High output ear canal transducer for active noise reduction

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ABSTRACT

Military personnel operating on the deck of an aircraft carrier can be exposed to noise levels of 140-150 dB. Passive methods of noise reduction such as external muffs and ear canal plugs are able to reduce this noise at the eardrum to 110-120 dB, a level that severely restricts the use of and communication with servicing personnel. An active noise reduction system that employs a small transducer is to be placed in the earplug is added to the system in order to reduce the noise to 80-90 dB. This requires a transducer small enough to fit in the ear canal and robust enough to produce sound levels in the range of 120-125 dB with sufficient phase stability to operate within an ANR system. Ordinary hearing aid transducers are unable to meet these requirements. Acentech Inc. of Cambridge. MA is cooperating with Intricon Tibbetts of Camden ME to develop transducers based on design concepts by RH Lyon Corp of Belmont, MA to meet these requirements. A description of these transducers and their expected performance is presented (Work supported by the US Air Force).

1 INTRODUCTION

According to Air Force estimates (2004) there are about 22,000 claims for hearing loss to the Air Force, Navy, and Marines per annum at a cost of $630 M. These numbers have more than doubled since 2004. The cost of hearing loss is in addition of course to the loss in duty time for those serving and the potential hazards of lost communication and situational awareness in high noise environments, as well as the personal cost to service people who must live with tinnitus and hearing loss.

With noise levels approaching 150 dB on the deck of an aircraft carrier, conventional protection such as muffs and deep insert earplugs are not sufficient to protect hearing, even when worn properly. For that reason, the Air Force and Navy have joined in a joint program to develop active noise reduction (ANR) earplugs to provide added noise reduction and improved communication. A part of that effort is the design of transducers (drivers or loudspeakers) to be embedded in the plugs capable of sufficient output to cancel the intruding noise.

The work described here was initiated as a US Air Force SBIR Phase I contract with RH Lyon Corp in cooperation with Tibbetts Industries, and continued in Phase II (2005) in the RH Lyon Division of Acentech Inc. The basic design concepts were established in Phase I and included three electro-dynamic designs (balanced armature, magnetostrictive, and voice coil) and two electrostatic designs (piezoelectric and electret). Evaluations of the designs were based primarily on paper results (modeling and computation) and discussions with fabricators and materials suppliers. In Phase II these were reduced to two designs, balanced armature and piezoelectric bimorph. The work continues on those two designs and is described here.

Ordinary earplug drivers for hearing aids are based on balanced armature designs, a driver mechanism that dates from the earliest days of radio and sound reproduction. Hearing aid transducers typically have outputs limited to about 110 dB, insufficient to match the 130 dB levels that may reach the eardrum on the flight deck, even with passive protection. The drivers must fit within the ear canal, limiting their size, and since they are part of a feedback system, their gain and phase stability over the frequency range from a few hundred to a few thousand Hertz is an issue. These are some of the issues that have been controlling in the design of the transducers discussed here.

Although our discussion is as thorough as possible, it will not be possible to present performance data since the testing period is not complete and some transducers only exist in prototype form. Nevertheless, the description of the designs (patents pending) will be complete.

2 THE BALANCED ARMATURE DESIGN

A pair of balanced armature “motors” within a common housing is shown in Figure 1. A beam (the armature) sits midway between the poles of a permanent magnet (PM). A signal coil surrounds the armature and the signal current causes the end of the armature to become a north pole (say) and it therefore deflects away from the north pole of the PM and toward the south. This reverses of course when the signal current is reversed. A “drive pin” connects the moving armature to a diaphragm which moves the air and produces sound. The sensitivity of the system depends on the strength of the PM field, the reluctance of the path for the signal flux, and the number of turns in the signal coil.

