Design, construction, and evaluation of a 1:8 scale model binaural manikin

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Abstract: Many experiments in architectural acoustics require presenting listeners with simulations of different rooms to compare. Acoustic scale modeling is a feasible means to create accurate simulations of many rooms at reasonable cost. A critical component in a scale model room simulation is a receiver that properly emulates a human receiver. For this purpose, a scale model artificial head has been constructed and tested. This paper presents the design and construction methods used, proper equalization procedures, and measurements of its response. A headphone listening experiment examining sound externalization with various reflection conditions is presented that demonstrates its use for psycho-acoustic testing.

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1. Introduction

The span of auditory memory is short enough that it is not possible to make accurate direct comparisons of geographically separated rooms or even adjustable acoustic rooms if the adjustment requires more than a short time interval. Room acoustic researchers surmount this obstacle using auralizations or room simulations that can be presented on a virtual auditory display sequentially and interchangeably. Auralization is achieved by convolving anechoically recorded signals with measured or calculated binaural room impulse responses. Such experiments have been conducted recently by Brandewie and Zahorik (2010), Lokki et al. (2011), and Valente and Braasch (2010), among others. Using properly equalized reproduction equipment, sound pressure signals can be presented to the eardrum that are equivalent to those which would be received in the actual room, so that multiple rooms can be compared sequentially.

Because systematic changes in configurations of architectural enclosures are costly and time consuming, scale modeling is a useful tool for room-acoustic investigations. Acoustic behavior in a scale model of an enclosure is highly similar to a the full size enclosure if the acoustic frequency is increased by the same factor that the enclosure is reduced, materials have appropriate absorption characteristics at the scaled frequencies, and the atmosphere is adjusted for proper absorption. In this manner, the acoustic field of a complex performance venue can be studied with relatively little expense. Additional considerations in properly executing an acoustic scale model

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include utilizing a source that is able to generate the frequency and directivity of an equivalent full-size source, and properly simulating a human receiver by utilizing a scale model artificial head with embedded microphones.6

This paper presents the design and construction of a miniature artificial head at 1:8 scale. The head related transfer functions (HRTFs) of the model have been measured, and the equalization process for producing auralizations is explained. Auralization via this binaural scale modeling renders audible samples that are used to validate the suitability of the scaled artificial head for room acoustic simulation and psychoacoustic testing. Finally, listening test results are presented as validation of the utility of the scale model.

2. Design and construction

The artificial head is modeled after the dimensions of an AachenHead™ manufactured by HEAD Acoustics GmbH Germany and designed by Klaus Genuit.7 Dimensions were transcribed from photographs into Rhinoceros™ three-dimensional modeling software. The head was printed out on a Stratasys Dimension Fused Deposition Modeling™ rapid prototyping machine in rigid ABS Plastic. Figure 1 (left) illustrates the 1:8 scale artificial head. ANSI Standard S3.36–1985 (r2006) specifies dimensions for a manikin that will produce a frequency response similar to that produced by the median human head and torso. While these dimensions are not prescriptive, they serve as a reference for design. Table 1 provides a comparison of some key dimensions.

The head is designed with a removable back to accommodate two G.R.A.S. Type 40DP Microphone Capsules on B&K U160 Adapters with G.R.A.S. Type 26AC preamplifiers and G.R.A.S. Power Module Type 12AA. These microphone capsules have a flat response ±2 dB within the working range of 500–128 000 Hz. For this work, a scale factor of 1:8 is utilized. This correlates to a 1:8 model frequency range of 500–128 000 Hz, which scales down to an audio frequency range of 63–16 000 Hz.

3. Equalization

To exactly reproduce the pressure signal a listener would receive if he or she was in the full size version of the scale model sound field, the transfer function of each component of the transmission chain must be properly considered. There are several steps in the chain where frequency dependent linear distortions are introduced, including at...
the sound source, artificial head, and headphone reproduction system; these distortions must be corrected for authentic reproduction. For this reason, an equalization step is introduced to ensure authentic simulation of sound field conditions. The equalization function in the frequency domain is expressed as

$$E(f) = E_{hp}(f)E_M(f')$$

with

$$E_{hp}(f) = \frac{H_p(\phi_0, \delta_0, f)H_{ec}(z_T, f)}{H_{hp}(z_T, f)H_{rep}(f)}$$

$$E_M(f') = \frac{1}{H_p^M(f')\cdot H_p(\phi_0, \delta_0, f')H_{ec}^M(z_T^M, f')H_{rec}(f')}$$

where $H_p(\phi_0, \delta_0, f)$ is the transfer function between a reference point in the free field and the listener’s outer ear, $H_{ec}(z_T, f)$ is the transfer function of the listener’s ear canal, $H_{hp}(z_T, f)H_{rep}(f)$ is the transfer function of the reproduction system and headphones, $H_p^M(f')$ is the transfer function of the sound source, $H_p(\phi_0, \delta_0, f')H_{ec}^M(z_T^M, f')$ is the transfer function of the artificial head, pinna, and ear canal, and $H_{rec}(f')$ is the transfer function of the artificial head microphones and recording equipment. The term $f'$ is in the scale frequency domain, and $f$ is in the audio frequency domain. Figure 2 illustrates the electroacoustic communication chain of the entire system and the necessary equalization considerations.

