Finite Element Analysis of the Cymbal-Type Flextensional Transducer

James F. Tressler, Wenwu Cao, Kenji Uchino, *Member, IEEE*, and Robert E. Newnham, *Member, IEEE*

***Abstract*—The effect of material properties and dimensional changes on the fundamental resonance frequency of the cymbal transducer has been investigated using the ANSYS® finite element software. Vibration mode shapes, resonance frequencies, and admittance spectra for both air- and water-loading are calculated. Very good agreement is observed between the modeled and experimentally measured admittance spectra in the frequency range up to 200 kHz, establishing the validity of the model. The calculations show that the fundamental resonance frequency can be manipulated easily by changing the cymbal cap material or dimensions.**

I. Introduction

Flextensional transducers have seen a resurgence in interest in recent years as low frequency (i.e., typically less than 5 kHz) moderate to high acoustic output power underwater electroacoustic projectors [1]. Flextensionals consist of a piezoelectric or magnetostrictive ring, disk, or stack sandwiched between and mechanically coupled to curved metal shells or plates. Unfortunately, they are typically quite large in size and heavy.

The so-called moonie and cymbal type transducers are essentially miniaturized versions of flextensionals. These patented designs were originally developed as high sensitivity hydrophones and micropositioning actuators [2]–[5]. The only difference between the moonie and cymbal is in the shape of the caps. Their cross-sectional views, including the standard dimensions, are compared in Fig. 1. The operational principle of the moonie and cymbal are the same: the caps convert and amplify the small radial displacement and vibration velocity of the piezoceramic disk into a much larger axial displacement and vibration velocity normal to the surface of the caps. Conversely, the caps can mechanically transform and amplify an incident axial direction stress, such as from a weak hydrostatic pressure wave, into a much larger radial direction stress, thereby enhancing the electrical charge developed on the electrodes of the piezoceramic disk. The advantages of the cymbal transducer over the moonie design include an easier and less expensive fabrication procedure as well as more easily tailorable performance characteristics. The fabrication procedure has been detailed previously [4], [5].

Manuscript received September 19, 1997; accepted February 9, 1998. Financial support was provided by the Office of Naval Research, contract number N00014-96-1-1173.

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Various classes of flextensional transducers have been modeled by finite element methods quite extensively [6]–[9] as has the moonie design [3], [10]. This paper will report the results of FEA on the cymbal and compare them with experimental data where possible. Particularly, the effect of materials and design parameters on resonance frequency and admittance spectra will be described.

II. Finite Element Modeling

A. Principle

The purpose of finite element analysis is to numerically solve complex partial differential equations so as to mathematically describe, or predict, the physical behavior of an actual engineering system under various loading conditions. FEA allows the designer to manipulate and test the effects of all the possible design variables using computer analysis rather than by the more tedious alternative of actually building and testing prototype designs. Finite element analysis of the cymbal transducer was performed using the ANSYS® software package version 5.1 (Swanson Analysis Systems, Inc., Houston, PA) using a SPARC-10 workstation. In addition to the standard structural analyses, this modeling code also has the capability of modeling coupled-field phenomena (e.g., piezoelectricity) as well as acoustic fluid and fluid-structural interface effects. A complete theoretical treatment of the finite element method, including derivation of the structural matrices, etc., can be found in the ANSYS User's Manual [11] or in a large number of texts written on the subject. Basically, it is assumed that the structure being modeled consists of a finite assembly of elements that are meshed by a series of nodes. A load only can pass through these nodes.

ANSYS version 5.1 has the capability of performing six different types of structural analysis: static, harmonic, transient dynamic, modal, spectrum, and buckling. Harmonic analysis ascertains the steady-state response of a structure to loads that vary sinusoidally with time. In this case, the structural response is calculated at several different frequencies and a graph of the response output versus frequency is generated. Modal analysis is used to determine the natural frequencies and mode shapes of a structure. In this paper, only results from these two types of analyses will be discussed.