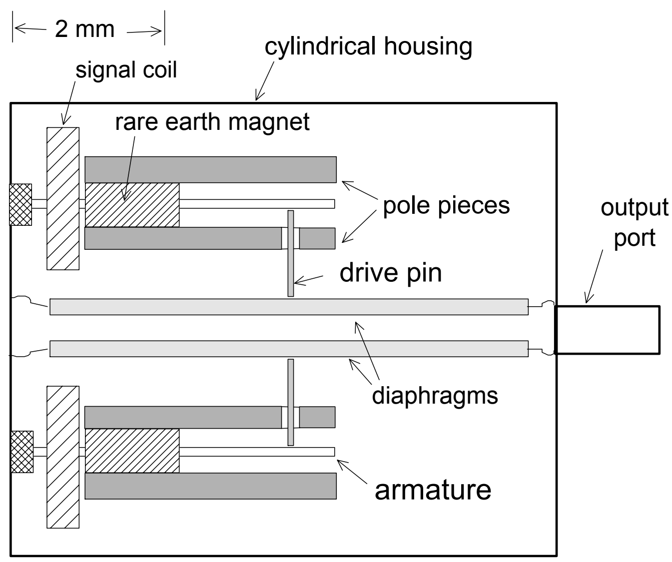

Figure 1: Scheme of a pair of balanced armature motors operating together to “pump” sound through a common exit port

This assembly is more clearly laid out in the exploded view of Figure 2. This driver is 7 mm long and 6 mm in diameter. It meets the specified dimensional limit in the contract, but will be a snug fit in the ear canal of some users. It would be challenging to make the unit smaller based on current technology but not out of the question. The two motors operate in phase so that they squeeze the air in the forward volume, between the two diaphragms.

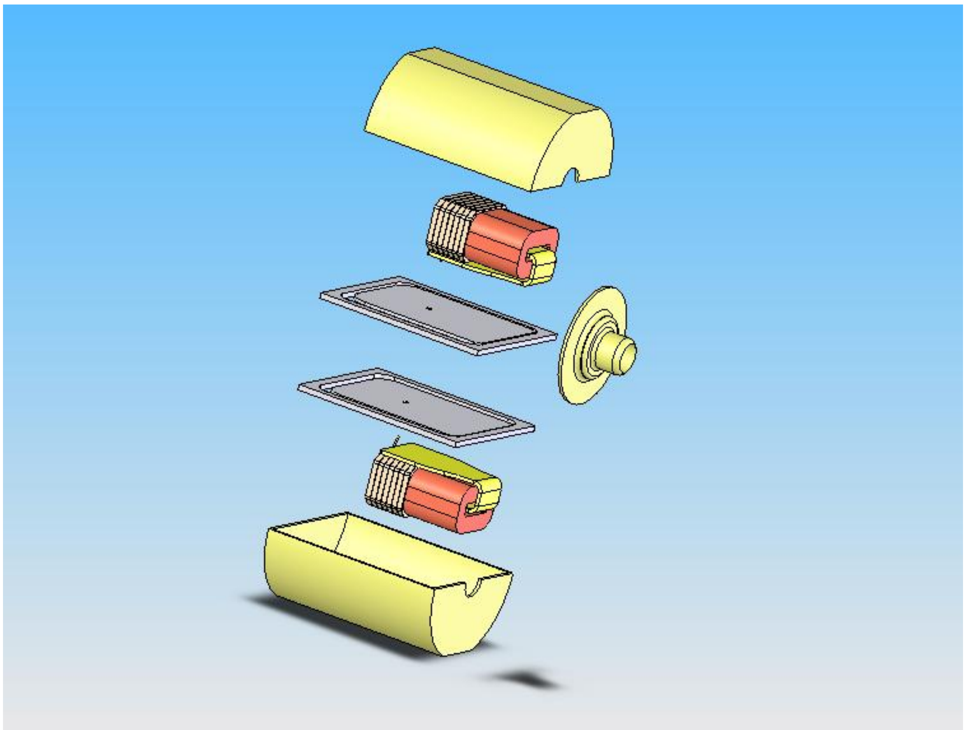

Figure 2: "Exploded" diagram of the "push pull" or "squeeze-draw" balanced armature driver

