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INFLUENCE OF BONE CONDUCTION TRANSDUCERS POSITION AND CONSTRAINT ON PROPAGATION TO THE EAR

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ABSTRACT

Solid-state transducers are nowadays integrated in communication headsets that open the way to a new category of headsets that are of interest in both military and civil applications. Sounds are stimulated to the inner ear directly through the bones and cartilage of the skull. The main advantage of this technology is to offer the user the possibility to have the ear clear to remain alert to his environment or to use earplugs with a high level of protection while continuing to communicate via a radio system. Different types of transducers are used in a measurement protocol to determine the influence of the bearing force and position of the transducer on the propagation from the skin to the reception by a listener. The measurement setup includes laser vibrometry measurements on the skin and solid-state hearing threshold measurements.

1. INTRODUCTION

Bone conduction (BC) or solid-state transducers are now deployed as communication devices in the military. They can be found either as stand-alone devices like the ELNO BCH300 headset or integrated in head-mounted equipment as the ELNO HOPLITE. Their advantage consists in transmitting any communication signal to the user's hearing system without occluding them, thus allowing the user to either normally perceive his acoustic environment or to wear hearing protection. Recording the user's voice through bone conduction is also possible without placing a microphone in front of his mouth. Speech intelligibility can, however, be degraded using such transducers [1–3]. The search for optimal speech rendering through bone conduction needs a complete knowledge of the transducer's signal transmission to the listener's ears.

The vibration of the transducer is transmitted to the hearing system via three identified pathways represented in Fig. 1 [4–6]. The direct air path comes from an aerial acoustic wave generated by the transducer and received by the ear. The bone-air path consists in the transmission of the vibration through bone and cartilage and in the formation of an acoustic wave inside the ear canal. Direct bone vibration transmitted from the transducer to the sensory organ forms the direct bone path. Using a loudness perception test, it can be shown that the bone-air path is predom-

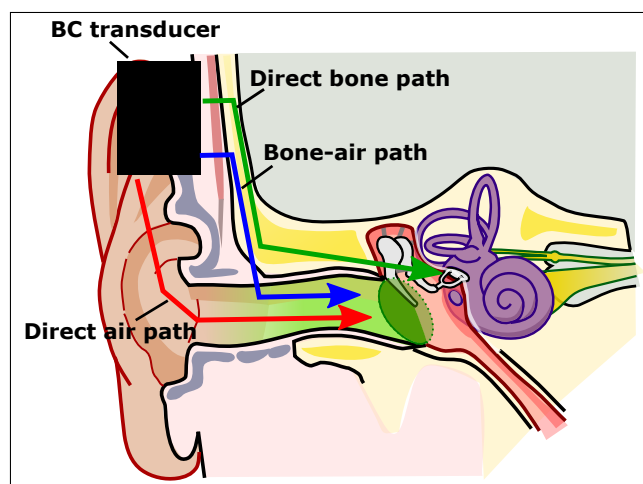


Figure 1: Representation of the three identified pathways between the bone conduction transducer and the hearing system. (Modified from Wikipedia, licensed under CC BY 2.5)

inant at frequencies below 1 kHz and the direct air path is for higher frequencies [6].

BC transducers were firstly used in audiology to assess the hearing threshold of hearing-impaired patients. Regular audiometry techniques can be employed to estimate the actual transducer's frequency response on a normal hearing listener, by comparing his air and bone conduction hearing thresholds [7]. Similarly, loudness equalization can be performed to obtain the frequency response at working levels [8]. Frequency response constitutes an important characteristic of the transducers and can therefore be evaluated with the device placed at different positions of the skull and with different supporting forces.

