Journal of Electroceramics, 14, 221–229, 2005

Tunability of Cymbals as Piezocomposite Transducers

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Submitted April 12, 2004; Revised August 31, 2004; Accepted December 17, 2004

Abstract. The cymbal design is a metal-piezoceramic composite which is based on the concept of the flextensional transducer. As actuator the cymbal design combines high displacements and moderate generative forces as well the advantage to tailor the properties through the endcap characteristics.

The majority of the impedance spectra of cymbals show a double peak instead of a single main endcap resonance peak. In addition, the cymbals with a pure endcap resonance peak show a resonance frequency distribution. Through an adequate variation of the mass endcap both problems can be overcome. In this way, the resonance and the non-resonance application can benefit of appropriate tuned frequencies and operation ranges. Both problems can be solved by the variation of the mass endcap.

This paper explores the possibility of both the tuning of the resonance frequencies and the performance of the cymbal device once it has been fabricated. Two approaches have been studies related to the external mass addition to the cavity and to the liquid-addition inside the cavity.

Keywords: cymbal, piezocomposite, resonance frequency, tunability, finite element analysis

Introduction

Piezoelectric materials transform electrical energy into mechanical or acoustical energy and vice versa [1], and several transducer devices exploit these properties. Sensors use the direct piezoelectric effect in which mechanical stress is converted into electrical charge. The converse effect where the application of an electric field, E, leads to a strain, ε, is exploited by actuators. If the piezoelectric charge coefficient, d, is assumed to be constant the resulted strain can be expressed as.

$$\varepsilon = s^E \cdot \sigma + d \cdot E \tag{1}$$

Where s^E is the compliance at constant electric field, d is the piezoelectric coefficient tensor and σ the mechanical stress. For a ceramic disk polarized in the axial direction under an electric field parallel to the polarization direction the following strains are achieved: in the radial direction $\varepsilon_1 = \varepsilon_2 = d_{31}E_3$, and in the axial direction $\varepsilon_3 = d_{33}E_3$.

In 1989 a composite device made from a piezoelectric ceramic and metal endcaps was invented by Newnham et al. at The Pennsylvania State University [2, 3]. Due to the hollow crescent cavities of the metal endcaps, the design was called "Moonie". The Moonie design was modified in the same laboratories [4, 5], by using truncated cone shaped endcaps. The new design was called "Cymbal". The cymbal consists of an electroded and polarized lead zirconate titanate (PZT) ceramic disk sandwiched between two metal endcaps using epoxy as a bonding agent. The metal endcaps serve as mechanical transformers to convert and amplify the radial motion of the ceramic disk into a large axial displacement normal to the endcaps. Both the $d_{31}(= d_{32})$ and the d_{33} coefficient of the ceramic contribute to the axial displacement of the composite, resulting in a very high effective d_{33} value. Moonie and cymbal transducers have a great potential for both the

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sensor and the actuator applications as resonant micropositioners, pressure sensors, shape controllers or ultrasonic emitters [6, 7].

The cymbal design has demonstrated higher displacement, effective piezoelectric coefficient, temperature stability and generative force than the Moonie design [8]. The production seems easier because the endcaps are punched and later pressed but not machined like in the case of Moonies.

The majority of the impedance spectra of cymbals shows a double peak instead of a single main endcap resonance peak. This splitting is not desirable. As the cymbal can only be operated at one frequency at a time, this fact limited the effectiveness of the transducer. In addition cymbals with a single endcap resonance peak show a resonance frequency distribution that need to be adjusted. Both problems have to be overcome to allow reliable commercial applications of the cymbal as transducer [9]. At the laboratory level, it is assumed that industrial production facilities problems could reduce the frequency splitting as well narrowed frequency distribution but the advances in this sense are not clear. The resonant frequency of piezoelectric transducer is generally tuned by adding a mass. In particular, resonance frequency changes due to the addition of studs (i.e., mass) to the cymbal device have been reported [10].

This paper is focused on fitting the resonance characteristic of the cymbal and their implication in the piezocomposite response.