The performance of this driver is calculated using the equivalent circuit shown in Figure 3. This is an "acoustical" circuit in which the drop variable is volume velocity and pressure is the flow variable. The impedances are the electrical and acoustical impedances of the various elements. The parameter N_{em} is the electromagnetic "turns ratio" and is inversely proportional to the strength of the electro-dynamic coupling

$$N_{em}^{-1} = N_{sig} \Phi_g \mu_0 / d_g A_d \tag{1}$$

where μ_0 is the permeability of air, N_{sig} is the number of turns in the signal coil, Φ_g is the flux in, and d_g is the length of, the air gap, and A_d is the diaphragm area.

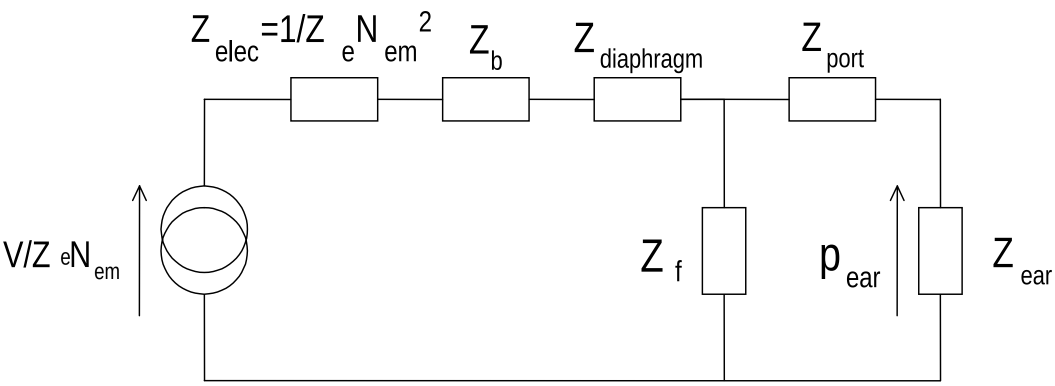

Figure 3: Equivalent circuit model for the balanced armature driver showing the major components

The predicted amplitude, phase, and group delay performance of this transducer is shown in Figure 4. The ear is represented by a small fixed volume (three choices). At low frequencies, the sensitivity is about 40 dB re 1 Pa (134 dB re 20 µPa) per volt, dropping off 30 dB at 5 kHz. The phase shift is about 1 radian at low frequencies due to the electrical impedance of the signal coil, a matter of concern since the transducer is part of a feedback system. The group delay shows peaks at the internal acoustic resonances of the transducer.