Artificial mastoids could also be employed for the measurement of the frequency response, but most of today's BC headphones are placed on the listener's temporal bone or mandibular condyle. The results might therefore not be representative of the actual wearing of BC headphones. Furthermore, artificial mastoids should be used with a support force up to 5 N, corresponding approximately to the force of the classical RadioEar B-71 audiometry vibrator. However, the support force of BC headphones would rather be comprised between 2 and 2.9 N [9]. Decreasing the sup-



Figure 2: Two bone conduction transducers evaluated in this paper: (a) B1, prototype from the ELNO company, (b) B2, commercial sports headset.

port force improves comfort without necessarily degrading the transducer's efficiency [10].

This study aims to explore possible measurements for the characterization of different bone conduction transducers. Our experiments include audiometry, perceptive loudness evaluation, acoustic measurement inside the ear and Scanning Laser Doppler Vibrometry (SLDV). The effect of the contact force on the response of the transducers is also assessed. The influence of the position of the devices should also have been evaluated, but we were unfortunately limited by the integration of the solid-state transducers that were only available as temporal bone headsets.

2. MATERIALS AND METHODS

2.1 Bone conduction transducers

Two electrodynamic BC transducers are evaluated in this paper and presented in Fig. 2. The first one is a prototype from the ELNO company and is further referred to as B1. The second transducer is a commercially available sports headset called B2 in the following. They are both placed on the listener's temporal bone. The main difference between B1 and B2 lies in their respective headset integration: B1 is encapsulated in soft silicon while B2 is integrated in a rigid shell.

2.2 Listeners

The six co-authors of this paper participated to all the measurements except the loudness difference test. They all present hearing thresholds below 20 dB(HL) for frequencies up to 2 kHz. A few listeners showed thresholds over 20 dB(HL) at 4 and 8 kHz. They are kept in the results because all perceptive experiments involve audiogram differences that eliminate their hearing losses. The loudness difference experiment involves the participation of 10 listeners accustomed to perceptive testing and without known hearing problems. Their audiograms were not estimated in the context of this study.

2.3 Frequency response at hearing thresholds

Hearing thresholds are measured for the 1 kHz octaves from 125 Hz to 8 kHz using a fixed frequency Bekesy procedure [11] with a GN OTOMETRICS Madsen Astera 2

audiometer. For each frequency, the listener pushes a button as long as he perceives the stimulus and releases it when he doesn't. The next frequency is tested after 6 button push/releases. This test allows estimating the hearing threshold as the median value between rising and falling thresholds.

Aerial audiograms A_{air} in dB(HL) are obtained using standard TDH 39 earphones and bone conduction audiograms A_{bc} with the tested transducers. The earphones' response is corrected by the audiometer using a built-in function. The BC transducers are evaluated using the same audiometer channel as the earphones so the previously mentioned correction is also performed and should therefore be compensated. The compensation in dB H_{comp} is the same as $N_s - A_2$ in [7]. The frequency response at hearing thresholds H_{bc} of a BC transducer is finally computed in dB as:

$$H_{bc} = A_{air} - A_{bc} + H_{comp} \quad . \quad (1)$$

2.4 Inside the ear acoustic measurement

The frequency response of the solid-state transducers is also estimated at working levels using a Svantek SV 102A+ Class 1 dual channel dosimeter. This device is only employed as an in-ear microphone in this study. The response is measured for the 1 kHz octaves from 500 Hz to 8 kHz using 5 s sines sent to the BC transducer. For each frequency, the sound pressure level inside the ear canal is computed as an RMS value of the time signal bandpass-filtered around this frequency. Since the microphone can be inserted inside a standard 3M triple-flange earplug, measurements are repeated with the ear occluded in order to identify the occlusion effect.

2.5 Loudness difference between open and occluded ear

In the same test as in [6], a 1 s sine is presented sequentially to the listener's ears using a BC transducer. With one ear occluded by a 3M E-A-R Classic foam earplug, the listener indicates the side at which he perceives the loudest stimulus. 1 kHz third-octave frequencies from 500 Hz to 2.5 kHz are tested.