B. Procedure

Because the cymbal transducer exhibits axisymmetry about its central axis, it was modeled as a two-

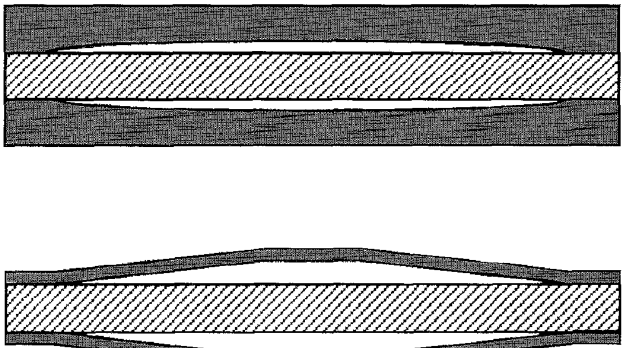

Fig. 1. Cross-sectional views of the moonie-type (top) and cymbal-type (bottom) transducers. The cross-hatched area represents the PZT disk and the dark areas are the metal caps. Standard dimensions for the moonie are: PZT thickness = 1.0 mm, cap thickness = 1.0 mm, maximum cavity diameter = 9.0 mm, maximum cavity depth = 0.3 mm, overall diameter = 12.7 mm. The cymbal standard dimensions are: PZT thickness = 1.0 mm, cap thickness = 0.25 mm, base cavity diameter = 9.0 mm, apex cavity diameter = 3.0 mm, maximum cavity depth = 0.3 mm, overall diameter = 12.7 mm. The standard PZT type is PZT-552 (similar properties to a PZT-5H) from Piezokinetics (Bellefonte, PA).

dimensional axisymmetric body. A two-dimensional axisymmetric model offers the advantage over the corresponding three-dimensional model in that the size of the model is smaller and consequently calculation time is much less.

A cymbal transducer consists of three parts: the metal caps, the active piezoelectric element, and an epoxy adhesive. For the caps and the epoxy, it was assumed that their material properties were linear and isotropic. The piezoelectric properties were taken to be linear and anisotropic. The values of the requisite material properties necessary for this analysis are listed in Table I. The boundary conditions were such that any translational motion of the model was prohibited and the appropriate symmetry conditions were flagged. In addition, a damping coefficient, which has to be obtained empirically, was included. When including the effects of water loading, the amount of water modeled was determined from the radiation impedance associated with a rigid circular piston located within an infinite baffle [12]. Assuming the piston (i.e., the cymbal) is small relative to one wavelength, the piston added mass term (from the water) approaches a constant value of $(8/3)\rho a^3$, where ρ is the density of the medium and a is the outer radius of the cymbal cap. This term is equivalent to the mass of a cylinder of the acoustic medium with the same radius as the cymbal and a height of $8a/3\pi$, which is the minimum height of water over the surface of the cymbal that needs to be modeled (in this case is ≈ 6 mm). A radiation boundary was included at the edge of the water layer to prevent reflection of acoustic energy.

Unless otherwise noted, the results reported in this paper are for brass-capped cymbal transducers with the dimensions given in the caption of Fig. 1. The cymbal vibration modes, the in-air and in-water fundamental resonance frequencies, and a demonstration of the capability of generating the in-air and in-water admittance spectra by FEA will be shown.