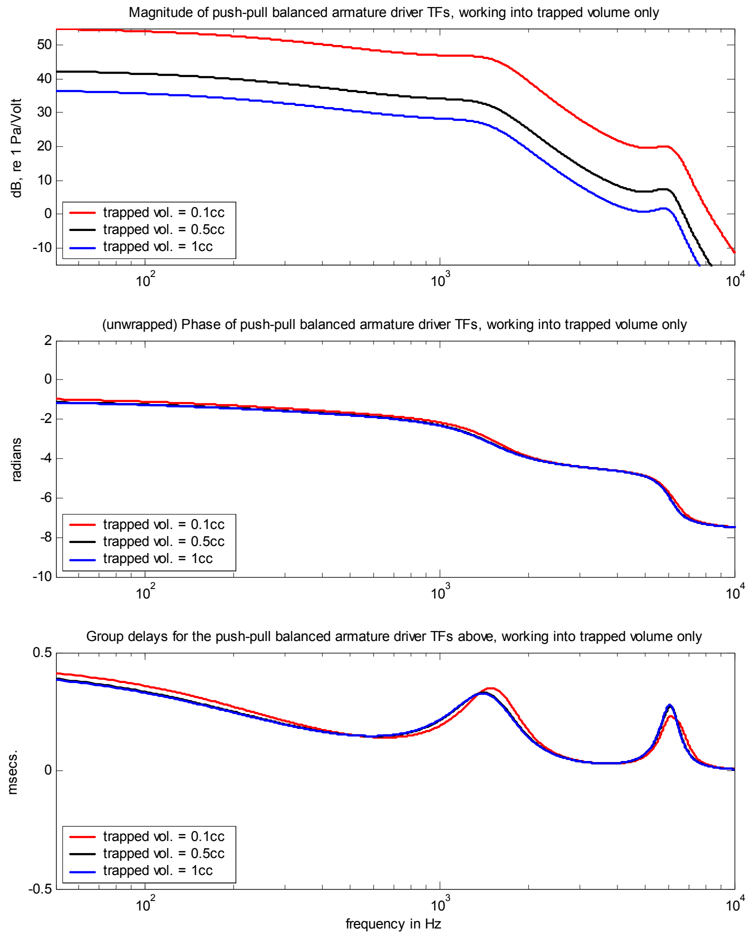

Figure 4: Performance of the push-pull balanced armature driver calculated using the model in Figure 3. Low frequency sensitivity is about 130 dB/volt

3 THE PIEZOELECTRIC BIMORPH DESIGN

In the ‘70’s a new class of electrostrictive ceramics was discovered based on single crystal solutions of lead titanate in lead-magnesium-niobate ((1-*x*)PMN-*x*PT). When polarized, these materials have electromechanical strain coefficients d_{ij} several times greater than polycrystalline lead-zirconate-titanate (PZT) and fracture strains greater than 1 %. Example properties of this material are presented in Table 1 for 0.30. Because of our desire for greater output of the driver, it was decided to use this material in the design.

Table 1: Comparison of electrical and mechanical properties of PZT and PMN-PT

Property	**PZT**	**PMN-0.35PT**
Dielectric constant	1300-3000	5500-7500
Loss factor (electrical)	0.004-0.02	<0.01
d13 (pC/N)	60-200	~800-1000
Max reverse field	5 – 15 kV/cm	2 kV/cm
Fracture stress (MPa)	60-75 (~0.1 % strain)	~300 (~2.5%strain; polished)
Curie temp	190-375° C	140 – 160° C
Density (kg/m3)	8000	8000
Modulus (GPa)	48-77	~ 12
Mech. loss factor	0.001-0.07	0.025

The bimorph push-pull design is shown in Figure 5 in both exploded and cutaway drawings. Each bimorph element consists of a pair of PMN-PT plates with a common center signal electrode and upper and lower (outer) electrodes at ground potential. The plates are polarized so that the applied voltage causes the upper plate to stretch and the lower to shrink (and vice versa) through the d_{13} coupling. These elements are mounted on a frame that forms the common forward volume as in the balanced armature design. The displaced air travels out through the port into the ear cavity.

The equivalent circuit model shown in Figure 6 contains many of the same elements as in Figure 3, although the layout for the electrical elements is different because this is a form of an electrostatic transducer with a conversion "turn ratio" N_{es}. This parameter, as in the case of the electro-dynamic transducer, is inversely proportional to the strength of the coupling:

$$N_{es}^{-1} = 8d_{13}Dk^2 / h_p^2 \qquad (2)$$

where d_{13} is the electro-static strain parameter, D is the bending rigidity of the element, k is a shape parameter for the bending mode, and h_p is the piezoelectric plate thickness. The product $d_{13}D$ is called a piezoelectric stress coefficient.

