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USE OF A WATER IMPEDANCE TUBE TO EVALUATE THE PERFORMANCE OF A SMART SKIN PISTON ELEMENT

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ABSTRACT

The concept of a smart skin embodies the philosophy of a multilayer structure that includes sensing elements, actuation elements and a controller. Such an embedded system has been developed for under water vehicle applications where the objective is the control of both near and far field noise. Acoustic/structural characterization is a necessary part of optimal design, however the simulation models available for prediction of the acoustic performance of complex structures such as these are inadequate. The transfer functions necessary for control of the piston actuator elements in the array skin are derived from direct experiment using a Water Impedance Tube. This paper describes the experimental system used, the analysis performed, transfer function results and their implications in active underwater acoustic control systems.

INTRODUCTION

The smart skin concept in this embodiment consists of a system that includes an array of piston elements covering the basic structural shell of the underwater vehicle. The array is continuous array over the surface with the piston element size dictated by the minimum wavelength of interest. Figure 1 shows the cross-section of a typical piston element. The key features that make it smart are a surface mount pressure sensor(piezo polymer) and accelerometer(piezoelectric), ceramic (electrostrictive) multilayer actuator elements and amplifier driver/control electronics in a backplane. Functionally, the sensor elements determine the local surface acoustic pressure and the head mass velocity, this data used by the local controller to drive the actuators effectively modifying the skin boundary impedance, thus achieving the desired acoustic field control.

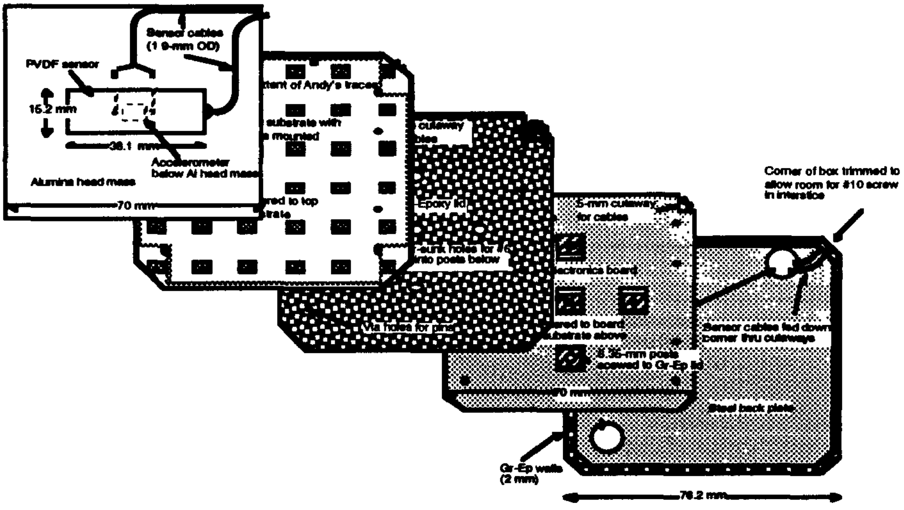

Figure 1. Smart Skin Piston Element Actuator Concept

The design of this smart skin to meet a performance specification requires a system model that includes the sensor transfer functions, the actuator response functions, the amplifier drive characteristics, the structural response of the supports, the coupling of the piston head to the water and the latency inherent in the control system. The actuator displacements are of the order of microns thus even the thickness and modulus of adhesive layers are significant variables. The available models of the complete system were inadequate to analyze the system variables and fabrication options with any veracity, thus experiment was necessary to assess the effect of design options within the project time constraints. The major design variables considered were 1) head mass thickness, 2) tail mass thickness and material type, 3) actuator chiplet formfactor, 4) structural mounting configuration.

FABRICATION SUMMARY OF WATER IMPEDANCE TUBE

The impedance tube, a.k.a., "Z" tube or Kundt's tube, is a device whose function is to determine the absorption coefficient and complex acoustic impedance (as a function of frequency) of a sample material with the acoustic wave at normal incidence)[1]. This technique is well known and used for material characterization in air and is the subject of many standards (e.g. ASTM, [2]). The measurement with a water column is more challenging, however, Corbett in his thesis [3] provides excellent insight into successful operation.

