

DIRECTIVITY OF HUMAN AND ARTIFICIAL SPEECH

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ABSTRACT

This paper is a study on how directivity characteristics of artificial mouths correspond to the directivity of a real speaker. The motivation for the research is the measurement methods that are applied in the telecommunication industry for the microphones of phones and their accessories.

Responses of artificial mouth simulators of Brüel&Kjær HATS 4128, Brüel&Kjær 4227 and Head Acoustics HMS II.3 HATS were measured to several positions. The same measurements were repeated for a group of test subjects. The measurement positions corresponded to the same positions were the microphones of phones and their accessories, so called headsets, would lay.

The basic mechanisms that produce the directivity pattern are discussed and also the contribution of the speech content is shown. The main contributor to the directivity is the mouth aperture size. The acoustical characteristics of the upper body are also a significant factor if the position is not directly in front of the mouth.

More than a 10 dB-difference was found between artificial mouths and test subjects. It appeared that B&K HATS is too directional for high frequencies. To improve the correspondence of the telephonometry to the real speakers, a simple equalization scheme and two structural improvements to B&K HATS are proposed.

1. INTRODUCTION

When a microphone module is designed for a new phone model the frequency response of the microphone is typically measured with an artificial mouth. The distance of the microphone to the mouth depends on the dimensions of the phone. The trend is that the size of mobile phones are getting smaller and thus the microphones in the phones are substantially further away from the mouth compared to the microphones of old landline phones.

Wider use of accessories, for example headset equipment, set also new requirements for the telephonometry. In these accessory gadgets the microphones lay on the chest, hang on the wire or is situated somewhere else not in a familiar phone microphone position. Generally speaking the directivity of the artificial mouths should cover nowadays accurately a larger set of positions than they were originally designed for. Still it is not well known what are the frequency response and sensitivity characteristics of current artificial mouths used in acoustical measurements in off-axis positions.

There is no extensive literature on the subject. Some studies can be found where the directivity of the mouth as a sound source is measured with a group of test subjects [1, 2, 3, 4, 5, 6, 7, 8]. Also some publications, standardization, and product specifications can be found on the directivity of artificial mouths [9, 10, 11, 12, 13]. Nevertheless the directivities of artificial mouths are not systematically compared to test subjects by similar measurements in any of these studies. thus there is clearly a need for measurement-based information how accurately the artificial mouths simulate the real human mouth and should their design be improved.

There are standards that define guidelines for the directivity pattern of the artificial mouths. The most important ones are: ITU-T P.58, Head and torso simulator for telephonometry and ITU-T P.51, Artificial mouth [10, 11].

Artificial mouths, especially the so-called Head and Torso Simulator (HATS), will most probably be used in future for wide band measurements, even though the mouth subassembly and its standardization should be improved in any case. The standards do not define especially in near field the directivity pattern for the positions that the microphones of the headsets and small phones use. In the narrow frequency bandwidth (300 Hz - 3400 Hz) the directional features are not yet affecting considerably and so the simulators are adequate. But in the wide frequency bandwidth (150 Hz - 7 kHz) the situation is significantly different, as we will see later in this paper.

This study concentrates on both directivity characteristics of the human and artificial mouths. The main comparison is done between human and B&K HATS 4128 mouths. The most important part of the study is to determine if there is a difference between the directivities of simulators and an average person. As a result the study should give basic information how the artificial mouth measurements for phone handsets should be designed and how the potential difference between the directivities should be compensated in the results.

Behaviour of mouth directivity is also studied in general level. The far and near field conditions are discussed. The sound radiation pattern affected by head and torso is studied both by measurements and by modeling. Also characteristics of speech content affecting to the directivity are discussed.

The structure of the paper is mainly leaning on the measurements and the outcome of those. The details of the measurements are listed in the next section. Two simple models for a mouth as sound source are presented in Section 3. The results are shown by various figures in Section 4. In Section 5 the improvement proposals for telephony are discussed and finally in the end of the document the outcome of the study is gathered in a short conclusion.

2. MEASUREMENTS

Some kind of key requirements have to be defined as the basis for the measurements. The measurement system and process had to be compact and specified accurately to ensure reliable results. To ensure the easy conduction of the measurements, a multi-channel recording system was designed for the test subject measurements. The same system with minimum changes was used throughout all the measurement activities. The artificial mouths were measured using two-channel impulse response measurement system.

There were several objectives in the measurements. First of all the directivities of artificial mouths were to be determined to several positions by transfer functions that are referred to a fixed reference position. Next the measurements were to be repeated for a group of test subjects using the same measurement positions. The speech material was selected so that it would represent on average the content of natural speech. Some additional measurements were conducted for the HATS to study the characteristics of the sound field in general.

In phones and headsets the microphones lay normally near the cheek or chest. Depending on the phone model there are several different positions for microphones between the ear and the mouth. If we count in also the positions for other accessories, the amount of possible positions gets really large. All of these self-evidently cannot be covered in the study. Nevertheless the scope is to find some general features for directivity relying on an adequate amount of measurements. The microphone positions are defined in Section 2.2.

2.1. Equipment

The artificial mouths were measured in an anechoic chamber at Nokia facilities at Salo, Finland. The chamber ensures the free field conditions down to 90 Hz. B&K HATS was the main target on the study because it is most widely employed in telecommunication measurements [13].

The MLS feature in the APWin measurement platform from Audio Precision was applied to acquire the impulse responses between mouth and microphones. The measurement itself was a set of consequent cases with outcome of impulses responses for two channels. 32 kHz sampling rate and 32767 sample MLS were the parameters for measuring. Two B&K measurement condenser microphones 1/4 inch in diameter were the pick-ups.

The directivity of the test subjects had to be studied by recording the speech. Measurements took place in an anechoic chamber at Helsinki University of Technology. The data acquisition system was built up from IOTech Wavebook/516 measurement system (IOTech, WaveBook/516, 16-bit 1-MHz Data Acquisition System). IOTech system has 8 input channels. One of the channels was reserved as the reference. So the system enabled directivity measurement by 7 transfer function estimates in parallel.

The IOTech is a separate DSP unit that can be connected over LPT-cable to a laptop computer. IOTech does the A/D conversion and laptop acts as storage for the data. The IOTech Wave book has 16-bit A/D conversion for each 8 channels. 32 kHz sample rate was selected also for these measurements.

Small electret microphones (Sennheiser KE 4-211-2) seemed to be the best choice for the test subject measurements because they could be easily attached to the test subjects. The diameter of the microphones is 4.75 mm. The responses of the microphones were calibrated by comparing each one to a B&K condenser microphone.

The measurement acquisition was controlled with dedicated IOTech user interface software. Signal levels were monitored and amplified with microphone pre-amplifiers (E.A.A. Professional Stereo Preamplifier, PSP-2) so that adequate SNR was achieved. The acquisition system was wired outside the anechoic chamber where the measurement operator could steer the session. Beside the acquisition system a test subject monitoring and guidance system was built up. Both a video and an audio link was between the test subject inside the chamber and the operator.