Because one ear is occluded, frequencies, for which the direct air path is preponderant, are heard louder at the other ear. Due to the occlusion effect, the inverse is observed when the bone-air path is predominant. The goal of this test is to determine the frequency range in which the pathway change from bone-air to direct air occurs.

2.6 Contact force control

Tekscan FlexiForce A201 sensors are fixed to the solid-state transducers so that they are placed between the device and the listener's skin. The effect of the presence of such sensors on the efficiency of the BC transducers is neglected throughout this paper. Load measurement is performed using the FlexiForce OEM development kit that allows to calibrate the sensors in order to output load values in grams. Every control measurement of the contact



Figure 3: Photograph of the SLDV measurement setup. 15 measure points (in red) are placed on the subject's tragus.

force in this study is averaged from 300 values recorded at a 10 Hz rate. It should be noted that the force sensor is less than 1 cm² and that it not necessarily reflects the force applied on the total surface of the transducers.

2.7 Scanning Laser Doppler Vibrometry

An Optomet Scanning Laser Doppler Vibrometer is employed to realize vibration measurements on a subject's head when excited by a bone conduction transducer. The device uses a short-wavelength infrared (SWIR) laser that allows correct measurements on poorly reflective surfaces like skin while remaining eye-safe. To prevent the listener from moving during the process, he's asked to lie down on a foam mattress and his head can be blocked using a modified caliper. The latter also allows to control the support force of the transducer.

A mesh of 15 measure points is placed on the subject's tragus as illustrated in Fig. 3. This position near the transducer was previously found to provide exploitable results. For each point, the SLDV sends a swept sine with frequency ranging from 100 Hz to 10 kHz to the BC transducer and records the vibration velocity. The process is repeated 10 times in order to eliminate noises by averaging. The SLDV software finally returns the frequency response function (FRF) at the measure point with the original swept sine as the reference signal. The coherence between the original signal and the measured velocity is also provided and is used to assess the validity of the measurement.

Both BC transducers are tested using SLDV on every listener and under 4 contact force conditions: with the natural wearing force and with the application of additional low, moderate and high load. The force value is controlled using the previously described setup. The effect of the force is assessed by computing the ratio of the FRF with additional load over the FRF with natural wearing force.

3. RESULTS

3.1 Frequency response at hearing threshold

Fig. 4 represents the mean frequency response of the two BC transducers measured at hearing threshold on both ears with 95 % confidence intervals. Positive values reflect

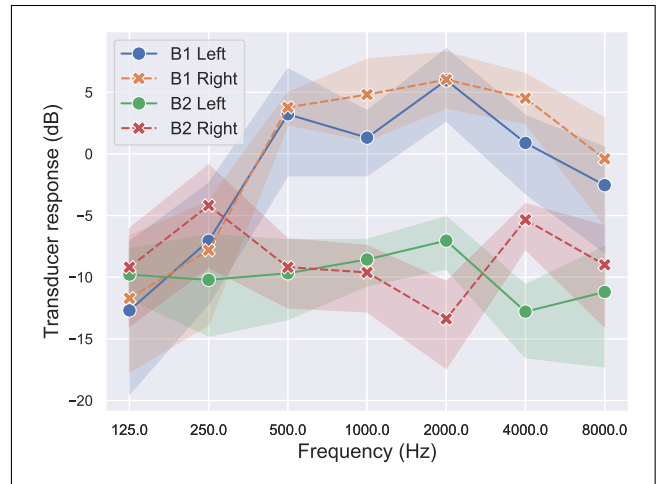


Figure 4: Frequency response of BC transducers at hearing threshold for both ears.

lower hearing thresholds for BC conduction than for air conduction, i.e. good performance of the transducer. Results for the left ear are very similar to results for the right ear with B1 considering the overlapping confidence intervals, confirming that the transducer is symmetrical. For B2, differences greater than 5 dB are observed between the ears at 250, 2000 and 4000 Hz. They seem particularly significant for the latter two. This transducer still presents a flatter response than B1 but is also less efficient since the measured values stay around -10 dB. The B1 transducer's response exceeds 0 dB between 500 Hz and 4 kHz, but substantially decreases at low frequencies and at 8 kHz. It reaches a maximum near 5 dB at 2 kHz.