Experimental Procedure

The piezoelectric ceramics used to build up the composite transducers were piezoceramic disks type PZT-5A. Kovar alloy was chosen as the metal endcap material because its thermal expansion coefficient is quite similar to the PZT one and, thus, the Thermally Induced Displacement (TID) is reduced [8]. In a first step metal disks with a diameter of 12.7 mm were punched from 0.25 mm thick Kovar sheets. In a second step the metal disks were shaped using specially shaped dies by uniaxial pressing at 74 MPa. Endcaps were selected after shaping process by their mass and dimensions in order to avoid differences among the cavities. In some of the endcaps a hole of 1 mm diameter was drilled centered in the flat top region to allow the introduction of a liquid into the cavity.

In addition small flat Kovar disks 0.25 mm thick, 3 mm in diameter, and with weights of approximately 13.3 ± 0.1 mg were punched. These 3 mm flat metal disks served to cover the endcap holes and as additional endcap mass for tuning experiments.

Then one endcap for asymmetric cymbals or two endcaps for symmetric cymbal were bonded to a ceramic disk with a two component epoxy (Epo-Tek) and cured under a small load applied on the bonding area in a special die. The epoxy was spread just in the circumferencial bonding area carefully keeping the cavity free from it.

Under vacuum the asymmetric cymbals having top hole were covered with distilled water; then the vacuum was removed forcing the water into the cavity. The introduced amount of water was determined by weighing with an accuracy of ±0.1 mg. The filling level was decreased stepwise by evaporating the water at 60°C.

To investigate the influence of increased endcap mass, brass bars of 3 mm diameter, 10 mm length and about 0.6 g weight were bonded to the flat top part of the cymbal endcaps (Fig. 1). The brass mass was decreased by grinding.

The electrical impedance was measured as a function of the frequency with an impedance analyzer, HP 4192A using a frequency resolution of 0.1 kHz. To avoid clamping and suppression of the vibration a sample holder was designed that allowed holding the cymbals between two tips positioned in the bonding area. A resonance peak is formed by an impedance minimum at the resonance frequency, f_r, followed by an impedance maximum at the antiresonance frequency, f_a.

The effective electromechanical coupling factor, k_{eff}, for a certain vibration can be calculated from:

$$k_{\mathrm{eff}}^2 = \frac{f_a^2 - f_r^2}{f_a^2} \tag{2}$$

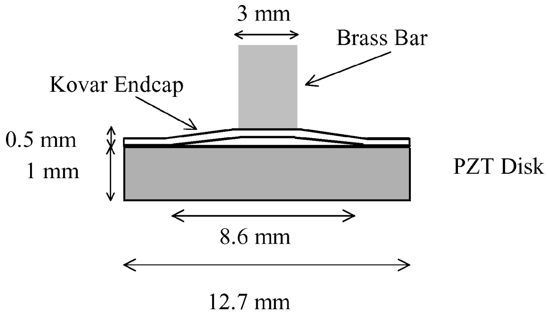

Fig. 1. Small Kovar disk attached to asymmetric cymbals.

The electromechanical coupling factor is defined as the amount of electrical energy converted to mechanical energy. Its maximum value is 1.

The effective piezoelectric coefficient d_{33}^{eff} consists of the d_{33} of the PZT disk and the contribution of the disk's d_{31} which is redirected by the cymbal endcaps. It was measured with a Berlincourt Meter at a frequency of 100 Hz. In former paper the effective coefficient has been studied and calculated in detail by using a mechanical approach [11]. Starting from the polarization vector due to the stress acting on the polycrystalline piezoelectric it is possible calculate the effective piezoelectric coefficient for an asymmetric cymbal:

$$d_{33}^{\text{eff}} = -d_{31}\frac{r_T(r_T - r_1)}{t_h \cdot (t_c + t_m)} + d_{33} \tag{3}$$

where r_1 is the radius of the top part of the endcap cavity, r_t is the radius of the bottom part of the cavity, t_h is the height of the cavity, t_c is the thickness of the ceramic disk, t_m is the thickness of the metal endcap. It is interesting to remark that because of the negative values of the d_{31} the piezoelectric radial motion contributed to the overall d_{33}^{eff}. This radial contribution was modulated by a ratio between the cavity diameter parameters and the thickness parameter of the cymbal.