2.2. Target positions

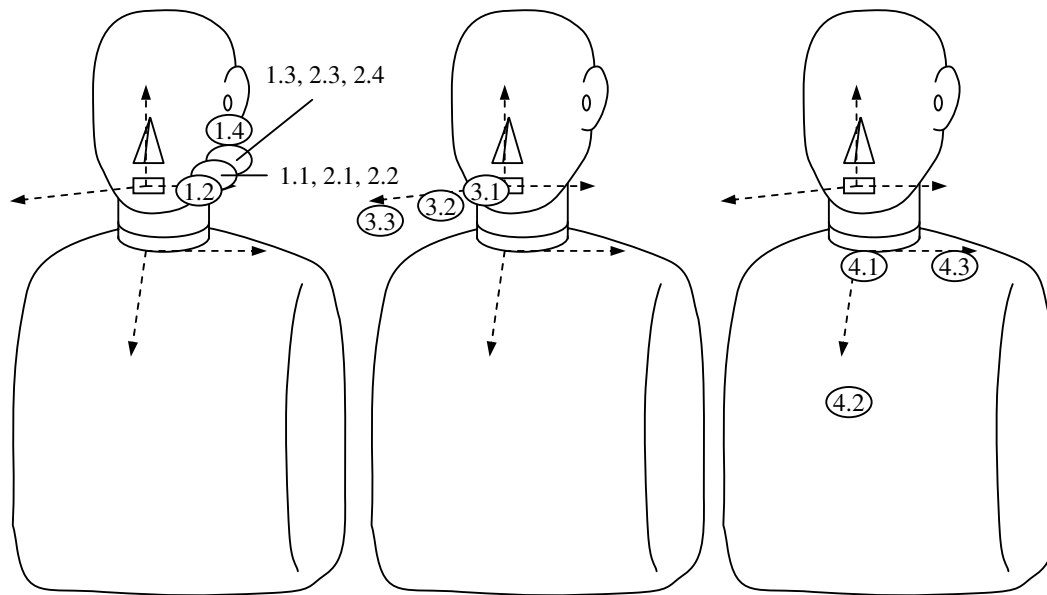


Figure 1: *Measurement positions.*

The measurement positions are illustrated in Figure 1. B&K HATS 4128 was measured in all positions in parallel with the Mouth Reference Position (MRP) i.e. position 3.1. B&K 4227 and HA HMS II.3 HATS were measured in positions next to cheek, i.e. 1.1-1.4 and in the front of the mouth 3.1 and 3.4.

The recording system for test subjects had eight channels. So the same eight positions were used throughout the activity: positions near the cheek 1.1 - 1.4, on the chest 4.1 - 4.3, and as reference 3.4. The far field reference

Table 1: *Measurements positions defined by coordinates. The coordinate axes are referred to the lip plane and its perpendicular (see Figure 1). On chest the positions are directly on the chest and the axes run downwards and sideward.*

Position	On axis	Off axis horizontal	Off axis vertical	Description
1.1	0	60	0	Cheek, large phone, normal angle
1.2	-10	70	-40	Cheek, very large phone, normal angle
1.3	-30	85	10	Cheek, small phone, normal angle
1.4	-70	100	30	Cheek, very small phone or boom HS
2.1	-10	85	-20	Cheek, large phone, pointing down
2.2	0	100	0	Cheek, large phone, far from cheek
2.3	-50	95	-15	Cheek, small phone, pointing down
2.4	-45	110	0	Cheek, small phone, far from cheek
3.1	25	0	0	MRP
3.2	100	0	0	Far field
3.3	250	0	0	Far field
3.4	500	0	0	Far field, reference point for test subjects
3.5	1000	0	0	Far field
	Downwards	Sideward		
4.1	50	0		On chest, near throat
4.2	200	0		On chest, middle of chest
4.3	0	100		On chest, near shoulder

was chosen because the positioning of a microphone to MRP with test subjects was seen difficult as well as the noise caused by the airflow from the mouth.

A sophisticated measurement helmet was designed and built to attach the measurement microphones as exact as possible to the specified positions in test subject measurements. Also the microphones in the close to chest were attached to each other in an array. The positioning equipment can be seen in Figure 2.

The microphone positioning was referred to lip ring and its perpendicular. This is directly adopted from the ITU standardization [10, 11]. On the chest the positions lay freely and therefore the axes run from the throat downwards and sideward (see Figure 1).

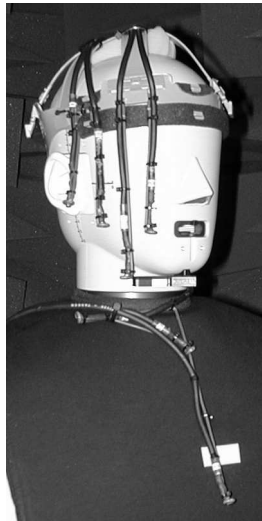


Figure 2: *The measurement helmet and the chest microphone array can be seen on the B&K HATS 4128. The microphones (Sennheiser KE 4-211-2) are the in the positions that were used throughout the test subject measurements.*

2.3. Measurement procedures

B&K HATS 4128 was measured in all of the positions three times: with and without the measurement vest (B&K 0600 shoulder damping fabrique) and also without the torso. The output of each measurement case was two 32767-sample impulse responses at 32 kHz sample rate for the reference point (MRP) and the point of interest. In addition some extra measurements were conducted. In two positions near the cheek the measurement was repeated with different mouth sizes: normal (30 mm × 11 mm), blocked to half of its width (15 mm × 11 mm), and without the mouth adaptor (42 mm × 16 mm). Other artificial mouths were measured similarly than B&K HATS but without vest or mouth size modifications and with a smaller set of measurement positions.

A sentence in Finnish was selected to test subject recordings because Finnish-speaking test subjects were the easiest to recruit. Every subject had to pronounce the sentence “Kaksi vuotta sitten kävimme Ravintola Gabrielissa Helsingissä, ja söimme siellä padallisen fasaania banaanilla höystettynä.” (in English: “Two years ago we went to Restaurant Gabriel in Helsinki and we ate there a pot of pheasant larded with banana.”) and it was recorded with the eight microphones at the same time. In the sentence there is at least one occurrence of all vowels and consonants of the Finnish language. There are altogether 95 separate short or long phonemes in the sentence.

The measurement session was repeated for 13 test subjects: 5 female and 8 male. Age of the subjects vary between 20 and 30 years. The group consisted of different body sizes from 160 cm tall to 190 cm. Test subjects were sitting in a small chair and were wearing casual summer cloths. None of the test subjects had speech defects and all had Finnish as the mother tongue.

Test subjects were instructed to speak clearly and stay hold during the recording. A headrest was attached to the chair and two microphone stands was lined in front of the speaker, so that it would be easy to focus to keep the head still. The recordings were always repeated if some mistake were heard in articulation or movement was noticed in video monitoring.

