$$\alpha = 3.06\times 10^{-5} f^{1/2}/a \qquad (15)$$

The Q of the tube is then

$$Q = 2.98\, a f^{1/2} \qquad (16)$$

for air at 23 °C. (Beranek[5] suggests a value of 3.18×10^{-5} for the coefficient in Eq. (15); this will give the coefficient in Eq. (16) the value 2.87. On the other hand, Eq. (7) above, inserted into Eq. (10), gives the coefficient in Eq. (16) the value 3.06. This last value, taken from values of the gas constants for air is given in the literature,[6] is probably to be preferred.)

(Other errors can be corrected here: Eq. (8) in Ref. 4 should read

$$Z = (\rho c/A_0)/\alpha l\,. \qquad (17)$$

The right hand side of Eq. (20) Ref. 3, should be multiplied by $j^{1/2}$.)

To determine the characteristic impedance Z_0, it is convenient to introduce a different effective boundary layer δ'' given by

$$\delta'' = \delta_v - (\gamma - 1)\delta_t \qquad (18)$$

$$= 0.354\,\delta' \qquad (19)$$

Using Eq. (18), we find for the characteristic impedance

$$Z_0 = (\rho c/\pi a^2)(1 + \delta''/a\sqrt{2})(1 - j\delta''/a\sqrt{2})\,. \qquad (20)$$

Expressing this in terms of Q by using Eqs. (10) and (19) above, we have

$$Z_0 = (\rho c/\pi a^2)(1 + 1/5.65Q)(1 - j/5.65Q)\,. \qquad (21)$$

In practice, it appears that Eq. (21) can be used in simplified form. A computer program was set up and run to determine the resonance frequencies and impedances at the resonances of a tube with two side holes. This program was run with (a) Eq. (21) as it stands, and (b) with all the Q terms deleted. The calculated resonance frequencies for the two cases differed by less than 1 cent and the impedance values differed by less than 2%. To this accuracy, therefore, it is presumably sufficient to use the simplified form

$$Z_0 = \rho c/\pi a^2\,. \qquad (22)$$

This work was supported by the National Science Foundation, whose assistance is gratefully acknowledged.

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[5] L. Beranek, *Acoustic Measurements* (Wiley, New York, 1949), p. 73.

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Effect of leakage on the low-frequency calibration of supraaural headphones

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The general validity of calibration of supra-aural headphones by the method of an inserted probe tube is examined. In particular, the possibility of the probe tube affecting the seal between the headphone and the ear is considered. Experimental proof that this can occur is obtained by the use of a small microphone located within the ear canal. Furthermore, attention is drawn to the fact that single cavity couplers such as the NBS9A make no attempt to simulate the ear's impedance and so a discrepancy between probe and coupler responses can be expected. In the light of these factors, some recommendations about the design of artificial ears are made.

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INTRODUCTION

Differences are often found to occur between the response of supra-aural headphones as measured on a coupler and the subjective loudness perceived at frequencies below about 500 Hz. The discrepancy remains even when allowance is made for the subjectively measured falling response of the ear at low frequencies. This had been substantiated by probe-tube measurements,[1,2] which show the SPL at the ear-canal entrance to be less than that which is expected from coupler calibrations. The discrepancy is generally thought to be due to the imperfect seal between the headphone cushion and the ear. While this leakage effect is un-

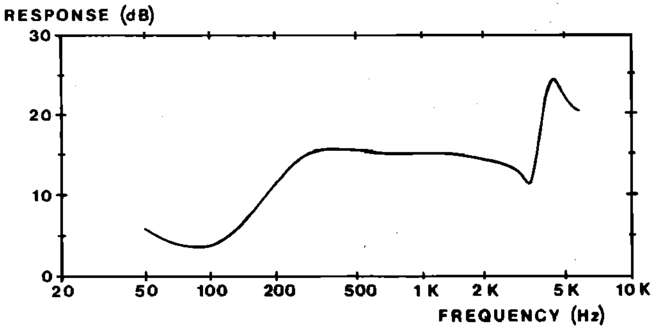

FIG. 1. Relative sound pressure level at ear channel entrance using a high impedance, well-sealed earphone (From Bruel *et al.*,[3] by permission).

doubtedly present, its magnitude may have been overestimated significantly because of two factors.

A. Ear impedance

In measurements made prior to designing the Bruel and Kjaer type 4153 artificial ear, Bruel, Frederiksen,[3] and Rasmusson ensured a good seal between earcap and ear by the use of vaseline. They then proceeded to determine the pressure response at the ear-canal entrance with the enclosed cavity driven by a high-impedance source (Bruel and Kjaer type 4134 microphone mounted in an earcap). Assuming that the source is stiffness controlled at low frequencies, a flat response should be measured in a simple cavity. An actual response is reproduced in Fig. 1.