And, the effective piezoelectric coefficient for symmetric cymbals is:

$$d_{33}^{\text{eff}} = -2d_{31}\frac{r_T(r_T - r_1)}{t_h \cdot (t_c + 2t_m)} + d_{33} \tag{4}$$

The results from the present work were applied to cymbals showing originally two distinct endcap resonance frequencies. This key experiment demonstrate the power of the developed tuning capabilities.

Finite Element Analysis

A commercially available Finite Element Analysis, FEA, program (ATILA) was used in this study for the design and development stages of the PZT-Kovar composite transducer.

For the studies it is assumed a base model consisted of PZT-5A of 1mm thickness, 0.25 mm thick Kovar endcaps with 0.25 mm cavity depth and 8.6 mm cavity diameter, and 0.04 mm thick epoxy bond. Brass bars of 3 mm diameter and different lengths were added to the model for the study of the effect of changing the added mass. A 0.04 mm thick epoxy bonding layer between the brass bar and the kovar endcap was also included in the model. The relationship between displacement and applied force was calculated using 2-D axisymmetric elements. Mesh with quadrilateral-shaped elements of four nodal points was employed. The mesh used is shown in Fig. 2. Using the electrical boundary conditions on the piezoelectric elements, the ATILA code solves the matrix (Eq. (5)) for the eigenvalues under short circuit (resonance modes) and open circuit (antiresonance modes) conditions.

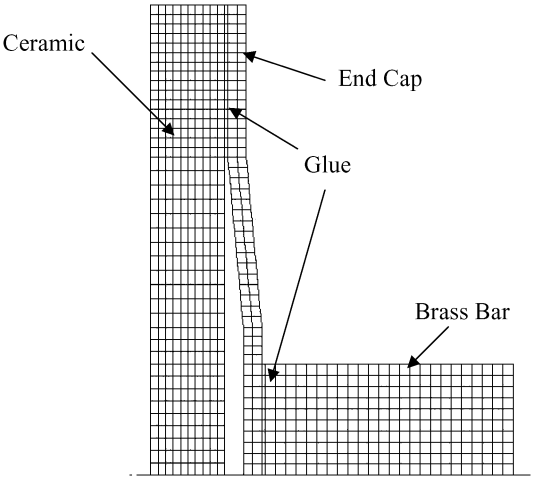

Fig. 2. Two-dimensional axi-symmetric ATILA finite element mesh used for calculations of the cymbal structure.

$$\begin{bmatrix} [K_{uu}] - \omega^2[M] & [K_{u\phi}] \\ [K_{u\phi}]^T & [K_{\phi\phi}] \end{bmatrix} \begin{bmatrix} \underline{U} \\ \underline{\phi} \end{bmatrix} = \begin{bmatrix} \underline{0} \\ \underline{-q} \end{bmatrix} \tag{5}$$

$[K_{uu}]$ = stiffness matrix; $[K_{u\phi}]$ = piezoelectric matrix; ω = angular frequency; $[K_{\phi\phi}]$ = dielectric matrix; $[M]$ = consistent mass matrix; U = displacement field vector values; ϕ = electrical potential vector values; q = vector values of electrical charges.

Results and Discussion

Figure 3 shows a typical cavity impedance spectra for symmetric and asymmetric cymbals. Both plots are on the same scale but the asymmetric one is displaced for more clarity. The resonance peak is related to the endcap cavity mode and occurs between 27 and 35 kHz for the selected endcaps [12]. A single resonance

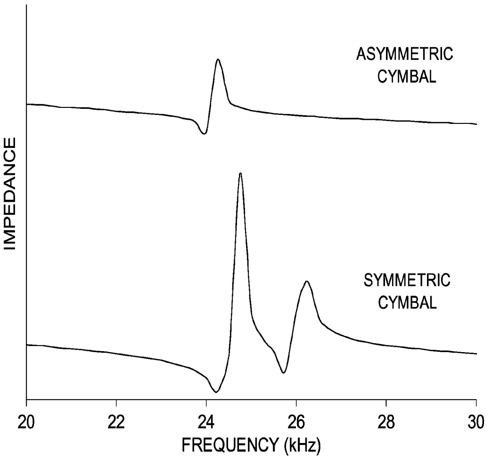

Fig. 3. Impedance spectrum for symmetric and asymmetric cymbal.

peak is found only in 20% of the symmetric cymbals, whereas the majority of the impedance spectra shows a double peak. Splitting of the resonance peak leads to the energy sharing between two resonance frequencies.

