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Piezoelectric Energy Harvesting under High Pre-Stressed Cyclic Vibrations

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Abstract. Cymbal transducers have been found as a promising structure for piezoelectric energy harvesting under high force (∼100 N) at cyclic conditions (∼100–200 Hz). The thicker steel cap enhances the endurance of the ceramic to sustain higher ac loads along with stress amplification. This study reports the performance of the cymbal transducer under ac force of 70 N with a pre-stress load of 67 N at 100 Hz frequency. At this frequency and force level, 52 mW power was generated from a cymbal measured across a 400 kΩ resistor. The ceramic diameter was fixed at 29 mm and various thicknesses were experimented to optimize the performance. The results showed that the PZT ceramic of 1 mm thickness provided the highest power output with 0.4 mm endcap. In order to accommodate such high dynamic pressure the transducer and cap materials were modified and it was found that the higher piezoelectric voltage constant ceramic provided the higher output power. Electrical output power as a function of applied ac stress magnitude was also computed using FEM analysis and the results were found to be functionally coherent with experiment. This study clearly demonstrated the feasibility of using piezoelectric transducers for harvesting energy from high magnitude vibration sources such as automobile.

Keywords: piezoelectric energy harvesting, cymbal transducer, piezoelectric generator

1. Introduction

Electrical power generation from the high vibration sources such as automobile engine using piezoelectric materials has received a significant interest in the research and industrial community. In addition to generation of electrical energy [1–4], the removal of mechanical energy from vibrating engine by piezoelectric energy harvesting system provides vibration suppression or damping. Implementation of power harvesting devices in the automobiles will provide an alternative resource for charging the battery thereby reducing the fuel consumption. This technology has significant implications for futuristic hybrid automobiles.

Previously, investigations performed on a cymbal transducer having ceramic of dimensions $\phi 29 \times 1.00$ mm under ac force of 7.8 N and 100 Hz showed that a power of 39 mW can be successfully transferred across the low impedance load [5]. However, some critical questions remained to be answered, which are: (i) performance of cymbal transducer under high ac force conditions (∼100 N), (ii) size and electrical load dependence of the cymbal transducer under a given experimental conditions, and (iii) interrelationship between the applied dynamic stress and observed output charge. These questions are the subject of this study.

The magnitude of the transducer action is governed by the product of the effective piezoelectric field constant d^{eff} and piezoelectric voltage constant g^{eff}. The magnitude of the product $d \cdot g$ provides a boundary condition for the selection of the piezoelectric ceramics. The secondary factor for the transducer selection is mechanical stability. Cymbal transducer provides higher $d^{\mathrm{eff}} \cdot g^{\mathrm{eff}}$ than that of other transducer structures such as multilayer stacks and bimorphs. The actual piezoelectric coefficient of the cymbal is amplified several times due to the presence of cavity which allows the

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steel end-caps to serve as a mechanical transformer for transforming and amplifying a portion of the incident axial stress in the radial stresses of opposite sign [6]. Thus, the d_{33} and d_{31} contributions of the PZT now combine to provide the effective d^{eff} value of the cymbal as

$$d^{\text{eff}} = d_{33} + A|d_{31}| \tag{1}$$

where A is amplification factor. The amplification factor A can be very large in the range of 10–100 depending on the design of the caps. For a cymbal of 12.7 mm diameter and 1.7 mm total thickness, for example, an effective piezoelectric constant of more than 15000 pC/N has been reported [7]. Thus for a given volume of ceramic, a cymbal has a high electromechanical transduction rate and stress in comparison with a bimorph, and produces a displacement much higher than that of a multilayer stack. Further, the ac force that can be applied on the cymbal is considerably higher than other transducer structures, due to the thick steel caps that enhance the endurance of the ceramic to sustain higher force levels, and the compressive bias stress on the PZT disk generated through its fabrication process via thermal expansion difference between metal and the PZT.

2. Experimental Procedure

Figure 1 shows the dimensional details of the cymbal transducer. Steel caps were bonded on the ceramic disk using Stycast 1264 epoxy (Emerson and Cuming, Inc.) followed by curing at 120°C. The electrical connection was made on the cymbal by soldering the conductive wires at the edge of the transducer. Table 1 shows the electrical parameters of the three types of piezoelectric materials investigated in this study. The materials used in this study span a wide range of PZT compositions providing sufficient information in order to allow the selection of suitable material for energy harvesting. As can be seen from Table 1, the piezoelectric material D210 has the highest magnitude of the $d{\cdot}g$ product value because it has the lowest dielectric constant.

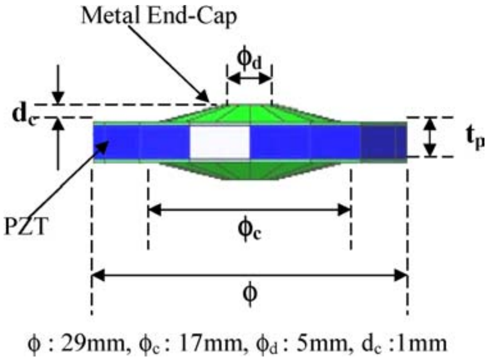


Fig. 1. Dimensional details of the fabricated cymbal transducer.

