THE DESIGN OF HIGH EFFICIENCY TRANSDUCER ELEMENTS AND ARRAYS

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Introduction

The detection of low frequency sound waves by parametric techniques has created a need for pump transducers capable of continuous generation of intense sound fields. The transducer must have good heat transfer to the surrounding media and minimum internal electrical and mechanical losses. A transducer element has been developed where the ceramic has excellent thermal contact with the water and the mechanical resonance has a high quality factor when not water loaded. Arrays built from the design to be described have a large power handling capability, and the measured directivity index is very close to the maximum calculated for the aperture.

Design Approach

The evaluation of various means of transducer element mountings and coupling to the water has been done in relation to the quality of resonance observed between the unloaded air response and the tone burst response when radiating sound in the water. The decay of a resonant system when a steady state drive is terminated allows a measurement of the energy loss per cycle indicated by the number of cycles, n, for the excitation to decay to 1/e of the steady state value, as shown in Figure 1. The Q of the circuit is given by the product $n \times \pi$. The result of loading a transducer element by water shows a significant change in the Q when the element is delivering a large proportion of its input power to the water load. The relative efficiency is indicated by the change in the Q value.

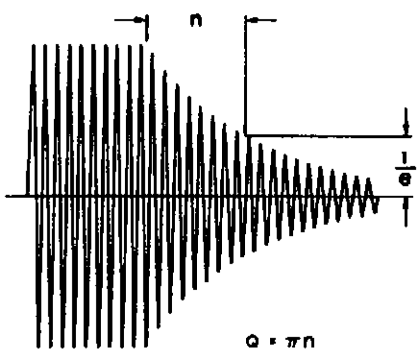

FIGURE 1
Q MEASUREMENT

An experimental program to determine a design with optimized loading efficiency has resulted in a practical and low cost construction technique. The first data base for the ceramic material was obtained by measuring the Q of a suitable cylinder form operated in axial mode resonance. A solid piece of PZT 8 or similar material was proportioned so that the radial mode frequency was higher than the axial length mode, the intention being to operate the transducer as a piston element at the lower frequency. A typical ceramic cylinder resonates with a Q of 75 to 120 in air. One such cylinder was mounted with a rubber suspension as shown in Figure 2. The face of the piston was covered with a thin layer of RTV rubber and the cylinder was held in place by "O" rings. The results were relatively good and the air loaded Q was reduced to 35. This allows an estimate of an equal division of power loss between the ceramic material and the suspension rubber. When the element was placed in water the Q further reduced to about 14 permitting an estimate of power division: 20% in ceramic, 20% in rubber, and 60% in the sound radiation. When the resonance is simple and the Q measurements are single valued, this set of data points can be used to estimate where the power from the driving amplifier is being expended. This particular mounting was subjected to a 10 W drive for about 10 min and the material failed due to overheating. The design investigation was now concentrated on removing the heat being generated in the ceramic.

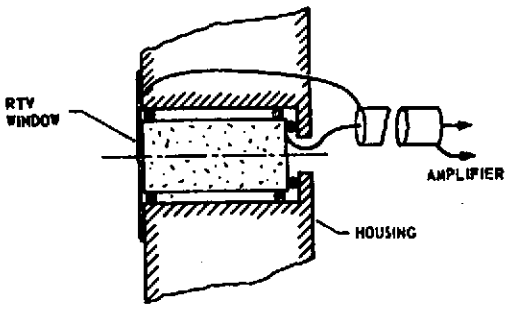

FIGURE 2
O-RING SUSPENSION

Element Development

It was obvious that the suspension of the element was causing mechanical losses and heat and that the heat was being retained in the ceramic. Since the basic vibration of such a cylinder is axial and the cylinder is a half wavelength long, there would be a primary node at the quarter wave point when operating at the fundamental frequency. To minimize mounting losses, the ceramic should be supported at this nodal point.

