity*
U_{sft}	Sensitivity of standard force transducer	0.161	*normal*	2.000	1	0.080	*infinity*
T_{tf}	Component for temperature variation of force transducer	0.020	*rectangular*	1.732	1	0.012	*infinity*
T_{ca}	Component for temperature variation for charge amplifier	0.020	*rectangular*	1.732	1	0.012	*infinity*
L_x	Typical repeatability	0.150	*normal*	1.000	1	0.150	5
$U_c(L_x)$	Combined uncertainty		*normal*			0.190	*infinity*
U_T	Expanded uncertainty		*normal(k=2)*			0.380	*infinity*

APPENDIX D. REPORT ON MEASUREMENTS MADE BY PTB

PTB 1.41 **October 1999**

EUROMET intercomparison on the calibration of bone-conduction audiometers (EUROMET project A 401)

U. Richter and P. Gössing

D1. Introduction

An intercomparison of calibrations on audiometric bone vibrators and devices to measure these bone vibrators (called mechanical couplers) has been started within the EUROMET group "Acoustics". This project is a follow-up of an earlier EUROMET intercomparison (A 399) on audiometric earphones. The principle objectives of both projects are:

- to compare calibrations of audiometers by national standards laboratories
- to test the consistency of standards for air- and bone-conduction audiometry and
- to identify the cause of any anomalies, if existing.
-

Laboratories from 9 European countries (DK, DE, CH, UK, ES, AT, PO, SL and SE) are participating in this intercomparison with NPL working as pilot laboratory. The bone-conduction project is split into three parts:

- In Part A the mechanical impedance and the force sensitivity of one mechanical coupler has to be measured. This part is set up as a round robin investigation.
- In Part B the sensitivity levels of two bone vibrators driven by a defined voltage have to be determined. This part is set up as a radial investigation.
- In Part C, finally, the dependence of the sensitivity level of a B 71 bone vibrator on relative humidity is investigated. This part only is performed at PTB.
-

D2. Measurements on the mechanical coupler

A.1.1 Measurement set-up	as given in Fig. 1
A.1.2 Test signals	pure tones of audiometric frequencies between 125 Hz and 8000 Hz
A.1.3 Impedance head	Type B&K 8000 # 619565 with a front plate mass of 1,18 g, calibrated at PTB
A.1.4 Mechanical coupler	NPL owned coupler B&K 4930 # 1895330 <u>in its condition before March 1998</u>
A.1.5 Calibration compensation unit.	a) mechanical impedance measurement by means of the non-compensated front plate mass of the used impedance head at 500 Hz and by calculating the corresponding impedance (Z=ωm) for level and phase. This mass was

	determined beforehand by means of 5 different masses in the range from 14 g to 25 g. b) force sensitivity measurement set-up by summing up the force output sensitivity of the used impedance head (determined at 1000 Hz by the corresponding PTB section) and all gain values of the measurement chain as for instance cable capacity (106 pF), amplifiers and the mass
A.1.6 Preparation of the coupler	The mechanical coupler under test was stored 24 hours prior to the measurements in a box stabilised to 23 °C ± 1 °C.
A.1.7 Static force of application	set to 5,4 N ± 0,3 N, checked by a known mass
A.2 Measurements	Mechanical impedance levels and force sensitivity levels were measured on five different days at PTB on the NPL owned mechanical coupler. The mass compensation was performed for both measurements at 500 Hz
A.3 Results	
A.3.1 Mechanical impedance	The resulting impedance levels are printed in Table 14.1 together with the phase at 250 Hz and the climatic conditions on the different days
A.3.2 Force sensitivity levels	The resulting force sensitivity levels are given in Table 14.2

B. Measurements on bone vibrators

B.1.1 Measurement set-up	as given in Fig. 2
B.1.2 Test signals	pure tones of audiometric frequencies between 125 Hz and 8000 Hz with a level of 0,1 V (1,0 V at 6 kHz)
B.1.3 Mechanical coupler	PTB owned mechanical coupler B&K 4930 # 1307981 with a resonance frequency of the mechanical impedance between 3000 Hz and 3150 Hz. The coupler was stored 24 hours prior to the measurements in a box stabilised to 23 °C ± 1 °C
B.1.4 Calibration	The mechanical coupler was calibrated as described in Clause A. The gain of the measurement chain was determined by means of a calibrated DVM
B.1.5 Static force of application	produced by a mass of 450 g on the top of the loading arm, which results together with the weight of the B-71 and of the loading arm to 5,4 N ± 0,3 N
B.1.6 Mounting procedure	The bone vibrator was placed several times on the top of the coupler (middle of the plastic layers) until at 4 kHz a maximum output was found
B.1.7 Bone vibrators	Two samples of type Radioear B-71 without serial numbers. The vibrators were marked as #1 and #2 by PTB
B.2 Measurements	sensitivity levels of the bone vibrator were measured on five different days at PTB on the PTB owned mechanical coupler
B.3 Results	The resulting coupler sensitivity levels of the bone vibrators are given in Tables 14.3 and 14.4.

C. Humidity dependency

C.1.1 Measurement set-up	as given in Fig. 2, however both, the mechanical coupler and the PTB owned bone vibrator were placed in a climatic chamber of type Heraeus Vötsch VUK 02/10000s
C.1.2 Test signals	pure tones of audiometric frequencies between 125 Hz and 8000 Hz with a level of 0,1 V (1,0 V at 6,3kHz and 8 kHz)
C.1.3 Mechanical coupler	PTB owned mechanical coupler B&K 4930 # 1307981. The coupler was stored 24 hours prior to the measurements in a box stabilised to 23 °C ± 1 °C
C.1.4 Humidity range	The measurements were performed at 40 % and at 80% r.H.
C.2 Measurements	The mechanical coupler was placed in the climatic chamber together with the dismounted bone vibrator. The climate was set to 23 °C and to the humidity under test with a stabilising time of 7 hours. At the end of this stabilising time the vibrator six times was mounted on top of the coupler (in a way described in B.1.6) and each time the coupler sensitivity level was measured as a function of the audiometric frequencies (this time including 8 kHz). The mean of these six readings was taken as the result at the actual humidity under test.
C.3 Results	The standard deviations of the six readings at each humidity point ranged from 0,1 dB to 0,3 dB for frequencies 125 Hz to 4000 Hz and from 0,4 dB to 0,8 dB for 6 kHz and 8 kHz. The difference of the coupler sensitivity levels of the B-71 bone vibrator at 40 % and at 80 % relative humidity are given in Table 5.
C.4 Conclusions	The results in Table 14.5 show that the coupler sensitivity levels of a bone vibrator of type B-71 measured on a coupler type B&K 4930 practically do not depend on humidity.
D.Measurement uncertainties	(preliminary calculation, confidence level 95 %)

Frequency range	Measurement uncertainty (k=2)		
	Mech. impedance	Force sensitivity	Coupler sens. B-71
125 Hz to 2000 Hz	≤0,4 dB	≤0,5 dB	≤0,8 dB
3000 Hz	< 0,5 dB	< 1 dB	≤2,5 dB (1,3 dB)[1]
4000 Hz to 8000 Hz	< 1 dB	< 1,5 dB	≤1,3 dB

[1] The value of 1,3 dB is valid in case of using only mechanical couplers with a resonance frequency of the mechanical impedance below 3000 Hz.

Table 14.1 Level of mechanical impedance of the mechanical coupler B&K 4930 # 1895330 together with the phase value (250 Hz only) measured on 5 different days

Frequency in Hz	Level of mechanical impedance (re 1Ns/m) in dB						
	13.1.98	14.1.98	15.1.98	16.1.98	19.1.98	Mean value	Stand. dev.
	23,1 °C (coupl) 23,9 °C (air) 100,04 kPa 41,9 % r. H.	23,0 °C (coupl) 23,6 °C (air) 99,88 kPa 46,3 % r. H.	23,0 °C (coupl) 22,9 °C (air) 100,55 kPa 45,7 % r. H.	22,8 °C (coupl) 22,9 °C (air) 99,82 kPa 44,5 % r. H.	22,5 °C (coupl) 22,3 °C (air) 97,83 kPa 43,3 % r. H.		
125	48,5	48,3	48,6	48,5	48,6	48,50	0,12
250	44,1	43,9	44,2	44,1	44,3	44,12	0,15
500	39,9	39,7	40,1	40,0	40,2	39,98	0,19
750	37,6	37,4	37,8	37,7	37,9	37,68	0,19
1000	35,9	35,7	36,1	36,0	36,1	35,96	0,17
1500	33,1	32,9	33,3	33,2	33,4	33,18	0,19
2000	30,9	30,8	31,2	31,1	31,3	31,06	0,21
3000	28,4	28,2	28,7	28,5	28,7	28,50	0,21
4000	29,5	29,4	29,7	29,5	29,6	29,54	0,11
6000	33,9	33,7	34,0	33,9	34,0	33,90	0,12
8000	34,9	34,8	35,0	35,1	35,2	35,00	0,16
	Phase value of mechanical impedance						
250	60,0°	59,8°	59,7°	59,8°	59,6°	59,78°	0,15°

Table 14.2 Force sensitivity level of the NPL owned mechanical coupler B&K 4930 # 1895330 measured on 5 different days

Frequency in Hz	Force sensitivity level (re 1 V/N) in dB						
	13.1.98	14.1.98	15.1.98	16.1.98	19.1.98	Mean value	Stand. dev.
	23,1 °C (coupl) 23,9 °C (air) 100,04 kPa 41,9 % r. H.	23,0 °C (coupl) 23,6 °C (air) 99,88 kPa 46,3 % r. H.	23,0 °C (coupl) 22,9 °C (air) 100,55 kPa 45,7 % r. H.	22,8 °C (coupl) 22,9 °C (air) 99,82 kPa 44,5 % r. H.	22,5 °C (coupl) 22,3 °C (air) 97,83 kPa 43,3 % r. H.		
125	-17,5	-17,5	-17,5	-17,5	-17,5	-17,50	0
250	-17,4	-17,4	-17,4	-17,4	-17,4	-17,40	0
500	-17,2	-17,2	-17,2	-17,2	-17,2	-17,20	0
750	-17,0	-17,0	-17,0	-17,0	-17,0	-17,00	0
1000	-16,7	-16,7	-16,7	-16,7	-16,7	-16,70	0
1500	-16,0	-16,1	-16,1	-16,1	-16,1	-16,08	0,04
2000	-15,5	-15,5	-15,5	-15,5	-15,6	-15,52	0,04
3000	-15,9	-16,0	-16,0	-15,8	-15,8	-15,90	0,10
4000	-19,1	-19,1	-19,1	-18,9	-18,7	-18,98	0,18
6000	-23,6	-23,7	-23,6	-23,5	-23,4	-23,56	0,11
8000	-23,6	-23,6	-23,5	-23,5	-23,4	-23,52	0,08

