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ENVIRONMENTAL AND TRANSDUCTION EFFECTS ON CLOSED-LOOP STABILITY IN ACTIVE HEARING PROTECTORS

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1. ABSTRACT

A computer model of a closed loop active cancellation device using straightforward compensated feedback control is used to examine stability sensitivity to environmental changes. Typical environmental factors of interest include changes in earcup position on the users head, changes in barometric pressure, and temperature and humidity variations. Transduction stability due to variations in sensitivity and phase are also modelled. The result of these system simulations are guidelines for stability bounds of the closed-loop system which translate into active attenuation performance curves. Particular devices can obviously achieve better or worse performance due to artful arrangement of the transducers in the earcup and the user's unique pina. However, this work provides a useful framework to recognize the relevant physics and control stability issues in any active hearing protector design.

2. INTRODUCTION

Since the original invention of the active noise cancelling hearing protector by Hawley and Simmhauser [1] in 1961 (Olson [2] first published the general idea in 1953), the problem of understanding the physical parameters affecting cancellation bandwidth and stability has limited practical active noise control (ANC) performance. In this work we bring together a complete physical model of a typical ANC headset including environmental effects on the transducers as well as the mechanics of the human ear. No attempt has been made to optimize the feedback control performance, but rather, we simply illustrate the physical relationship between the closed-loop system response and the environment. We start by modeling a typical back-electret microphone's response to temperature and barometric pressure (humidity does not appear to play an important role provided no condensation occurs).

3. ELECTRET MICROPHONE MODEL

Figure 1 shows a sketch of the modeled electret. The "back electret" design allows a lightweight diaphragm to serve as a movable plate of a capacitor where the charge stored on the electret material provides an electrostatic bias voltage for linear operation. Temperature can affect the tension in the diaphragm, while barometric pressure will effect the air density inside the cavity, thus causing changes to the stiffness provided by the cavity. High-tension electrets (usually more expensive) are more sensitive to temperature while (usually less expensive) low-tension electrets are generally more sensitive to barometric pressure changes.

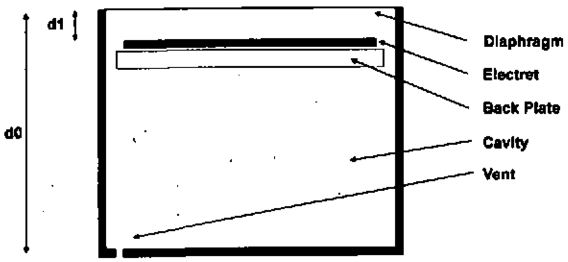

Figure 1 Schematic diagram of back-electret type microphone used in the active headset model

A model for the sensitivity in Volts per Pascal for the electret is developed by including thermal expansion into the typical electret transduction equations [3]. However, Fraden's development on electrets contains an error. We find the sensitivity equation including thermal expansion and barometric pressure effects is

$$M(\omega) = \frac{\sigma_e}{\epsilon_0}\left(\frac{1}{\dfrac{a^2}{8T_m} + \dfrac{d_0}{\gamma P_0}}\right) \tag{1}$$

where $T_m = T_{m0} - k_m \alpha 2a\Delta t$, Δt being the change in °C of the diaphragm.

Table 1 Electret microphone parameters

Parameter	Value	Description
σ_e	3.5×10^{-6}	surface charge density on electret (C/m^2)
ϵ_0	8.84×10^{-12}	dielectric constant for air ($C^2/Nt\text{-}m^2$)
a	0.003	circular diaphragm radius (m)
d_0	0.00178	depth of acoustic cavity in microphone (m)
T_{m0}	90	mechanical tension of steel diaphragm (Nt/m)
k_m	170,000	mechanical stiffness of steel diaphragm (kg/s^2)
α	11×10^{-6}	temperature expansion coefficient of steel (/˚C)

Figure 2 shows the results of the electret model for temperatures ranging from -20 to +50˚C (0 to 120˚F) and barometric pressures corresponding to altitudes from sea level to 3000m. Altitude sensitivity is of high interest for aircraft use of ANC headsets. As can be clearly seen in Figure 2, the barometric pressure sensitivity is much greater than the temperature sensitivity given our fairly low diaphragm tension T_{m0}=90 Nt/m. Even with a low tension diaphragm, the electret environmental sensitivity is seen to be quite low from the perspective of the ANC closed loop system stability, although it does account for about 2 dB of gain margin.