It is quite clear from this experiment that even with no leakage present, the SPL at the ear-canal entrance decreases as frequency decreases below about 350 Hz. Since both Shaw, and Morgan and Dirks used an NBS 9A coupler to make comparisons with their probe measurements, and since this coupler is just a simple 6-cm^3 cavity, it is reasonable to expect that the difference between the probe and the coupler measurements would be due at least in part to the decreasing impedance of a well-sealed ear at low frequencies.

B. Effects of probe

A pair of Beyer DT-48 headphones with the flat cushions had been calibrated in a Bruel and Kjaer type 4153 artificial ear. No use was made of vaseline to improve the seal, and the flat plate adapter DB0843 was not used. In order to ascertain how well this calibration predicted the SPL's actually measured in a subject's ear, a 1-mm-o.d. probe microphone tube (Bruel and Kjaer type DB0241) was inserted under the earphone cushion and the signal at the canal entrance measured. Although the measurement required no subjective response by the subject, a subjective response incidentally reported was that the addition of the probe microphone decreased the perceived loudness of the tone noticeably. If leakage is an important factor in the low-frequency response, then it is possible that an added probe could have an effect on the leakage. The effect could conceivably be positive or negative as the probe could either fill up an existing gap between the ear and the earphone cushion or create a new one. An objective measurement method is required in order to confirm or disprove the existence of any effects caused by the probe.

One method would be to insert a second probe through a hole drilled in the earphone if a suitable location can be found. A less disturbing (and destructive) method is to use a miniature ceramic microphone which can be completely contained inside the ear and located at the ear-canal entrance. The only connections needed to be brought out are three fine wires. The size of the microphone used is $5\times7\times2$ mm and so occupies a volume of 0.07 cm^3, which is considerably less than the 4–7 cm^3 usually enclosed by supra-aural earphones. As the diameter of the canal is approximately 7 mm and the cross section filled by the microphone is only 5×2 mm, there is no chance of the canal being blocked. Thus the addition of the microphone is unlikely to have any significant effect on the impedance of the ear, especially at the low frequencies and hence long wavelengths being considered.

In a pilot study, one subject only was used and the response of the Beyer DT48 headphones with flat cushions was measured at the canal entrance by the two methods under consideration.

(1) Probe tube removed, SPL inside ear measured by a Tibbetts ceramic microphone type T1-1331-1H, fed into a Bruel and Kjaer amplifier type 2112, and recorded by a level recorder (Bruel and Kjaer type 2305).

(2) Probe tube inserted, SPL inside ear can be measured by probe microphone and the same amplifier and recorder as before. The ceramic microphone still remained within the ear for this measurement but its output was not monitored.

These two responses are shown in Fig. 2. Also shown there for comparison is the response of the Beyer headphones measured on the artificial ear. The ceramic and probe microphones were calibrated using the Bruel and Kjaer probe microphone calibrator type DB0260, and the two lower curves in Fig. 2 have been corrected for these responses. The curves have been normalized at 1 kHz.

The probe response shows a greater roll off than the artificial-ear response suggesting that the earphone is presented with a different impedance in both cases. That the ceramic response lies between the other two implies that the probe itself has modified the effective impedance seen by the earphone. Increased leakage due to the probe appears to be the most likely cause of this.

In order to determine more precisely the effect of the probe the following procedure was adopted. The ceramic microphone was placed inside the ear and the headphones placed on the subject. A response was obtained and the headphones were partially removed to facilitate the placement of the probe tube. This was located immediately above the tragus and the tube brought out in the valley above the cheek bone as sug-

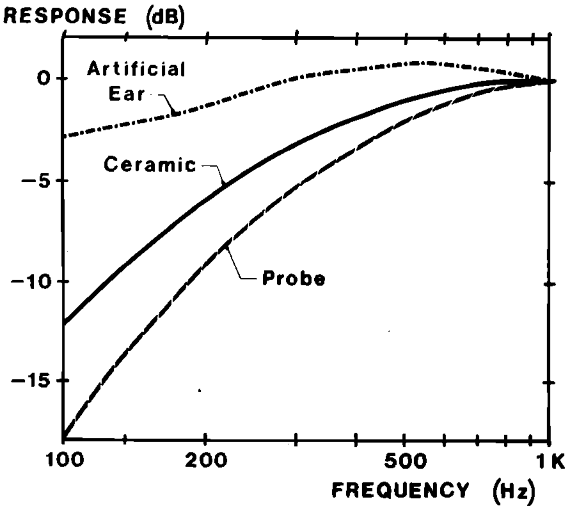

FIG. 2. Relative sound pressure level under Beyer DT48 headphones measured by three methods; (i) headphones mounted on B & K type 4153 artificial ear, (ii) headphones on a human subject and measurements made by a ceramic microphone completely contained within ear, and (iii) headphones on a human subject and measurement made by a probe microphone inserted between earcap and ear.

gested and used in Refs. 1 and 2. Two different size probe tubes were used, 2 and 1 mm outside diameter, each 20 cm long and terminated with a Bruel and Kjaer type DB0264 dummy microphone. A response was measured, the probe removed, and the process repeated, alternating measurements with and without the tube being present. A flexible connection in the tube was not considered necessary as no bulky microphone and cathode follower were required on the end of the tube. A clamp supported the free end.