3. MODELING

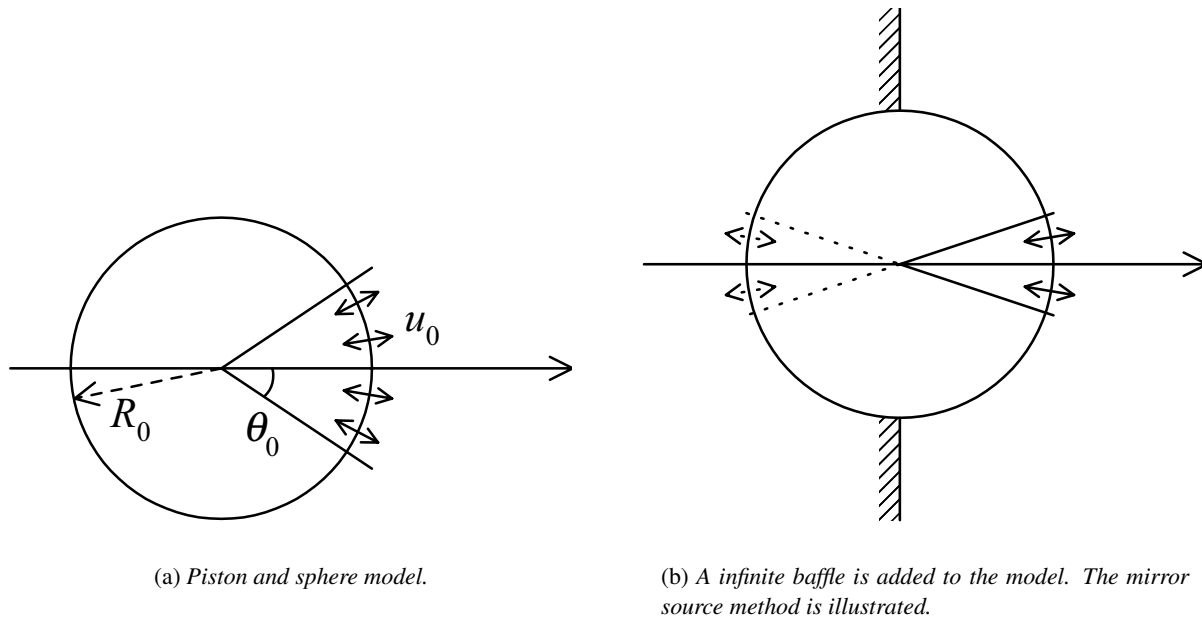


Figure 3: Models that are applied in the study.

The directivity of the voice production system can be estimated by various kinds of models. Later on the results are assessed comparing them to modeling. Also the reasons for the directivity characteristics can be predicted by altering the parameters in the models.

The simplest model for the head is to model it with a sphere. The mouth is approximated with a round piston on the sphere. By these means the rotationally symmetrical coordinates can be acquired and therefore there is just two axes: the radius from the center of the sphere r and the angle from the piston perpendicular θ . The model is illustrated in Figure 3(a).

The particle velocity u_r on the surface of the sphere is

$$u_r = \begin{cases} u_0 & , \theta \leq \theta_0 \\ 0 & , \theta > \theta_0 \end{cases} \quad (1)$$

In other words a circular part of the sphere radiates and the rest of the surface is fixed and baffled. The displacement on the piston is radial and in this case it is an adequate approximation because the mouth aperture is very small compared to the head radius.

When the sound field is harmonic, the pressure field $p(r, \theta)$ for a general axisymmetric spherical sound source is

$$p(r, \theta) = i\rho_0 c_0 \sum_{n=0}^{\infty} \kappa_n \frac{h_n^{(2)}(kr)}{h_n^{(2)}(kR_0)} P_n(\cos \theta). \quad (2)$$

P_n is Legendre polynomial, $h_n^{(2)}$ Hankel function, k the wave number, ρ_0 the density of air, and c_0 the velocity of sound. Coefficients κ_0 are dependent of the displacement pattern on the sphere. In this case they are

$$\kappa_n = \frac{u_0}{2} [P_{n-1}(\cos \theta_0) - P_{n+1}(\cos \theta_0)]. \quad (3)$$

[14, 15].

The model has two parameters: the radius R_0 and the mouth aperture angle θ_0 . When the model is later on applied, these parameters have to be selected within some reasonable principles. The head dimensions cannot be applied directly to the model because the head and body dimensions are not axisymmetric. Nevertheless some kind of average value gives reasonable results. For the head radius 10 cm value was used. The mouth aperture angle was set so that the mouth cross-section area would be 3 cm² or close to it depending on the case.

The model represented above gives only a simplified view how the head interacts with the radiation from the mouth. Self-evidently the whole body affects to the sound field. At least shoulders and chest diffract, reflect, and absorb the sound.

If we consider the sound field close to the lip plane perpendicular and positions on the chest, the most significant effect of the body is the direct reflection. It causes a comb filtering shaped response to the field. One direct and simple way to model this reflection can be seen in Figure 3(b) where the space is divided with an infinite baffle. The head model itself is the same.

The main advantage in the presented baffle model is that it can be formulated using a mirror source method. The total field with the reflection can be expressed with the following equation

$$p(r, \theta) = p_{\text{direct}}(r, \theta) + p_{\text{mirror}}(r, -\theta). \quad (4)$$

4. RESULTS

4.1. Analysis overview

There were two approaches to analyze the measurement data due to two different measurement systems used. In both cases the aim was to obtain transfer function estimates from a reference position to other positions in the field.

The data from artificial mouth measurements was directly impulse responses. Therefore the transfer functions were directly obtained by FFT. By supposing that the system is linear and the reference position identical in each case, the transfer functions from point to point can be calculated by dividing the FFTs.

Transfer function estimates were calculated from the test subject recordings by windowing the active signal in the recordings in 1024 sample frames (32ms at 32kHz sample rate) with a 50% overlap. The delay difference between channels was compensated. The delay was estimated by calculating cross correlation between channels. FFT was applied to each frame and by averaging the frames a transfer function estimate was acquired [16]. The transfer functions were averaged to 1/3 octave resolution.

4.1.1. Reliability consideration

The simplest means to consider the reliability of the measurement data is to examine the coherences and signal-to-noise ratios (SNR). Both SNR and coherence are obtained by cross spectrum estimates and auto spectrum estimates [16, 17]. The noise sample was taken from the end of each recording starting from the end of the last segmented active speech. The artificial mouth measurements can omitted here in the consideration because the reliability of those measurements was far better than test subject measurements in all cases.

SNR and coherence were adequate on all frequency bands that were considered. The worst SNR in all channels was greater than 25 dB over the wide band. The coherence between the reference position and other positions were greater than 0.8 on narrow band and greater than 0.65 on wide band. The values imply that the transfer function estimates are reliable on wide band and very reliable on narrow band [16, 17].

If results are averaged from a large set of data, the confidential intervals are one way to see by statistical means how reliable the results are. The confidential intervals are included in Figures 14, 16, and 17 for whole data and 11 for each vowel group. The distribution is calculated from the unoverlapped frames. The intervals stay mostly within a ± 1 dB range. This implies that the results are very representative. [16]

4.2. Directivity features of mouth

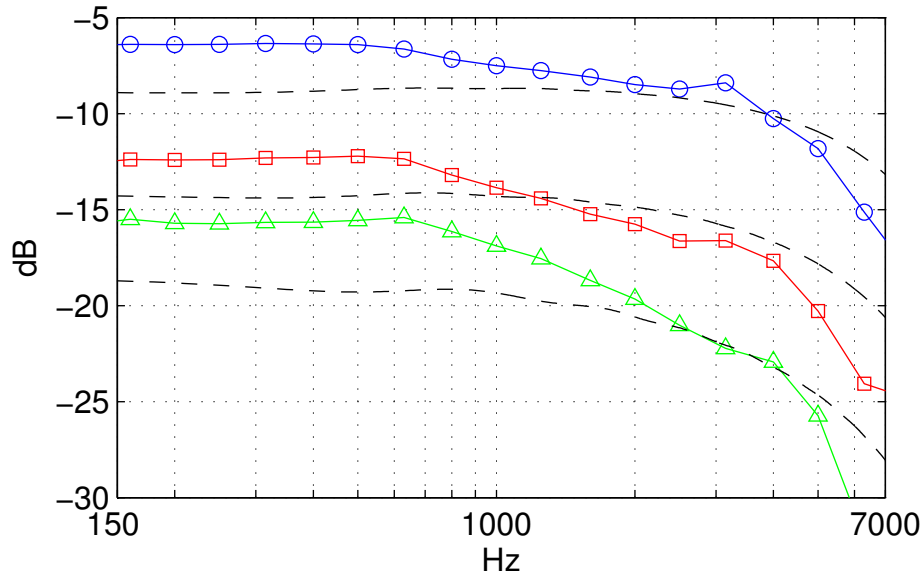


Figure 4: Transfer functions of B&K HATS from position 3.1 (MRP) to positions 1.1, 1.3, and 1.4 (\circ , \square , and \triangle). Corresponding modeled cases are included for the same positions.

