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Cavity-Loaded Piston Resonators

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A piston-type resonant element for use in underwater sound-transducer arrays is described. The acoustic loading on the piston is varied by the use of a shallow cavity. The element is stable under high hydrostatic pressure, and its efficiency is higher than 90% over a broad bandwidth. An equivalent circuit that successfully reproduces the measured characteristics of the transducer is developed.

INTRODUCTION

A SHALLOW cavity will vary the load impedance on a piston in somewhat the same manner that a horn does. The radiation resistance can be increased to a value several times that of a plane piston of equal area, and the bandwidth of a resonator can be increased by loosely coupling a cavity resonance to the mechanical resonance.

The use of a cavity to load piston elements may offer a practical solution to the problem of mutual impedances in arrays because each element can be heavily loaded without support from surrounding members. The "packing factor" can be reduced without unloading the elements, and elements can be spaced far enough apart so that there is little or no mutual impedance. When a high packing factor is desirable for the radiation of more power with a specified directivity, the various elements can be acoustically tuned, which will possibly improve the characteristics of the array. At least the cavity allows acoustical tuning in addition to electrical tuning, which makes the system more versatile. Also, this technique permits the production of higher acoustic power with less mechanical strain on the joints and ceramic than does a plane piston.

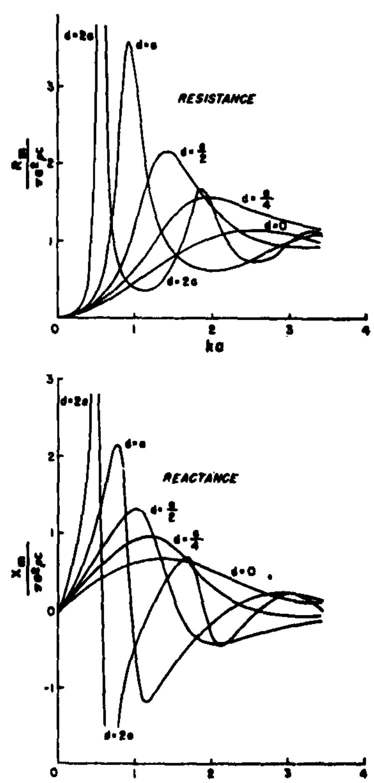

FIG. 1. Acoustic impedance at the piston face for a cavity with a flange as a function of wavenumber. R_m and X_m are acoustic resistance and reactance, d=depth of cavity, a=radius of cavity, k=wavenumber, ρ=density of water, and c=speed of sound in water. The condition $d=0$ corresponds to a circular plate in an infinite baffle. (Data taken from Nomura and Inawashiro, reference 1.)

THEORY

The impedance at the piston face for a cavity with a flange is given by Nomura and Inawashiro[1] as shown in Fig. 1. It can be seen from this that, with proper choice of dimensions, a mechanical resonator can be made to drive the acoustical cavity resonance for which the radiation resistance is several times ρcA for a small piston. Some degree of detuning of the two resonant systems has the effect of increasing the bandwidth. The system described here was designed so that the mechanical resonance in air occurred at $ka\approx 1.1$. The curves of Fig. 1 show that the cavity can be tuned to give a wide variety of characteristics around this ka number.

The mechanical resonator shown in Fig. 2 consists of a stack of PZT–4 ceramic disks driving an aluminum horn, backed by a steel mass that effectively clamps the motion at the rear. The resonator was designed for good efficiency by reducing the losses caused by shearing of rubber in the water seal. The center of gravity of the resonator is centered between the two O rings on the back mass; the O-ring seal is thus relieved of the weight of the front mass, and there is less rubber and less clamping at the point of maximum velocity. When the tube is oil-filled, this front O ring is eliminated. The use of disks instead of a cylinder for the active element results in more rugged construction and higher coupling coefficient.

[1] Y. Nomura and S. Inawashiro, "On the Acoustic Radiation from a Cylindrical Cavity with Vibrating Piston at the Bottom," Sci. Rept. Research Inst. Tôhoku Univ., Ser. B 12, No. 21, 126 (1960).

