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Effect of Head Covers on Directivity Pattern of Human Head

Dejan Todorovic

Dirigent Acoustics, Takovska 45A, 11000 Beograd, Serby
dgtdejan@yahoo.com

In this paper, the experimental results of changes in directivity patterns of the artificial head affected by three different types of a head covers are presented. The mathematical model of a human head which is approximated by radially vibrating spherical cap set in a sphere is discussed. For the purpose of this research, the physical model of a human speaker head is constructed, and the far field detailed directivity patterns of the model with and without head covers are measured. The sound barriers such as hair as porous absorber, a cap and a straw hat, are discussed, as well as their influence on the sound wave propagation. Detailed directivity pattern changes affected by head covers in far field are calculated in step of 10 degrees for spherical coordinates (polar angle and azimuth) and presented in form of two- and three-dimensional polar plots.

1 Introduction

Mathematical model of a speaker head, used to derive mathematical expression for directivity pattern, has shown good agreement with experimental results. Primordial mathematical model of the head was a sphere of appropriate radius with a piston (or a cap) membrane used as the sound source. Although this model has shown good agreement with measurements [1], it was further improved and next approximation was prolate spheroid of appropriate dimensions [2]. For the purpose of this experiment, the physical model of a human head (an artificial head) was made, and detailed directivity patterns were measured. Results turned out to coincide with mathematical predictions. More complex approximation of a speaker model, that would include torso, would not permit possibility of a simple mathematical approach for obtaining mathematical expression for directivity pattern. For this reason, directivity patterns for a head and torso determinate by measurement. Analysis of the effect of common head covers on directivity pattern of constructed model was the main goal of this research project. The head covers used in this research were hair, cap and straw hat. All measurements were performed at the Laboratory of Acoustics anechoic chamber of the Faculty of Electrical Engineering, Belgrade.

2 Mathematical Model

If the continual unsteady air flow, which is necessary for producing human voice, is excluded, a human speaker could be approximated with the system consisting of a piston membrane (dimensions of mouth aperture) set in a rigid sphere and torso.

Excluding torso, a physical approximation of a human speaker head is a sphere of the appropriate radius with built-in piston membrane (Figure 1). Better approximation is obtained when the sphere is replaced with the prolate spheroid, and the radially vibrating cap replacing piston membrane. This case is theoretically considered in papers [2,3].

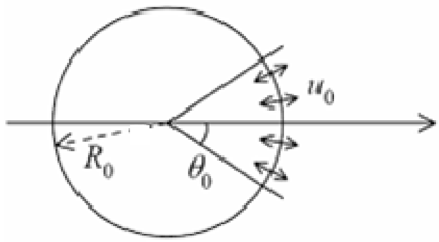

Figure 1 Mathematical approximation of a human speaker head with radially vibrating spherical cap set in a sphere

Mathematical expression for directivity function of the sound source presented in Figure 1, could be derived by solving wave equation in general spherical coordinates (1) with the appropriate boundary conditions [1].

$$\frac{\partial^2 \Phi}{\partial r^2}+\frac{2}{r}\frac{\partial \Phi}{\partial r}+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\Phi}{\partial\theta}\right)+\frac{1}{r^2\sin^2\theta}\frac{\partial^2\Phi}{\partial\varphi^2}=\frac{1}{c^2}\frac{\partial^2\Phi}{\partial t^2} \quad (1)$$

Expression for the pressure in a far field pressure takes the form:

$$\underline{P}=\rho c\frac{V_n^0 P_n(\cos\theta)}{B_n(kR_0)}\frac{e^{-j\left[kr-(n+1)\frac{\pi}{2}-\delta_n(kR_0)\right]}}{kr}, \quad (2)$$

where P_n - Legendre polynomial,

B_n - amplitude of spherical wave,

$\delta_n = x-\frac{1}{2}\pi(n+1)$, and

V_n^0 obtained from the expression for velocity of spherical cap in a form of spherical harmonics (3).

$$V=\sum_{n=0}^{\infty}V_n^0P_n(\cos\theta)= \quad (3)$$
$$V_0\left\{\frac{1-\cos\theta_0}{2}+\frac{1}{2}\sum_{n=1}^{\infty}[P_{n-1}(\cos\theta_0)-P_{n+1}(\cos\theta_0)]P_n(\cos\theta)\right\}.$$

According to the expression (2) directivity curve of the pressure generated by radially vibrating spherical cap set in a sphere is drawn in Figure 2.

