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WHAT DOES IT MEAN FOR AN HRTF NOT TO HAVE THE MINIMAL PHASE PROPERTY?

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1. INTRODUCTION

Head-related transfer functions (HRTF) are transfer functions describing the sound transmission from free field to a point in the ear canal of a subject or a dummy head for certain directions of incidence. Measurements of HRTFs have already been described in the literature [1, 2, 3, 4, 5, 6, 7,8, 11]. Based on experimental investigations comprehensive model simulations of higher stages of the human auditory system have been proposed, including the evaluation of artifical heads, computer synthesis of binaural signals, and binaural techniques (e.g. auralisation) [8, 9, 10]. It was found by measuring sound transmission from free field to the eardrum that HRTFs measured at the entrance of the blocked ear-canal offers the full spatial information.
Measurements of head related impulse response functions (HRIR) show interaural time differences. Some selected HRIRs do not represent a minimal phase system [12,13]. It is well known, that direction-dependent peaks and dips are seen occurring at slightly different frequencies in HRTFs and there is a considerable inter-individual variation in these characteristics for most directions and for each subject. Above 8 kHz the variation is increased considerably. What is more, although it is rarely emphasized, the relative position of head, shoulders, arms, hands and chest has a great influence on HRTFs, so in reality the problem has many more degrees of freedom than the two or three usually considered. Objects close to the head have similar effect. So it is probably does not worth to build very exact models, not to mention the formidable difficulties in calculating HRTFs directly from realistic head and body geometry. A quasi-realistic artificial head seems to be the right one to start with, because its HRTF-s are expected to show all the

important features except those related to head and body motion, while the measurement is far simpler than with real persons.

2. THE MEASUREMENT

The HRTFs of a B&K Artificial Head &. Torso (Type 4128) were measured in the $25\,m^3$ anechoic chamber of our lab, in $5°$ steps azimuth at elevation angles $-15°,-10°,-5°,0°,5°,10°,15°,20°,25°,30°,40°,50°,60°,75°\,and\;90°$, measured in the usual head-related co-ordinate system. The azimuth angle was set by a computer controlled turntable, while for elevation the sound source (a 125 mm diameter loudspeaker) was moved by strings. The correct position and orientation was set using a laser beam anglometer and a little mirror attached to the housing of the loudspeaker. The distance of the source from the head was 2 meters. The HRTF-s were measured by MLS excitation with a period of about 80 msec. The reference signal was captured by an 1/2 inch B&K condenser microphone, dummy head removed, placed where the center of the head was before. The sampling rate was 50 kHz, with 16 bit resolution. Signals from both ears were measured simultaneously. The overall S/N ratio was about 60 dB. The measured HRTFs are valid up to 10 kHz.

3. HRTF AND MINIMAL PHASE SYSTEMS

For minimal phase systems the logarithmic amplitude and the phase of the transfer function are Hilbert transforms of each other. The same is true for the logarithmic derivative of the amplitude and the group delay. The latter is easier to handle, because one does not have the problem of the 2π phase jumps. So for a minimal phase system, whose (complex) transfer function is $G(\omega)$,

$$t(\omega) = \mathbf{H}\,\mathrm{Re}\frac{G'(\omega)}{G(\omega)} - \mathrm{Im}\frac{G'(\omega)}{G(\omega)} = 0 \qquad (1)$$

where $G'(\omega) = \dfrac{\partial\, G(\omega)}{\partial \omega}$ and **H** denotes the Hilbert transform. Now, if $G(\omega)$ is a simple delayed version of a minimal phase system, we get