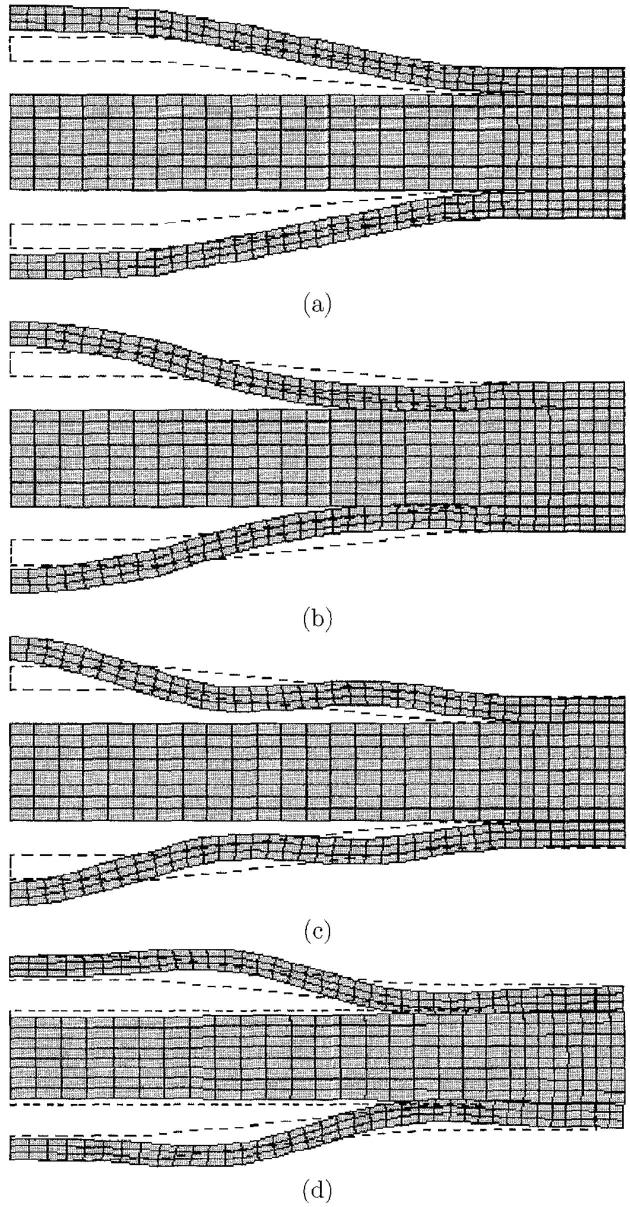

Fig. 2. Calculated vibration mode shapes (exaggerated scale) of the cymbal transducer. (a) is the $(0, 1)$ mode, (b) is the $(0, 2)$ mode, (c) is the $(0, 3)$ mode, and (d) is the PZT radial mode. The dashed lines show the structure at rest.

III. Modeling Results

A. Vibration Modes

Fig. 2 shows the calculated cymbal cap vibration mode shapes corresponding to the $(0, 1)$, $(0, 2)$, $(0, 3)$, and PZT disk radial modes. The modes are designated by the ordered pair (m, n) where the integer m is the number of

TABLE I
VALUES OF THE MATERIALS PROPERTIES USED IN THIS ANALYSIS[1].

Cap material[2]	ρ (kg/m^3)	E (GPa)	σ	
Aluminum (Al)	2700	70.6	0.345	
Brass	8550	100.6	0.35	
Titanium (Ti)	4500	120.2	0.361	
Steel	7860	207.0	0.30	
Molybdenum (Mo)	10,200	324.8	0.293	
Tungsten (W)	19,300	411.0	0.28	
Epoxy[3]	1430	2.5	0.36	
PZT type[4]	ρ (kg/m^3)	ε_{33} (nF/m)	e_{31} (C/m^2)	s_{11} (pm^2/N)
552	7500	13.0	−6.59	16.5
5A	7750	7.35	−6.8	16.4
4	7500	5.62	−5.2	12.3
8	7600	5.31	−3.0	11.5

[1] ρ = density, E = Young's modulus, σ = Poisson's ratio, ε_{33} = permittivity, e_{31} = piezoelectric stress coefficient, s_{11} = elastic compliance.
[2] E. A. Brandes, Ed., *Smithell's Metals Reference Book*, 6th ed. New York: Brandes, Butterworth, 1983, Table 15–1, pp. 15.2–15.3.
[3] *Eccobond® 45LV Technical Data*, Emerson & Cuming, Inc., Woburn, MA 1989.
[4] For a complete listing of all the required stress coefficients and elastic compliances, see *Piezoelectric Technology—Data for Designers.* Vernitron Piezoelectric Division, San Diego, CA.

radial node lines and the integer n is the number of azimuthal nodal circles. Because a two-dimensional axisymmetric body was modeled in this analysis, the cap vibration always will be symmetric, hence m is always zero. The $(0, 1)$ mode is known as the first, or fundamental, vibration mode of the cymbal caps. The frequency of the vibration modes depends on the cap material and geometry and will be discussed in further detail in later sections.