Table 14.3 Coupler sensitivity level of a bone vibrator B-71 # 1 measured on a PTB owned mechanical coupler B&K 4930 # 1307981

Frequency in Hz	Coupler sensitivity level G_c of a bone vibrator (re 1N/V) in dB						
	05.03.98 22,5 °C (coupl) 22,0 °C (air) 994 kPa 43 % r. H.	06.03.98 22,5 °C (coupl) 22,0 °C (air) 100,53 kPa 44 % r. H.	10.03.98 22,7 °C (coupl) 22,2 °C (air) 101,94 kPa 43 % r. H.	11.03.98 22,5 °C (coupl) 22,2 °C (air) 100,53 kPa 40 % r. H.	12.03.98 22,7 °C (coupl) 23,0 °C (air) 105,7 kPa 40 % r. H.	Mean value	Stand. dev.
125	-21,91	-21,94	-21,98	-21,98	-21,96	-21,95	0,03
250	-8,58	-8,50	-8,57	-8,57	-8,62	-8,57	0,04
500	+1,55	+1,17	+1,43	+1,40	+1,47	+1,40	0,14
750	-4,76	-4,94	-4,82	-4,89	-4,83	-4,85	0,07
1000	-6,42	-6,42	-6,42	-6,46	-6,42	-6,43	0,02
1500	-3,14	-3,21	-3,27	-3,25	-3,21	-3,22	0,05
2000	-11,86	-12,11	-11,97	-11,97	-11,97	-11,98	0,09
3000	-18,23	-18,48	-18,29	-18,34	-18,45	-18,36	0,11
4000	-12,25	-12,68	-12,59	-12,55	-12,92	-12,60	0,24
6000	-33,52	-33,74	-33,83	-33,90	-33,92	-33,78	0,16

Remark.

The standard deviation of repeated measurements of G_c on the same day was:

< 0,10 dB for frequencies 125 Hz to 1000 Hz, with the exception of 500 Hz
< 0,20 dB for frequencies 1500 Hz to 3000 Hz and 500 Hz,
< 0,25 dB for frequencies > 3000 Hz.

Table 14.4 Coupler sensitivity level of a bone vibrator B-71 # 2 measured on a PTB owned mechanical coupler B&K 4930 # 1307981

Frequency in Hz	Coupler sensitivity level G_c of a bone vibrator (re 1N/V) in dB						
	05.03.98 22,5 °C (coupl) 22,0 °C (air) 994,6 kPa 44 % r. H.	06.03.98 22,5 °C (coupl) 22,0 °C (air) 100,55 kPa 44 % r. H.	10.03.98 22,7 °C (coupl) 22,5 °C (air) 101,94 kPa 43 % r. H.	11.03.98 22,5 °C (coupl) 22,4 °C (air) 100,52 kPa 40 % r. H.	12.03.98 22,7 °C (coupl) 23,1 °C (air) 105,7 kPa 40 % r. H.	Mean value	Stand. dev.
125	-21,01	-21,01	-21,01	-21,01	-21,01	-21,01	0
250	-7,57	-7,44	-7,46	-7,44	-7,44	-7,47	0,06
500	+2,04	+1,87	+1,83	+1,92	+1,84	+1,90	0,09
750	-4,10	-4,25	-4,24	-4,25	-4,24	-4,22	0,07
1000	-6,03	-5,98	-5,91	-5,93	-5,95	-5,96	0,05
1500	-3,05	-2,89	-2,97	-2,94	-2,83	-2,94	0,08
2000	-11,70	-11,86	-11,95	-11,92	-12,00	-11,89	0,12
3000	-17,89	-18,02	-18,08	-18,08	-18,07	-18,03	0,08
4000	-12,43	-12,64	-12,67	-12,62	-12,97	-12,67	0,19
6000	-33,47	-33,99	-33,88	-34,02	-34,11	-33,89	0,25

Remark.

The standard deviation of repeated measurements of G_c on the same day was:

< 0,10 dB for frequencies 125 Hz to 1000 Hz, with the exception of 500 Hz
< 0,20 dB for frequencies 1500 Hz to 3000 Hz and 500 Hz,
< 0,25 dB for frequencies > 3000 Hz.

Table 14.5 Mean difference of coupler sensitivity levels of a bone vibrator of type B-71 at 40 % and 80 % relative humidity as a function of frequency

Frequency in Hz	Difference of coupler sensitivity level in dB at 40 % and 80 % r. H.
125	0
250	0
500	0,2
750	0,1
1000	0
1500	0,1
2000	0,2
3000	-0,3
4000	0
6000	-0,4
8000	0

APPENDIX E. REPORT ON MEASUREMENTS MADE BY OFMET

E1. Calibration Preparation

No details have been provided.

E2. Set-Up & Calibration of mechanical coupler system

No details have been provided.

E3. Uncertainties

It is understood that OFMET require that for bone conduction audiometry, measurement uncertainty should not exceed 0.3 dB.

E4. Results

Table 8. Mechanical impedance results reported by OFMET

Table 8. Mechanical Impedance (dB re 1Ns/m) measurement results

Frequency	Res. 19.4.	Res. 20.4.	Res. 20.4.b	Res. 21.4.a	Res. 21.4.b	Res. 21.4.c	Mean	STDEV
100	52.1	51.8	51.9	51.9	52.1	52.1	**52.0**	0.13
125	50.5	50.2	50.3	50.3	50.5	50.4	**50.4**	0.12
168	48.4	48.1	48.3	48.3	48.3	48.4	**48.3**	0.11
200	47.3	47.1	47.1	47.2	47.3	47.2	**47.2**	0.09
250	45.8	45.6	45.7	45.7	45.8	45.8	**45.7**	0.08
315	44.3	44.0	44.2	44.2	44.4	44.4	**44.3**	0.15
400	42.9	42.7	42.8	42.9	43.0	43.0	**42.9**	0.12
500	41.6	41.3	41.4	41.4	41.5	41.6	**41.5**	0.12
630	40.3	40.1	40.2	40.2	40.4	40.4	**40.3**	0.12
800	38.7	38.5	38.6	38.6	38.8	38.8	**38.7**	0.12
1000	37.5	37.2	37.3	37.4	37.5	37.6	**37.4**	0.15
1250	36.0	35.7	35.8	35.9	36.1	36.1	**35.9**	0.16
1600	34.2	33.9	34.1	34.1	34.3	34.4	**34.2**	0.18
2000	32.6	32.3	32.4	32.4	32.6	32.9	**32.5**	0.22
2500	30.6	30.4	30.5	30.7	30.8	31.2	**30.7**	0.28
3150	29.3	29.1	29.3	29.3	29.4	29.8	**29.4**	0.23
4000	29.8	29.8	29.8	29.6	29.8	29.6	**29.7**	0.10
5000	32.3	31.9	32.0	31.9	32.3	32.3	**32.1**	0.20
6300	35.0	34.7	35.0	35.0	35.3	35.0	**35.0**	0.19
8000	36.9	36.9	36.9	36.9	36.9	36.4	**36.8**	0.20
10000	37.3	37.1	37.4	37.3	37.4	36.6	**37.2**	0.31

Table 9. Force sensitivity results reported by OFMET. Force was measured in terms of dB ref. 1V/N

Table 9. Force sensitivity (dB re 1 V/N) measurement results.

Frequency	Res. 19.4.	Res. 20.4.	Res. 20.4.b	Res. 21.4.a	Res. 21.4.b	Res. 21.4.c	Mean	STDEV
100	-17.9	-18.0	-18.2	-18.1	-18.2	-17.9	**-18.1**	0.14
125	-17.8	-17.9	-18.0	-17.9	-18.0	-17.7	**-17.9**	0.12
168	-17.7	-17.6	-18.0	-17.5	-17.8	-17.6	**-17.7**	0.18
200	-17.8	-18.1	-17.9	-17.9	-18.0	-17.8	**-17.9**	0.12
250	-17.7	-17.9	-18.0	-17.7	-17.9	-17.7	**-17.8**	0.13
315	-17.6	-17.7	-17.9	-17.8	-17.8	-17.7	**-17.8**	0.10
400	-17.6	-17.7	-17.9	-17.7	-17.8	-17.6	**-17.7**	0.12
500	-17.7	-17.9	-18.0	-17.7	-17.9	-17.8	**-17.8**	0.12
630	-17.7	-17.8	-18.0	-17.7	-17.9	-17.8	**-17.8**	0.12
800	-17.5	-17.6	-17.7	-17.6	-17.7	-17.6	**-17.6**	0.08
1000	-17.3	-17.4	-17.6	-17.4	-17.6	-17.4	**-17.5**	0.12
1250	-17.0	-17.2	-17.3	-17.2	-17.3	-17.2	**-17.2**	0.11
1600	-16.6	-16.7	-16.9	-16.7	-16.5	-16.9	**-16.7**	0.16
2000	-16.2	-16.4	-16.4	-16.3	-16.5	-16.5	**-16.4**	0.12
2500	-15.8	-16.0	-16.1	-16.1	-16.3	-16.2	**-16.1**	0.17
3150	-16.3	-16.4	-16.5	-16.4	-16.6	-16.6	**-16.5**	0.12
4000	-18.6	-18.5	-18.6	-18.3	-18.7	-18.8	**-18.6**	0.17
5000	-21.8	-21.6	-21.8	-21.5	-21.9	-21.6	**-21.7**	0.15
6300	-24.1	-24.2	-24.4	-24.0	-24.5	-24.1	**-24.2**	0.19
8000	-24.9	-24.9	-25.1	-25.1	-25.3	-24.0	**-24.9**	0.46
10000	-23.8	-24.1	-24.4	-24.0	-23.9	-23.1	**-23.9**	0.44