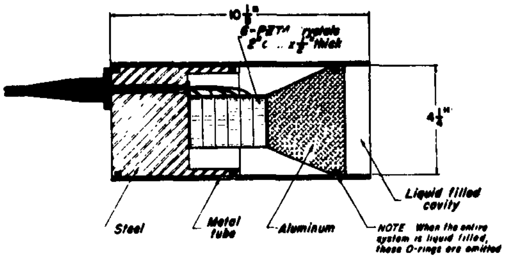

FIG. 2. USRL type G15 resonator.

The equations for the cavity in the end of a long tube without a baffle were not available. To approximate the impedance for this condition the cavity was assumed to be a short transmission line and the Mason approximation[2] for the analog of a transmission line was coupled to the analog of the radiation load for a piston in an infinite baffle.[3] The impedance of this analog is in good agreement with the theoretical curves as shown in Fig. 3, which indicates that the Mason approximation adequately represents the cavity impedance. The radiation impedance for the unflanged long tube[3] was then coupled to the cavity analog, which allows the use of the equivalent circuit given in Fig. 4 for the entire system; if it is assumed that the back mass blocks the motion, the cavity walls are stiff, and the acoustic impedance of the annular gap between the cylinder wall and the aluminum horn is very high. The measured characteristics of the resonator with a 1½-in.-deep water-filled cavity are shown in Fig. 5 along with the measured

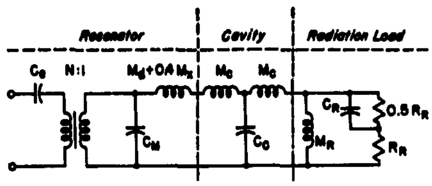

FIG. 4. Equivalent circuit for resonator system, assuming clamped drive and 100% efficiency. C_e = electrical capacitance of free ceramic element; C_M = open-circuit compliance of ceramic; M_A = mass of aluminum horn; M_s = mass of ceramic stack; $M_c = \frac{1}{3}\rho A d$, where ρ is the density of water, c is the speed of sound in water, and d is the depth of the cavity; $C_c = (8/\pi^2)(d/\rho c^2 A)$, where A is the area of the cavity; M_R, C_R, and R_R are empirically derived approximations to the radiation load; N = transducer turns ratio.

characteristics of the analog circuit. The agreement is good, which shows that the cavity loading is properly represented.

MEASUREMENTS

Considerable data have been taken on the basic resonator with different cavities and tubes, with the tube liquid filled and air filled, at various static-pressure levels. The curves of Fig. 5 are for a thick-walled tube with a 1½-in.-deep water-filled cavity, air in the tube, sealed with a small O ring at the cavity. The fairly close coupling between the mechanical and acoustical resonant systems in this condition produces the smooth, low-Q output.

Measurements made with a thin brass case indicate that the wall rigidity of the cavity influences the amount of coupling between the mechanical and acoustical

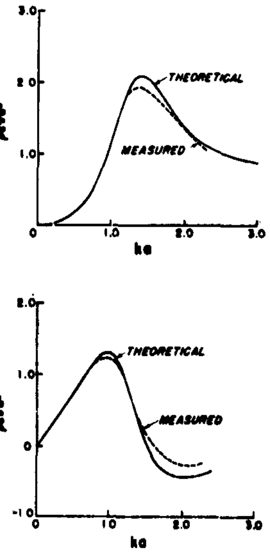

FIG. 3. Theoretical impedance of a cavity whose depth is half its radius, and measured impedance of its analog. The cavity is in an infinite baffle. R_m and X_m are resistance and reactance, a = radius of cavity.

