Equalization Filter for Eardrum-Pressure Recording Using a KEMAR Manikin*

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Eardrum-pressure recordings exhibit spectral peaks caused by the natural resonances of the external ear. Under diffuse-sound-field recording conditions (which are encountered in most music-listening settings), the principal peak amounts to approximately 15 dB at 2700 Hz. In many cases, use of the simple bridged-T equalization filter described here will provide improved naturalness in the reproduction of eardrum-pressure recordings.

0. INTRODUCTION

The equalization filter described below grew out of a need to make reproducible comparisons among different types of sound-reproduction systems (loudspeakers, headphones, and hearing aids) without introducing undue bias into the subsequent listening-test evaluations. The same equalization considerations apply to true binaural eardrum-pressure sound-field recordings if they are to be reproduced over conventional headphones or loudspeakers.

Binaural recordings made from the output of eardrum-position microphones mounted in a properly designed manikin have several advantages. For recordings made from headphones or hearing aids, the proper acoustical load impedance can be presented to the earphones. For recordings made in a sound field, the normal spectral cues to localization provided by the pinna and concha are preserved, which may be desirable under some playback conditions.

In the paragraphs below, a brief discussion of the need for an equalization filter is followed by a presentation of recent data on the random-incidence eardrum-pressure response of the KEMAR manikin. A simple bridged-T filter is shown to provide an equalization which may be adequate for many purposes. Finally, the proper choice of filter location in the record–reproduce chain is discussed.

1. THE NEED FOR EQUALIZATION

The KEMAR manikin [1] includes a pair of modified Zwislocki-type ear simulators [2] which closely approximate the average earcanal and eardrum impedance values in man. If binaural recordings are made from the output of the eardrum-position microphones in a KEMAR manikin, and then reproduced over earphones having a flat eardrum-pressure frequency response,[1] the subjective impression can be remarkably similar to that obtained listening directly to the live performance, or to the original headphones or hearing aids. In the more usual case, however, the binaural recordings will be played back over a loudspeaker or stereo-headphone system whose frequency response is relatively flat when referred to the sound field. In the latter case, the response peak of approximately 15 dB at 2700 Hz introduced by the external-ear resonance of the manikin is added to a similar peak in eardrum pressure produced by the external-ear

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[1] For applications requiring a nearly flat eardrum-pressure frequency response out to 9 kHz, for example, a pair of Knowles BP 1817 hearing-aid earphones with the damped tubing described in [3] may be used. A flat *eardrum-pressure* frequency response is not typical for good stereo headphones, whose responses are intentionally tailored to produce a flat *field-referenced* frequency response [4]. A nearly flat eardrum-pressure frequency response may be obtained with such headphones by preequalizing the headphone amplifier using the bridged-T filter shown in Fig. 2.

resonance of the listener, so that the listener experiences the sound modified twice by external-ear resonances rather than the normal once.

To avoid the duplication of earcanal resonance, an equalization filter is normally used when eardrum-pressure recordings are to be made. Bauer *et al.* [5] discussed an equalization filter built for the CBS manikin. The equalization filter of Bauer *et al.* was referred to the earcanal-entrance position (that is, it corrected the pressure sensed at the eardrum to the canal-entrance pressure). For many purposes, however, an equalization referred to the sound field is more useful.

The principal choices for sound-field reference conditions appear to be 0° incidence (sound arriving from directly in front) and random incidence. Two considerations argue against the 0°-incidence choice. First, over 80% of the incident sound energy in most (indoor) listening situations is reflected energy (see Olson [6]). The sound arriving after reflections from the walls, ceiling, and floor more nearly represents a random-incidence sound field than a 0°-incidence sound wave (which can only be achieved under anechoic conditions). A second consideration is the strong minimum which occurs in the eardrum-pressure response for 0°-incidence (and near 0°-incidence) sound in the 8-kHz to 10-kHz region, a minimum due to a cancellation provided by the concha antiresonance [7]. Measurements on a KEMAR manikin indicate that this dip in the eardrum-pressure frequency-response curve can vary between 15 and 30 dB in depth, depending on the exact relationship between the sound source and the manikin positions. This minimum can be easily heard by anyone with access to an anechoic chamber.[2] Equalization of this minimum would require a high-Q peak in the equalization filter, a peak which would be readily audible for sound arriving from other directions.

2. THE RANDOM-INCIDENCE RESPONSE OF THE EAR

Fig. 1 (solid curve) shows an estimate of the random-incidence sound-pressure response of the ear. This estimate is based on the average of several measurements made on a KEMAR manikin in the IRPI reverberation room.[3] Also shown in Fig. 1 (dotted curve) is an estimate based on the data obtained by Shaw [9] using a KEMAR ear mounted in a small baffle. At high frequencies, a 3-dB half-space-to-whole-space correction is required for such half-space measurements, and has been added to the data before plottings. (At low frequencies that 3-dB correction is not required with a baffle of small dimensions, which explains the 3-dB discrepancy between the two curves at low frequencies).