Physically, the device consists of a constant area tube, with a sound source at one end, and the test sample at the other. Sound is generated and the wave travels to the sample, constrained by the tube and is modified by the sample, some energy being reflected and some absorbed. The incident and reflected waves are measured by one or more microphones placed in the tube and the amplitude and phase of these waves are used to calculate the absorption coefficient and complex impedance.

Sound sources used are traditionally continuous wave (CW) being either single frequency or broadband random. In addition pulsed sources can also be used. The physics of the measurement are best described in CW terms. A standing wave is set up in the tube and the measurement technique requires an estimate of the standing wave ratio (the dB difference between maxima and minima) and the position of the minima with respect to the test sample face. The mathematics of the analysis is fully described in standard texts or can be found in the ASTM standard [2].

The tube requirements are that there be enough length to accommodate one standing wave (one half wavelength between minima) of the longest wavelength (lowest frequency) of interest, and a cross-section small enough such that the first crossmode of the shortest wavelength (highest frequency) of interest cannot propagate (i.e., it is "cutoff"). This ensures that only plane waves exist at all times. Ideally, the tube should not affect the measurement, i.e., only the sample should affect the sound field, thus no energy should be absorbed into or contributed by the tube itself. This is difficult to achieve in practice with a water medium, but can be minimized by careful design.

The impedance tube cannot simulate the scattering situation of any size of piston arrays. It cannot provide any information on the local or near field influence functions of piston arrays. It can provide a starting point for prediction based on the assumption of locally independent point sources. This is valid at low frequencies where the piston element is small compared to the wavelength.

The current impedance tube design shown in Fig. [2] contains water, with a length of 10 feet and cross-section nominally 3ins x 3ins. This results in the first crossmode with a cutoff frequency near 10 kHz. A pair of moving hydrophones are located at the tube center attached to a traverse that moves about four feet along the duct. The sound source is an underwater sound projector, and the sample end has a holder that is tailored for a piston element size of 3"x3". A PC based data acquisition system measures the RMS Sound Pressure Level, hydrophone position, and water temperature, which is controlled by a laboratory recirculating chiller. The z-tube is extruded aluminium, internally covered with a thin layer of closed cell foam which minimizes water to tube wall acoustic coupling.

Figure 2. Overall view of Water Impedance Tube

The piston sample holders (Figure 3) are of quick disconnect design, with a thin limp latex rubber diaphragm permanently mounted on the tube end to contain the water and protect any exposed electronics in the piston elements (a further parameter of interest to the program includes the effects of potting all or part of the piston elements with urethane type material). Edge coupling of the actuator head mass to the tube walls was controlled by use of a shallow taper on the sample holder and silicone rubber seal around the head mass edge. This enabled centering of the element and fluid sealing by progressive slight compression on insertion into the holder. Variation in the backplate mounting is also a design feature, the materials of interest varying from lead to steel and aluminium.