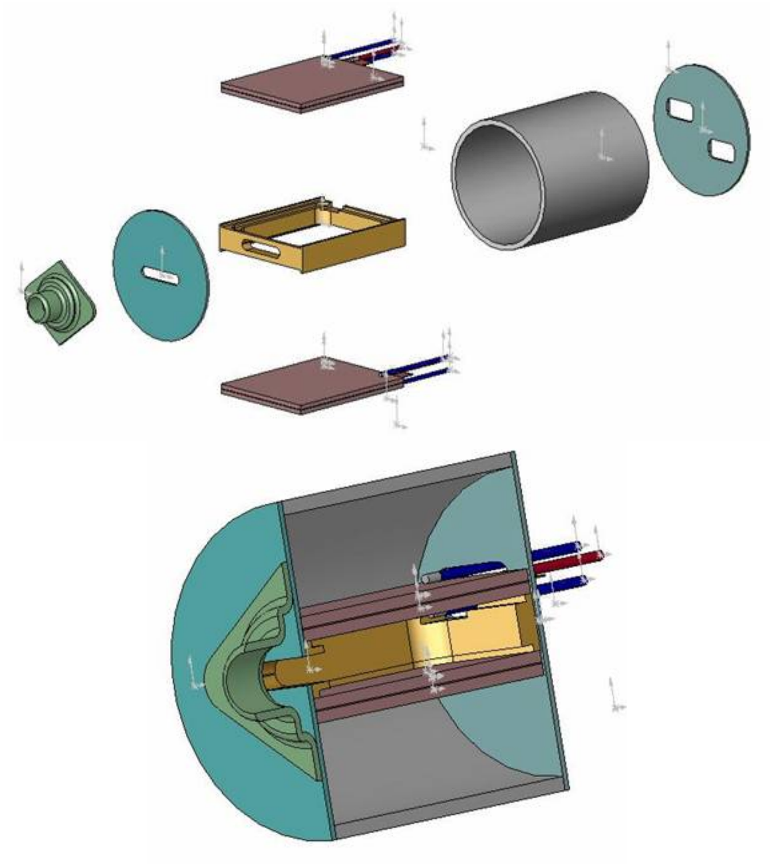

Figure 5: Earplug driver using a pair of piezoelectric bimorph elements in the push-pull configuration

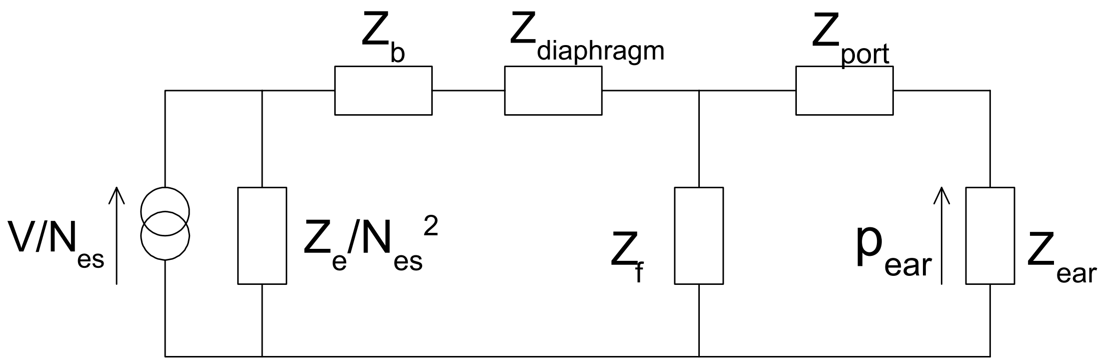

Figure 6: Equivalent circuit model for the bimorph piezoelectric driver

The calculated performance for a transducer having the same external dimensions as the balanced armature design is shown in Figure 7. At low frequencies, the sensitivity is about 1 Pa/volt or 94 dB/volt, about 40 dB less sensitive than the balanced armature design. This means it will take about 63 volts of signal to produce the desired 130 dB of output. However, the response is quite flat, so that at 5 kHz it is only 10 dB less sensitive than the balanced armature design. The electrical impedance of the transducer (that of a small capacitor) means there is no phase shift when the load is a simple cavity until the mechanical resonance of the bimorph element at 8 kHz is reached.