Table 10. Acceleration sensitivity results reported by OFMET. Acceleration was measured in dB ref. 1V/ms^2

Table 10. Acceleration sensitivity (dB re 1 V/ms^2)measurement results

Frequency	Res. 19.4.	Res. 20.4.	Res. 20.4.b	Res. 21.4.a	Res. 21.4.b	Res. 21.4.c	Mean	STDEV
100	-23.1	-23.5	-23.3	-23.3	-23.2	-23.7	**-23.4**	0.22
125	-25.9	-26.2	-26.2	-26.1	-26.1	-26.4	**-26.2**	0.16
168	-30.2	-30.6	-30.5	-30.4	-30.4	-30.5	**-30.4**	0.14
200	-32.8	-33.1	-33.1	-33.0	-33.0	-33.1	**-33.0**	0.12
250	-36.0	-36.4	-36.4	-36.3	-36.2	-36.2	**-36.3**	0.15
315	-39.4	-39.7	-39.8	-39.6	-39.5	-39.5	**-39.6**	0.15
400	-42.8	-43.1	-43.2	-43.0	-43.0	-42.9	**-43.0**	0.14
500	-45.9	-46.3	-46.4	-46.2	-46.2	-46.1	**-46.2**	0.17
630	-49.6	-50.0	-50.1	-49.9	-49.8	-49.8	**-49.9**	0.18
800	-53.0	-53.3	-53.3	-53.2	-53.2	-53.1	**-53.2**	0.12
1000	-56.1	-56.5	-56.5	-56.3	-56.3	-56.2	**-56.3**	0.16
1250	-59.3	-59.5	-59.7	-59.5	-59.4	-59.2	**-59.4**	0.18
1600	-62.7	-63.0	-63.1	-62.9	-62.9	-62.7	**-62.9**	0.16
2000	-65.8	-66.3	-66.3	-66.2	-66.1	-65.9	**-66.1**	0.21
2500	-69.3	-69.6	-69.7	-69.5	-69.5	-69.1	**-69.5**	0.22
3150	-73.1	-73.3	-73.4	-73.2	-73.2	-73.0	**-73.2**	0.14
4000	-77.0	-77.0	-77.1	-77.1	-76.8	-76.9	**-77.0**	0.12
5000	-79.6	-79.4	-80.0	-79.1	-79.3	-79.5	**-79.5**	0.31
6300	-81.3	-81.5	-81.9	-81.3	-80.6	-81.1	**-81.3**	0.43
8000	-82.2	-82.4	-82.6	-82.0	-82.1	-82.1	**-82.2**	0.23
10000	-82.4	-82.7	-82.8	-82.5	-82.3	-81.1	**-82.3**	0.62

During the measurements, the environmental conditions were monitored. The mean of the recorded conditions is give below.

- Pressure: 948.2 mbar
- Temp. (air): 23.5ºC
- Temp: (mast): 23.2ºC
- Humidity: 31.2%

APPENDIX F. REPORT ON MEASUREMENTS MADE BY DPLA

F1. Intercomparison Measurement made by DPLA, Denmark

This section sets out the procedures employed by DPLA, detailing preparatory measurements, systems checks and conditions, the calibration set up and specific process for measuring impedance and force sensitivity, identifies the uncertainties likely to arise from the measurements, and sets out the available measurement results.

F2. Calibration Preparation

In line with NPL, it is understood that DPLA conducted system calibrations and ensured that the environmental conditions were appropriate for the intercomparison measurements.

DPLA recognizing the importance of calibrating all parts of the measurement system, described in a detailed technical report, methods for calibrating the impedance transducer (or 'head') in the whole frequency range. It is explained that while the impedance sensitivity can be determined by fairly simple means, the absolute sensitivity of the force transducer part requires a comparison with a calibrated reference, usually a reference accelerometer. At DPLA an impedance transducer is usually calibrated by comparing the accelerometer part with a reference accelerometer using laser interferometry. Indeed, this method is employed at NPL, as explained earlier. However, DPLA note, in addition to this check, the force transducer must be calibrated by loading the transducer with a known mass and calculating the applied force using the measured acceleration of that mass. In an attempt to abridge these preparatory calibration requirements, which call for the use sophisticated calibration equipment, DPLA conducted an additional specific investigation to simplify the method. This work is however beyond the scope of this report. Reference should be made to the DPLA report.

In terms of environmental conditions, DPLA noted that measurements were performed in a temperature controlled room (23 ± 1,5 °C) and the temperature of the mastoid base were measured to be within the range 22,6 - 23,3 °C.

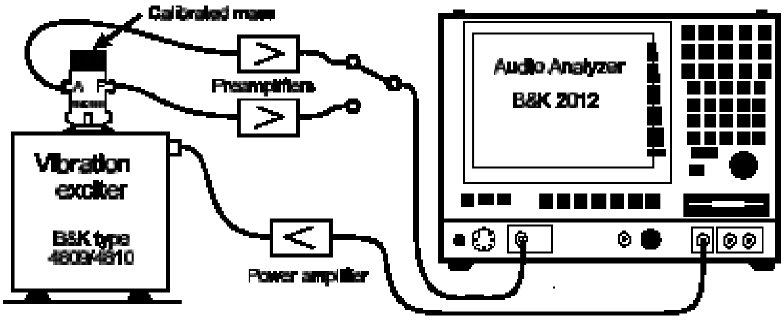
F3. Set-Up & Calibration of mechanical coupler system

DPLA explain that the calibration of the artificial mastoid (mechanical coupler) falls in two parts;
determination of the mechanical input impedance of the device and

determination of the output force sensitivity.

At DPLA the measurements are performed using the setup as illustrated in figure 1. The arrangement in figure 1 is placed upside down on top of the artificial mastoid and a counter balance system is applied to ensure that the static force loading the mastoid is 5,4 N. In the actual arrangement the exciter (B&K type 4810) with the impedance transducer is hanging downwards in a calibrated spring balance. The calibration is performed by substituting the artificial mastoid with anelectronic Mettler precision balance thereby determining the resulting force on the contact surface, ie the driving platform of the impedance transducer B&K type 8000.

Figure 1 Arrangement for determining the impedance sensitivity of the impedance transducer B&K 8000



DPLA note that care should be taken to ensure that the mechanical impedance of the mastoid is determined perpendicular to the contact surface. At DPLA, similarly to NPL, a spirit level is used to ensure that the mastoid base surrounding the rubber plates is horizontal. Next, the impedance transducer mounted on the exciter is positioned vertically in the centre of the rubber plate using a static force of 5,4 N. The angle of contact is controlled visually by ensuring that the small opening angles between the curved surface of the rubber plate and the flat surface of the driving platform of the transducer is the same to both sides of the transducer and for all viewing angles.

F4. Mechanical impedance measurement

For the measurement arrangement described above, the impedance of the artificial mastoid (mechanical coupler) can be determined by calculation. This requires measurement of the *Force/acceleration* ratio without load, (i.e. for a free hanging exciter/transducer system). The mastoid impedance is effectively determined by multiplying the difference between the ratio of the impedance transducer for a free hanging system (*F/a*) and when attached to the mechanical coupler with the angular frequency ω divided by the impedance sensitivity of the transducer.

It is noted that the impedance of the impedance transducer has been applied as a constant value independent of frequency. This has been done in order to facilitate the comparison of results among the laboratories taking part in the present EUROMET project 401.

F5. Force measurement

For a constant excitation velocity of 1 mm/s the *Force/acceleration* ratio is measured for a free hanging impedance transducer. The impedance transducer is then positioned on the mastoid using a static force of 5,4 N and the *F/a* ratio of the transducer is measured again. Finally the force output of the mastoid is measured. The sensitivity of the force transducer built into the mastoid is determined by a comparison with the force transducer unit of the impedance transducer (B&K 8000) and applying a correction for the influence of the driving platform mass. The ratio of the output signal from the two force transducers units is multiplied by the *F/a* ratio of the impedance transducer when loaded with the mastoid and divided by the difference of the *F/a* ratios under loaded and unloaded conditions. The resulting force ratio is finally divided by the sensitivity of the force transducer unit in the impedance transducer.

It is noted that the force sensitivity of the impedance transducer has been applied as a constant value independent of frequency. This has been done in order to facilitate the comparison of results among the laboratories taking part in the present EUROMET project 401.

F6. Uncertainties

Individual uncertainties provided by DPLA have been included in Tables 10 and 11.

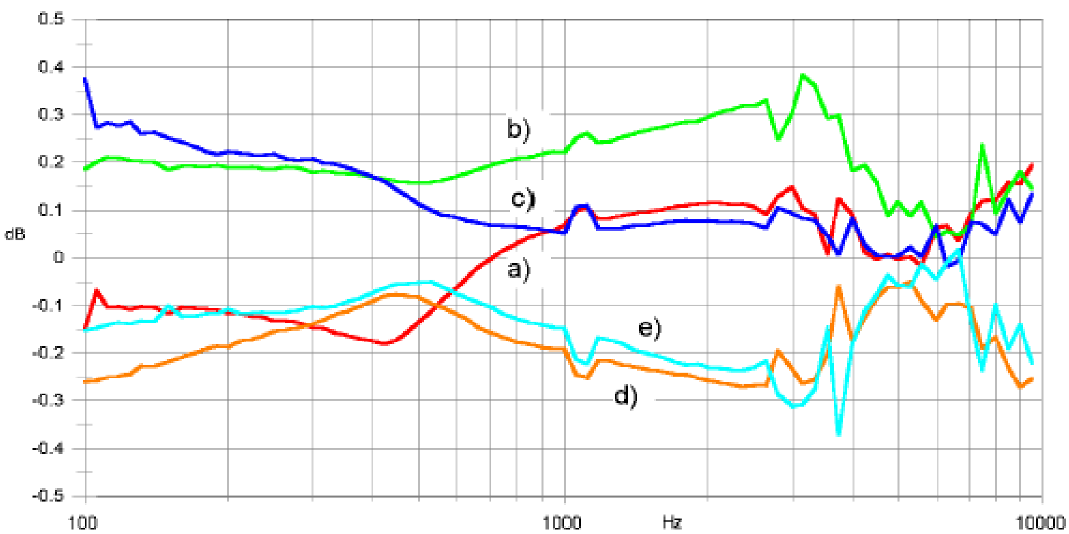
F7. Results

The following provides extracts of the results presented by DPLA in a technical report.