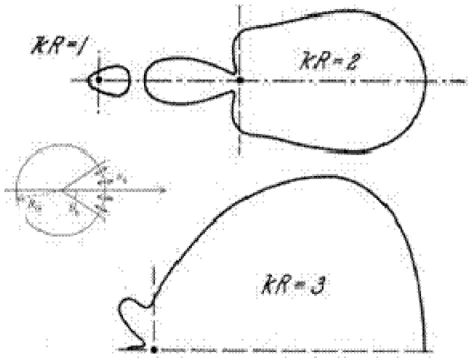

Figure 2 Directivity curve for the square of pressure radiated by spherical cap set in a sphere of radius R, $\theta_0 = 60°$ [1]

3 Head Covers

For the purpose of this research, effect of several head covers on directivity pattern of the artificial head was discussed. Basic construction of the artificial head has been made of hard plastics. For this reason, the first chosen head cover was – a hair. Other types of a head covers were different types of caps and hats. Apart from these, helmets, modern hats and some other could be considered. However, in this experiment, effect of a hair, sporting cap and a straw hat on directivity pattern of the artificial head were measured.

Hair is a porous absorber. Considering internal structure of this porous absorber, estimation of the absorption coefficient is evaluated. Some average data for its mechanical characteristics were used for evaluation, and calculated estimation is presented in Figure 3. Input data used for calculation were: volume mass of **10 kg/m^3**, thickness **1 cm**, air flow resistance **3 kN s/m^5**.

Sporting cap cover was made of hard plastics. Dimensions and shape of cap are shown in Figure 4. Cover has total mass $m = 32$ g, surface area $P = 175$ mm X 75 mm = $1.31 \cdot 10^{-2}$ m^2, and $h = 2$ mm thick. Mass per unit area of the cover material is $\rho_s = 2{,}44\, {}^{kg}\!/_{m^2}$.

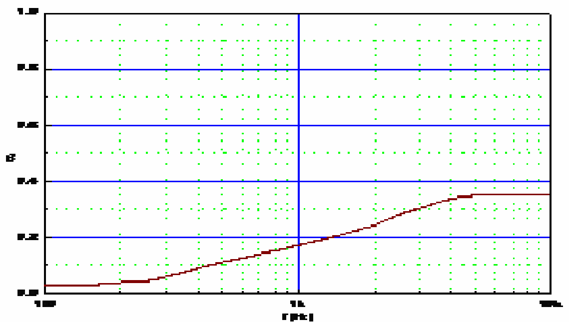

Figure 3 Estimation of the absorption of a human hair

Straw hat was round shaped; dimensions and shape are shown in Figure 4. Material thickness is $h = 2$ mm, and mass per unit area is $\rho_s = 0{,}22\, {}^{kg}\!/_{m^2}$.

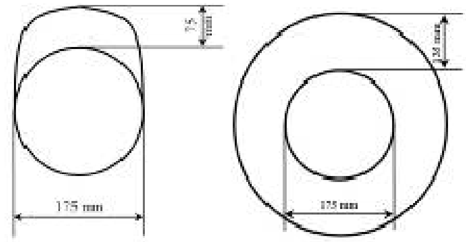

Figure 4 Sporting cap (left) and straw hat (right) dimensions and shape (top projection)

Important parameter for discussing effect of a head covers on directivity is its transmission loss. In case of low transmission loss, it is correct to assume that sound passes through barrier, and there are no changes in directivity pattern. At low frequencies, changes in the sound field around the source are expected to be negligible, because of small dimensions and low transmission loss of barriers. With the frequency increasing, transmission loss through barriers increases. At some frequencies, dimension of barrier is comparable to wavelength, and transmission loss is large enough, to make the noticeable differences in directivity.