Generally speaking it is assumed that both problems have their origin on the asymmetries in the cymbal endcaps. Cymbals bonded having the same endcap weight and cavity thickness showed frequently different frequencies because the lack of symmetry on manually bonded composites. Two different resonance frequencies are thus related to slightly different cavities [9, 13]. Even when carefully selected endcaps were chosen the bonding differences are unavoidable at the laboratory level. The double resonance peak and the resonance frequency distribution could be in part minimized by the automatization of the cymbal assembling. However it is of particular interest to know which type of asymmetry is responsible for the different resonance frequencies, and as a consequence which is the procedure to cancel this effect. The out coming idea is to overcome asymmetries by filling or partially filling the endcap cavities with a liquid or by clamping the endcaps by attaching a external mass.

In all asymmetric cymbals only single resonance peaks appeared for the main vibration mode of the cavity. When the symmetric cymbal shown a single cavity peak the peak amplitude, ΔZ, is up to six times higher than asymmetric ones, as well, the effective electromechanical coupling factor is doubling its value. However asymmetric cymbals are adequate for tunability studies because of their single cavity resonance mode.

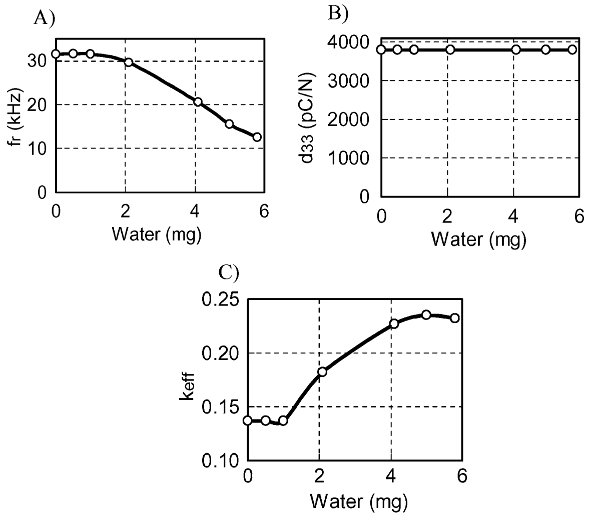

Fig. 4. Effect of water filling on asymmetric cymbal: (A) The resonance frequency of the endcap vibration, f_r. (B) The effective piezoelectric coefficient, d_{33}. (C) The electromechanical coupling factor, k_{eff}.

Water filling of cymbal decreased the endcap cavity resonance frequency. The shift of the resonance frequency, the behavior of the electromechanical coupling factor, and the effective piezoelectric coefficient are shown in Fig. 4.

The resonance frequency of a resonator is determined by its mass and dimensions through:

$$f_c = \frac{1}{2\pi}\sqrt{\frac{k_c}{M_c}} \tag{6}$$

where f_c is the resonance frequency of the vibration mode, k_c is the stiffness of the ceramic and M_c is the equivalent mass of the ceramic. Increasing the mass of the resonator results in a decreasing of its resonance frequency. Stiffening shifts the resonance to higher frequencies. However the resonance frequency does not change for small amount of water. The capillary effect near the bonding area concentrates the water in this region, resulting in a stiffening of the lateral wall that compensate the slight mass increase. It is only after a critical amount of water when the resonance frequency starts to decrease. The d_{33}^{eff} coefficient remains at the same value with independence of the amount of added water. The k_{eff} remains constant up to a certain amount of introduced water, as in the case of the resonance frequency, and then, increases rapidly.