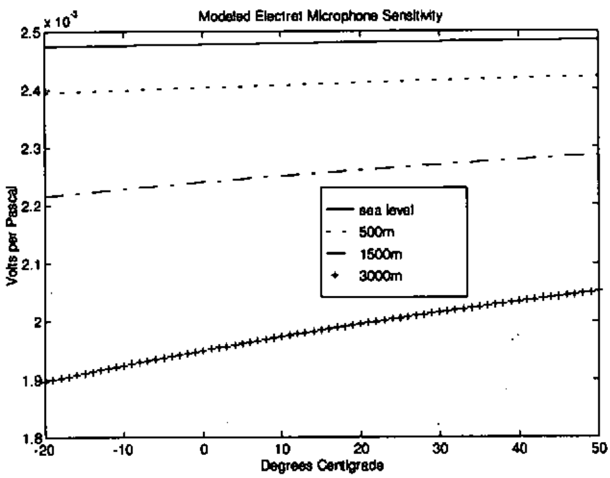

Figure 2 Receiving sensitivities as a function of temperature and barometric pressure changes due to altitude

4. ANC HEADSET SYSTEM MODEL

Figure 3 provides a sketch of the complete ANC headset system model showing the eardrum damping and compliance and cavities including the ear canal, pina cavity, and front and read headset cavities. The geometries used in the simulation are given in Table 2.

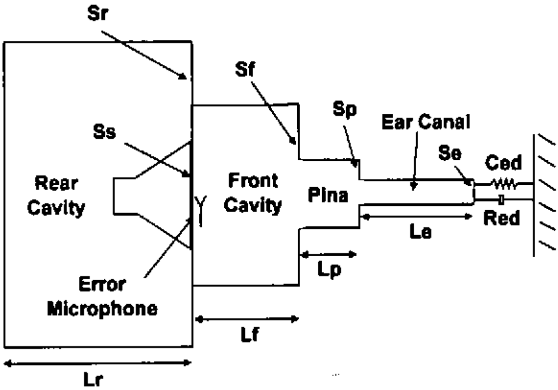

Figure 3 Modeled active headset system including all cavities and the compliance of the eardrum

Table 2 ANC headset model parameters

Parameter		Description
Le=0.030	Se=2.83 x 10^{-5}	ear canal length and cross-sectional area (m, m^2)
Lp=0.015	Sp=1.13 x 10^{-4}	pina cavity length and cross-sectional area (m, m^2)
Lf=0.020	Sf=1.26 x 10^{-3}	front cavity length and cross-sectional area (m, m^2)
Lr=0.030	Sr=6.36 x 10^{-3}	rear cavity length and cross-sectional area (m, m^2)
Ced=440 x 10^{-9}	Red=1.46 x 10^{6}	impedance of eardrum (m^2-s/Rayls, Rayls/m^2)

Figure 4 shows the results of the system model in the form of the pressure at the error microphone location and its sensitivities to barometric pressure. The "ripple" in the response curve is due to the eardrum compliance and its interaction with the loudspeaker's 72 free resonance (Ss=2.83 x 10^{-3}). The changes in barometric pressure change the acoustic compliance of the cavities, but not the eardrum. The barometric pressure effect on the microphone is somewhat balanced by the loudspeaker in terms of open-loop system gain. The cavity response was not significantly affected by temperature variations, and its safe to assume a closed ANC headset will be close to the temperature of the human body when used.