The directivity of the mouth is approached by considering what are the key aspects that play the most important role. Measurement data for artificial mouths is more reproducible and B&K HATS measurements are used for the consideration.

The sound field is produced by the radiation from the mouth aperture and modified by the head and torso depending on their dimensions and position. Generally speaking there are three different aspects that affect the sound field:

1. Mouth cross-section area.
2. Far field \leftrightarrow Near field.
3. Reflections from body.

Next there is some explanation on each of these items on the list.

The cross-section area and shape of the mouth aperture are connected to how much the bare mouth directs. If the size of the mouth is substantially large compared to the wavelength the mouth starts to direct. On low frequencies the mouth is more or less a simple omnidirectional point source.

Second, near field and far field differ because of the head dimensions. The study is only concentrated to the field near the mouth perpendicular. In far field on high frequencies, the head enhances the directivity the same way as the mouth if assembled to an infinite wall. On low frequencies the head does not affect. On the other hand if the position is shifted off the perpendicular, for example behind the head, the head shadows the sound on high frequencies.

Third, reflections, diffraction, and absorption from the upper body modify remarkably the sound field. Near the mouth, for example close to the cheek, these fluctuations are not strong enough so they can be omitted. On the other hand in far field and especially near the chest significant fluctuations can be seen.

Generally speaking the directivity of the mouth is seen as reduction of high frequencies when the position shifted towards the ear (see Figure 4). The same kind of effect is seen when the position goes downwards the chest (see Figure 5). The reduction of high frequencies is more or less monotonic and when the position is closer to the ear the slide is steeper.

HATS 4128 can be worn with a dedicated about 2 cm thick measurement vest. The vest is intended to enhance the correspondence with the human upper body in binaural recordings. Applying the vest to phone and accessory measurements is not that straight forward.

In Figures 5 and 6 we see that the chest reflections cause peaks and dips to the responses. Close to 1 kHz there is a strong dip in the transfer functions for the position in 0.5 m distance (Figure 6). The dip around 1 kHz implies that there is about 15 cm difference in the path of reflected and direct sound. This is in correspondence with the dimensions. The mouth in the model is in the center of the head and therefore the path difference from mouth to chest is longer and the dip is on a lower frequency. If the vest is taken off the dip shifts to higher frequency because the reflection comes faster i.e. the sound velocity in vest is less. In the curve for bare head we see only the 3 dB level difference between high and low frequencies.

In the Figure 5 we see a dip near 5 kHz that is caused by the reflection through the vest. If the vest is taken off the position is directly on the hard surface and so only duplication of pressure field occurs. The dips in both Figures 5 and 6 are repeated on higher frequencies in comb filtering shape but the frequency smoothing omits it.

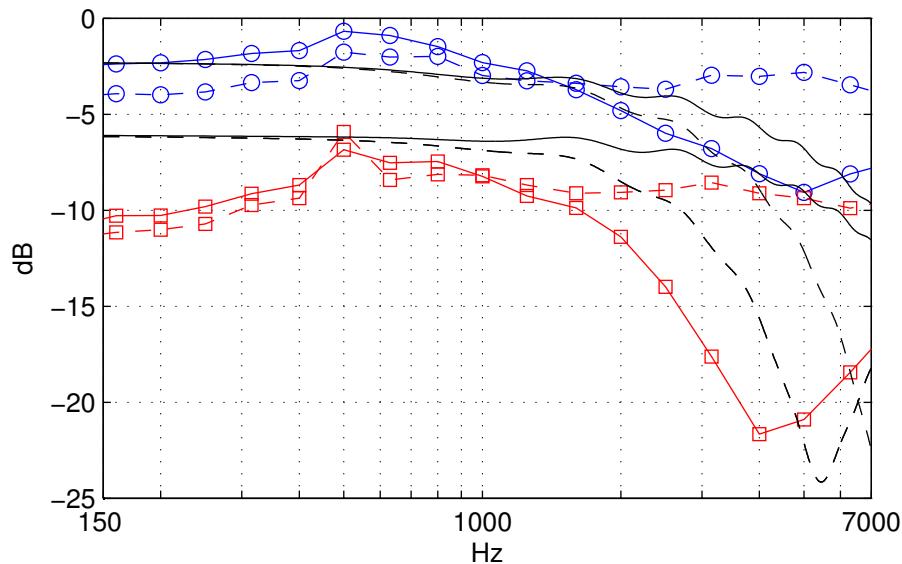


Figure 5: Transfer functions of B&K HATS from MRP to positions 4.1 and 4.2 (\circ and \square) and the same measurements without the vest (dashed \circ and \square). Corresponding modeled cases with the infinite baffle are included for the same positions. Both positions are modeled with two different distances from the infinite baffle: 1 cm (solid) and 8 cm (dashed)

4.3. Artificial mouths compared to test subjects

The differences of the averaged test subjects and artificial mouths can be seen in Figures 7, 8, 9, and 10 in five positions. The curves are calculated by dividing transfer function for averaged person with the transfer function

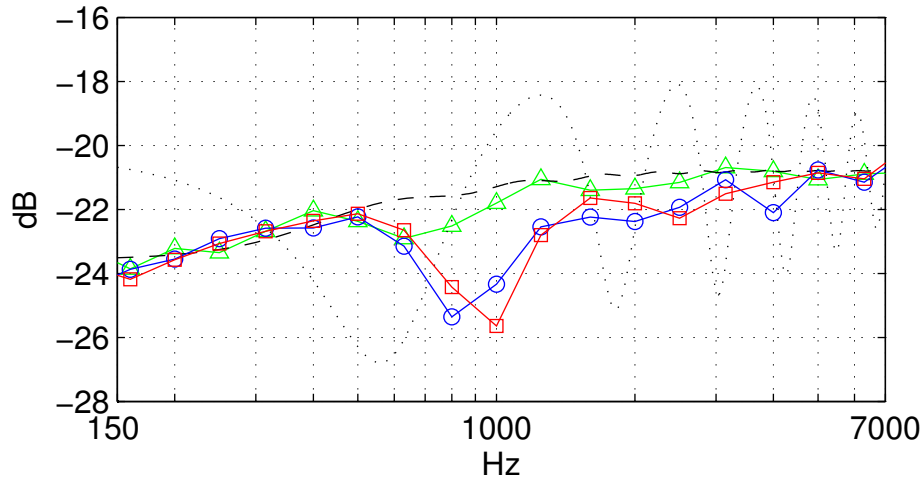


Figure 6: Transfer functions of B&K HATS from MRP to positions 3.4 (0.5 m in front of mouth) with the vest, without the vest, and without the torso (\circ , \square , and \triangle). Corresponding modeled cases with and without the infinite baffle are included.