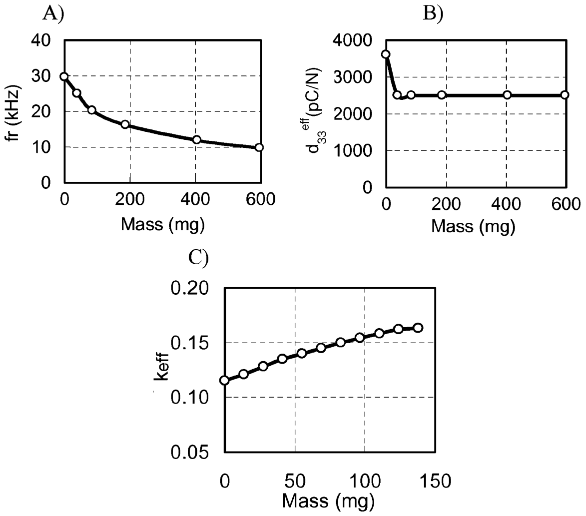

Fig. 5. Influence of attaching and grinding a brass bar to an asymmetric cymbal on: (A) The resonance frequency of the endcap vibration, f_r. (B) The effective piezoelectric coefficient, d_{33}. (C) The electromechanical coupling factor, k_{eff}.

In this study the water filled asymmetric cymbals are not closed pieces. The water's surface tension maintains the water inside the cavity. For real long time applications this is not practicable due to the slow water evaporation. Closing the endcap hole by covering it, for example, with a small metal disk would introduce new asymmetries.

In order to attach a external mass the flat top part of the metal endcap was selected because it is assumed that remains in this shape during actuation [4]. The shift of the resonance frequency, the effective piezoelectric coefficient and the change in electromechanical coupling factor for a 3 mm brass bars attached to a cymbal top are shown in Fig. 5. In contrast with the water filled endcap there is an immediate change of the resonance frequency and the electromechanical coupling factor. Besides d_{33}^{eff} is decreased by 31% when the shortest bar is attached but does not suffer any further decrease with heavier bars. As in the water filled asymmetric cymbals, the decreasing of resonance frequency of the cavity occurs with an improvement of the k_{eff}. This increase of the vibration effectiveness could be attributed in part to the decreasing of the vibration frequencies.

The preferable technique seems to be the external attachment of mass to one of the endcaps. For the water filled cymbals a resonance shift of 19 kHz along with a decrease in resonance peak amplitude of 92% is produced, whereas a resonance shift of 21.9 kHz was achieved by attaching metal weights along with a peak amplitude decrease of only 15%. Attaching a metal bar does not affect the resonance peak amplitude of the main endcap vibration meanwhile the water filled cymbals experiment a strong broadening of the resonance peak. However other applications could benefit of this characteristic.

Next, the systematic difference between cavity filling and external weight attachment is studied. Similar resonance frequency shifts are reached by water filling with masses equivalent to almost two orders of magnitude smaller than those for externally added metal bars. For example, to reach a resonance frequency decrease of 15 kHz in an asymmetric cymbal a external mass of 140 mg or only 5 mg of water are required. Thus the resonance frequency shift cannot just be a mass effect and thus the vibration of the endcap must be taken into account. In this sense, we suggest that the endcap vibration can be related to three different sections: a flextensional motion at the top part, a rotational motion in the hinges, and a flextensional motion in the lateral wall. These motions are not independent and gave the natural mode of vibration of the endcap.

In previous works it was established that there is no deformation at the top part of the cymbal endcap [4]. Also, as a matter of fact, when a metal bar is attached to this planar area a decrease of the effective piezoelectric coefficient, d_{33}^{eff}, occurs (Fig. 5(B)). This decrease is attributed to flextensional motion restriction of the top part. Once the flextensional motion is cancelled, the effective piezoelectric coefficient remains constant. Filling the endcap cavity with water does not change the effective piezoelectric coefficient of the cymbal actuator (Fig. 4(B)) because it does not limit the endcap deformation.

The idea is that preferentially weakening or canceling one of the three mentioned motions leads to the observed decrease in resonance frequency. In the case of adding metal mass on the top, this part of the endcap is stiffened. Thus primarily the flextensional motion of the top part is weakened and contributes in a different way to the overall resonance frequency, so a different resonance frequency is observed. In the case of introducing water there is no modification of the flextensional top part motion. Starting with a completely filled cavity and evaporating the water leaves the remaining water in the edge formed by the endcap and the PZT disk. Here the flextensional motion of the lateral wall and the rotational motion of the lower hinge are restricted. These motions are weakened or finally