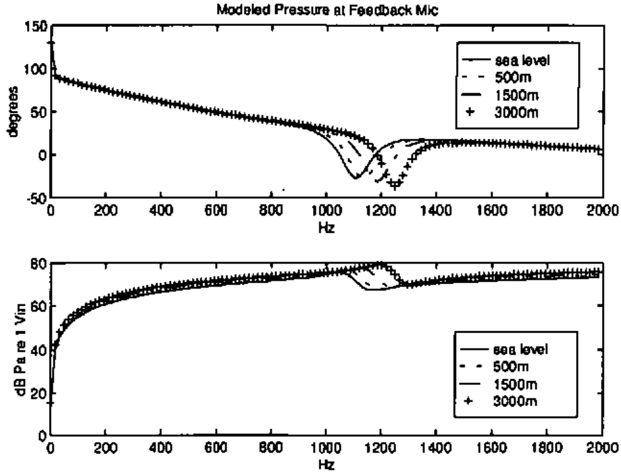

Figure 4 Pressure at the error microphone location just in front of the loudspeaker and its sensitivity to barometric pressure

5. ENVIRONMENTAL EFFECTS ON GAIN/PHASE MARGIN

To stabilize the closed-loop system, a 3rd-order Bessel 2 kHz low-pass filter is connected between the error microphone output and +75dB gain amplifier and loudspeaker. The low-pass filter is required to limit the feedback frequency response to a range where negative feedback is maintained. We find a similar moderate sensitivity to barometric pressure as seen in Figure 4. However, using a range for normal eardrum impedances [4] (220 - 700 x 10^{-9} m^2-s/Rayls as defined by Typanogram measurements), we find a very significant response variation. Figure 5 shows the significance of the eardrum impedance for normal hearing adults on the ANC response, which nearly goes unstable for the stiffer eardrum impedance.

6. CONCLUSIONS

Human variability in ear geometry, ear canal length and condition, and eardrum impedance, appears to play a very important role in the effectiveness of ANC headsets when used by individuals. The model for the electret microphone provides some insight into the effect of temperature and barometric pressure on sensitivity, but this effect appears to be fairly small in the context of the closed-loop system response's sensitivity to the ear physiology. Designing a robust ANC headset with an optimized compensation filter is full of comprimises when the ANC headset must work "out-of-the-box" for the general public. However, it should be possible to maximize ANC performance by individualizing the design.

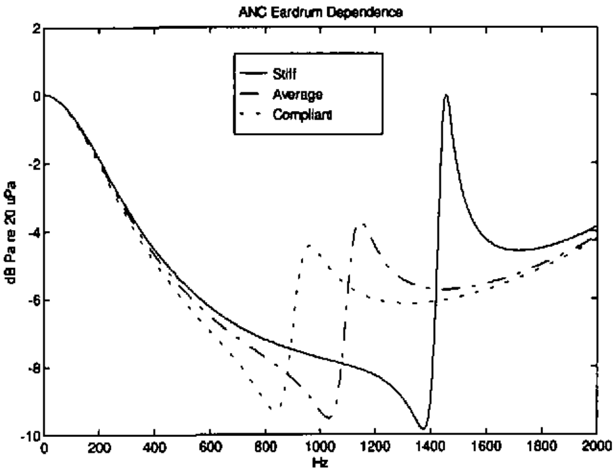

Figure 5 ANC performance dependence on the user's eardrum compliance using a fixed 3rd-order Bessel low pass compensation filter to suppress feedback above 2 kHz

7. REFERENCES

1. M.E. Hawley and E.D. Simmhauser, "Noise Reduction System", US Patent No. 2,972,018, Feb. 14, 1961.

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3. J. Fraden, *AIP Handbook of Modern Sensors*, (New York: AIP, 1994).

4. H.A. Newby, *Audiometry*, 4th ed., (Englewood Cliffs: Prentice-Hall, 1979) p193.