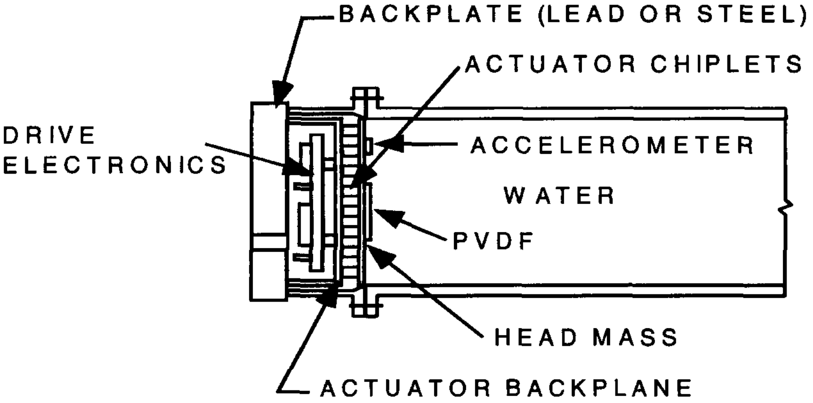

Figure 3. Cross-section of Impedance Tube Sample Section

The piston elements have pressure sensors and accelerometers mounted which are also recorded. In their passive mode, the measured acoustic impedance is a total system characteristic that includes the actuators, mounting boxes, base plate, electronic component masses etc. Thus the contribution of any one component can only be determined by a rigorous experimental sequence that systematically builds up (or removes) one effect at a time. For example, effects of base plate mounting, urethane encapsulation, head mass, quiescent bias voltage, structural support base posts, etc. all have specific transfer functions that need to be verified for use in model simulations.

In particular, the presence of a resonant frequency within the system response will be evidenced by strong reactive change in impedance, with high rates of phase change with frequency, shown as rapid movements of the standing wave minima and standing wave ratios.

SIGNAL PROCESSING SYSTEM AND TEST PLAN

The piston element has internal signal monitoring capability as well as surface pressure and head mass acceleration sensing. Voltages and currents to both input amplifier and actuator can be monitored and cross-correlated with head mass pressure and acceleration or with either of the two in-tube hydrophones. Signal output data was input to a dual channel analyzer (HP 3567) that calculated crosspower spectra and coherence. The primary excitation was broadband random noise, thus coherence spectra above 0.9 was indicative of valid data.

A series of single piston experiments in this one dimensional acoustic environment was designed to clarify major design issues in a representative environment. Reported here are representative data from a series of pistons each fabricated with a different critical parameter such as head mass, actuator chiplet type, or actuator board baseplate construction. Data for "before" and "after" head mass potting configurations were also taken. The test system incorporated water temperature control, piston component temperature monitoring, and all electrical signal parameter monitoring as well as the acoustic impedance parameters.

ACTUATOR CHIPLET OPTIMIZATION

Two types of actuator chiplets made by AVX were under consideration. The first (designated 1418) were optimized for performance, but were expensive and showed wide dimensional tolerances. This forces extensive size matching or lapping in an attempt to maximize power coupling through the adhesive bonds to the head mass. The second type, designated 1812, were produced more cheaply on a standard capacitor fabrication line with much higher quality and good dimensional tolerances. However, displacement output was 25% less. The experimental task was to assess the magnitude of overall system performance and verify the hypothesis that the 1812 configuration would be acceptable.

Figure 4 shows the transfer function magnitude between the PVDF pressure transducer and the input signal to the piston amplifier for each actuator chiplet type. The data confirms that the better 1812 coupling efficiency balances out the lower displacement, since power to the water is equal to or greater than the 1418 style over almost all the frequency range.