$$t(\omega) = \tau = \text{constant}, \qquad (2)$$

where is the time delay. For HRTF-s it can be considered, roughly speaking, the time needed for the first wavefront to reach the ear. (Free field propagation of plane waves is a good approximation of a delay line for the distances and frequency range we deal with.) In fact, for most directions of sound incidence (2) seems to be a good approximation, so if $t(\omega)$ is computed for real HRTF-s, it is really constant except some minor fluctuations due to noise. However, for some directions it is not constant at all: there is a large bump on it somewhere between 5 and 10 kHz, but never more than one. Now, let us consider a system with an impulse response of the form $g(t)=\delta(t-t_0)+b\delta(t-t_0-t_1)$, where (t) denotes an impulse at time $t = 0$. If $|b|<1$ it is a minimal phase system plus a delay t_0, but if $|b|\geq 1$ it is not. In the latter case

$$t(\omega)=t_0+t_1\frac{b^2-1}{b^2+2b\cos t_1\omega+1} \tag{3}$$

It is exactly the kind of function we are looking for, with a bump at $=\frac{\pi}{t_1}$. The height of the bump depends on b, the closer it is to 1, the higher (and narrower) the bump will be. If a functon of form (3) is fitted to each curves compudted from the measured HRTFs, the three parameters t_0, t_1, b can be determined. This way the directions of sound incidence can be found for which the HRTFs can not be considered minimal phase systems plus pure delay. Fig. 1. shows the results. The figure is for the left ear, X stands for directions where the HRTF is of minimal phase up to 10 kHz. All directions outside the range covered by the figure are also belong to minimal phase HRTFs. The signs O and D stand for *not minimal phase directions*. For directions marked by O, $t(\omega)$ varies in a regular way. In the middle of this angular domain the bumps are around $9\,kHz$, which corresponds to some $55\,\mu\,\text{sec}$ relative delay (t_1), while toward its edges (except the corner marked D) this frequency shifts upward, at the edges exceeding 10 kHz.

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XXXXXXXXXOOOOOOOOOOOOOXXXXXXXX   30° E
XXXXXXXOOOOOOOOOOOOOOOOOXXXXXX   25° L
XXXXXOOOOOOOOOOOOOOOOOOOOXXXX    20° E
XXXXOOOOOOOOOOOOOOOOOOOOODDDXX   15° V
XXXOOOOOOOOOOOOOOOOOOOOOODDDDDX  10° A
XXOOOOOOOOOOOOOOOOOOOOOOODDDDDD   5° T
XXOOOOOOOOOOOOOOOOOOOOOOODDDDDD   0° I
XXOOOOOOOOOOOOOOOOOOOOOOOODDDDX  -5° O
XOOOOOOOOOOOOOOOOOOOOOOOOODDDX  -10° N
XOOOOOOOOOOOOOOOOOOOOOOOOOODDX  -15°
|      |      |      |      |      |      |      |
40°    20°    0°    -20°   -40°   -60°   -80°  -100°
A      Z      I      M      U      T      H
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Fig. 1. Non minimal phase angular domain for the left ear (O, D)

In the area marked D the situation is more difficult. The bumps vary in an apparently uncontinuous manner as a function of direction, sometimes jumping as low as 5 kHz. This phenomenon is probably due to angular undersampling [6], because HRTFs vary very much with angle, when sound comes from the direction of the opposite ear, so the 5° resolution is not enough for this angular domain.

Naturally we do not know what happens for elevations lower than -15°, because that range was not measured.

4.CONCLUSIONS

The above model is certainly a phenomenological one. There are much more than two sound paths from a source in free field to the ear. But the HRTF system behaves up to 10 kHz *as if* there were no more than two, with the same filter characteristics, but with different delays an gain. The structure described above is so regular, at least for the domain marked O, that it can be considered a hidden anatomical feature. The real anatomical correlates are probably the pinnae. The 55 μsec time difference corresponds to a 19 mm difference in path length. It is in good accordance with the dimensions of the pinna. To decide whether it is the case or not, requires further investigations, for example with modified pinnae, or pinnae removed. It is also interesting to note, that the domain marked O, united for both ears is almost exactly the same as the visual field. So this feature probably has some psychoacoustical relevance in spatial hearing. Further work is needed in this direction, too.

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