Three subjects were used and initial measurements indicated that the presence of the probe had a considerable effect for two of the subjects but no measurable effect for the third. For each of the two subjects showing the effects, eight pairs of probe/no probe measurements were made for each of the two probes. The average results are for each subject shown in Fig. 3 as the difference between the responses measured with and without the probe being present.

I. ANALYSIS

The response at 1 kHz was found to be stable to within 0.5 dB for a particular subject and to within 1.5 dB between subjects, independent of the presence of the probe. The amount of roll off can thus be conveniently characterized as the difference between the response at 1 kHz and that at 100 Hz. Using these figures and assuming that the measurements are approximately normally distributed, a t test indicates that the differences between the mean responses caused by the addition of the probe to be statistically significant at better than the 0.5% confidence level, for three of the four cases shown. The attenuation produced by the 1-mm tube with subject S. F. is significant only at the 10% confidence level.

II. CONCLUSIONS

Coupler calibrations of supra-aural earphones at low frequencies are likely to be in error for two reasons. First, single-cavity couplers do not display the changing impedance properties of real ears. Secondly, even more complex couplers do not allow for the imperfect seal between the earcap and the ear. Further, attempts to calibrate via a probe microphone technique are likely to affect the tightness of this seal for at least some subjects, even when reasonable precautions (such as using a thin, properly located probe) are taken.

This conclusion is not limited by the small number of subjects used since the primary purpose of this paper is to draw attention to the fact that it is possible for the probe used in checking a headphone response to affect that response in some subjects.

A further conclusion arising from these results is that artificial ears would better approximate the impedance of real ears if they had a mating surface equal in irregularity to the "average" external ear. Because of the immense variety of human-ear shapes and sizes, one could not hope to predict the exact low-frequency response in any subject. However, one of the main uses of artificial ears is for the comparison of different headphones, and the inclusion of a ripplelike surface would provide an extra piece of information about the

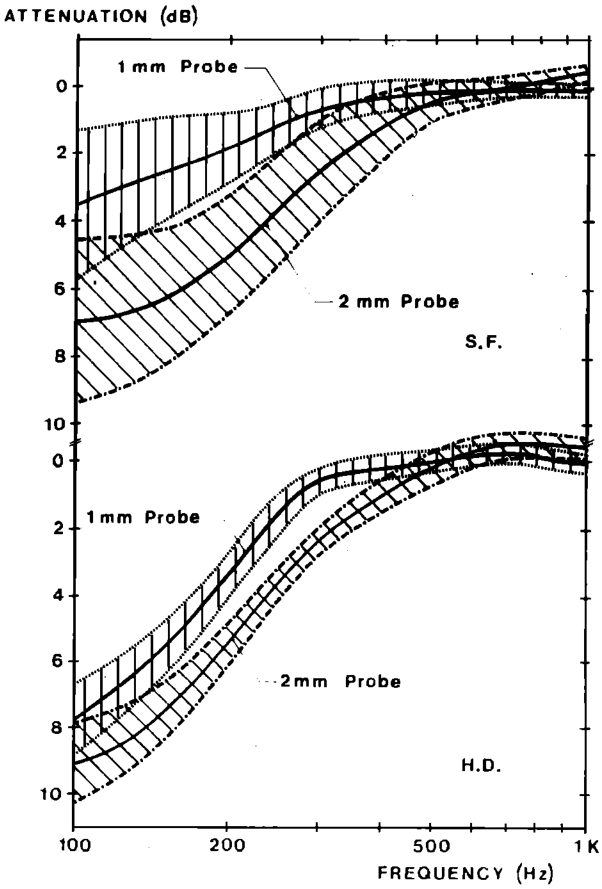

FIG. 3. Attenuation at ear-canel entrance due to addition of 1 and 2-mm probe tubes for two subjects. Hatched areas show the one-standard-deviation limits based on eight responses with and eight responses without probe present.

headphones, i. e., their potential "leakage." With smooth-surfaced artificial ears, two headphones differing only in headband tightness and cushion sponginess would display almost identical responses. Substitution of a ripple surface for the smooth surface in the artificial ear would then indicate that the headphones with a lower tension headband and/or less spongy cushions would display considerably more roll off at low frequencies and this roll off would by typical of actual impedances obtained from real ears. If a probe microphone is used to check a response, then the probe ought to be introduced to the ear via a hole in the earphone itself, not between the earcap and the ear. Another (untried) alternative is to use a sealing compound such as vaseline in the region surrounding the probe. It is emphasized that these results apply to supra-aural earphones only, circumaural earphones having less leakage and less variability of response.[2]

ACKNOWLEDGMENTS

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