Estimation of transmission loss starts from using mass law. The normal (or fixed angle) incidence of direct sound is expected. Total transmission loss is, according to the mass law:

$$R = 20\log(f \cdot \rho_s) - 52, \tag{4}$$

for $\rho_0 c = 414\, {}^{kg}\!/_{sm^2}$.

When the sound arrives in some incidence angle to flat and thin plate, forced bending vibrations in a plate are generated. Coincidence frequency is that at which, for a fixed nodal line pattern, half the sound wavelength is equal to the distance between nodal lines. At the coincidence frequency, transmission loss of the plate is reduced in comparison to what is expected by the mass law. This reduction is 10 -15 dB. Condition for coincidence takes the form

$$\lambda_{tr} = \frac{\lambda}{\sin\alpha} = \lambda_f, \tag{5}$$

Where λ_{tr} is trail of the sound wavelength, and

λ_f is wavelength of plate vibration,

and coincidence frequency calculates as

$$f_k \approx \frac{c^2}{1{,}8hc'_m} \approx \frac{c^2}{1{,}8h}\sqrt{\frac{\rho_m}{E}}. \tag{6}$$

According to measured quantities of material and calculation explained above, transmission loss is predicted. Calculated coincidence frequencies are well above 10 kHz, in both samples. The estimation of transmission loss is shown at Figure 5.

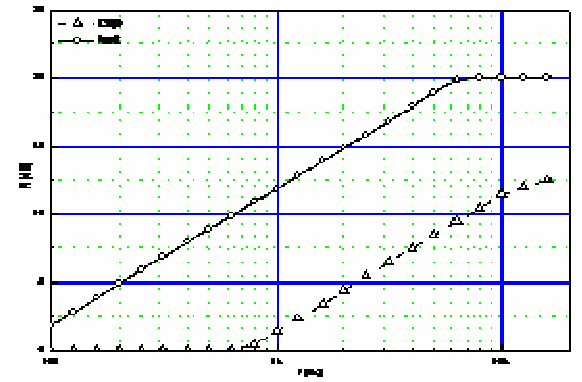

Figure 5 Estimated transmission loss for a cap and a straw hat material

From the results shown at Figure 5, in case of a cap, it is obvious that the reduction of direct sound transmitting through material is greater than 10 dB in a wide range of frequencies (above 200 Hz), so the conclusion in this case is that this influence should not be neglected. In case of a straw hat, transmission loss of direct sound for frequencies less than 2 kHz is less than 10 dB, and the assumption is that it can be neglected. For this reason, changes in directivity pattern of a head with the straw hat are not expected.

4 Directivity Measurements

Measurement of directivity patterns was performed in anechoic conditions, at the Laboratory of Acoustics anechoic chamber of the Faculty of Electrical Engineering, Belgrade. The working space inside anechoic chamber is 4 m X 2,5 m X 2 m (L X W X H). For this reason, the measuring distance of 1 m was chosen. Other important parameters of measurement settings were:

a° Angular rotation speed of turntable carrying the model was 0,0785398 rad/s (revolution time equal to 80 s). Depending on duration and type of measuring signal, achievable azimuth resolution of measurements was as fine as 1°.

b° Polar angle resolution of measurements was 10°

The measurement procedure was semi-automatized except for changing of a head covers.

The measuring setup with model carried by continually rotating turntable was limited in respect to measuring techniques. For this reason the time invariance during the measurements could not be establish, excluding measuring techniques demanding for time invariance, as MLS. Finally, the pink noise excitation signal with added synchronization signal was used for directivity measuring. Acquired data were post processed using octave digital filters. The central frequencies for octaves of interest were 125 Hz to 16 kHz. Digital filters were constructed according to IEC 61260, IIR type filters. During processing it was possible to choose azimuth resolution of measurements. Chosen resolution was 10º, same as the polar angle resolution.