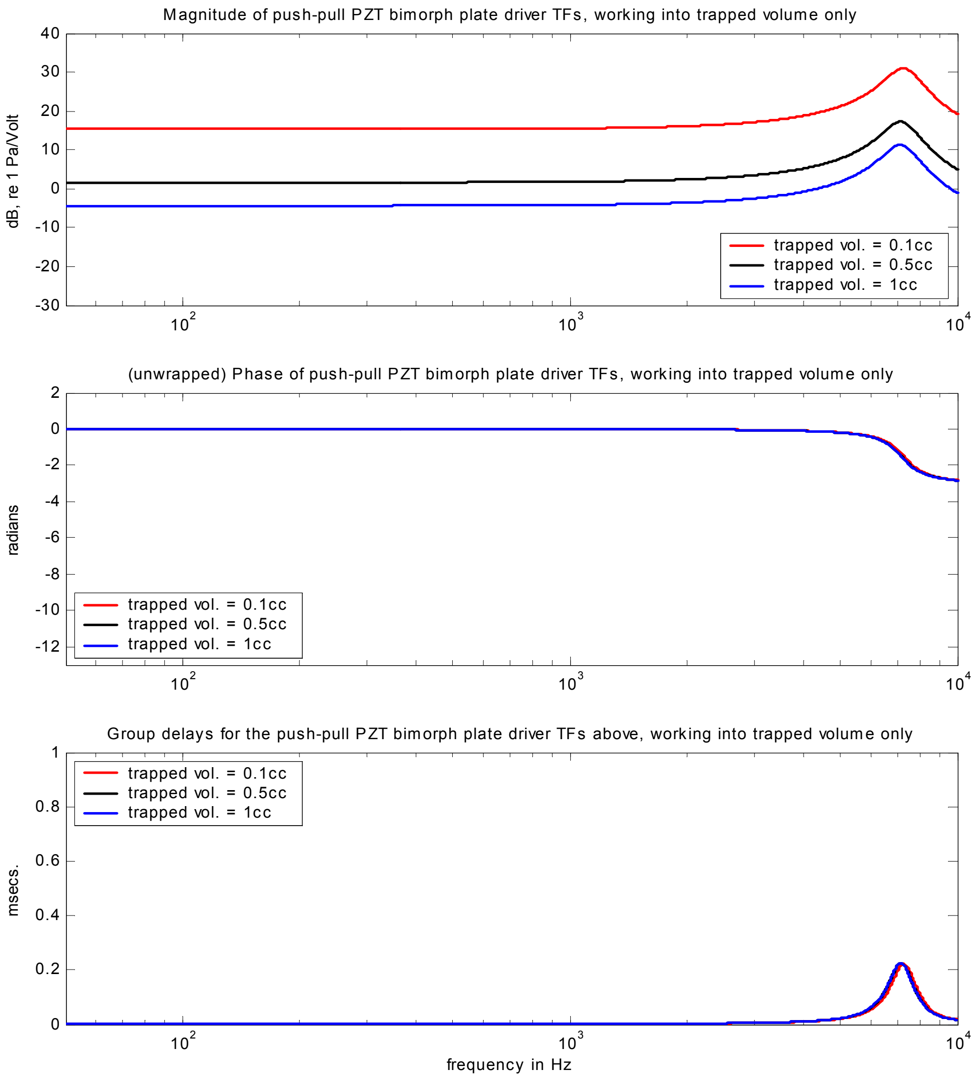

Figure 7: Performance of the push-pull piezoelectric bimorph driver calculated using the model in Figure 6. Low frequency sensitivity is about 95 dB/volt

4 SUMMARY AND CONCLUSIONS

Both the balanced armature and the piezoelectric bimorph designs appear promising as drivers for the ANR earplugs. Each has its limitations and advantages, but the bimorph design has a unique advantage. It is simpler in construction, and can be made smaller if desired, a property not shared with the balanced armature design.