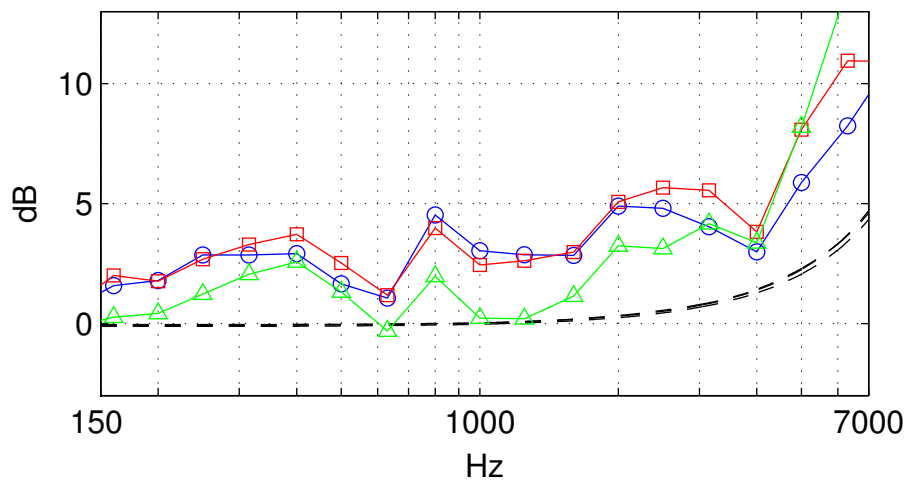


Figure 7: Difference of averaged test subject and B&K HATS. The comparison is done for transfer functions from microphone position 3.4 to 1.1, 1.3, and 1.4 (\circ , \square , and \triangle). A positive dB value implies that the B&K HATS is more directional on that frequency. Three corresponding models are included where the mouth aperture radii for corresponding B&K HATS and averaged person in the direct models are 1.5 cm and 0.5 cm.

for an artificial mouth to same position. So if the curve has positive values the artificial mouth is more directional and vice versa.

In the test subject measurements the reference position was in 500mm distance because MRP would have been difficult to implement to the measurements. So the reference position in far field causes same fluctuation to the curves because there is also difference in reference between test subjects and artificial mouths.

The difference curves near the cheek are substantially flat on narrow band but on wide band the directivity difference is significant. Interesting remark is that the differences are more or less independent of the position. There is a little more difference if the position is closer to the ear if the overall level difference is omitted.

The two positions near the chest shown in Figure 8 indicate that there is significant difference in reflection

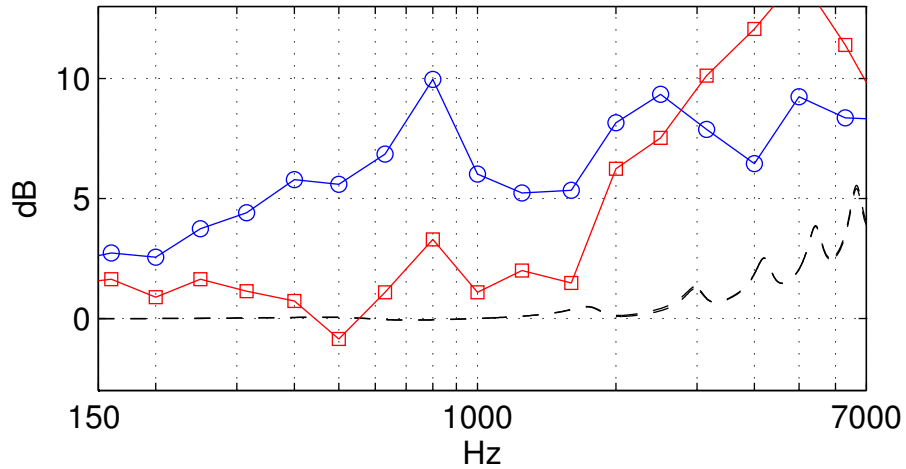


Figure 8: *Difference of averaged test subjects and B&K HATS. The comparison is done for transfer functions from microphone position 3.4 to 4.1 and 4.2 (○ and □). A positive dB value implies that the B&K HATS is more directional on that frequency. Two corresponding models are included where the mouth aperture radii for corresponding B&K HATS and averaged person in the baffled models are 1.5 cm and 0.5 cm. The positions in the models are in a 1 cm distance from the baffle.*

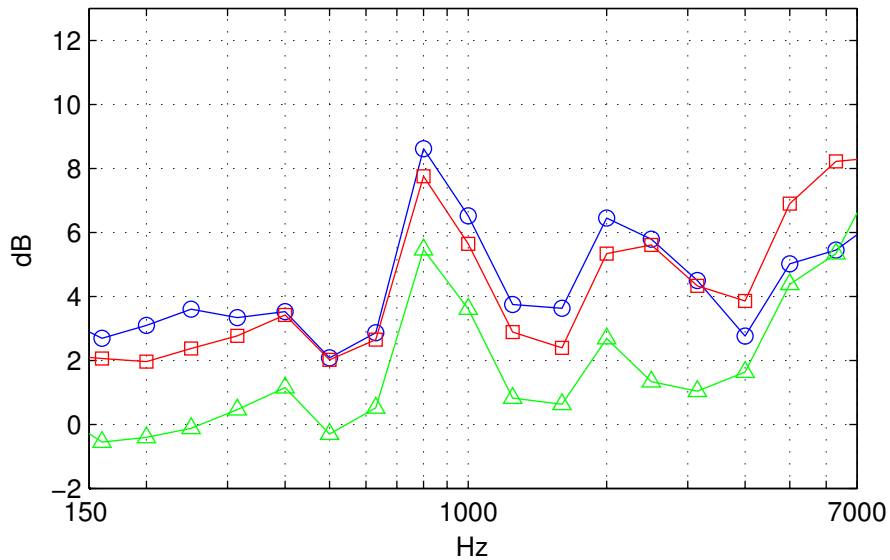


Figure 9: *Difference of averaged test subject and B&K 4227 Artificial Mouth. The comparison is done for transfer functions from microphone position 3.4 to 1.1, 1.3, and 1.4 (○, □, and △). A positive dB value implies that the artificial mouth is more directional on that frequency.*

from chest of B&K HATS compared to the test subjects. This is seen near 800 Hz for the reference and near 5 kHz for the close to chest reflection.

4.4. Speech content

As we saw within the results comparing test subjects and B&K HATS in previous section, the size of the mouth seems to be an essential factor in the difference. The curves in Figures 7 and 8 were modeled using two different

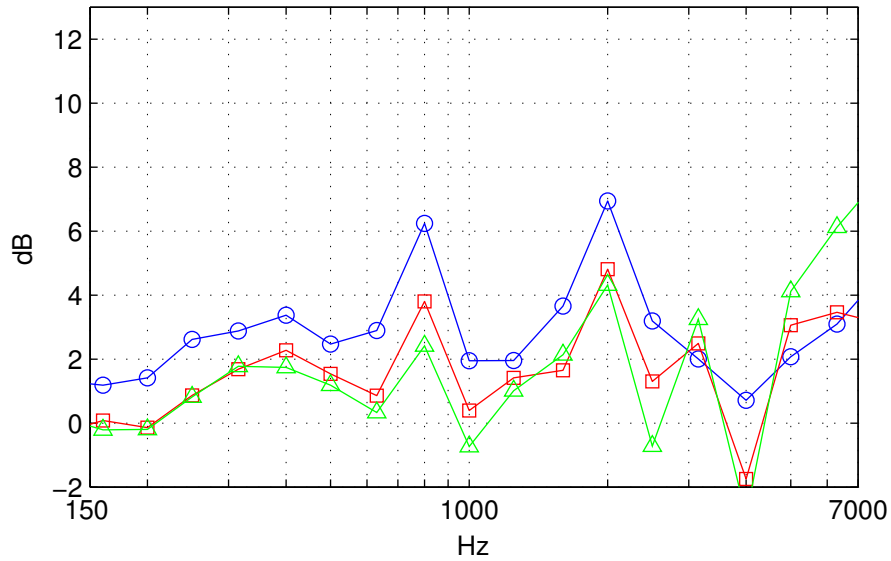


Figure 10: *Difference of averaged test subject and HA HMS II.3 HATS. The comparison is done for transfer functions from microphone position 3.4 to 1.1, 1.3, and 1.4 (○, □, and △). A positive dB value implies that the HA HATS is more directional on that frequency.*