F8. Effect of different excitation signals

It is well known that the elastic properties of rubber materials depend not only on temperature and static compression but also on the level and frequency of excitation. DPLA conducted a series of measurements to demonstrate this behavior. Figure 2 below shows the relative changes in the mechanical impedance level of a mastoid for various excitation signals. More than 0.5 dB differences are observed, indicating that the results of measurements of the mechanical impedance of such mastoid should be accompanied by a specification of the excitation level. The standard[12] does not specify any excitation level and in order to improve the reproducibility all measurements have been performed using an excitation signal giving a constant velocity of 1 mm/s. Such a signal will be independent of the type of exciter and also results in a reasonable signal-to-noise ratio without stressing the exciter.

Figure 2. Measured relative impedance levels for an artificial mastoid B&K type 4930 using different excitation levels on the exciter B&K type 4810



a) Constant driving voltage 1 Volt
b) Constant driving voltage 0,5 Volt
c) Driving voltage proportional to frequency
d) Driving voltage shaped to obtain a constant velocity of 1 mm/s
e) Driving voltage shaped to obtain a constant velocity of 0,5 mm/s

The sensitivity of the force transducer in the mastoid does not show the same dependence of excitation signal. From the network in figure 3 it can be seen that in the stiffness-controlled frequency range, below 3 kHz, the force transmitted to the transducer is equal to the driving force independent of any changes in the stiffness of the rubber plates. However, above 3 kHz the influence of the excitation signal is significant as can be seen on figure 4 which shows the relative changes in the force sensitivity for the same excitation signals as used in figure 2. Consequently the force sensitivity has also been measured using a constant velocity of 1 mm/s as excitation signal although it could be argued that a constant force should be used.

Figure 3. Lumped parameter model of the Artificial Mastoid

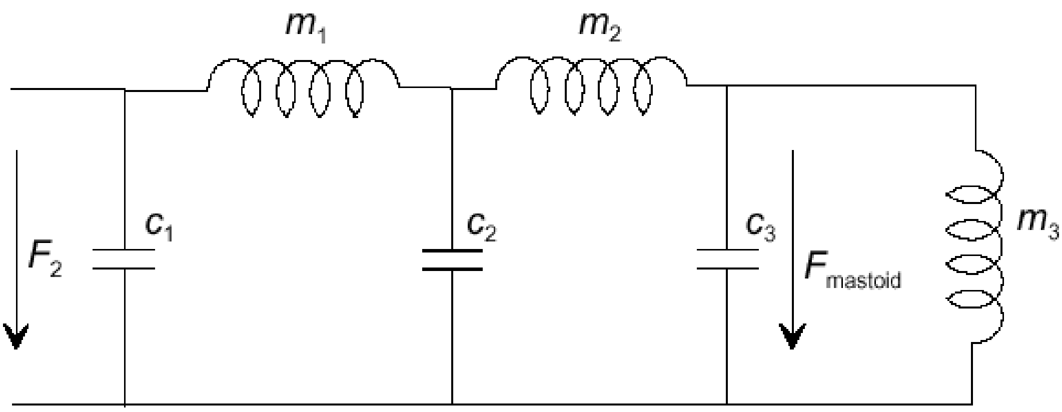
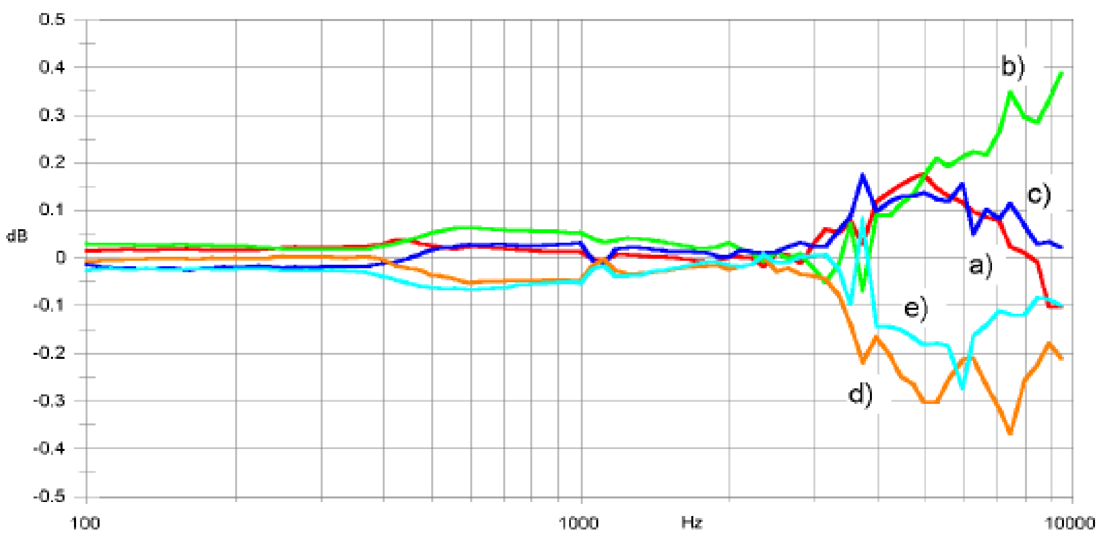


Figure 4. Measured relative force sensitivity levels for an artificial mastoid B&K type 4930 using different excitation levels on the exciter B&K type 4810

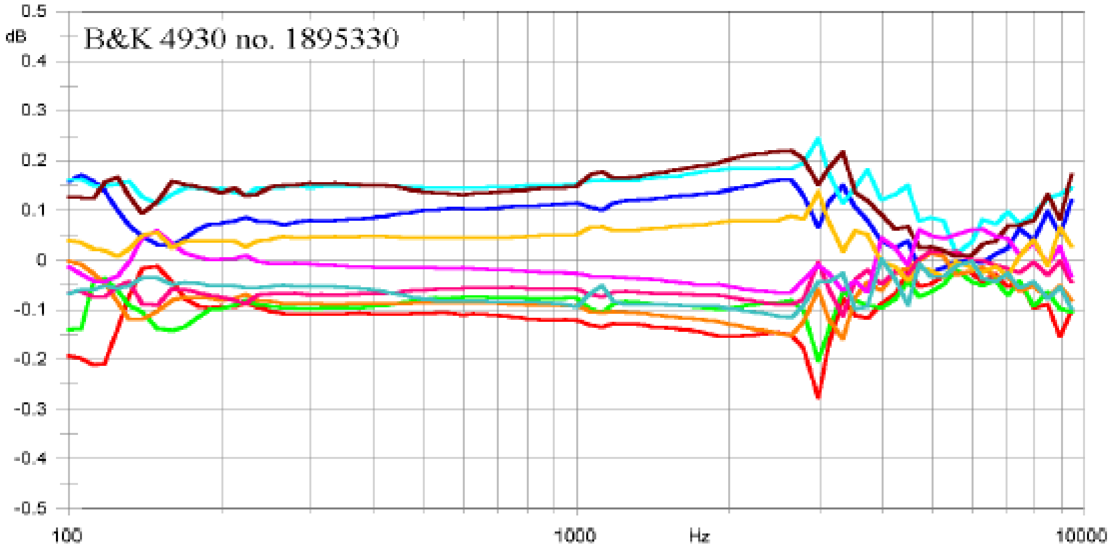


a) Constant driving voltage 1 Volt
b) Constant driving voltage 0,5 Volt
c) Driving voltage proportional to frequency
d) Driving voltage shaped to obtain a constant velocity of 1 mm/s
e) Driving voltage shaped to obtain a constant velocity of 0,5 mm/s

F9. Impedance measurement results

Impedance measurements were performed as part of the calibrations, as described briefly above, and in the DPLA report. The deviations of each impedance measurement from the average value of 10 measurements are shown on figure 5, below. The results are given in Tables 11A, B and C.

Figure 5. Reproducibility of 10 measurements of the mechanical impedance level of an artificial mastoid plotted relative to the average value



F10. Force sensitivity measurement results

The force output signal from the mastoid was measured together with the impedance measurements described above. The deviations of each force measurement from the average value of 10 measurements are shown on figure 6, below. The results are given in Table 12A, B and C. The reproducibility shows a very good agreement in the stiffness-controlled range as could be expected and a variation above 3 kHz following the same pattern as for the impedance measurements below 3 kHz.

Figure 6. Reproducibility of 10 measurements of the force sensitivity of an artificial mastoid plotted relative to the average value