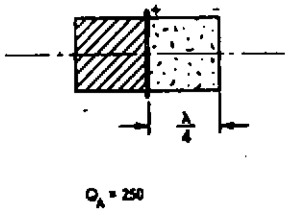

FIGURE 3
CERAMIC-BRASS RESONATOR

A simple way to do this is to replace half of the ceramic with a metal piston having an integral flange at the node. The flange would serve to suspend the transducer element in the housing. The resulting construction shown in Figure 3 now had an air resonant Q much higher than the ceramic alone; this is due to the higher quality of resonance in the quarter wave piston. Several other advantages were now apparent. The piston is solidly supported so that the transducer can be exposed to high hydrostatic pressure. The ceramic can be enclosed in a sealed, air-filled housing with nothing touching the surface to absorb power by mechanical friction. Acoustic radiation can not occur through the rear air loaded face of the ceramic so the front-to-back radiation ratio should be very high. The design problem now concentrated on how to couple the vibration from the metallic quarter wave piston to the water.

The piston was first mounted so that it was flush with the front of the transducer housing plate and various types of seals were applied to exclude the water. All such seals created significant mechanical losses. It was eventually found that removing the seal and allowing the entire quarter wave piston to be exposed to the water did not significantly diminish the operating quality. By allowing a totally exposed piston to be the radiating element the piston design parameters can include variations in shape as well as material. This freedom can be used to achieve an improved impedance match between the ceramic and the water; the shape can be used in array design where a large percentage of the aperture is active. The choice of the metal used for the piston greatly alters the operating Q and the resulting transducer bandwidth.

A set of pistons has been made of both brass and aluminum with conical flaring between the diameter of the ceramic driver and the radiating face. Flare angles were made in the range of 0 to 100°.

In each test sample the metal material was machined such that the resonant operating frequency was a constant, thus assuring that the ceramic was operating in the quarter wave resonance and the support flange was at the vibrational node. The correct operating frequency for a sample of ceramic is determined by axially attaching two identical pieces of ceramic with epoxy so that the assembly operates in the simple half wave resonance mode. When the metal piston is substituted for the two ceramic pieces, the ceramic/metal piston combination will be in proper resonance when the assembly is tuned to the same frequency. Typical elements tuned to 65 kHz provided a bandwidth of 4 to 5 kHz for brass pistons and 18 kHz for aluminum pistons. The relative Q measured by tone burst signals for the brass elements operated in air and in water are given in Figure 4. At the higher flare angles the edge becomes too flexible and decouples from the piston so the upper limit of 60° begins to show a rapid change in Q. The admittance diagram for a typical element is shown in Figure 5 for air and water loaded conditions.

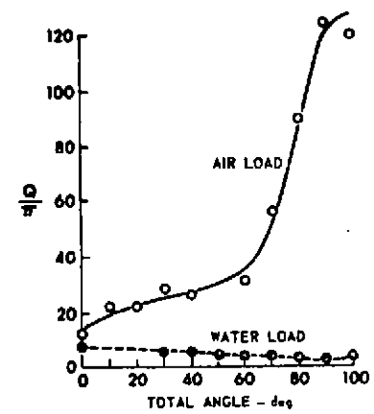

FIGURE 4
RESONANT QUALITY FOR VARIATIONS IN CONE ANGLE

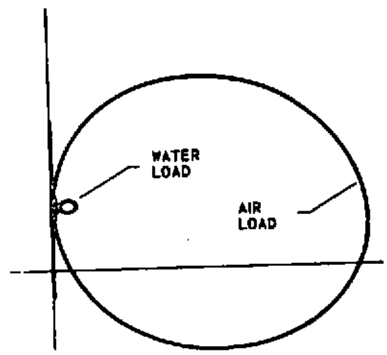

FIGURE 5
ADMITTANCE DIAGRAM

An element design using brass with 60° conical flare was subjected to a drive of 6000 Vp-p or about 70 W of electrical input. There was no apparent overheating after a period of continuous excitation at this high level. The metal piston coupled directly to the water forms an effective heat sink. The power capability of an array should approach the sum of the individual elements.