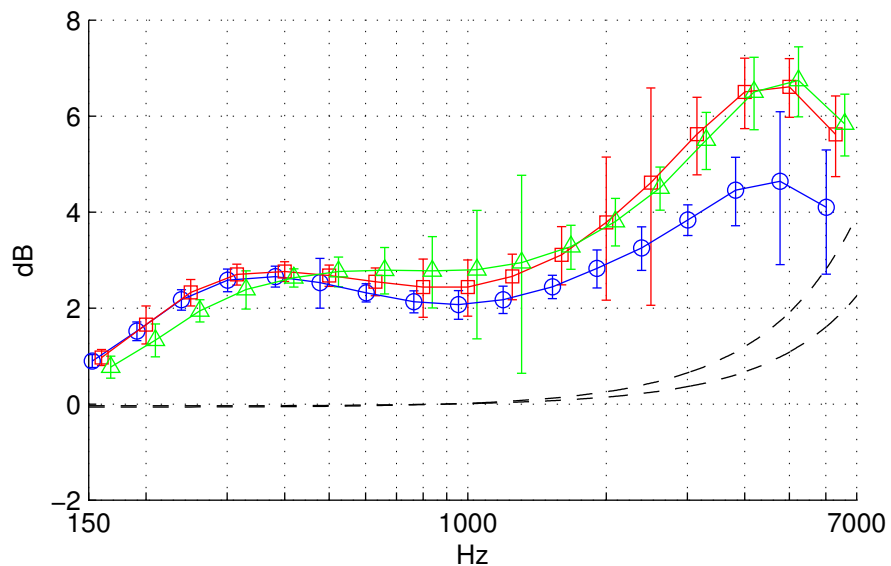


Figure 11: *Difference of averaged test subjects and B&K HATS between different vowels. The comparison is done for transfer functions from microphone position 3.4 to 1.3 for open (○), close-mid (□), and close (△) articulated within the sentence. Two modeled cases are included where the mouth aperture radii for corresponding B&K HATS and averaged person in the direct models are 1.5 cm and 0.5 cm and for downmost curve 1.5 cm and 1.5 cm. 95% confidential intervals can be seen for each frequency band. Curves are smoothed in in frequency.*

mouth aperture sizes for corresponding B&K HATS and average test subject. As it is seen the general trend of the measurement results follows the modeled curves. As the mouth aperture size seems to be one key factor we proceed on with the analysis. One important aspect is to see if the mouth aperture size during speech can be predicted using directivity features. The traditional mouth and vocal tract size measurements using imaging methods can be found

for example in [18, 19, 20, 21].

It is important to emphasize that the mouth aperture size is effective relative value in acoustical sense. The physical absolute size is difficult to directly measure or yield from the acoustical measurements.

There are several factors that cause variance in speech data: the test subject, phoneme, speech volume, etc. Same of these factors should directly be linked to the mouth aperture size.

The recordings of test subjects were labeled so that the data could be divided into phoneme groups and the transfer function estimates for the phone groups could be obtained. In Figure 11 is shown differences between averaged test subjects and B&K HATS by using three different phonemes as an input data. Basically if the mouth is larger the curve should be on high frequencies closer to the 0 dB axis. In the figure we see that the open vowels (a, ä) are more closer the directivity of the B&K HATS than the close-mid (e, o, ö) and close (i, y, u) vowels [22].

5. IMPROVEMENTS PROPOSALS FOR TELEPHONOMETRY

5.1. Mouth aperture size in B&K HATS

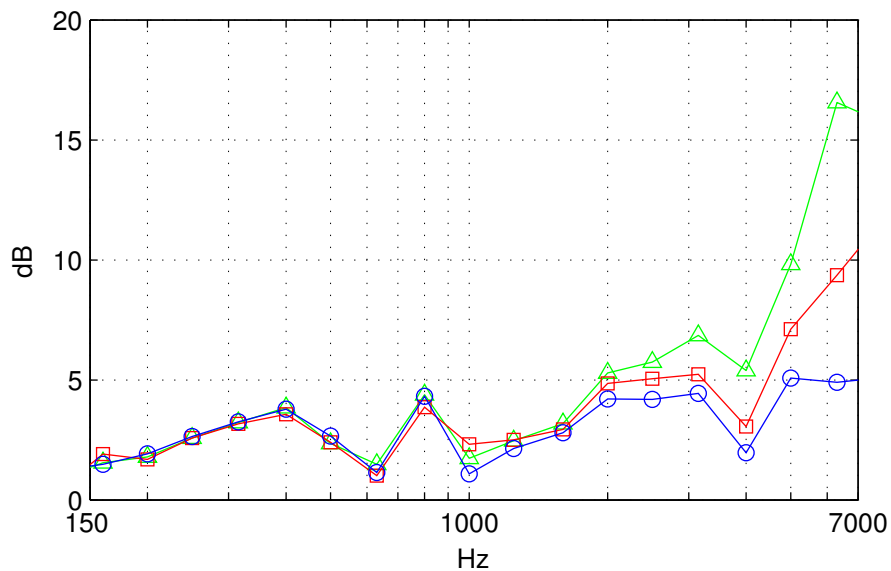


Figure 12: Comparison between averaged human and B&K HATS 4128 in position 1.3 with three different mouth sizes: 30 mm × 11 mm (□), 15 mm × 11 mm (○), and 42 mm × 16 mm (△).

We saw that the mouth aperture size is the most important parameter, which affects the directivity especially close to the mouth. On the other hand the measurements showed that the directivity of B&K HATS 4128 does not comply with the averaged test subjects. So could the difference be somehow corrected by tuning the mouth aperture size in HATS?

In Figure 12 the averaged test subject and B&K HATS with three different mouth sizes are compared. We see that the reduced mouth size gives even with full wide bandwidth almost flat correspondence if the small fluctuation is omitted.