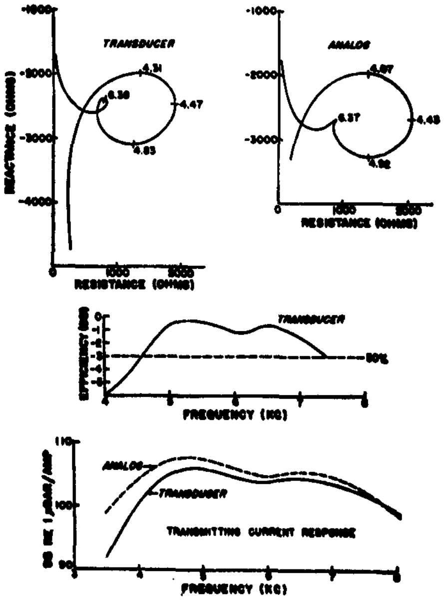

FIG. 5. Characteristics of a 1.5-in. cavity resonator transducer and its analog.

[2] W. P. Mason, *Electromechanical Transducers and Wave Filters* (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1942), pp. 205–206.

[3] L. L. Beranek, *Acoustics* (McGraw-Hill Book Company, Inc., New York, 1954), p. 121.

resonances. The characteristics of the resonator in a ⅛-in.-thick air-filled brass tube are shown in Fig. 6. The cavity is water-filled and the transducer is tuned with an 80-mH inductor. The efficiency is good through the whole bandwidth, because resistance and response are changing with frequency in the same direction.

Figure 7 shows the response of the thin-walled unit completely filled with an electrical insulating oil. The greater spread between the two peaks in this condition is believed to be caused by the differences in bulk modulus and density of oil and water; however, this has not been fully investigated as yet. Acoustic power output higher than 400 W at 4 kc has been produced at high hydrostatic pressure with the oil-filled resonator. This is about 4.5 W/cm². At low hydrostatic pressure, the instrument has been driven with cw at cavitation for several minutes without apparent damage. The char-

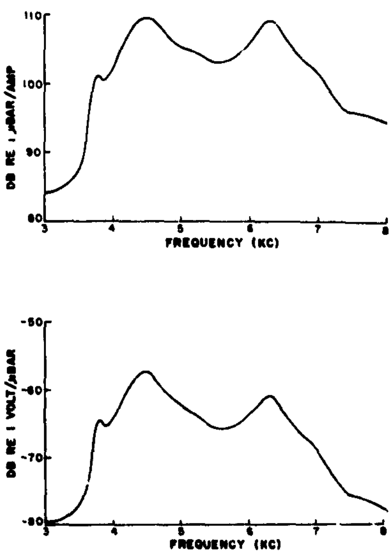

FIG. 6. Transmitting current response (above) and free-field voltage sensitivity (below) of thin-walled tube with 1-in. cavity, without oil, 80-mH inductance in series.

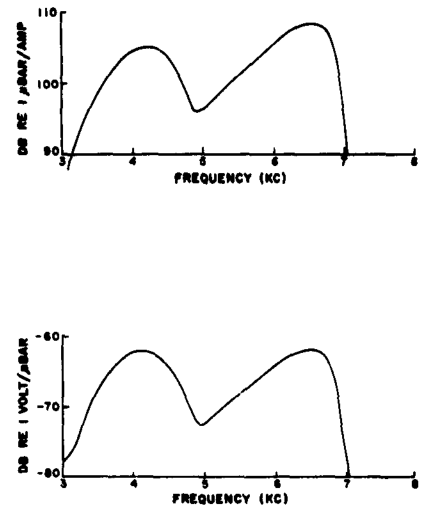

FIG. 7. Transmitting current response (above) and free- voltage sensitivity (below) of thin-walled tube with 1-in. ca oil-filled, no electrical tuning.

acteristics of the heavy-walled oil-filled tube did change with hydrostatic pressure to 1000 psi.

The directivity factor is slightly greater with cavity than with a plane piston in a long tube. The b radiation is apparently quite well blocked even with back mass in contact with the water. If the back r ation is not completely reduced, it can be eliminatec the addition of an oil cavity and mass on the back. back radiation varies more through the 4 to 7 kc re with the cavity than would be expected for a p piston. These effects have not been analyzed.

CONCLUSION

A conventional piston resonator can be made to l high efficiency and broader bandwidth by the addi of a shallow cavity. The cavity also provides a fle acoustic load with the possibility of a mechanical-tu technique in addition to electrical tuning.