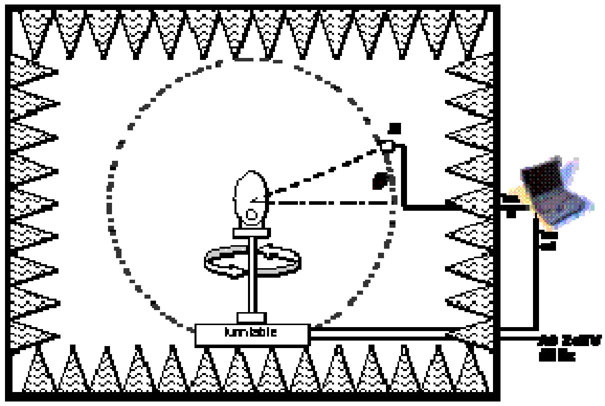

Figure 6 Measurement setup

5 Results

Detailed directivity patterns of physical model (an artificial head) with and without head covers (wig, cap and straw hat) were measured. Relative differences in level for all spherical coordinates (azimuth and polar angle) were calculated. These level differences represent the effect of a head covers on directivity pattern of a human head model. Results are shown in a form of two- and three-dimensional graphs. Two dimensional graphs (Figure 7 – 12.) present results for horizontal and vertical plane. Three dimensional plots are in the form of colored balloons (Figure 13 – 16).

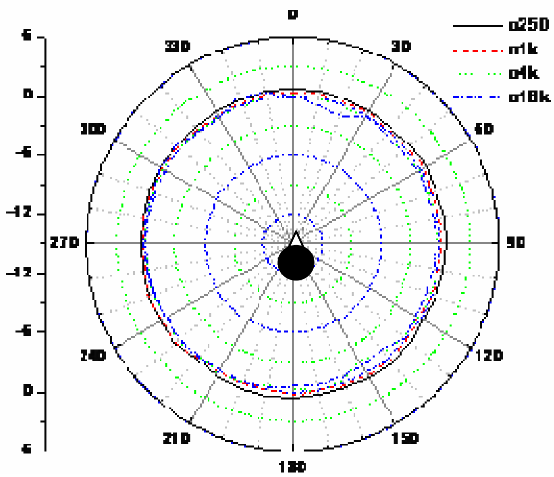

Figure 7 2D polar plot of a wig effect on directivity pattern of the artificial head in horizontal plane

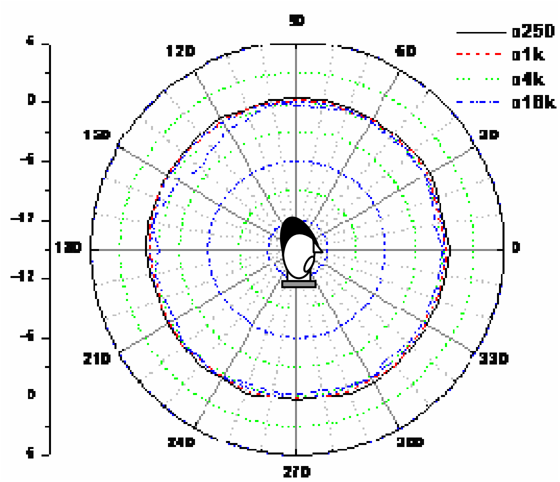

Figure 8 2D polar plot of a wig effect on directivity pattern of the artificial head in vertical plane

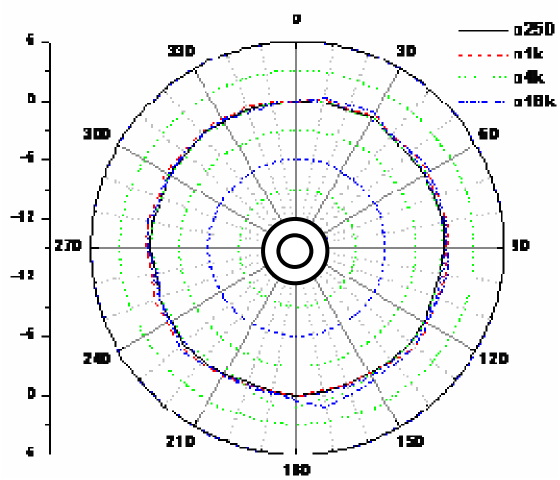

Figure 9 2D polar plot of a straw hat effect on directivity pattern of the artificial head in horizontal plane