B. Admittance Spectra

The calculated and experimentally measured admittance spectra of a standard size brass-capped cymbal with dimensions described in Fig. 1 are compared in Fig. 3. Satisfactory agreement is observed between the two, indicating that ANSYS models the cymbal behavior quite nicely in-air. When in-water, the fundamental resonance shifts to a lower frequency due to mass loading as described in Section II. The calculated and experimentally obtained admittance spectra in the neighborhood of the first resonance frequency for in-air and in-water conditions are compared in Fig. 4. Again, excellent agreement is observed between the measured and calculated in-air and in-water results.

C. Resonance Frequencies

1. PZT Type and Thickness: As evidenced by Fig. 5, the fundamental resonance frequency is affected very little by either the type of PZT driving element used or its thickness. In general, the cymbals driven by piezoelectrically hard PZT (e.g., 4 or 8) exhibit about a 1 kHz higher resonance frequency than those driven by a soft PZT (e.g., 5A or 552). The resonance frequency appears to reach a constant value when the PZT thickness exceeds about 2.5 mm

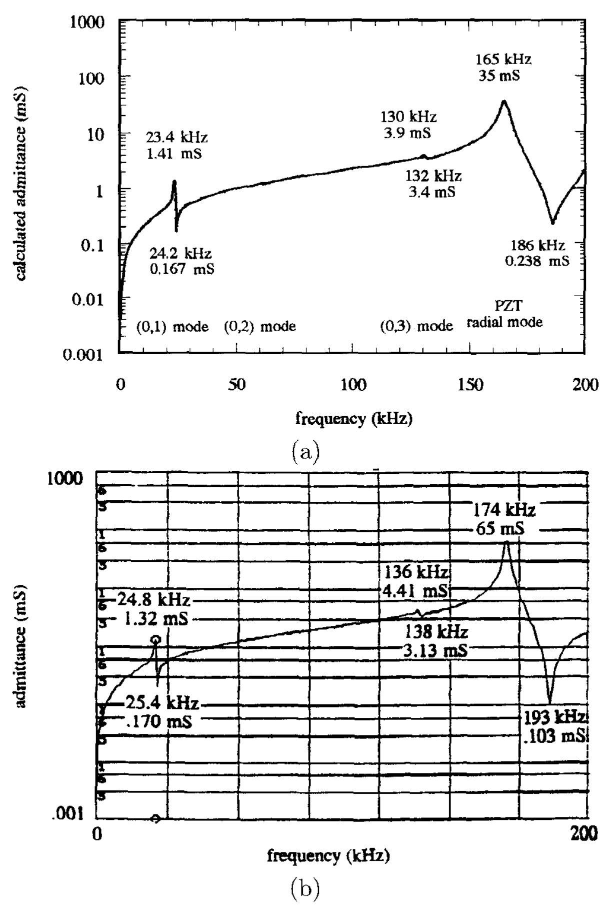

Fig. 3. (a) Calculated and (b) experimentally measured admittance spectra for a standard size brass-capped cymbal transducer in-air.