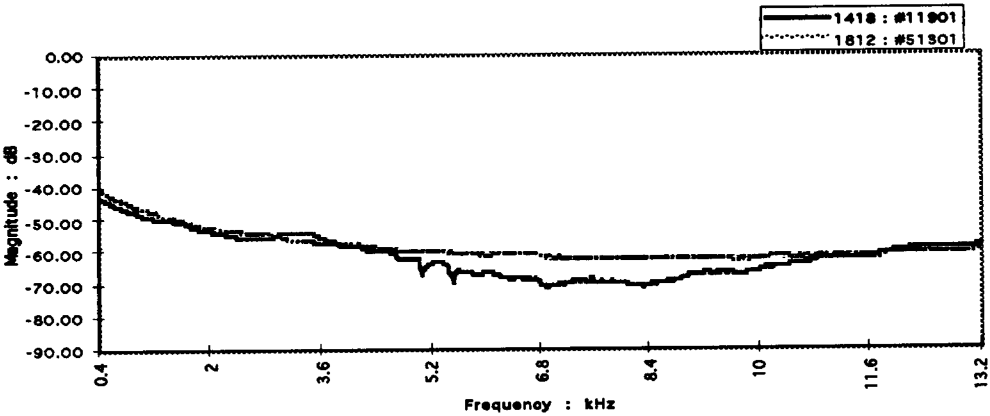

Figure 4. PVDF Data for 1418 and 1812 Style Chiplets Comparison

HEAD MASS EFFECTS

Two head mass thickness' viz., 0.1" and 0.025" (both made of alumina) were tested and the comparison data is shown in Figure 5 as differences in crosspower spectra of pressure and acceleration for each head mass thickness. Not unsurprisingly, the thicker headmass shows superior performance, being some 2-12 dB better over the frequency range. This effects can be ascribed to the thin head mass plates tending to deform or flex between the actuators, i.e. the whole is not acting as a uniform piston, thus subsequently contributing less power to the water as the frequency increases.

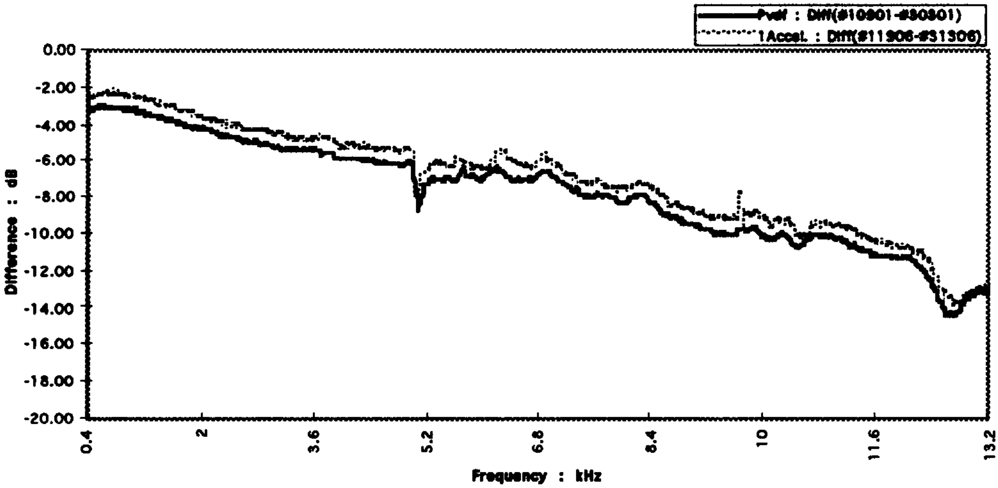

Figure 5. PVDF and Accelerometer Data Showing dB Difference Between Headmass Thickness of 0.10 in. and 0.025 in.

TAILMASS/BACKPLANE CONSTRUCTION

The actuator chiplets are mounted on a ceramic (alumina) circuit board (thickness 0.040"), which is bonded to a rigid structure, that itself reacts to the actuator forces. Alumina was originally selected for it's high modulus. However, the ceramic is brittle, with tendencies to hairline cracking, and processing (including actuator chiplet placement and wave soldering) expensive, thus a conventional fiberglass printed circuit board was evaluated as an option. Figure 6 compares the two options and shows the fiberglass accelerometer response to be consistently lower by 1 to 5 dB, increasing with frequency. While this deficit was deemed acceptable at low frequencies, it was marginal at higher frequencies. Subsequently, the margin was improved by mounting the actuator chiplets on a thin (0.015") fiberglass circuit board, thus exploiting cost and fabrication benefits.