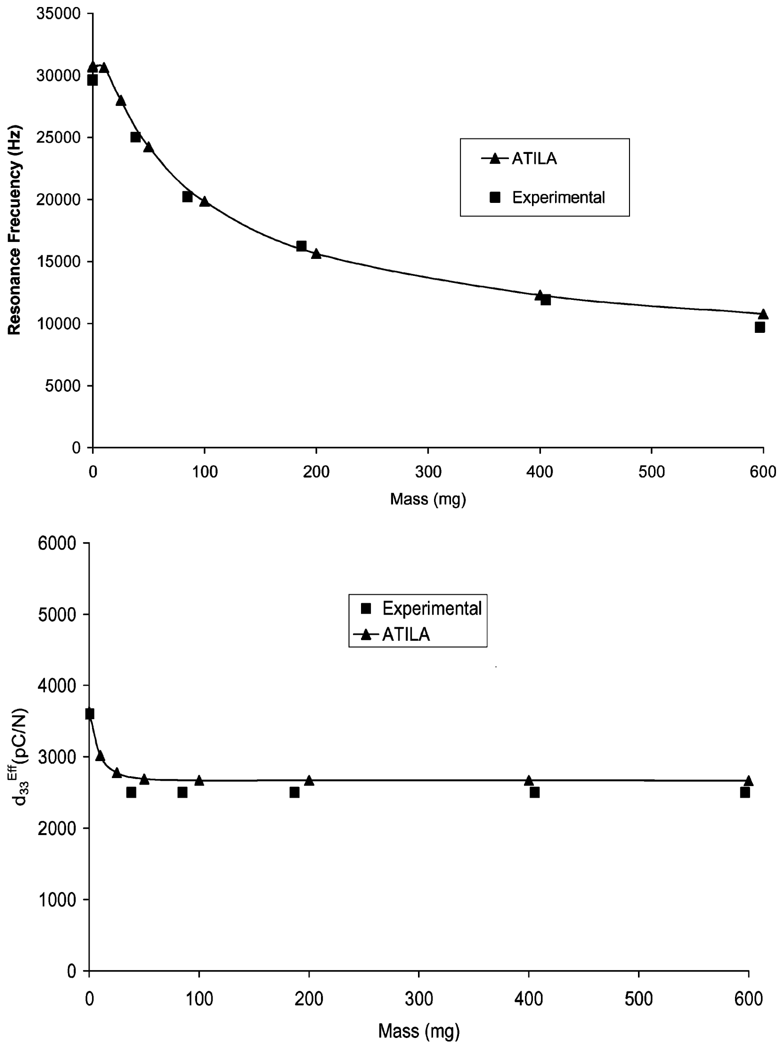

Fig. 6. Calculated and experimental cavity resonance frequency and effective piezoelectric coefficient, d_{33}^{eff}, of the asymmetric cymbal with different attached mass.

canceled depending on the filling level. Thus the overall resonance frequency is changed. Because endcap filling and mass attachment influence different motions their effect on the resonance frequency is different.

In order to verify this behavior the main resonance of the cymbal with a external mass addition was simulated by FEA. The resonance frequencies and the piezoelectric effective coefficients experimental and calculated with FEA, for cymbals with different attached bars are plotted as a function of the added mass in Fig. 6. This results show the consistency of the FEA calculations and experimental results, indicating that ATILA codes can be used to model the behavior of the cymbal. Figure 7 shows the displacements associated with the cavity resonance mode for both the single asymmetric cymbal (A) and the attached asymmetric cymbal (B). The flextensional motion of the top part in the single cymbal and its motion cancellation in the attached one is clearly showed.

Tuning Experiment

In order to exploit the previous results, the following experiment try to balance the asymmetry of two endcaps leading to resonance frequency splitting. For this