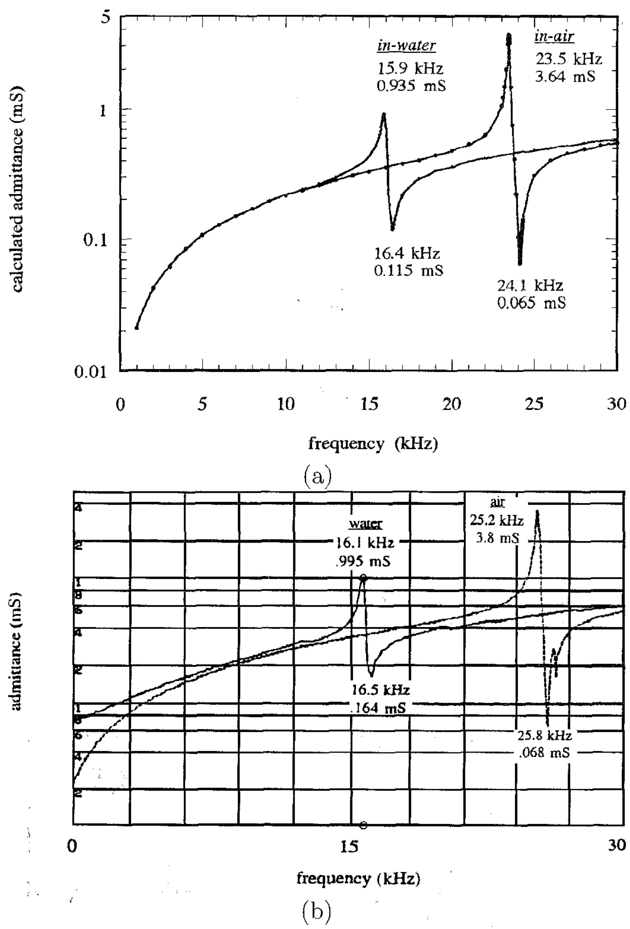

Fig. 4. (a) Calculated and (b) experimentally measured admittance spectra in the neighborhood of the first resonance for a standard size brass-capped cymbal transducer both in-air and in-water.

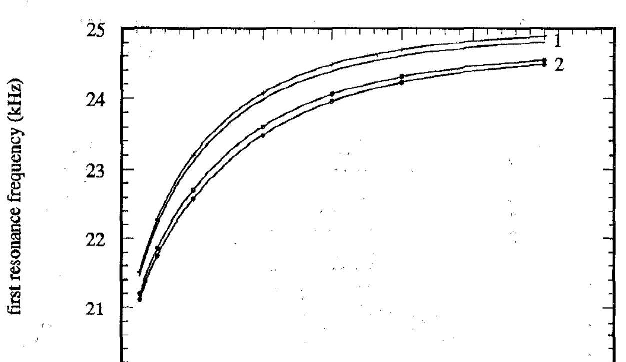

Fig. 5. Calculated thickness dependence of the first resonance frequency of brass-capped cymbal transducers with standard size brass caps with different types of PZT disks. The numeral 1 corresponds to curves associated with PZT-8 (upper) and PZT-4 (lower). The numeral 2 corresponds to curves associated with PZT-5A (upper) and PZT-552 (lower).