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Table 1. A comparison of dimensions specified by the ANSI standard and of the final model.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>ANSI S3.36-1985 (r2006)</th>
<th>Scaled Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head width (mm)</td>
<td>152</td>
<td>165</td>
</tr>
<tr>
<td>Head length (mm)</td>
<td>191</td>
<td>232</td>
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<td>Menton-vertex length (mm)</td>
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<td>245</td>
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<tr>
<td>Head height (mm)</td>
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<tr>
<td>Triagon to wall (mm)</td>
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<td>102</td>
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<tr>
<td>Ear width (mm)</td>
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<tr>
<td>Ear length (mm)</td>
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<td>78</td>
</tr>
<tr>
<td>Pinna protrusion (mm)</td>
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<td>15</td>
</tr>
<tr>
<td>Protrusion angle (°)</td>
<td>160</td>
<td>165</td>
</tr>
</tbody>
</table>

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Fig. 2. A schematic representation of the equalization process for binaural auralizations. Equalization as such will preserve the transmission path of a signal through the room to a listener. From Ref. 6.
In practice, this reduces to one transfer function that can be applied to the anechoic recordings, which will make them ready to convolve with any scale model room measurement made with the artificial head. Generating this transfer function represents a three-step process. First, the measured transfer function of the scale model sound source is obtained by taking a free-field measurement of the source with the same microphones utilized in the artificial head. The scaled inverse of this measurement is the first part of the equalization transfer function and has the benefit of also removing the transfer function of the microphones from the transmission chain. Second, utilizing a full size artificial head of the same design as a reference subject, the scaled response of the miniature artificial head for a particular direction, e.g., frontal, is set equal to the transfer function of the calibrated full size artificial head for the same direction. This accounts for any linear distortions or directionally independent behavior within the miniature head. The transfer function required to set the frontal response of the miniature head equal to that of a full size head is the second portion of the equalization transfer function and is applied to all directions to obtain free field equalization. Alternatively, the diffuse field response of each head could be used. Finally, the inverse of the headphone response, as measured on the subject, in this case using the full size artificial head as a reference subject, is incorporated into the equalization function. The equalization function is then transformed into a minimum-phase impulse response, to be convolved with the anechoic recordings prior to auralization with scaled miniature head related impulse responses. The so-equalized anechoic recordings are then ready to be convolved with artificial head measurements for binaural rendering. For a more thorough discussion of the equalization process, see Ref. 6.

Using this method, an accurate reproduction of the sound field one would experience in the actual room can be presented to listeners.

4. Subjective evaluation

The free-field impulse response of the eighth scale head was measured in $1^\circ$ increments in the horizontal plane. Measurements were taken with a wide-band ultrasonic source as described in Ref. 5 in a scale model anechoic chamber. Signal-to-noise ratio for all 1/3 octave bands was, on average, 53 dB. Figure 1 (right) illustrates the scaled frequency response for each direction in the form of inter-aural level differences. Spectral peaks and notches in the measured response of the head demonstrate good agreement with expected patterns. After the aforementioned equalization, the head-related impulse responses were convolved with anechoic sound signals to create spatialized simulations. Three simulations were produced, the first is anechoic in which the source revolves twice around the head in the horizontal plane. The second follows the same pattern and a trailing reflection is added, 20° to the left and 25 ms delayed. This reflection is intended to reduce front-to-back ambiguities by introducing a secondary localization cue because head tracking was not utilized. The third sample includes a reflection, calculated by the image source method, from a sidewall 25° to the left of the listener and the source at a simulated distance of 20'. This simulation is intended to reduce front to back ambiguities and to provide an external distance cue. The source material is an anechoic recording of Mahler’s Symphony no. 1, recorded by the Auralization Group at the Aalto University School of Science and Technology.

5. Results

The samples were presented to listening subjects to validate externalized localization. Because each listener’s head related transfer function is different, evaluation of the correctness of an artificial head rests on its ability to provide accurate lateralization and externalization for most listeners. Listening tests were conducted to evaluate the performance of the artificial head. Subjects from the Rensselaer Polytechnic Institute community were asked to listen to the samples and trace the trajectory of the sound source as they heard it. Signals were presented over Sennheiser HD238 headphones connected to a MOTU Traveler A/D converter. Thirteen subjects’ traces were then digitized, and
the traced outlines were shaded and overlapped to demonstrate an average response. In addition, the traces are normalized to the most externalized point in order to create comparable results. Finally, because front to back confusions are a common phenomena when using headphone reproduction with the absence of cues from head movements, responses that are correctly lateralized, but reversed from front to back, have been mirrored. Figure 3 illustrates the results. It is evident that the artificial head response consistently produces correct lateralization, though externalization is weaker in the anechoic case. In addition, a single reflection, either trailing the source or from a fixed sidewall, substantially improves externalization and localization.

6. Concluding remarks
A scale model binaural artificial head has been produced to enable binaural simulation of various room conditions rapidly and efficiently. Measurements demonstrate that the artificial head produces a suitable directional frequency response and that high signal-to-noise is achievable. Auralizations made using the manikin have been utilized to perform listening tests, which reveal correct lateralization and externalization. This measurement instrument will allow future investigations into psychoacoustic phenomena in room-acoustic research.

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References and links