3. A BRIDGED-T FILTER

Fig. 2 shows the schematic and frequency response of a simple bridged-T filter which provides a reasonable approximation to the *inverse* of the random-incidence eardrum-pressure response of the KEMAR manikin.

The component values shown in Fig. 2 were selected to within 0.5% tolerance, and produce a 15.0-dB minimum at 2.9 kHz. In practice it is usually easier to use 10% tolerance capacitors, with variable resistors for R2 and R3. Although the resistor adjustments interact, the depth of the minimum is influenced most by the value of R3. Tuning of the filter is thus easily accomplished by 1) adjusting R3 for a 15-dB minimum, 2) adjusting R2 for a 2.9-kHz minimum frequency, and then repeating that pair of adjustments until an acceptable match is achieved. The process converges rapidly, especially if R2 and R3 are initially set close to the correct values with an ohmmeter.

Also shown in Fig. 2 are the KEMAR random-incidence response (solid curve) and the inverse of the bridged-T filter response (dashed cruve), a comparison which illustrates the closeness of fit between the two curves. Fig. 3 shows the equalization error, that is, the difference between the random-incidence response of the

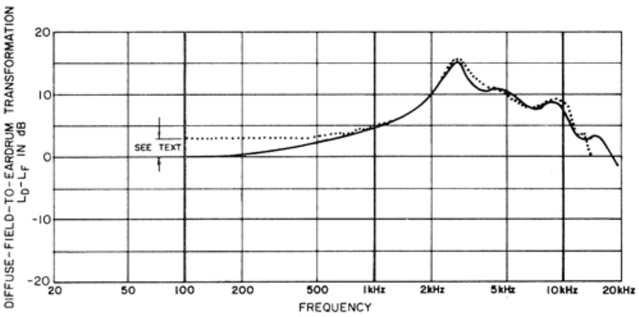

Fig. 1. Random-incidence eardrum-pressure response of KEMAR manikin. —— IRPI estimate, average of left and right ears; · · · · Shaw estimate, KEMAR ear mounted in small baffle. The 3-dB difference between the curves at low frequencies, a small-baffle effect, is discussed in the text.

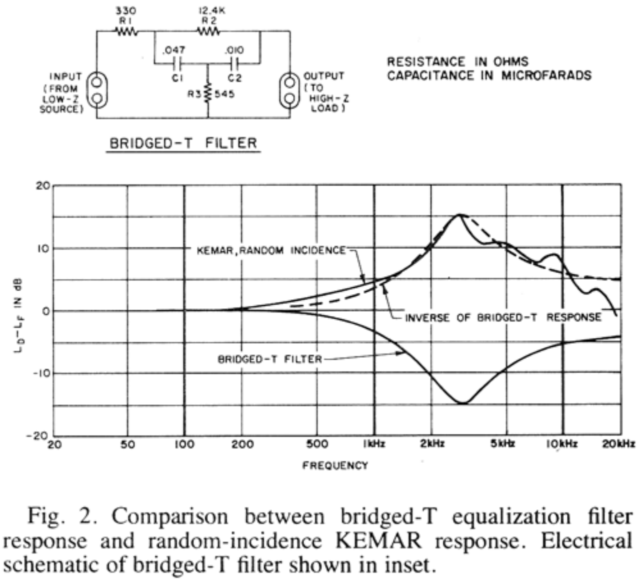

Fig. 2. Comparison between bridged-T equalization filter response and random-incidence KEMAR response. Electrical schematic of bridged-T filter shown in inset.

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[2] Since the frequency of this minimum depends primarily on the elevation of the sound source [7], slowly nodding one's head while listening to a fixed-frequency tone (at 8 kHz, for example) in an anechoic chamber is the simplest demonstration. This variable-frequency minimum provides us with one of the auditory cues to source elevation; see, for example, the references given in Butler and Belendiuk [8].

[3] The width, length, and height of the IRPI reverberation room are 2.42 m, 3.58 m, and 3.64 m, respectively. The response data were obtained using a warble tone with ± 50-Hz deviation and a 10-Hz triangular-wave modulation (modulation index of 10).

KEMAR manikin and the correction provided by the filter, based on the preliminary IRPI estimate (solid curve) and on the Shaw data (dotted curve). By either estimate it is seen that the random-incidence response of the manikin with equalization is within ± 3 dB of the diffuse-field sound pressure (without manikin) up to approximately 14 kHz. In a typical concert-hall listening environment, therefore, the one-third octave spectrum of the signal recorded from the eardrum of an equalized KEMAR manikin should be within approximately ± 3 dB of the spectrum of the signal which would be recorded with a small omnidirectional microphone at the same location (manikin absent).