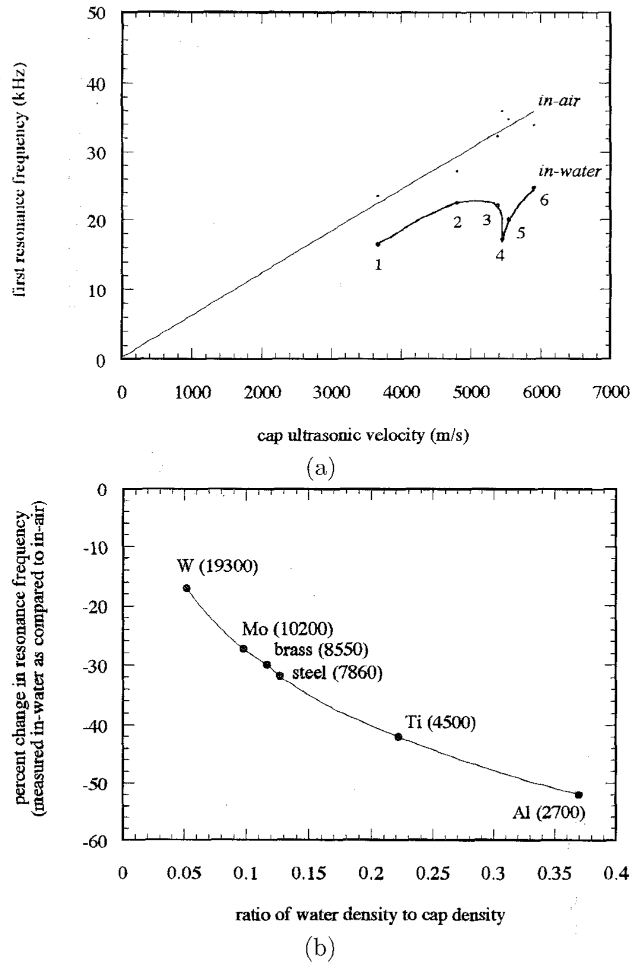

Fig. 6. (a) Effect of cap material on the first resonance frequency of standard size cymbals both in-air and in-water: 1 = brass caps, 2 = tungsten, 3 = steel, 4 = aluminum, 5 = titanium, and 6 = molybdenum. (b) The percent change in first resonance frequency from in-air to in-water as a function of the ratio of water density to cap material density. The numbers in parentheses are the cap densities in terms of kg/m^3.

and decreases by about 15% for very thin drive elements due to an overall reduction in stiffness of the structure.

2. Cap Material: For transducers with caps of equal dimensions made with different materials, the fundamental resonance frequency is proportional to the ultrasonic velocity of the cap material, or $\sqrt{E/\rho(1-\sigma^2)}$ (symbols defined in Table I). The resonance frequency is plotted as a function of cap velocity in Fig. 6(a). The results show that, for a transducer of fixed size, the first resonance frequency can be easily adjusted simply by changing the cap material. Included on the plot is the resonance frequency when the transducer is water-loaded. The linear trend in the data is no longer observed. This is due to the variation in the densities of the cap materials. Equation (1) shows how the in-water resonance frequency ($f_{r,w}$) can be

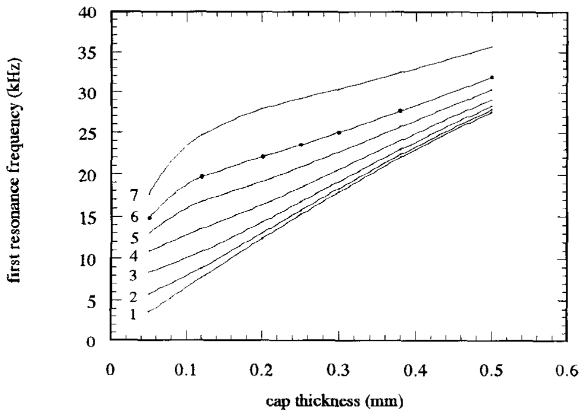

Fig. 7. Effect of cap thickness on the first resonance frequency of brass-capped cymbal transducers with different cavity depths. Curves associated with different maximum cavity depths, d_c, are represented by the numerals 1–7. 1, $d_c = 0.02$ mm; 2, $d_c = 0.07$ mm; 3, $d_c = 0.12$ mm; 4, $d_c = 0.18$ mm; 5, $d_c = 0.25$ mm; 6, $d_c = 0.30$ mm; 7, $d_c = 0.47$ mm.

calculated from the in-air resonance frequency $(f_{r,a})$ [13].

$$f_{r,w} \approx \frac{f_{r,a}}{\sqrt{1 + \left(\frac{8\phi}{3\pi}\right)\left(\frac{\rho_w}{\rho_c}\right)\left(\frac{0.7885}{t}\right)}}. \tag{1}$$

It is based on curve deflection theory for a thin plate clamped around its rim. The term 0.7885 arises from this boundary condition. In the equation, ϕ represents the cavity diameter at the base of the cap, t is the cap thickness, ρ_w is the water density, and ρ_c is the cap density. Plotting the percent change in resonance frequency when going from in-air to in-water as a function of the ratio of the water density to the cap density, the predicted one over square root behavior is observed [Fig. 6(b)]. Essentially, these data show that cymbals with cap materials which have a density closer to that of water (e.g., aluminum) will exhibit a much more marked shift in its fundamental resonance frequency when immersed in water than a cymbal capped with a higher density cap material, such as tungsten.