Table 1. Properties of PZT ceramics.

	Hard (APC 841)	Soft (APC 850)	High g (D210)
ε_r	1350	1750	681
k_p(%)	0.60	0.63	0.58
d_{31} (10–12 C/N)	109	175	120
g_{31} (10–3 Vm/N)	10.5	12.4	20
Q_m	1400	80	89.7
T_c (°C)	320	360	340
$d_{31} \cdot g_{31}$	0.99E-12	1.97E-12	2.4E-12

Hard and soft PZT ceramic specimens were fabricated by conventional mixed-oxide methods. The soft and hard PZT samples were fabricated using APC 850 and APC-841 powders, both obtained from American Piezoceramics Inc. (Mackeyville, PA). PZT disks of 34.8 mm diameter were pressed under a load of 5 tons for 1 min and then sintered at 1250°C for 2 h in PbO-atmosphere powder bed. After sintering, the disks had a diameter of 29 mm. Sintered disks were ground and machined to a thickness of 1mm. Machined PZT plates were electroded by firing silver paste (Dupont QS171). Poling was carried out at 120°C under an electric field of 30 kV/cm. A high-piezoelectric-voltage-coefficient ceramic D210 (Dong Il Technology, Korea) samples were provided in this study.

Figure 2 shows the photo of the experimental setup. A large amplitude vibrator was obtained from Bruel and Kjaer Instruments Inc. (Model Type 4808). This vibrator has the capability of applying a high force level up to 112 N in a frequency range of 5 Hz to 10 kHz. The vibrator was driven at various voltages and frequencies using the function generator (HP 33120 A) and a high-power current amplifier (Bruel and Kjaer Instruments Inc Type 2719) to produce a cyclic force of required magnitude and frequency. The output signal from the cymbal was monitored with Tektronix digital oscilloscope (TDS 420 A). The output voltage from the cymbal was passed through the rectifier and charged to the capacitor, and successively discharged through a resistive load. All experiments were performed on an isolated bench to avoid any interference

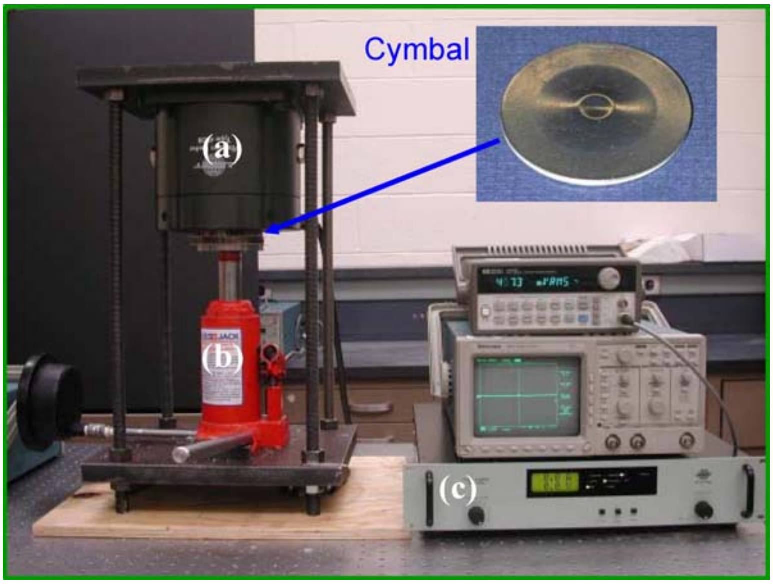


Fig. 2. Photograph of the experimental setup: (a)Vibration source (shaker), (b) Hydraulic press, and (c) Current amplifier.

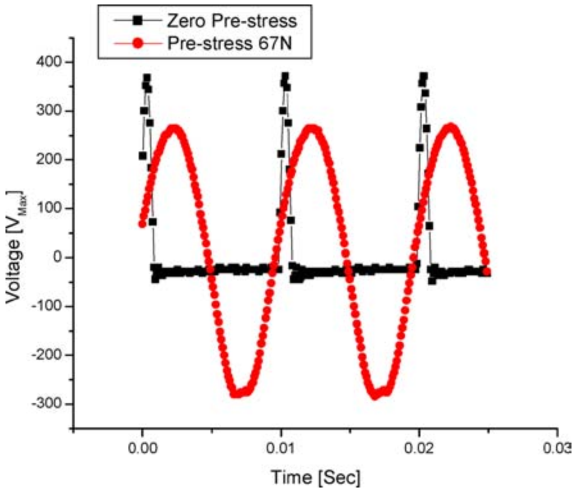


Fig. 3. Variation of the peak output voltage of the cymbal transducer depending on pre-stress condition. A force of 7.8 N and 40 N at 100 Hz was applied for zero pre-stress and pre-stress condition, respectively.