3.2 Inside the ear acoustic measurement

Fig. 5 presents the mean pressure level in the ear canal in open ear and occluded condition for both solid-state transducers. Inter-subject variability, illustrated by 95 % confidence intervals, doesn't exceed 10 dB(SPL). This is sufficiently low to compare the transducers and the hearing conditions, but it still reflects substantial differences between listeners.

As with the frequency response at hearing threshold, B1 shows a higher response in open ear condition and the peak at 2 kHz is retrieved. Furthermore, the drop at high frequencies is no longer present for B1 while B2 presents a 13 dB(SPL) drop between 4 and 8 kHz. The occlusion effect is observed in the occluded condition: low frequencies are amplified up to 20 dB(SPL) inside the ear canal and high frequencies decrease by 25 dB(SPL) at 8 kHz. Additionally, we observe that the frequency at which the level in the occluded condition drops below the level in open ear condition is higher for the transducer B2, approximately 1.8 kHz, than for B1, approximately 1.4 kHz. The significance of this result is, however, questionable since there are no measuring points between 1 and 2 kHz.

In the occluded condition for the transducer B1, a mean level of 84 dB(SPL) is obtained at 500 Hz and it even exceeded 90 dB(SPL) for one subject, which could become

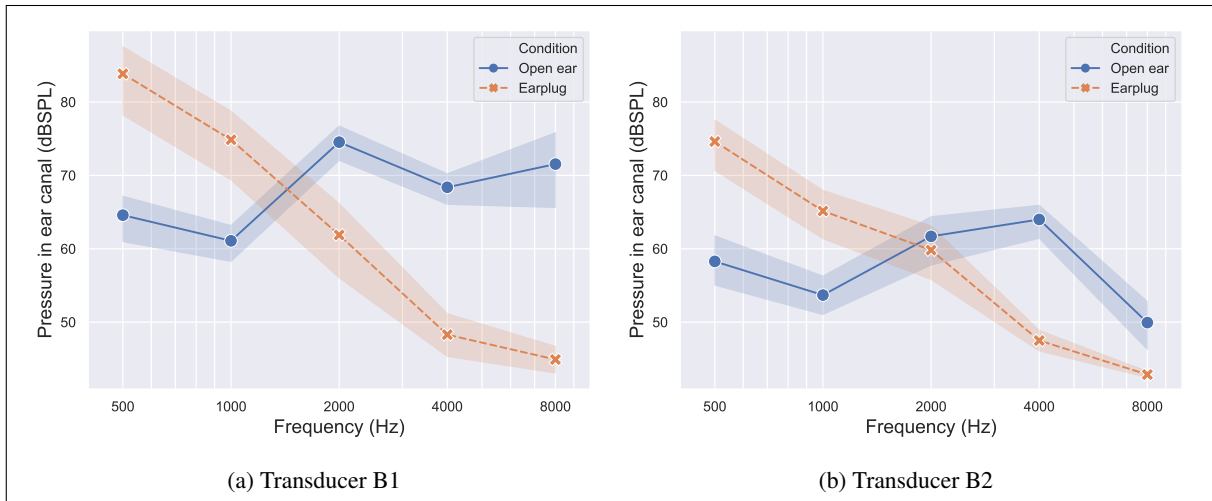


Figure 5: Mean pressure level in the ear canal when sines are played by the BC transducers B1 (a) and B2 (b). Results for both open ear and occluded conditions are displayed.