3. Cap Thickness and Cavity Depth: Fig. 7 shows the effect of cap thickness and maximum cavity depth on the first resonance frequency of the cymbal transducer in-air. The results clearly show that as cap thickness decreases, the first resonance frequency decreases linearly until very thin (< 100 μm) caps are reached. In contrast, as cavity depth increases, the first resonance frequency increases due to an overall increase in the stiffness of the cap. When water loaded, the graphs will exhibit the same trends, albeit with the fundamental resonance frequencies shifted down due to mass loading. The percent change in resonance frequency in going from air- to water-loading will increase for thinner caps, as predicted by (1), whereas the cavity depth has no effect.

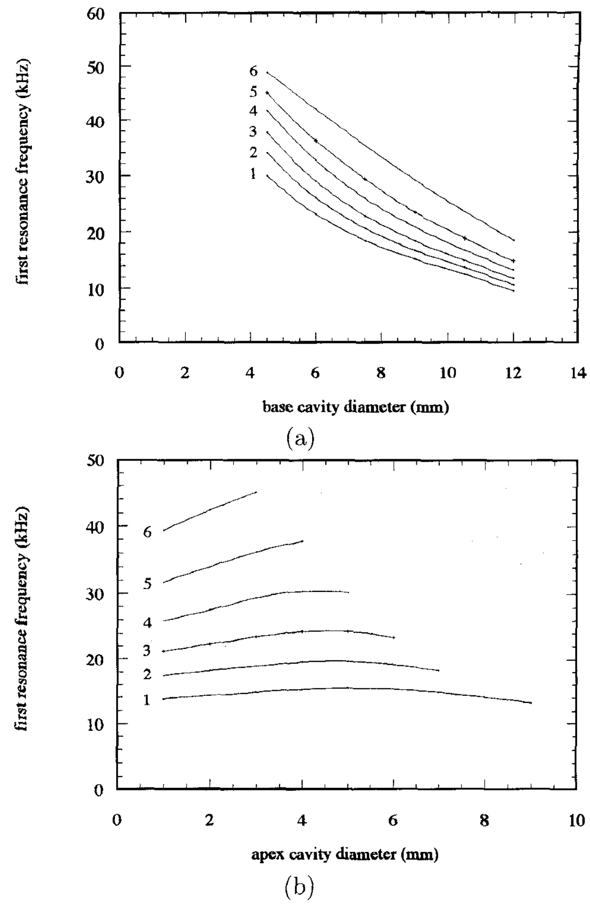

Fig. 8. Effect of (a) base cavity diameter associated with different maximum cavity depths on the first resonance frequency of a brass-capped cymbal transducer. Curves associated with different maximum cavity depths, d_c, are represented by the numerals 1–6: 1, $d_c = 0.02$ mm; 2, $d_c = 0.12$ mm; 3, $d_c = 0.18$ mm; 4, $d_c = 0.25$ mm; 5, $d_c = 0.30$ mm; 6, $d_c = 0.47$ mm. (b) Effect of apex cavity diameter associated with different base cavity diameters (ϕ) on the first resonance frequency. Curves associated with different base cavity diameters (ϕ) are represented by the numerals 1–6: 1, $\phi = 12$ mm; 2, $\phi = 10.5$ mm; 3, $\phi = 9.0$ mm; 4, $\phi = 7.5$ mm; 5, $\phi = 6.0$ mm; 6, $\phi = 4.5$ mm.