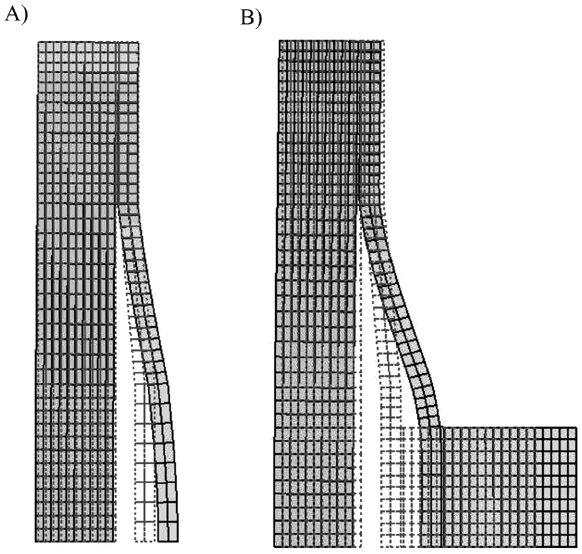

Fig. 7. Finite element modeling of the cavity resonance modes found for both the single asymmetric cymbal and the brass bar attached asymmetric cymbal.

purpose, a symmetric cymbal with pure resonance peak was splitted by attaching Kovar disks to one endcap. In this way two endcap resonance peaks appear (Fig. 8). Adding the same weight to the opposite side, the spectrum returns to a single resonance peak at lower frequency. Thus different endcap mass could be one of the possible origins for double peaks.

Figure 9 compares the original spectrum of a cymbal having two cavity resonance peaks and the resulting spectrum after tuning. The sum of the resonance peak amplitude of the two starting peaks almost corresponds to the amplitude of the tuned single peak. The tuned resonance frequency is lower than any of the original resonance frequencies.

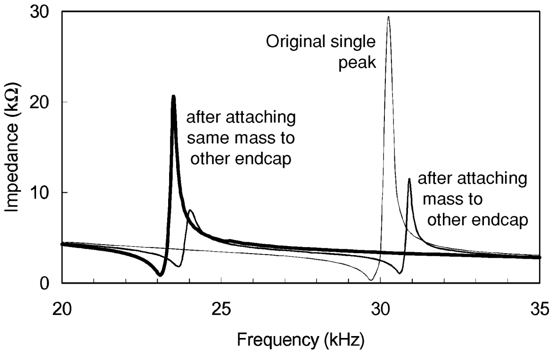

Fig. 8. Spoiling a symmetric cymbal's impedance spectrum with single resonance frequency and restoring it.

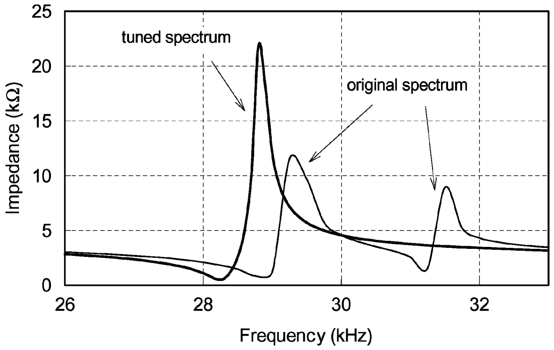

Fig. 9. Original symmetric cymbal spectrum with two resonance frequencies and tuned spectrum.

The original endcap peak separation before tuning and the required mass to bring the resonance frequencies together were measured in a set of ten cymbals. All cymbals could be tuned but the viewgraph does not show any correlation between the original peak separation and the tuning mass. The asymmetry is related to the different endcap parameters like cavity height, cavity diameter, bonding thickness and homogeneity, endcap deformations, ... that contribute to the double peak characteristic. It is clear that each of the two resonance frequencies are attributed to one of the two endcaps. The attaching of a mass to counterbalance their influence shows different effect depending on the types of asymmetry present. This explains e.g. why for tuning two cymbals with the same original peak separation of 2.2 kHz different tuning masses are required: in one case 13.7 mg and in the other 25.9 mg, almost twice as much. Apparently different endcap asymmetries are responsible for the double peak thus requiring different masses to be corrected although having the same original peak separation.