As one check on the adequacy of the equalization, a comparison between the equalized KEMAR manikin and a pair of high-quality cardioid microphones was included in a series of prerecorded AB listening-test comparisons conducted recently by the writer. The microphones were arranged in the ORTF configuration (17-cm spacing, 110° included angle [10]) and placed in the same location previously occupied by the manikin in a 6000-ft^3 (168-m^3) recording chamber. The source material for the comparison was a live voice. The ratings of the similarity in sound quality given by 26 of the 28 listening-test jury members ranged between "good" and "excellent," where "excellent" meant very little audible difference between the two recordings. The average similarity rating was comparable to that obtained in comparisons between two high-quality loudspeaker systems. In the judgment of the writer (as listener), the primary differences between the manikin and ORTF microphone recordings were in the sense of auditory space (reverberation, source location, etc.) rather than spectral balance. As would be expected, the manikin recordings better preserved the subjective sense of the recording space.

Further refinements in our knowledge of the random-incidence response of the ear will allow refinements in filter design. The phase shift introduced by the external-ear resonance, for example, could be more exactly compensated if known. The bridged-T filter of Fig. 2 introduces maximum phase shifts of approximately −45° at 1.5 kHz and +35° at 5.5 kHz, with a maximum slope (rate of phase shift) of 90° per octave at 2.9 kHz.[4] These values provide only a crude first-order correction to the phase shift introduced by the external ear.

4. LOCATION OF EQUALIZATION FILTER

The preferred location of the equalization filter in the recording (and reproduction) chain depends on the application. In some cases it is desirable to record the output of the unequalized eardrum-location microphones directly. Such a recording may then be properly reproduced either with special flat-eardrum-pressure-response earphones, in which case no equalization is required, or with conventional loudspeakers or earphones, in which case the equalization would be inserted prior to the reproducing power amplifier.

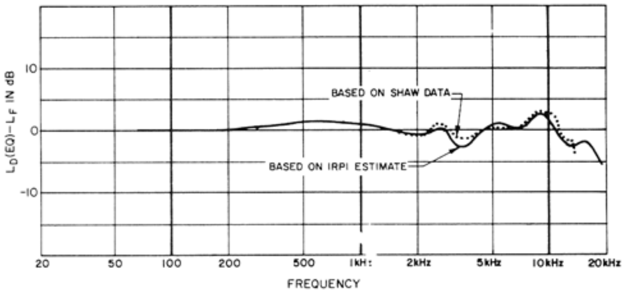

Fig. 3. Estimated equalization error versus frequency. Random-incidence response of KEMAR manikin after equalization.

For most purposes, however, there are advantages to equalizing before recording. Most tape recorders have high-frequency preemphasis added to improve the signal-to-noise ratio at the expense of high-frequency "headroom." In order to avoid overload on high-frequency sounds (sibilants, applause, cymbals, etc.), the input level to the tape recorder must often be dropped to −10 to −15 dB VU when unequalized eardrum-pressure recordings are made. Although subsequent equalization of such recordings will restore some of the signal-to-noise ratio lost in such low-level recordings, there will be a net loss of 5 to 10 dB in high-frequency signal-to-noise ratio over that obtainable with equalized eardrum-pressure recordings (which may be recorded at normal 0 VU levels). A better overall signal-to-noise ratio can be obtained, therefore, by equalizing before recording and, when required, inverse-equalizing (see footnote 4) the recording on playback to restore the normal eardrum-pressure peak at approximately 2700 Hz.

5. SUMMARY

The bridged-T filter described here provides an extremely simple equalization for eardrum-pressure recordings in order to remove the response peak introduced by external ear resonance. Although more accurate equalization is possible, the suggested equalization should prove adequate for many purposes.

6. ACKNOWLEDGMENT

The reverberation-room data on the random-incidence response of the KEMAR manikin were obtained by Ed Monser, who also performed much of the data averaging. Edgar Villchur and Mahlon Burkhard provided valuable comments on earlier drafts of this paper.

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[4] The inverse of the bridged-T filter response can easily be obtained by placing the filter in the negative-feedback loop of an operational amplifier. Conventional frequency compensation—such as found in the common LM 301 or μA 741 monolithic integrated circuit amplifiers—is all that is required since the maximum phase shift introduced by the bridged-T filter is only 45°

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THE AUTHOR

Mead C. Killion was born in Woodstock, Illinois in 1939. After receiving his B.A. degree in mathematics from Indiana's Wabash College in 1961, Mr. Killion went to work for Industrial Research Products, Inc. in Elk Grove Village, Illinois, where he is now senior engineer. He later earned his master's from the Illinois Institute of Technology in Chicago (1970).

Killion's work at IRPI has involved the design of electroacoustical transducers and instrumentation, leading to significant contributions to the development of, and literature on, miniature microphone cartridges for hearing aids. He has presented a number of papers before the Audio Engineering Society and the Acoustical Society of America, and is coauthor of several patents in the miniature transducer field. At present, Mr. Killion is finishing work on his Ph.D. in audiology.

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