4. Cavity Diameter: When keeping the device diameter constant, changes in the base cavity diameter have the greatest effect on the resonance frequency as compared with all other parameters [Fig. 8(a)]. For the standard size brass-capped cymbal, the resonance frequency can be manipulated from about 10 to 50 kHz when changing the cavity diameter from 12 to 4.5 mm and the cavity depth from 0.02 to 0.47 mm. Again, the water-loaded resonance frequency will be lower than the in-air value due to mass loading. The shift down can be calculated from (1), in which the percent change in resonance frequency will increase as the base cavity diameter increases. Changes in the cavity diameter at the apex of the cap typically have a smaller effect on the resonance frequency, especially for large base cavity diameters [Fig. 8(b)].

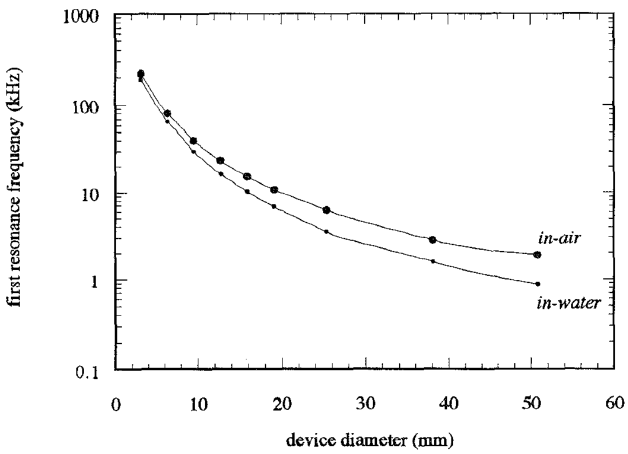

Fig. 9. Effect of device diameter on the first resonance frequency of the brass-capped cymbal transducer. The overall thickness is maintained at ≈ 2 mm. The water-loaded resonance frequency is shown for comparison.

5. Device Diameter: The effect of device diameter on the fundamental resonance frequency is shown in Fig. 9. The total height of the transducer was kept constant at nearly 2 mm while the radial dimensions were scaled proportionally. These results show that a two order of magnitude increase in total diameter (from 0.25 to 25 mm) resulted in a resonance frequency decrease from 200 to 7 kHz. The water-loaded resonance frequency is included in the graph for comparison.

IV. Conclusions

Very good agreement between the calculated and experimentally measured admittance spectra was obtained in our investigation, indicating that the ANSYS finite element program can model the behavior of the cymbal transducer quite well both in-air as well as in-water. The first resonance frequency is controlled primarily by the cap material, i.e., by both its elastic constants as well as its dimensions (geometry). For a 12.7 mm diameter cymbal in-air, the data show that the resonance frequency can be tailored anywhere between 5 and 50 kHz simply by changing the cap material or the cap geometry. This capability makes the cymbal-type transducer quite versatile for a number of piezoelectric sensor and/or actuator applications.

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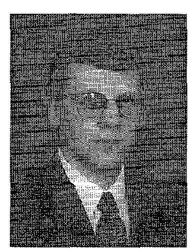

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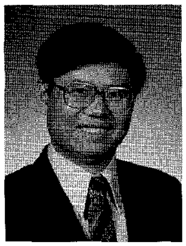

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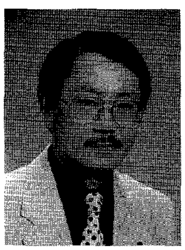

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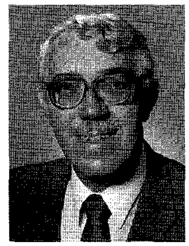
Dr. Uchino is a fellow of the American Ceramic Society as well as a member of the Japanese Technology Transfer Association, the New York Academy of Science, and the IEEE. He is also the Executive Associate Editor of the *Journal of Intelligent Materials Systems and Structures.*



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Dr. Newnham is a member of the National Academy of Engineering, a Distinguished Life Member of the American Ceramic Society, Turnbull Lecturer for the Materials Research Society, and Distinguished Lecturer for the IEEE.