5.2. B&K specific measurement vest

A dedicated 2 cm thick vest (B&K model DS 0900) can be used on B&K HATS 4128 in acoustical measurements. The covering should reduce the reflections from the torso so that it resembles better human body. The official name for the vest "shoulder damping fabric" describes best its original purpose. The vest is especially designed for the

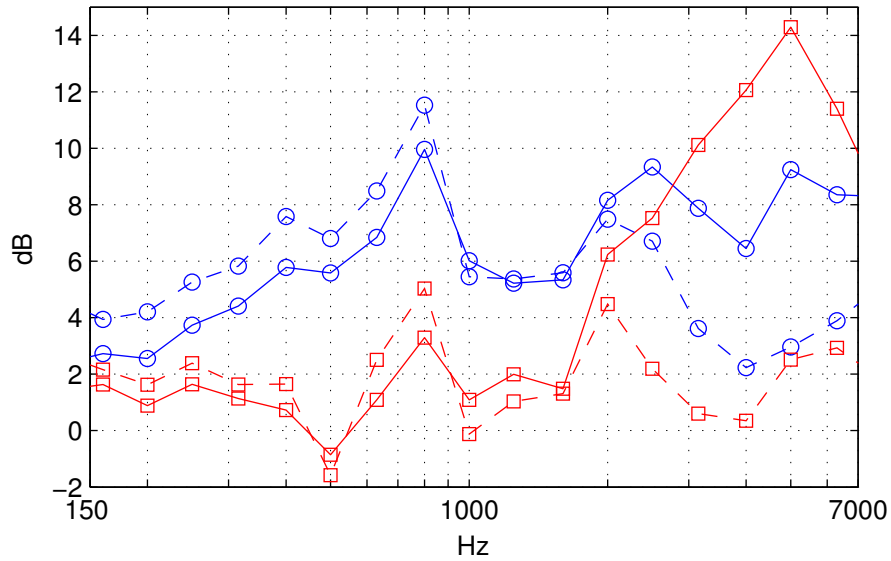


Figure 13: Comparison of B&K HATS to averaged test subject in positions 4.1 (○) and 4.2 (□) with (solid) and without (dashed) the vest on chest.

binaural measurements with the artificial ears and the close-to-mouth telephony. Strong reflections from the shoulder are in those measurements an undesired side effect.

Although the correspondence of the torso in B&K HATS to real human upper body is not known, it is widely used in headset measurements. The microphone positions 4.1 - 4.3 follow the same positions as the microphones in these phone accessories. By considering the measurement results for the position 4.1 and 4.2 in the Figure 13 significant differences can be seen between bare torso and the torso with vest.

If the general trend is considered in the curves (Figure 13) we see that the difference of the near chest reflection is omitted if the vest is taken off. The difference of the reference point still causes fluctuation near 800 Hz. The B&K HATS is slightly more directional than average person in high frequencies because of the difference of the mouth aperture size.

The final conclusion is that the usage of the measurement vest should always be considered carefully. It seems that close to torso it should not be applied especially when the microphone rests freely on the chest as in several headsets.

5.3. Equalization consideration

When the directivities of the artificial mouths and the averaged test subject were compared significant differences were found (see Figure 7, 8, 9, and 10). The starting point for the study was the frequency response measurement for microphones in phones and headsets. If artificial mouths do not correspond to the averaged directivity of a person some kind of compensation should be applied. Next a simple equalization scheme is introduced for B&K HATS.

There were two areas that were covered in the B&K HATS measurements: positions near cheek and near chest. The measurements of the chest positions were heavily affected by the reflections from the chest and the difference seems to be substantially linked to the torso and its covering (see Figure 8). For these reasons it is meaningless to yield equalization scheme for these positions and therefore they are omitted in this approach.

The curves for the positions near cheek in Figure 7 have some fluctuation, which is mainly caused by the difference of the reference points in far field in other words the difference of the chest reflections between B&K HATS and test subjects. The curves are therefore first smoothed and then used as the target responses for the

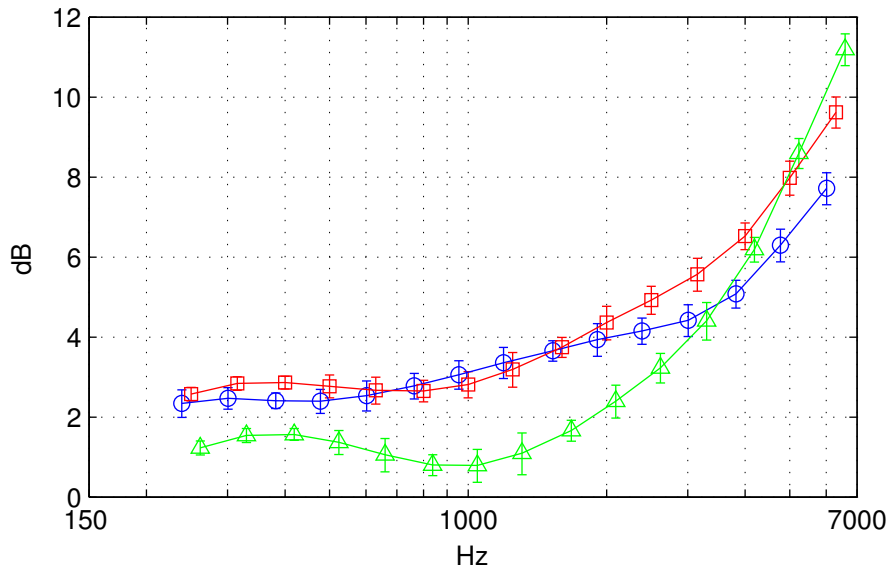


Figure 14: Smoothed differences of B&K HATS 4128 and averaged test subjects from Figure 7 between microphone position 3.4 and positions: 1.1, 1.3, and 1.4 (\circ , \square , and \triangle). 95% confidential intervals are included.

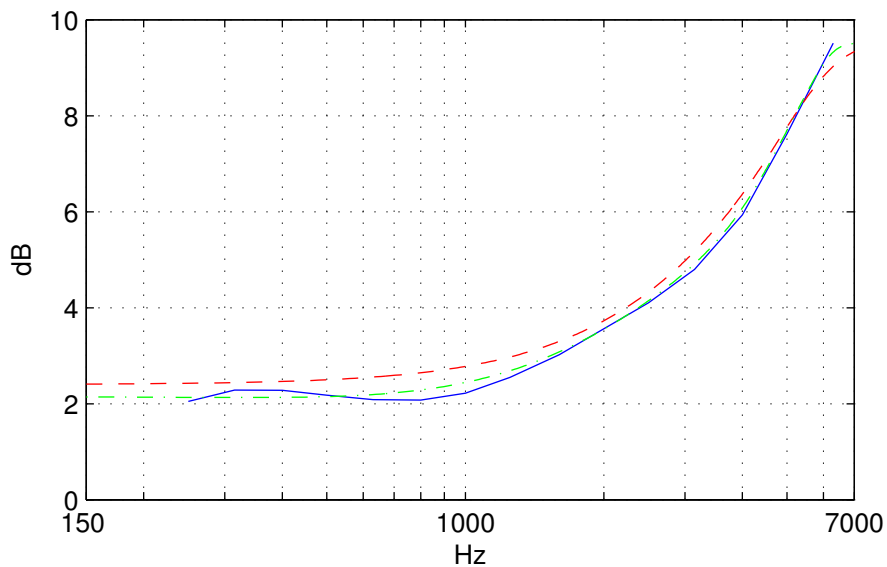


Figure 15: Target curve for the average equalization filter for B&K HATS 4128 (solid blue). Frequency responses for the filters where order is 3 (dashed red) and 7 (dash dotted green). Sample rate was 32kHz.

equalization. The smoothing is implemented averaging neighbor frequency pins weighting with Hanning window. Window size was nine so 4 frequency pins were used from both sides for averaging. This window size corresponds to three octaves. The smoothed curves for B&K HATS can be seen in Figure 14.

There are three possibilities to approach the equalization of the handset measurements. A starting point is that we have a set of curves of difference for certain positions and the differences are to be compensated with an equalization curve or curves. The different approaches are listed below.

1. Average frequency correction curve.

2. Separate frequency correction curves for each position.
3. A model based position dependent frequency correction.

A filter design scheme is next presented. The motivation is to see what kind of filter design fits to the target curves discussed above. Only the average of the curves in Figure 14 is covered as an example.