Several different arrays have been constructed using the brass piston assemblies with 60° conical angle. Since one electrode of the ceramic must be connected to the water it is necessary and actually beneficial to operate the array with half of the elements mounted with reversed polarity. This permits a balanced drive with the transducer housing electrically at water potential. Each half is connected in parallel and a center tapped transformer is used to couple to single ended circuits where required.

Arrays have been constructed with 4, 18, 84, and 432 elements arranged with equal spacing in a triangular cell. The outer perimeter is adjusted by choosing elements approximating a circular aperture. The pistons were machined on a turret lathe at a low cost per unit. The assembly was done with fast setting epoxy in a clamping fixture with rotational smearing to make the epoxy bond as thin as possible. Final tuning of each element was done in a lathe while dynamic measurement of resonant frequency was done with a sweep generator and oscilloscope. Elements were secured by conductive epoxy to a housing plate having a machined hole, with the necessary shoulder to support the water pressure. The backing plate was in contact with the housing plate around each mounting hole so that great depth capability was obtained. Tests show that such a construction can withstand about 2000 psi before the support flange is crushed. Electrical bus bars are mounted in machined slots connecting each row of mounting holes insulated with Teflon tubing. Small wires connect to each element from the bus bars. After assembly the entire face seal is made by flowing epoxy into annular grooves around each element and its integrally machined flange mounting. The face could be better protected by adding a window and filling the space with liquid, but such is not necessary for proper operation.

A photograph of an array having 84 elements is given in Figure 6 and the measured beam pattern is shown in Figure 7. Note that the pattern is well controlled and there is very little radiation to the rear. The side lobe at about 60° looks small but it actually contains about 10 percent of the total radiated power. The transmitting sensitivity is

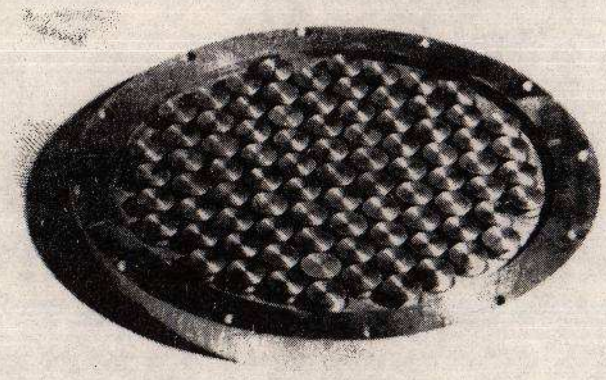

FIGURE 6
84-ELEMENT ARRAY

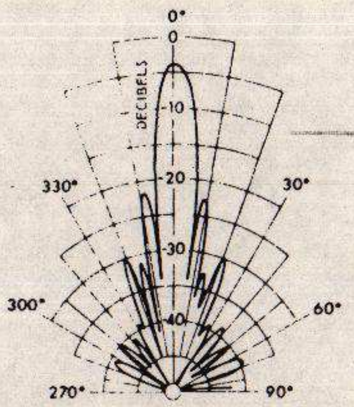

FIGURE 7
POLAR RESPONSE 84-ELEMENT ARRAY

about 201 dB (re 1 μPa at 1 m) for an input power of 1 W electrical. Assuming an electrical to acoustic efficiency of near 100%, a directivity index of near 30 is indicated. The physical aperture size indicates the same directivity and the measured beam major lobe size is in agreement. It would appear that the array performance is within 1 dB of perfect electrical to acoustic conversion. At this level of efficiency it is quite difficult to make measurements of sufficient accuracy to specify a value for the power conversion.

All indications are that the design gives excellent results and the construction is simple and low cost. There are no special techniques or skills required and the parts can be built in a rather modest machine shop. For any given application, the material should be chosen for the environment and adjusted for the desired bandwidth by mechanical and electrical tuning. The development of a simple high efficiency transducer element has made possible the continuous radiation of an intense acoustic beam with a modest electrical power input.