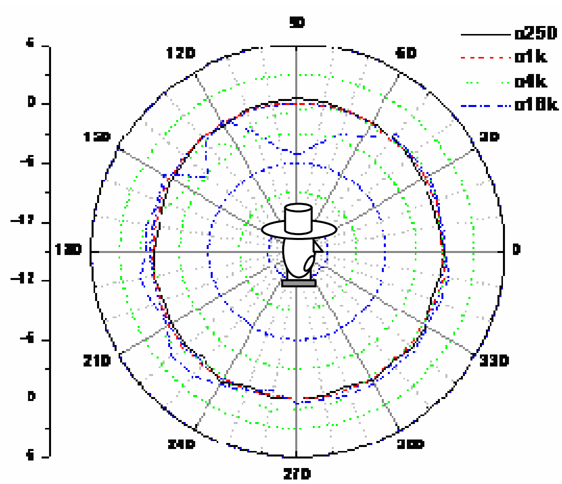

Figure 10 2D polar plot of a straw hat effect on directivity pattern of the artificial head in vertical plane

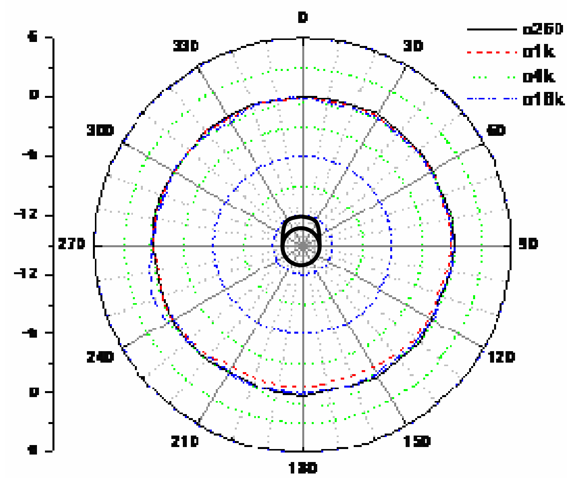

Figure 11 2D polar plot of a cap effect on directivity pattern of the artificial head in horizontal plane

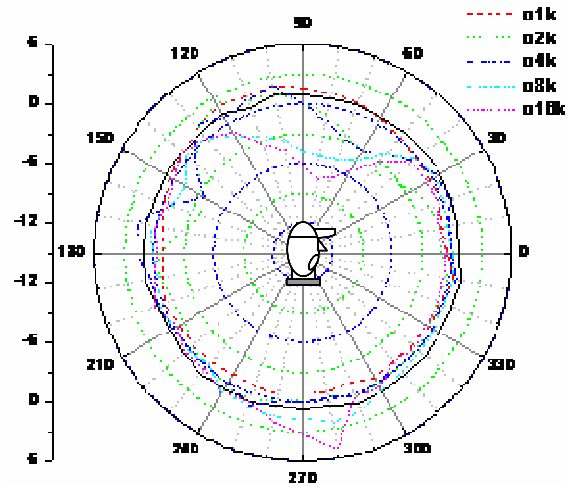

Figure 12 2D polar plot of a cap effect on directivity pattern of the artificial head in vertical plane