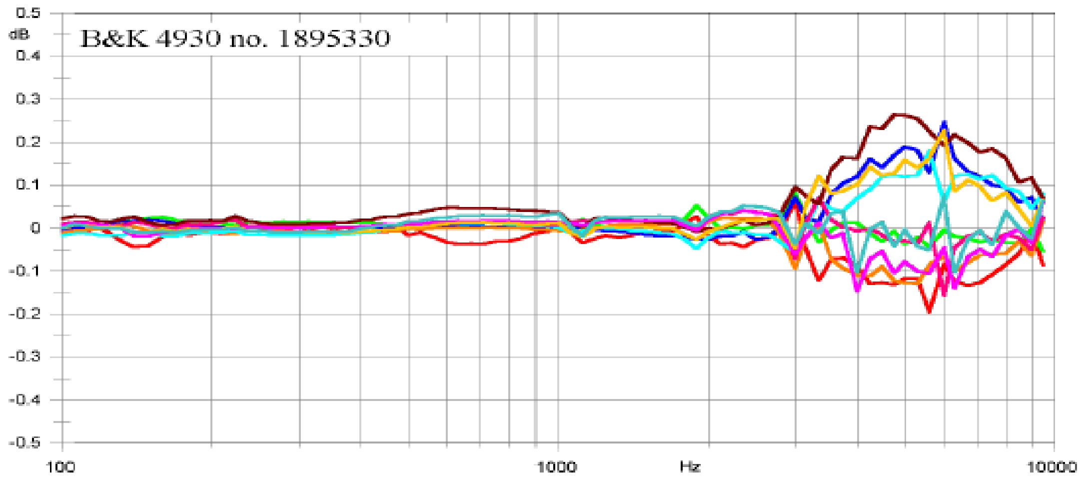


Table 11. DPLA Mechanical impedance (dB re 1 Ns/m) measurement results

	1	2	3	4	5	6	7	8	9	10			
Date	00-04-01	00-04-03	00-04-04	00-04-04	00-04-05	00-04-05	00-04-06	00-04-06	00-04-07	00-04-07	Average	U95 dB	IEC values
Temp °C	23	23.2	22.9	23.2	22.8	22.9	22.7	23.1	22.8	23.1			
Hz													
100	51.75	51.81	52.1	51.94	52.11	51.88	52.07	51.93	51.98	51.88	51.95	0.25	
125	50.16	50.23	50.39	50.21	50.45	50.24	50.46	50.26	50.3	50.23	50.29	0.21	48.9
160	48.62	48.52	48.69	48.58	48.79	48.6	48.82	48.69	48.68	48.61	48.66	0.19	47.4
200	47.13	47.13	47.3	47.15	47.37	47.15	47.36	47.23	47.26	47.18	47.23	0.19	45.8
250	45.72	45.73	45.9	45.74	45.96	45.75	45.97	45.81	45.86	45.77	45.82	0.19	44.3
315	44.28	44.29	44.47	44.3	44.54	44.32	44.54	44.38	44.43	44.34	44.39	0.2	42.9
400	42.83	42.84	43.02	42.85	43.09	42.87	43.09	42.92	42.98	42.88	42.94	0.2	41.3
500	41.47	41.5	41.68	41.49	41.72	41.52	41.71	41.56	41.62	41.5	41.58	0.2	39.9
630	40.08	40.11	40.29	40.1	40.33	40.13	40.32	40.17	40.23	40.1	40.18	0.2	38.5
750	39.02	39.06	39.24	39.05	39.28	39.08	39.28	39.12	39.18	39.05	39.14	0.2	37.4
800	38.63	38.67	38.85	38.66	38.9	38.69	38.89	38.72	38.79	38.66	38.75	0.2	37
1000	37.24	37.29	37.48	37.27	37.51	37.3	37.51	37.33	37.41	37.27	37.36	0.21	35.5
1250	35.81	35.85	36.05	35.83	36.1	35.87	36.1	35.9	35.99	35.85	35.93	0.23	34
1500	34.56	34.6	34.82	34.58	34.86	34.62	34.87	34.65	34.76	34.6	34.69	0.24	32.4
1600	34.09	34.14	34.36	34.11	34.4	34.16	34.41	34.18	34.3	34.14	34.23	0.25	31.9
2000	32.41	32.47	32.71	32.44	32.75	32.49	32.77	32.52	32.65	32.47	32.57	0.27	29.8
2500	30.73	30.79	31.04	30.73	31.07	30.79	31.1	30.81	30.96	30.77	30.88	0.29	27.8
3000	29.4	29.47	29.74	29.62	29.92	29.67	29.83	29.67	29.81	29.63	29.68	0.32	27.2
3150	29.23	29.26	29.52	29.28	29.57	29.34	29.58	29.37	29.47	29.35	29.4	0.26	27.3
4000	29.99	29.98	30.12	30.02	30.2	30.03	30.17	30.12	30.07	30.08	30.08	0.15	29.5
5000	32.33	32.31	32.35	32.39	32.46	32.4	32.4	32.43	32.36	32.35	32.38	0.09	32.6
6000	34.5	34.48	34.52	34.5	34.56	34.52	34.53	34.58	34.51	34.52	34.52	0.06	34.4
6300	34.99	34.99	35.03	35.02	35.12	35.04	35.07	35.1	35.01	35	35.04	0.09	34.6
8000	36.67	36.67	36.8	36.71	36.86	36.76	36.84	36.8	36.8	36.72	36.76	0.14	35.1

Table 12. DPLA Force Sensitivity (dB re 1 V/N) measurement results

Force												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
Date	00-04-01	00-04-03	00-04-04	00-04-04	00-04-05	00-04-05	00-04-06	00-04-06	00-04-07	00-04-07	Average	U95 dB
Temp °C	23	23.2	22.9	23.2	22.8	22.9	22.7	23.1	22.8	23.1		
Hz												
100	-18.14	-18.12	-18.13	-18.14	-18.14	-18.12	-18.11	-18.12	-18.13	-18.13	-18.13	0.02
125	-18.13	-18.11	-18.11	-18.12	-18.14	-18.11	-18.11	-18.11	-18.12	-18.12	-18.12	0.02
160	-18.14	-18.10	-18.11	-18.13	-18.14	-18.12	-18.12	-18.13	-18.13	-18.13	-18.12	0.04
200	-18.12	-18.10	-18.11	-18.12	-18.13	-18.11	-18.10	-18.12	-18.12	-18.12	-18.12	0.02
250	-18.11	-18.09	-18.09	-18.11	-18.11	-18.09	-18.09	-18.09	-18.10	-18.10	-18.1	0.02
315	-18.06	-18.04	-18.05	-18.06	-18.07	-18.05	-18.04	-18.05	-18.06	-18.06	-18.05	0.02
400	-18.01	-17.99	-18.00	-18.01	-18.01	-18.00	-17.99	-18.00	-18.01	-18.01	-18	0.02
500	-17.93	-17.91	-17.91	-17.91	-17.91	-17.90	-17.88	-17.90	-17.91	-17.89	-17.9	0.03
630	-17.82	-17.78	-17.77	-17.78	-17.77	-17.77	-17.73	-17.77	-17.77	-17.75	-17.77	0.04
750	-17.71	-17.68	-17.68	-17.68	-17.67	-17.67	-17.63	-17.66	-17.67	-17.65	-17.67	0.04
800	-17.67	-17.63	-17.63	-17.63	-17.63	-17.62	-17.59	-17.62	-17.62	-17.61	-17.62	0.04
1000	-17.42	-17.43	-17.43	-17.43	-17.42	-17.42	-17.39	-17.41	-17.41	-17.39	-17.41	0.03
1250	-17.19	-17.17	-17.18	-17.17	-17.17	-17.16	-17.15	-17.16	-17.17	-17.15	-17.17	0.03
1500	-16.90	-16.88	-16.90	-16.88	-16.89	-16.87	-16.87	-16.87	-16.89	-16.86	-16.88	0.03
1600	-16.77	-16.76	-16.79	-16.76	-16.78	-16.75	-16.75	-16.75	-16.77	-16.74	-16.76	0.03
2000	-16.44	-16.40	-16.45	-16.41	-16.45	-16.41	-16.43	-16.41	-16.44	-16.40	-16.43	0.04
2500	-16.16	-16.12	-16.15	-16.10	-16.14	-16.09	-16.12	-16.09	-16.11	-16.08	-16.12	0.06
3000	-16.16	-16.14	-16.15	-16.32	-16.28	-16.30	-16.13	-16.29	-16.27	-16.26	-16.23	0.15
3150	-16.44	-16.37	-16.37	-16.42	-16.39	-16.39	-16.32	-16.42	-16.35	-16.39	-16.39	0.07
4000	-19.07	-18.97	-18.86	-19.09	-18.91	-18.99	-18.82	-19.13	-18.88	-19.09	-18.98	0.22
5000	-22.27	-22.19	-21.96	-22.28	-22.03	-22.18	-21.89	-22.23	-21.99	-22.16	-22.12	0.28
6000	-24.42	-24.34	-24.09	-24.74	-24.28	-24.50	-24.01	-24.38	-24.11	-24.03	-24.29	0.47
6300	-25.27	-25.16	-24.98	-25.24	-25.02	-25.19	-24.92	-25.28	-25.06	-25.25	-25.14	0.26
8000	-25.80	-25.75	-25.63	-25.78	-25.63	-25.73	-25.56	-25.74	-25.64	-25.68	-25.69	0.16

APPENDIX G. REPORT ON MEASUREMENTS MADE BY GUM

G1. Introduction

This report describes the measurement method used in GUM, Poland, to measure the output of two bone vibrators received from NPL, UK, driven with 100 mV RMS sinusoidal voltage over the frequency range 125 Hz - 4 kHz. The measurements have been performed as a part of EUROMET Project 401 *Harmonisation of audiometry measurements within Europe – Part B.*

G2. Measurement conditions

Test bone vibrators: two Radioear bone vibrators type B71 marked:

Bone vibrator 1 – green/bronze
Bone vibrator 2 – silver/silver

Frequencies: 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 1,5 kHz, 2 kHz, 3 kHz and 4 kHz

Driving voltage: 100 mV

IEC 60373 mechanical coupler B&K type 4930 serial no. 2022816 calibrated in PTB, Germany on 16. September 1997; calibration certificate attached (sent as a separate fax message)

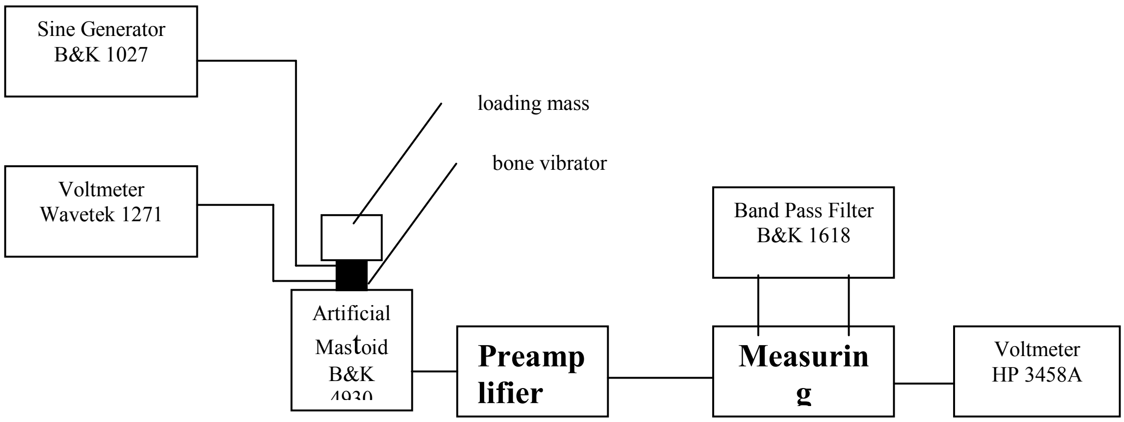
Environmental conditions: measurements were performed in the air-conditioned room; the air temperature varied from 23,3 °C to 24,0 °C and relative humidity from 40 % to 53 %