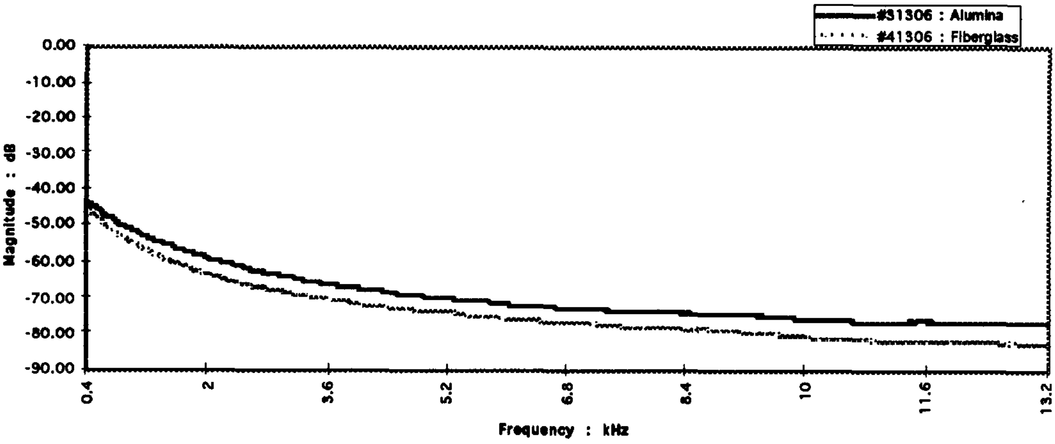

Figure 6. Comparison of Accelerometer Response of Alumina and Fiberglass Actuator Boards(0.040" thick)

STRUCTURAL RESONANCE ASSESSMENT

A number of models were exercised ranging from simple lumped parameter to complex finite element analysis in an attempt to determine where the structural resonance's were and to assess their impact on acoustic performance. However, these models failed to take damping into account, and could only agree with each other after questionable manipulation of critical parameters. The impedance tube resolved this issue. The basic experimental technique was to measure the complex acoustic impedance and look for the classic "step" in phase variations that are symptomatic of highly reactive(i.e. resonant) response conditions. Figure 7 shows the magnitude and phase of the impedance, and the linearity of the phase response clearly shows the lack of any significant resonant effects.

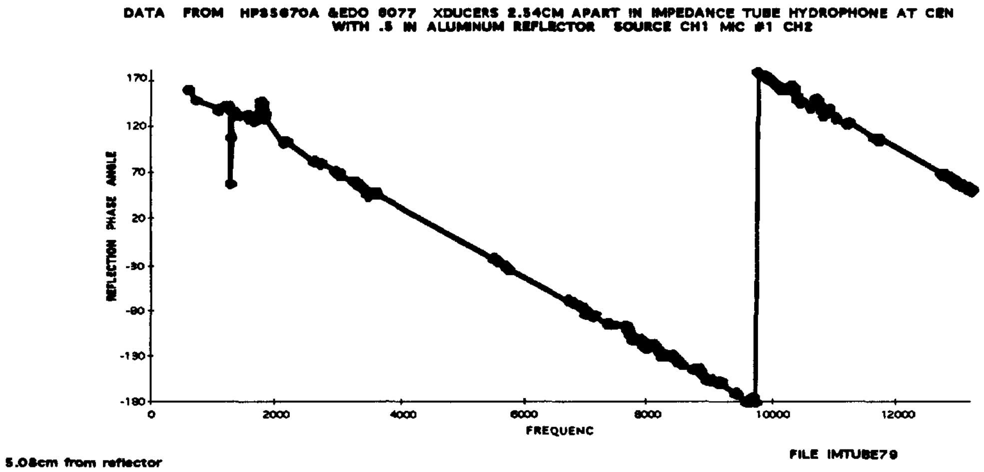

Figure 7. Phase Response of Piston Element Test Sample

CONCLUSIONS

A water impedance tube was developed for experimentally assessing the smart skin design and fabrication options. Both performance and cost are issues considered in the design. System simulations and overall performance models also benefit from incorporation of experimentally determined transfer functions. The next step is the use of the test system to evaluate noise control strategies for various acoustic pulse types incident on the test sample pistons. Using a pulsed source of sound requires the capture of the incident and reflected energy by the hydrophones, and calculating the attenuation (cancellation) on an amplitude or energy basis after removal of propagation (or time) delays in a dual channel analyzer or other digital signal processor. Thus active skin elements can be evaluated, their performance measured and modifications to these strategies explored easily at low cost.

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