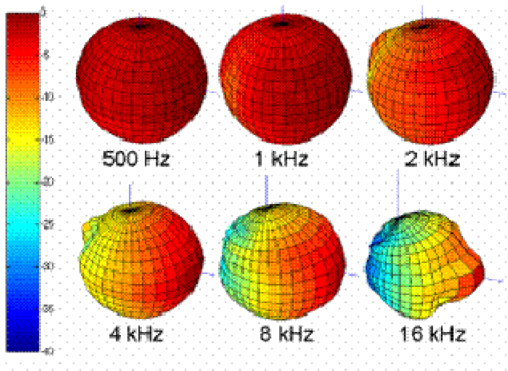

Figure 13 3D plot of detailed directivity pattern of the artificial head

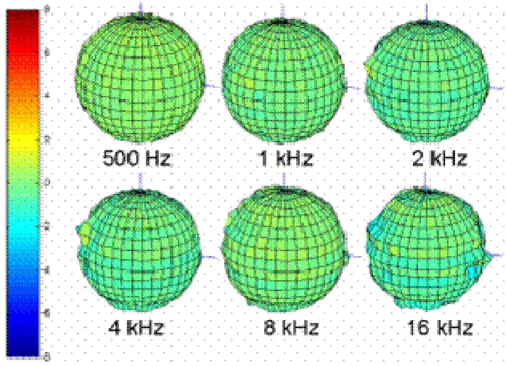

Figure 14 3D plot of the effect of a wig on directivity pattern of the artificial head

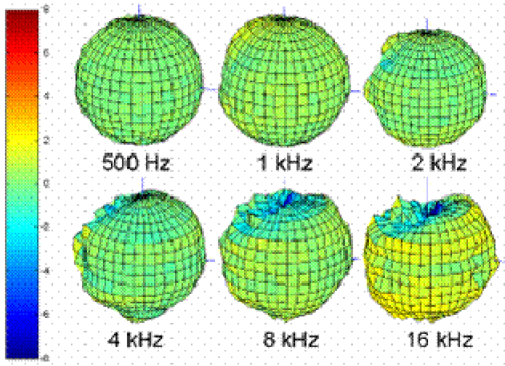

Figure 15 3D plot of the effect of a straw hat on directivity pattern of the artificial head

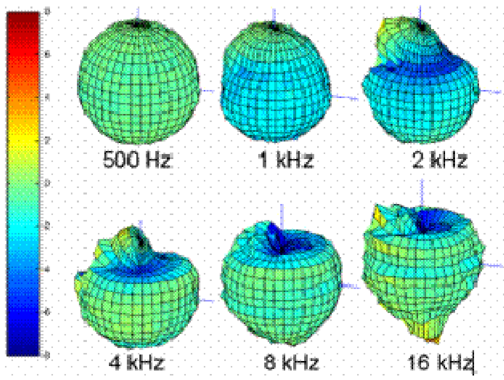

Figure 16 3D plot of the effect of a cap on directivity pattern of the artificial head

6 Conclusions

Physical model of a human head (an artificial head) is an acoustic tool for measurements in room acoustics. Electrical-mechanical-acoustical properties are its basic parameters. One of the most important parameters is the directivity pattern. This paper show results of mathematical analysis of acoustical properties of the artificial head and the evaluation of its directivity pattern. For measurement purposes, physical model (an artificial head) was constructed. Detailed directivity patterns of a model with and without different types of head covers were discussed and measured. According to physical properties of a head covers, their acoustical properties were calculated. In case of a hair (wig), the absorption coefficient was evaluated and transmission loss of direct sound was estimated for the cap and the straw hat. Measurements of directivity patterns were done in anechoic conditions, in far field. Results of measurements were presented in a form of two- and three-dimensional plots.

Comparing the results of measurements and estimation of acoustical properties of a head covers, final conclusion is that a head covers have effect on directivity pattern of a head when:

- the sound wavelength is smaller than dimensions of the sound barriers, and
- the transmission loss of direct sound exceeds certain value.

Based on presented results, conclusion is that the value of transmission loss necessary to produce appreciable changes in directivity pattern changes is 10 dB.

References

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[2] K.Sugiyama, H.Irii, „Comparison of the Sound Pressure Radiation from a Prolate Spheroid and the Human Mouth“, Acustica, Vol.73. (1991) p.271-276

[3] T.Halkosaari, „Radiation Directivity of Human and Artificial Speech“, Master Thesis, Helsinki University of Technology Laboratory of Acoustics and Audio Signal Processing, April 2004.