Equipment used:

Brüel & Kjaer Sine Generator type 1027 Serial No. 798588
Wavetek Multimeter type 1271 Serial No. 34908
Brüel & Kjaer Artificial Mastoid type 4930 Serial No. 2022816
Brüel & Kjaer Preamplifier type 2625 Serial No. 452512
Brüel & Kjaer Measuring Amplifier type 2610 Serial No. 798393
Brüel & Kjaer Band Pass Filter type 1618 Serial No. 823089
Hewlett Packard Multimeter type 3458A Serial No. 2823A 09694

G3. Measurement procedure

The measurement system used is shown in figure below:



Bone vibrator has been positioned centrally on the dome of mechanical coupler. This position resulted in maximum output from the mechanical coupler at high frequencies. The loading mass applied was a cylindrically shaped metal weight of 470 g mass. The B&K Sine Generator provided the driving voltage from the low-impedance output. This voltage has been measured directly at the bone vibrator terminals by the WAVETEK Multimeter. The output signal from vibration preamplifier has been passed through B&K Measuring Amplifier and B&K Band Pass Filter in order to ensure appropriate signal to noise ratio. The gain correction allowing for the combined gain of the measuring amplifier and appropriate 1/3-octave band pass filter, determined for each test frequency, has been taken here into account.

There were 5 measurements made one day, repeated over 5 days. Before each measurement the bone vibrator was removed from the coupler and positioned again visually. The results – bone vibrator outputs in dB re 1N/V and its standard deviations – have been presented as MS Excel 97 spreadsheet file.

G4. Uncertainty

1) Typical type A standard uncertainty does not exceed 0,3 dB

2) Main components of type B uncertainty

Source of uncertainty	Probability distribution	Rectangular distribution halfwidth, dB	Standard uncertainty, dB
Determination of force sensitivity of the mechanical coupler	normal	n/a	0,2
Measurement of driving voltage	rectangular	0,0007	0,0004
Measurement of the coupler output voltage	rectangular	0,0014	0,0008
Temperature measurement	rectangular	0,15	0,09
Correction coefficient	rectangular	0,0016	0,001
Rounding of final result	rectangular	0,01	0,006

3) Combined standard uncertainty does not exceed 0,4 dB.

4) Expanded uncertainty based on a standard uncertainty multiplied by a coverage factor k=2, providing a confidence probability of approximately 95 % does not exceed 0,8 dB.

G5. Results

Table 1 Measurement results for Bone vibrator 1 (green/bronze) Nov. 10, 1999

t_{air}=23.3 °C h = 50,3 %	Sensitivity level dB re 1 N/V					
Freq Hz/	1	2	3	4	5	mean	st.dev.
125	-22.05	-22.06	-22.07	-22.01	-21.92	-22.02	0.063
160	-17.63	-17.71	-17.66	-17.58	-17.44	-17.60	0.103
200	-13.58	-13.58	-13.55	-13.42	-13.30	-13.49	0.122
250	-9.02	-9.16	-9.03	-8.91	-8.67	-8.96	0.184
315	-3.05	-3.20	-3.01	-2.84	-2.51	-2.92	0.261
400	4.28	5.01	4.90	4.84	4.22	4.65	0.369
500	3.24	3.36	2.75	2.32	3.46	3.03	0.481
630	-2.00	-1.90	-2.13	-2.40	-2.79	-2.24	0.357
750	-3.96	-4.03	-4.19	-4.39	-4.60	-4.24	0.262
800	-4.60	-4.66	-4.75	-4.93	-5.14	-4.81	0.219
1000	-6.00	-5.91	-6.04	-6.10	-6.23	-6.06	0.120
1250	-6.17	-5.75	-5.54	-5.63	-5.54	-5.73	0.261
1500	-4.77	-4.79	-4.92	-5.09	-4.91	-4.90	0.130
1600	-4.58	-4.73	-4.72	-5.07	-5.57	-4.93	0.398
2000	-10.29	-10.54	-10.77	-11.25	-11.24	-10.82	0.427
2500	-16.84	-17.11	-17.15	-17.32	-18.02	-17.29	0.445
3000	-17.54	-17.88	-18.03	-18.30	-18.84	-18.12	0.486
3150	-16.92	-17.10	-17.32	-17.64	-18.17	-17.43	0.493
4000	-12.69	-12.49	-13.13	-13.50	-13.63	-13.09	0.495

Table 2 Measurement results for Bone vibrator 2 (silver/silver) Nov. 22, 1999

t_{air} = 23.6°C h = 50.6 %	Sensitivity level dB re 1 N/V						
Freq Hz	1	2	3	4	5	mean	st.dev.
125	-22.05	-22.06	-22.07	-22.01	-21.92	-22.02	0.063
160	-17.63	-17.71	-17.66	-17.58	-17.44	-17.60	0.103
200	-13.58	-13.58	-13.55	-13.42	-13.30	-13.49	0.122
250	-9.02	-9.16	-9.03	-8.91	-8.67	-8.96	0.184
315	-3.05	-3.20	-3.01	-2.84	-2.51	-2.92	0.261
400	4.28	5.01	4.90	4.84	4.22	4.65	0.369
500	3.24	3.36	2.75	2.32	3.46	3.03	0.481
630	-2.00	-1.90	-2.13	-2.40	-2.79	-2.24	0.357
750	-3.96	-4.03	-4.19	-4.39	-4.60	-4.24	0.262
800	-4.60	-4.66	-4.75	-4.93	-5.14	-4.81	0.219
1000	-6.00	-5.91	-6.04	-6.10	-6.23	-6.06	0.120
1250	-6.17	-5.75	-5.54	-5.63	-5.54	-5.73	0.261
1500	-4.77	-4.79	-4.92	-5.09	-4.91	-4.90	0.130
1600	-4.58	-4.73	-4.72	-5.07	-5.57	-4.93	0.398
2000	-10.29	-10.54	-10.77	-11.25	-11.24	-10.82	0.427
2500	-16.84	-17.11	-17.15	-17.32	-18.02	-17.29	0.445
3000	-17.54	-17.88	-18.03	-18.30	-18.84	-18.12	0.486
3150	-16.92	-17.10	-17.32	-17.64	-18.17	-17.43	0.493
4000	-12.69	-12.49	-13.13	-13.50	-13.63	-13.09	0.495

APPENDIX H. REPORT ON MEASUREMENTS MADE BY BEV

**Euromet Project 401 Harmonisation of audiometry measurements within Europe
Measurements of the output of the bone vibrators**

H1. Purpose

To compare measurements of the output of the IEC 60373 mechanical coupler when driven by a specified model of bone vibrator.

H2. Equipment

- A pair of Radioear B71 bone vibrators, serial nr. 401
- A 4 wire cable for driving the bone vibrators
- Artificial Mastoid Type 4930 (mechanical coupler) B&K, serial nr. 1929093
- Charge Amplifier/Multiplexer (BEV)
- HP 33120A Generator, serial nr. US 36023238
- Multimeter HP 3458, serial nr. 2823A20429
- PC
- 4 ways bridge (BEV)
- Bandfilter Type 1617, B&K serial nr. 2062598

H3. Method

The Radioear B71 bone vibrators force levels was measured by applying to our calibrated IEC 60373 type 4930 mechanical coupler. The bone vibrators was supplied with 4-wire cable (4mm plugs), using the 4 ways bridge prepared in BEV which allows the driving voltage to be measured directly at the bone vibrator terminals.

The signal was applied to one pair of red and black connectors and measured to the other pair. Each bone vibrator was driven with an r.m.s. sinusoidal signal of 100 mV ± 1 mV at frequencies of 250 Hz, 500 Hz, 750 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz and 4000 Hz. Measurement of this voltage was made at the end of one pair of cables on the leads supplied.

The output of the mechanical coupler (Mastoid) was determined in dB re 1N/V at each of the given frequencies. 5 sets of measurements (each of 5 measurements) made on the different days is presented in the table 1, 2 for the respective bone vibrator.

The bone vibrator was positioned centrally on the dome of the mechanical coupler. Visual positioning was used to achieve this, as well as the output voltage of the mechanical coupler at 1000 Hz, which should be maximal at the central position.

After the ISO 389_3, IEC 60373 and IEC 60645 the static force of 5.4 N ± 0,1 N which is applied to the bone vibrator. This is achieved by using the loading arm of the mechanical coupler with its tension spring detached and a metal (brass) block with 471,92 g ± 0,04 g Mass bolted to the arm immediately to the bone vibrator. The calculation of this mass is done as below:

Considering the mass of the loading arm 59 g ± 6 g and the mass of the bone vibrator 21,35 g (respectively silver bronze 21,34 g ± 0,02 g and black bronze 21,36g ± 0,02g).

The mass of 552g (± 6 g) corresponds to 5.4 N (± 0,1 N).

The temperature of the mechanical coupler during the measurements is given beside the measurements in the tables 1,2. Type A and Type B of standard uncertainty as well as the combined standard uncertainty are given in the tables 4,5 for the bone vibrators.