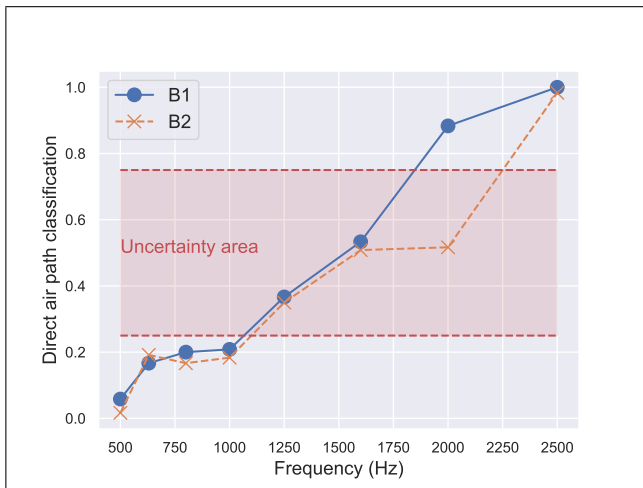


Figure 6: Classification of the main pathway as being the direct air path (1) or the bone-air path (0) as a function of stimulus frequency.

dangerous if the exposure lasts too long.

3.3 Loudness difference between open and occluded ear

Merging data from the left and right ear, each frequency is tested 12 times in the loudness difference experiment. Fig. 6 represents the normalized number of times, averaged across listeners, the open ear side is chosen as the loudest as a function of frequency. Values near 0 reflect the predominance of the bone-air path and 1 the preponderance of the direct air path. The complete impossibility of classifying the stimulus, i.e. when listeners chose the open ear side every second time, corresponds to 0.5 on the graph. Thus, values between 0.25 and 0.75 form an uncertainty area, where the probability to clearly define the main pathway is lower than 0.5. This threshold is chosen arbitrarily.

For both BC transducers, the bone-air path is predomi-

nant up to 1 kHz, as values in Fig. 6 are lower than 0.2 for those frequencies. For B1, the direct air path becomes preponderant above 2 kHz, while it occurs only at 2.5 kHz with B2. The uncertainty frequency range is therefore wider for the B2 transducer (750 Hz) than for B1 (350 Hz). It can be noted that the low number of studied frequencies prevents us from giving more accurate ranges. The linear interpolation between the points increases the range from 1070 Hz to 1850 Hz for B1, and from 1100 Hz to 2250 Hz for B2.

3.4 Contact force measurement

During the SLDV measurements, the contact force between the BC transducers and the listeners' skin is controlled using the FlexiForce sensor. Tab. 1 lists the mean loads and standard deviations in grams for the 4 tested force conditions (natural, low, moderate and high). Even if it was difficult to perfectly control the contact force in real time during the experiment, it can be noted that the obtained values for both BC transducers are very similar in each qualitative force condition.

For B1, the low force condition adds 13.5 g to the natural wearing force. 37 g (resp. 71.5 g) is added in the moderate (resp. high) condition. Those values respectively change to 24.5 g, 47 g and 78.5 g with the transducer B2. The high additional force condition barely exceeds 100 g (≈ 1 N) and was considered uncomfortable by the listeners with both bone conduction transducers.

3.5 Scanning Laser Doppler Vibrometry

The vibrometry software computes the coherence between the measured velocity and the reference signal. It's the squared magnitude of the normalized cross-spectral density and can be used to assess the validity of the measurement. We therefore decided to estimate a maximum frequency range in which the coherence is acceptable for each measurement. The acceptance threshold is arbitrarily set to 0.5 and coherence data obtained with the software are

Force condition	B1		B2	
	Mean	Std.	Mean	Std.
Natural	31.5	4	27	1
Low	45	6	51.5	7.5
Moderate	68.5	3	74	4
High	103	5	105.5	9

Table 1: Mean measured load, and standard deviation, in grams (g) between the BC transducers and the listeners' skin for the 4 different force conditions. Data from the FlexiForce sensor are averaged from 300 values.