The averaged target curve for the equalization can be seen in Figure 15. As we can see the curve has no dips or peaks so it can be modeled with a low order digital filter. An infinite impulse response (IIR) filter structure was selected for this consideration. It follows more accurately the target curve on same order than finite impulse response (FIR) filter.

In Matlab the IIR filters were recursively designed using a least-squares method (Yule-Walk function in signal processing toolbox). The target curve and two IIR filter responses are shown in Figure 15. The order three was the lowest design that stayed within 1dB from the target response.

The smoothed difference curves for B&K 4227 and Head Acoustics HMS II.3 HATS are shown in Figures 16 and 17. Similar high frequency difference as in B&K HATS 4128 do not exist with other mouths, but some desibel differences can still be seen.

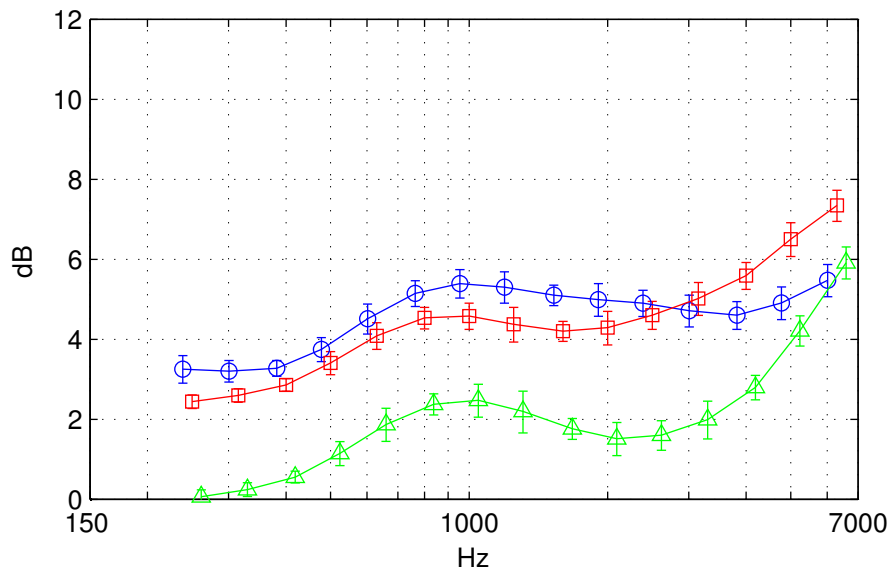


Figure 16: Smoothed differences of B&K 4227 Artificial Mouth and averaged test subjects between microphone position 3.4 and positions: 1.1, 1.3, and 1.4 (o, □, and △). 95% confidential intervals are included.

6. CONCLUSIONS

The objective of the study was to assess the directivity of the artificial mouths from telephonometry point of view. The B&K HATS 4128 is widely used in telecom industry so the study concentrated mainly on it, but also B&K 4227 and Head Acoustics HMS II.3 HATS were measured. The sound field around the head and upper body was studied to see the basic characteristics. The most important part of the study was to see how accurately the directivity of the artificial mouths would correspond to an averaged person. The speech content was also considered in a sense if it had an effect to the directivity.

In positions near the cheek the attenuation of high frequencies was found. If the position was closer to the ear there were more attenuation on high frequencies. Near the chest the reflection from the chest causes fluctuation but the high frequency attenuation is not that visible as near the cheek. In far field the chest reflection originated fluctuation is seen.

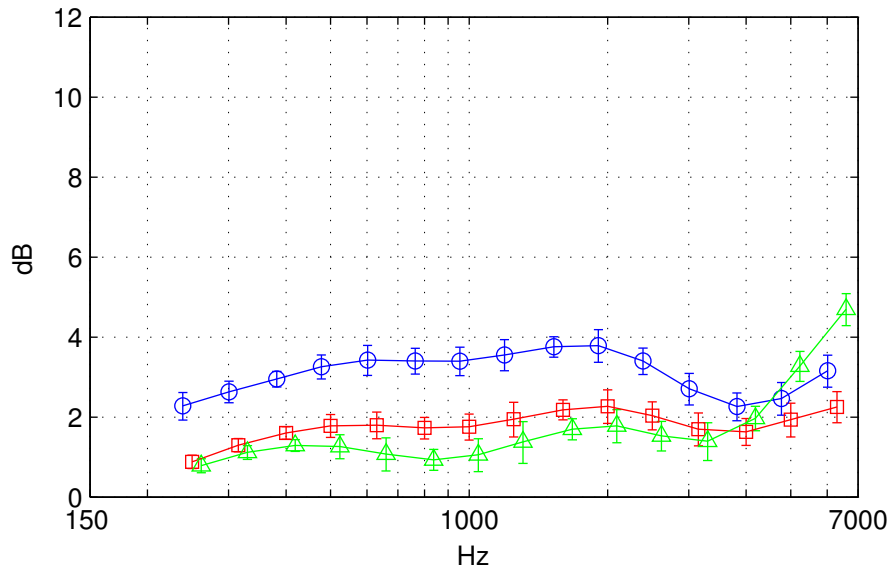


Figure 17: *Smoothed differences of Head Acoustics HMS II.3 HATS and averaged test subjects between microphone position 3.4 and positions: 1.1, 1.3, and 1.4 (○, □, and △). 95% confidential intervals are included.*

The speech content as well as the test subjects caused significant amount of variation to the directivity pattern. Nevertheless it was found that the directivity pattern could be linked to the speech content if the mouth aperture size during the articulation is known. For example comparing vowels and different kind of articulation the effect of the mouth aperture size was seen. The body size differences were omitted in the consideration because they self-evidently affect the sound field.

The test subject data was averaged and compared to artificial mouths in the same positions. Significant differences were found in the comparison. The difference between human mouth and B&K 4227 and Head Acoustics HATS near cheek was on average between 1 and 6 dBs, HA HATS having slightly smaller difference compared to the average human.

However the most significant difference between the average human and B&K HATS 4128 near cheek was found in high frequencies. It seems that the mouth size difference between B&K HATS and on average for test subjects is the key to the difference. The mouth aperture size of the speakers was during the articulation less than the size of the mouth in B&K 4128 HATS. Near the chest also the physical dimensions and features of the upper body caused differences in directivity.

Three improvement proposals were introduced in Section 5 to enhance the correspondence of the artificial mouth measurements to an averaged person. An equalization scheme for the handset measurements was discussed. There are several concepts to implement a compensation for the directivity error. In this study it is shown that a low order IIR filter meets the equalization requirements. Therefore the equalization scheme could be easily implemented to telephony.

A potential measurement vest usage in the accessory measurements was also questioned in a case where the microphone is laying on the chest, in the case of headset microphone for example. The measurement vest shifts the position of distance by its thickness from the hard surface of the torso of B&K HATS. This distance causes a delay between direct sound and reflection from the torso and the outcome of it does not comply with an averaged person. The bare torso seems to be a better simulation for the positions on the chest.

Because B&K HATS 4128 was measured with three different mouth sizes it was easy to see what mouth size gives best correspondence to averaged test subject. It was found that if half the width of the mouth was blocked the difference curves were almost flat on wide band.

As we saw there are open questions on the field of the directivity of artificial mouths. The artificial mouths studied in this paper did not fully correspond to the averaged test subjects. The future work should concentrate on improvement of the products as well as improvement of the standardization. Some temporary solutions to improve the telephonometry were introduced.

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