When the mass is added to the wrong side the higher frequency peak is not shifted but the lower peak is shifted to even smaller frequencies (Fig. 10). The impedance peak amplitude do not change significantly. Attaching a mass to the right side, leads to an impedance increase in the first resonance peak and a decrease in the second one. The second resonance peak also starts shifting towards the first one. Then also the first peak starts shifting to smaller frequencies but for a certain mass there is just one single peak with rather

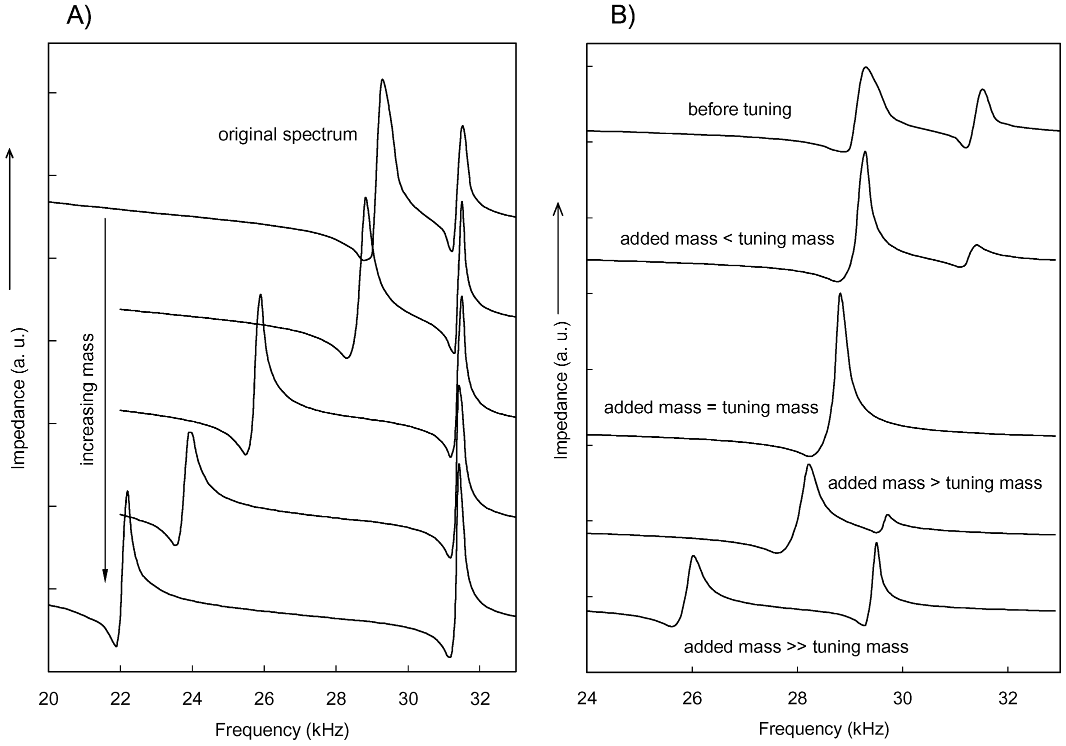

Fig. 10. Mass added to the wrong side (A), and mass added to the right side (B) of a symmetric cymbal.

high impedance left. If the mass is increased further the peak shifts to the left, looses amplitude and a second peak starts to appear at a higher frequency.

After tuning symmetric cymbals with originally double resonance peaks towards a single resonance frequency they can be further tuned to adopt any resonance frequency at least down to less than 10 kHz. By this method we reached shifts of almost 24 kHz. This behavior could be reached by both processes: the water filling and the external mass attachment. In this case all modifications have to be conducted symmetrically on both endcaps to avoid new resonance splitting. Again, from the arguments mentioned above, it is more reasonable to choose the way of attaching mass externally instead of filling the cymbal. Filling both endcap cavities and evaporating the same amount of water from both of them to reach a defined resonance frequency was not tested and is difficult to control. When a cymbal is selected for actuator applications a careful design of their frequency response must be taken into account to avoid a drastic reduction of the resonance frequency that could introduce distortion on the actuator performance.

Conclusions

The endcap asymmetries leading to split of the cavity resonance frequencies for cymbal piezoceramics can be corrected once it has been fabricated by adding a mass or by introducing water into the endcap cavity.

Attaching a mass seems to be the more practical and recommendable solution because the resonance peak amplitude is kept and the control of the mass is easier.

Cymbals showing two main resonance frequencies related to each endcap can be tuned to reach a single resonance frequency. Then this single resonance peak can be tuned to the required frequency.

Acknowledgments

The authors would like to express their gratitude for the support from EUREKA 2309 FACTORY-PAMIS and CICYT-DPI2002-0418-CO2-01. P. Ochoa was supported by a grant from FPI-CAM-FSE program.

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