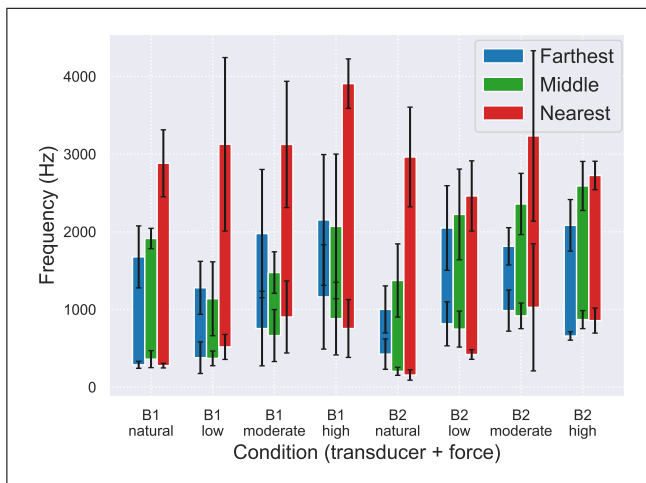


Figure 7: Frequency width for which the LSDV measurement is acceptable with respect to the coherence.

smoothed in sixth-octave bands beforehand. In the following, these estimations are averaged across subjects and separated in three sets according to the distance between the measure point and the transducer. The three sets are hereafter called the farthest, the middle and the nearest points.

As illustrated in Fig. 7, the coherence is acceptable within a wider frequency range for the points closest to the transducer, in any force condition. The acceptable frequency width ranges from 1.5 kHz to 3 kHz for these points, while barely reaching 1.5 kHz for the farthest and middle points. Also the inter-subject variability is higher for the latter two. In the following, only data from the nearest points are therefore kept and the frequency analysis is restricted to the range between 1 kHz and 2.5 kHz.

Data for each condition and subject is smoothed in third-octave bands. Frequency responses corresponding to listening conditions with an additional force are then divided by the response with the natural support force. This allows the representation of the amplification effect of additional forces on the frequency response. Calculated amplifications are finally averaged across listeners and transformed in dB values for graphical representation. Positive values therefore reflect better performance of the transducer with the additional force than with the natural contact force. 95 % confidence intervals are also given using

multiple estimations of the decibel mean value with a bootstrap method.

In Fig. 8a, calculated mean values of the amplification with the B1 transducer suggest that additional low to moderate pressing force increases the frequency response up to 4 dB. According to the confidence intervals, there seems to be an important variability across subjects, so the observed difference between low and moderate forces might not be significant. However, applying a higher pressing force to the transducer substantially degrades the frequency response compared with the natural wearing force. This degradation drops to approximately -4 dB at 1 kHz.

In Fig. 8b, the additional pressing force on the B2 transducer has a positive impact on the response at the observed frequencies. Mean values even suggest that the higher the force, the higher the amplification, but the significance of this observation can be questioned by the variability across subjects illustrated by the confidence intervals.

4. DISCUSSION

The frequency response at hearing thresholds still remains a very important measure characterizing a bone conduction transducer, since it is the only one that reflects the actual user's perception. In addition, the frequency range, for which the taken acoustic pathway is uncertain, also seems decisive to differentiate the transducers. Its precise estimation is, however, time-consuming using the perceptive loudness difference test, but this frequency range could nonetheless be estimated from measurements in the ear canal in open and occluded ear condition. Correct accuracy could be obtained from swept sine measurement instead of pure sines.

In the occluded ear condition, pressure levels that could potentially damage the listener's hearing were recorded and are caused by the occlusion effect. In order to preserve the listener's health and for the sound rendering of a BC transducer to be homogeneous in every hearing condition, the occlusion effect should be compensated when hearing protectors are worn.

The influence of the contact force on the BC transducers, attested by the vibrometry measurements, depends on the solidity of the shell of the device. With a soft encapsulation, an additional force quickly induces a blocking of the electrodynamic transducer, while it can improve the response for a rigid shell. In both cases, results suggest that an optimal contact force exists that allows an optimal use of the solid-state transducer. Knowing this optimum, a real-time estimation of the support force when the transducer is worn would be necessary in order to either inform the user to tighten or loosen his device or apply a correction to the output signal of the transducer. Such an estimation seems possible through electrical impedance measurement [12, 13] and the correction could lessen the physiological differences affecting the efficiency of the BC transducers [14].