Diagram

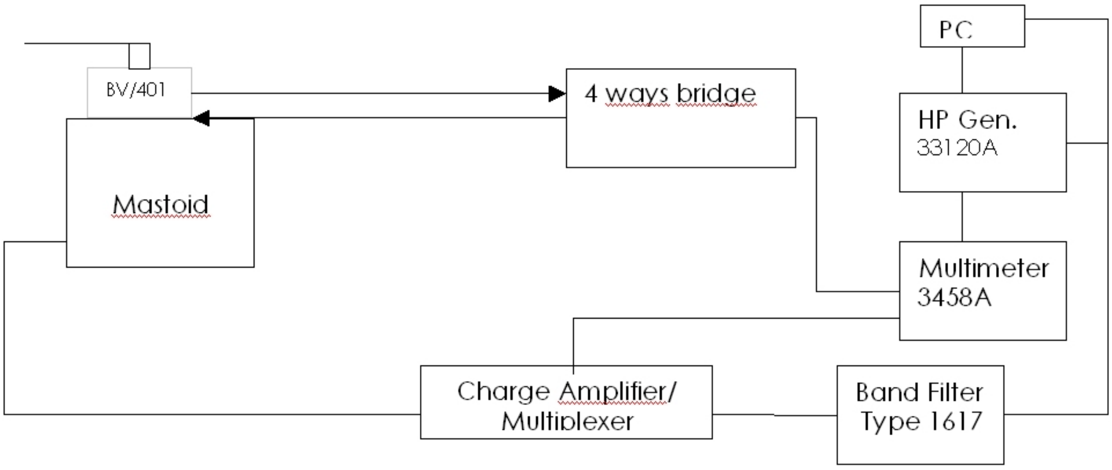


Table 1 Results of the measurements in dB re 1N/V, silver bronze bone vibrator

	set 1	14.12.2001	T_cou = 22,7 °C	T_air = 24,0 °C			
Freq [Hz]	1	2	3	4	5	mean/dB re 1N/V	stand.dev./dB
250	-7,14	-7,15	-7,16	-7,16	-7,16	-7,154	8,94E-03
500	4,11	4,18	4,2	4,21	4,22	4,184	4,39E-02
750	-2,78	-2,75	-2,74	-2,74	-2,74	-2,750	1,73E-02
1000	-4,32	-4,3	-4,3	-4,29	-4,29	-4,300	1,22E-02
1500	-3,3	-3,3	-3,3	-3,3	-3,3	-3,300	0,00E+00
2000	-8,63	-8,6	-8,59	-8,59	-8,58	-8,598	1,92E-02
3000	-16,31	-16,28	-16,27	-16,26	-16,26	-16,276	2,07E-02
4000	-11,78	-11,82	-11,86	-11,88	-11,9	-11,848	4,82E-02

	set 2	03.01.2002	T_cou = 22,6 °C	T_air = 23,7 °C			
Freq [Hz]	1	2	3	4	5	mean/dB re 1N/V	stand.dev./dB
250	-6,18	-6,18	-6,18	-6,18	-6,17	-6,178	4,47E-03
500	1,45	1,45	1,45	1,45	1,45	1,450	0,00E+00
750	-4,01	-4,02	-4,01	-4,01	-4,01	-4,012	4,47E-03
1000	-4,81	-4,8	-4,8	-4,8	-4,81	-4,804	5,48E-03
1500	-3,46	-3,46	-3,46	-3,47	-3,46	-3,462	4,47E-03
2000	-11,41	-11,41	-11,41	-11,41	-11,41	-11,410	0,00E+00
3000	-18,57	-18,57	-18,57	-18,57	-18,57	-18,570	2,38E-07
4000	-12,2	-12,21	-12,21	-12,2	-12,2	-12,204	5,48E-03

	set 3	08.01.2002	T_cou = 23,1 °C	T_air = 24,0 °C			
Freq [Hz]	1	2	3	4	5	mean/dB re 1N/V	stand.dev./dB
250	-6,33	-6,33	-6,33	-6,35	-6,34	-6,336	8,94E-03
500	1,89	1,89	1,88	1,88	1,88	1,884	5,48E-03
750	-3,67	-3,67	-3,66	-3,66	-3,66	-3,664	5,48E-03
1000	-4,65	-4,65	-4,65	-4,65	-4,65	-4,65	5,96E-08
1500	-3,4	-3,37	-3,37	-3,37	-3,4	-3,382	1,64E-02
2000	-11,39	-11,39	-11,38	-11,38	-11,38	-11,384	5,48E-03
3000	-18,47	-18,47	-18,47	-18,47	-18,47	-18,47	0,00E+00
4000	-13,62	-13,62	-13,62	-13,62	-13,62	-13,62	0,00E+00

	set 4	08.01.2002	T_cou = 23,4 °C	T_air = 24,0 °C			
Freq [Hz]	1	2	3	4	5	mean/dB re 1N/V	stand.dev./dB
250	-6,78	-6,79	-6,79	-6,79	-6,8	-6,790	7,07E-03
500	3,19	3,19	3,2	3,2	3,2	3,196	5,48E-03
750	-3,19	-3,19	-3,19	-3,18	-3,18	-3,186	5,48E-03
1000	-4,45	-4,45	-4,45	-4,44	-4,44	-4,446	5,48E-03
1500	-3,15	-3,15	-3,16	-3,16	-3,16	-3,156	5,48E-03
2000	-9,7	-9,7	-9,7	-9,7	-9,7	-9,700	0,00E+00
3000	-17,46	-17,46	-17,46	-17,46	-17,46	-17,460	0,00E+00
4000	-13,12	-13,12	-13,12	-13,12	-13,12	-13,120	0,00E+00

	set 5	08.01.2002	T_cou = 22,9 °C	T_air = 24,0 °C			
Freq [Hz]	1	2	3	4	5	mean/dB re 1N/V	stand.dev./dB
250	-7,13	-7,14	-7,14	-7,15	-7,16	-7,144	1,14E-02
500	4,31	4,31	4,31	4,32	4,32	4,314	5,48E-03
750	-2,6	-2,6	-2,6	-2,6	-2,6	-2,600	4,21E-08
1000	-4,28	-4,28	-4,28	-4,28	-4,28	-4,280	0,00E+00
1500	-2,76	-2,76	-2,76	-2,76	-2,76	-2,760	0,00E+00
2000	-8,36	-8,35	-8,35	-8,35	-8,35	-8,352	4,47E-03
3000	-16,34	-16,34	-16,34	-16,33	-16,34	-16,338	4,47E-03
4000	-11,79	-11,79	-11,79	-11,79	-11,78	-11,788	4,47E-03

Table 2 Results of the measurements in dB re 1N/V, black bronze bone vibrator

	set 1	14.12.2001	T_cou = 22,6 °C	T_air = 23,8 °C			
Freq [Hz]	1	2	3	4	5	Mean/dB re 1N/V	stand.dev./dB
250	-7,72	-7,74	-7,75	-7,75	-7,76	-7,744	1,52E-02
500	1,77	1,79	1,82	1,84	1,85	1,814	3,36E-02
750	-4,21	-4,19	-4,17	-4,16	-4,16	-4,178	2,17E-02
1000	-5,4	-5,39	-5,39	-5,39	-5,39	-5,392	4,47E-03
1500	-4,27	-4,26	-4,25	-4,25	-4,24	-4,254	1,14E-02
2000	-10,65	-10,61	-10,59	-10,57	-10,56	-10,596	3,58E-02
3000	-18,58	-18,56	-18,54	-18,53	-18,52	-18,546	2,41E-02
4000	-11,69	-11,65	-11,62	-11,6	-11,58	-11,628	4,32E-02

	set 2	03.01.2002	T_cou = 22,8 °C	T_air = 23,9 °C			
Freq [Hz]	1	2	3	4	5	mean/dB re 1N/V	stand.dev./dB
250	-7,52	-7,52	-7,53	-7,54	-7,54	-7,530	1,00E-02
500	1,51	1,51	1,52	1,52	1,53	1,518	8,37E-03
750	-4,38	-4,37	-4,37	-4,37	-4,37	-4,372	4,47E-03
1000	-5,48	-5,48	-5,48	-5,49	-5,48	-5,482	4,47E-03
1500	-3,6	-3,59	-3,59	-3,59	-3,59	-3,592	4,47E-03
2000	-10,68	-10,68	-10,67	-10,67	-10,67	-10,674	5,48E-03
3000	-18,7	-18,69	-18,69	-18,69	-18,69	-18,692	4,47E-03
4000	-11,73	-11,73	-11,73	-11,73	-11,73	-11,730	0,00E+00

	set 3	08.01.02	T_cou = 22,8 °C	T_air = 23,3 °C			
Freq [Hz]	1	2	3	4	5	mean/dB re 1N/V	stand.dev./dB
250	-8,17	-8,15	-8,17	-8,16	-8,17	-8,164	8,94E-03
500	2,82	2,83	2,84	2,84	2,84	2,834	8,94E-03
750	-3,72	-3,72	-3,72	-3,72	-3,71	-3,718	4,47E-03
1000	-5,21	-5,21	-5,21	-5,21	-5,21	-5,210	0,00E+00
1500	-4,15	-4,15	-4,15	-4,15	-4,14	-4,148	4,47E-03
2000	-9,64	-9,64	-9,64	-9,64	-9,63	-9,638	4,47E-03
3000	-17,59	-17,58	-17,58	-17,58	-17,58	-17,582	4,47E-03
4000	-11,58	-11,58	-11,58	-11,58	-11,58	-11,580	0,00E+00

	set 4	08.01.2002	T_cou = 23,0 °C	T_air = 23,9 °C			
Freq [Hz]	1	2	3	4	5	mean/dB re 1N/V	stand.dev./dB
250	-8,47	-8,47	-8,48	-8,47	-8,47	-8,472	4,47E-03
500	3,85	3,83	3,84	3,84	3,84	3,840	7,07E-03
750	-3,22	-3,22	-3,21	-3,21	-3,21	-3,214	5,48E-03
1000	-5,1	-5,1	-5,1	-5,1	-5,1	-5,100	0,00E+00
1500	-3,69	-3,68	-3,68	-3,68	-3,68	-3,682	4,47E-03
2000	-8,36	-8,36	-8,36	-8,35	-8,35	-8,356	5,48E-03
3000	-17,02	-17,02	-17,02	-17,02	-17,02	-17,020	0,00E+00
4000	-11,58	-11,58	-11,58	-11,58	-11,57	-11,578	4,47E-03

	set 5	08.01.2002	T_cou = 23,4 °C	T_air = 24,0 °C			
Freq [Hz]	1	2	3	4	5	mean/dB re 1N/V	stand.dev./dB
250	-7,89	-7,9	-7,9	-7,91	-7,91	-7,902	8,37E-03
500	1,68	1,69	1,7	1,71	1,71	1,698	1,30E-02
750	-4,11	-4,1	-4,1	-4,1	-4,1	-4,102	4,47E-03
1000	-5,52	-5,52	-5,52	-5,52	-5,52	-5,520	0,00E+00
1500	-3,52	-3,52	-3,52	-3,52	-3,52	-3,520	0,00E+00
2000	-10,7	-10,7	-10,7	-10,7	-10,69	-10,698	4,47E-03
3000	-18,75	-18,74	-18,74	-18,73	-18,73	-18,738	8,37E-03
4000	-12,8	-12,79	-12,79	-12,79	-12,79	-12,792	4,47E-03

Table 3 Arithmetical mean and type A standard uncertainty of bone vibrators

	black bronze 2002		silver bronze 2002	
Freq [Hz]	mean/dB re 1N/V	A stand.unc./dB	mean/dB re 1N/V	A stand.unc./dB
250	-7,962	0,367	-6,720	0,451
500	2,341	0,982	3,006	1,305
750	-3,917	0,459	-3,242	0,598
1000	-5,341	0,180	-4,496	0,227
1500	-3,839	0,337	-3,212	0,277
2000	-9,992	1,016	-9,889	1,467
3000	-18,116	0,773	-17,423	1,107
4000	-11,862	0,524	-12,516	0,815

Table 4 Combined standard uncertainty for the silver bronze bone vibrator

	Type B						Type A	
Freq [Hz]	Mastoid [dB]	Ch.ampl. [dB]	Voltage [dB]	Inp.Generator [dB]	Temp [dB/°C]	St. Force [dB/0,1N]	Reproduc [dB]	Comb. unc [dB]
250	0,52	0,05	0,1	0,001	0,11	0,02	0,45	0,71
500	0,53	0,05	0,1	0,001	0,27	0,08	1,31	1,44
750	0,53	0,05	0,1	0,001	0,12	0,04	0,60	0,82
1000	0,53	0,05	0,1	0,001	0,05	0,03	0,23	0,59
1500	0,53	0,05	0,1	0,001	0,13	0,02	0,28	0,62
2000	0,56	0,05	0,1	0,001	0,32	0,06	1,47	1,61
3000	0,56	0,05	0,1	0,001	0,40	0,07	1,11	1,31
4000	0,91	0,05	0,1	0,001	0,65	0,04	0,82	1,39

Table 5 Combined standard uncertainty for the black bronze bone vibrator

	Type B						Type A	
Freq [Hz]	Mastoid [dB]	Ch.ampl. [dB]	Voltage [dB]	Inp.Generator [dB]	Temp [dB/°C]	St. Force [dB/0,1N]	Reproduc [dB]	Comb. unc [dB]
250	0,52	0,05	0,1	0,001	0,11	0,02	0,367	0,66
500	0,53	0,05	0,1	0,001	0,27	0,08	0,982	1,16
750	0,53	0,05	0,1	0,001	0,12	0,04	0,459	0,72
1000	0,53	0,05	0,1	0,001	0,05	0,03	0,180	0,57
1500	0,53	0,05	0,1	0,001	0,13	0,02	0,337	0,65
2000	0,56	0,05	0,1	0,001	0,32	0,06	1,016	1,21
3000	0,56	0,05	0,1	0,001	0,40	0,07	0,773	1,04
4000	0,91	0,05	0,1	0,001	0,65	0,04	0,524	1,24

APPENDIX I. HISTORICAL BACKGROUND

This section provides some overall background on the historical development of bone conduction audiometry and on the rationale behind the proposal to conduct an intercomparison study on harmonisation of audiometry measurements within Europe

The purpose of bone-conduction audiometry is to measure the hearing threshold level, by bone conduction, of a subject relative to the reference threshold level established for normal individuals (Reference Equivalent Threshold Force Levels - RETFLs). This measure provides diagnostic information on the state of the subject's hearing. When used alongside air-conduction audiometry measurements, valuable information about the state of the subject's conductive hearing mechanism can be gained.

Where air conduction audiometry, uses earphones to transmit a known acoustic signal to a subject, bone conduction audiometry employs small attachable transducers known as bone vibrators for transmitting vibration signals to the ear.

The bone vibrator drive voltage is measured at the hearing threshold of the subject and in order to determine the bone conduction hearing threshold or the “Hearing Level” of the subject, the bone vibrator must be transferred to a mechanical coupler, which is essentially a reference mechanical device permitting comparison between the measured threshold level and the mean standardised threshold for normal individuals (ie the RETFL). The mechanical coupler aims to mimic the mechanical impedance of the human mastoid prominence and is therefore also referred to as the artificial mastoid.

Hugo Lieber invented “The Bone Conductor” around 1933. When placed on the cranium, this device acted as a vibrator, transmitting sound directly to the inner ear. It was used for all types of hearing losses, but was found to be most effective in assisting people with middle ear diseases.

By the 1950s, many hearing aids employing bone conduction were in use and a well-established technique for bone conduction audiometry existed, however little was known about the objective aspects of this subject. In 1954 Dadson *et al* published a paper entitled, “The mechanical impedance of the human mastoid”[7]. A number of other people had reported measurements of the mechanical impedance of the mastoid process, but up until this time no other detailed study had been carried out. The main aim of this project was to develop objective procedures for assessing the response characteristics of bone conduction devices by providing data for the design of an artificial mastoid. Up to this time several empirical designs had been described (Hawley [8], Greibich [9] and Carlisle and Pearson [10]) but none were based on experimental data and were considered to a give a poor representation of the impedance of the human mastoid process. Development work continued, until a design by the National Physical Laboratory (Delany and Whittle [11]) was taken into commercial production by Brüel & Kjær and others.

This original ‘artificial mastoid’ device, now commonly known as the ‘mechanical coupler’, was considered to provide a mechanical simulation of the human head, and was thus deemed to provide a reference for calibrating bone vibrators transducers. Essentially, the device incorporated a built-in force transducer to monitor the output of the transducer devices, which was mounted on a base-plate by resilient plastic spacers. The base-plate was carried on a suspension composed of three conical springs filled with foam rubber to provide damping. The natural frequencies of this suspension, which isolated the whole apparatus from external disturbances were all below 5 Hz, which is one-tenth of the low-frequency limit of the working range. The base-plate also carried a loading-arm and associated supports, the function being, to maintain the device to be calibrated reliably in position.

Some instruments were reputed to be unstable over time and in 1975 Brüel & Kjær, as the sole remaining manufacturer, introduced a design change to the rubber dome of the mechanical coupler which had the effect of improving the long-term stability of the device at the expense of the accuracy of its simulation of the mastoid prominence [13] (The change was introduced at about Artificial Mastoid Type 4930 Serial No.526226). This change was possible because, although IEC 60373:1971 [2] specified the mechanical impedance of the device as a function of frequency, there were no explicit tolerances on the mechanical impedance.

Recognising this change in the properties of the commercial device, it was decided that IEC 60373 be revised so that the specified mechanical impedance was more in accord with commercial production and also that it would place a tolerance on the mechanical impedance to limit the allowable production spread. The revised IEC 60373:1990 was published and implemented as a dual-numbered British Standard. British Standards set down a requirement for the bone-conduction part of pure-tone audiometers to be calibrated in terms of the hearing threshold of otologically normal young persons.

In striving to attain reliability in the accuracy of the results obtained from using bone conduction devices, so as to ensure confidence for those involved in the measurement of hearing levels and diagnosis of hearing problems, research and development work has continued. NPL carried out an investigation in 1971 to ascertain the variation in the mechanical impedances of the few artificial mastoids then in use and to discover the effect of these variations on the calibration of bone vibrators. At that time most audiometers were calibrated using the devices owned by the Royal Institute for the Deaf, including those in use by the NHS and the schools medical services. In the early 1980s, measurements were coordinated in the USA, F R Germany, and the UK (at NPL), to measure the threshold of hearing by bone conduction for normal individuals, in terms of force; measurements were referred to the second generation (post-1975) B&K mechanical coupler. This resulted in the publication in 1987 of ISO 7566 [5] which states the internationally-agreed reference equivalent threshold force levels (RETFLs) for hearing by bone conduction as a function of frequency in the range 250 Hz - 8 kHz.

In 1994, ISO 7566 was replaced by ISO 389 3:1994. There were no significant changes to the standard. The new standard was issued as part of a rationalised series of standards relating to audiometric equipment.

Acknowledging that the above historical developments have greatly improved the accuracy and reliability of bone conduction audiometry, the current standards, however, remain under some scrutiny, and are known to receive criticism on various grounds from experts in the audiometric community. For example there is concern that the mechanical impedance specified for the original artificial mastoid was derived from a compromise between discordant scientific data, and consequently it can only be approximated in physical realisations of the device. As a result the *de facto* standard has in practice become that of the principal mechanical coupler manufacturer who has, meanwhile, changed the design of the product slightly to improve its stability, thus introducing a question of consistency of output between devices.

There are specific concerns with respect to the physical design of the device. Though it is mounted on vibration isolating feet, the mechanical coupler is still very sensitive to spurious vibrations. This requires the coupler to be used in as quiet an area as possible. Even then, an octave or third-octave filter is essential for low-level measurements (below, say, 30 dB HL). The mechanical coupler is essentially simple in design and quite robust. However the major weakness of its design is the high dependence of its sensitivity on temperature. and the variation of the hardness of the rubber dome with temperature reported by Dowson and McNeill [12]. Another feature of the mechanical coupler is its large mass, which gives it, in turn, a large thermal capacity.

Consequently, IEC 60373:1990 defines a reference temperature of 23 ºC for the specification of the mechanical impedance of the coupler and the manufacturer is required to provide a calibration for the coupler at this temperature. This then places the user under an obligation to operate the coupler at this temperature.

It has been considered that if the temperature coefficient of the force sensitivity of the mechanical coupler was known, measurements carried out at temperatures other than the reference temperature could be corrected. However, a change in temperature affects both the force sensitivity and mechanical impedance of the mechanical coupler. The change in mechanical impedance in turn affects the actual force output of a bone vibrator under test. Therefore, in order to perform temperature correction it is necessary to account for both the sensitivity of the mechanical coupler and the change in the loading presented to the bone vibrator. The second factor will also depend on the bone vibrator itself, necessitating specific corrections for every device to be calibrated, which is clearly not practical.

In the light of these issues, the intercomparision described in the report was proposed to examine the consistency of measurements made in different laboratories under nominally similar conditions.