SLDV measurements are not completely satisfying in this study because they are valid only for a few points and for a restricted frequency range. Moreover, the latter lies in

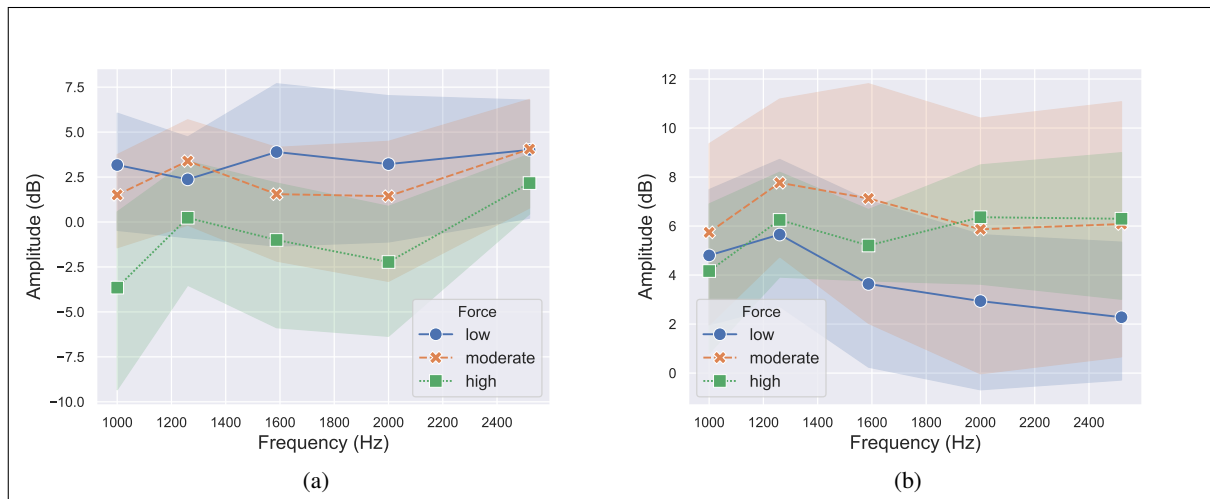


Figure 8: Amplification effect of additional transducer contact force on the skin vibration induced by the B1 (a) and B2 (b) transducers.

the uncertainty area concerning the acoustic pathway. No conclusion can be made about whether skin vibration or aerial acoustic wave is recorded by the vibrometer. Additional measurements should be realized by increasing the output signal level of the BC transducers and also by modifying the position of the measure points. Pressure level measurement inside the ear canal when changing the contact force of the transducers could also be compared to the SLDV measurements. Preliminary results with B1 suggest that the same effect of additional force to the transducer's response is found again. Additionally, the influence of contact force may be assessed at hearing thresholds so that the listener's perception is taken into account.

5. CONCLUSION

Various types of measurement for the characterization of solid-state transducers have been assessed in this study. Perceptive tests leading to the frequency response of the device remain the most reliable, but acoustic measurements inside the ear canal results in the same conclusion about the differences between the tested transducers. The frequency range, at which the main acoustic pathway changes, is also highlighted as an important characteristic of a BC transducer and could be accurately obtained with in-ear measurements.

The SLDV experiment revealed the probable existence of an optimal pressing force that will be further evaluated through similar tests as well as audiometric and in-ear experiments. This study therefore constitutes progress for the improvement of solid-state transducers by taking the contact force into account. Evaluating the influence of different positions of the devices on the user's skull and/or of different SLDV measure points would also complete the enhancement of bone conduction transducers.

6. ACKNOWLEDGMENTS

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