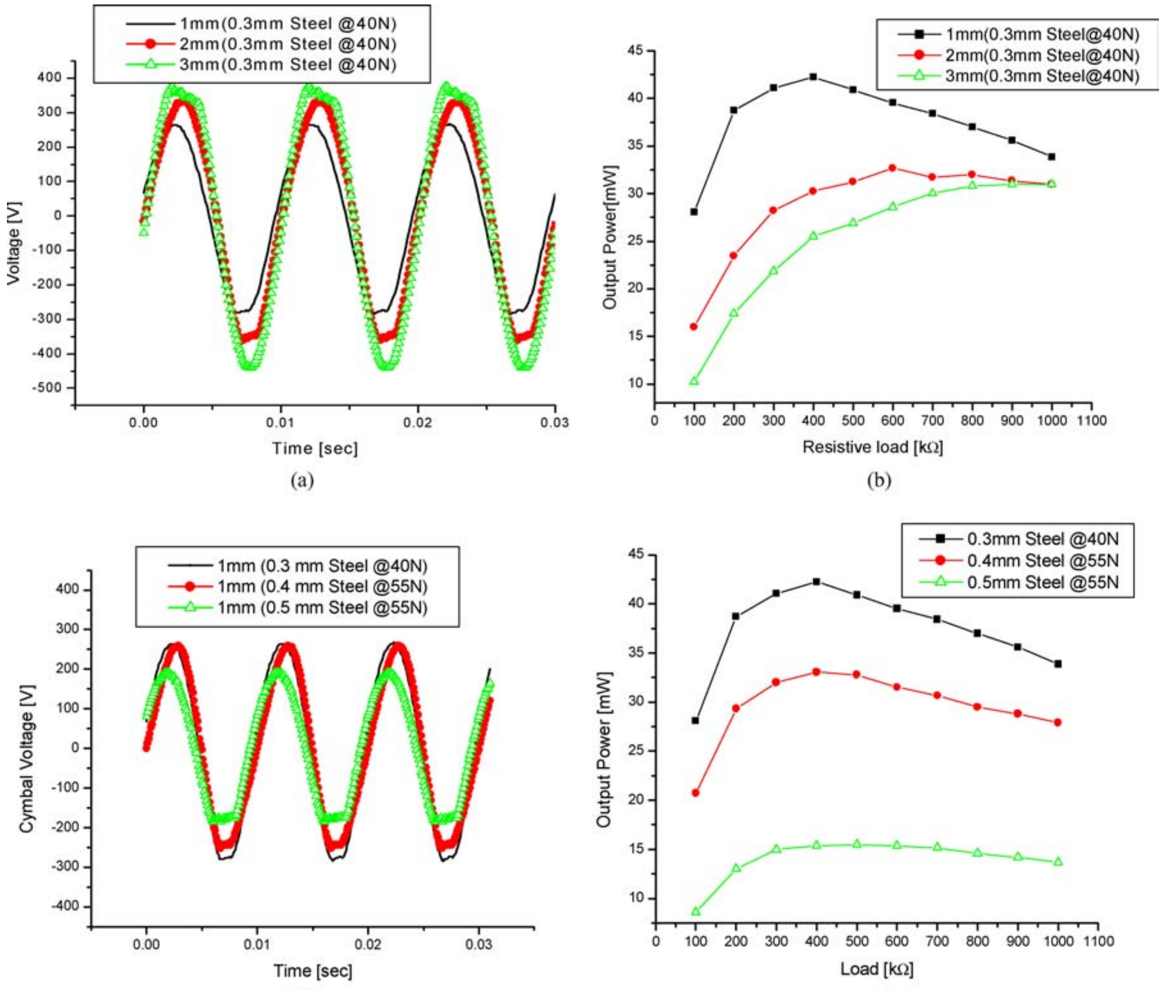
from the mechanical noise in the surrounding environment. Figure 3 shows the example output waveforms from the cymbal transducer showing the real time potential variation under a cyclic force depending on pre-stress condition at 100 Hz frequency. Pre-stress is the pressure applied by the mass of vibration source to the cymbal transducer. It is evident from this figure that the open circuit output voltage exhibits the highest in the high-g material which is expected from the constitutive Eqs. (2).

$$v = g \times \frac{F \times t}{A} \tag{2}$$

where g is piezoelectric voltage constant, F is applied force, t is the thickness of PZT element, and A is the surface area of the PZT element. The maximum power with zero pre-stress for the high-g material was around 39 mW at 400 kΩ load after the rectification circuit with a full wave rectifier and a capacitor for storing the generated electrical energy of the cymbal transducer [5].

3. Experimental Results with Pre-Stress

The cymbal transducers were tested under high vibration level with pre-stress conditions controlled by hydraulic press (Fred S. Carver INC.). Figure 4(a) shows the output voltage from the cymbal transducers with various thicknesses of the steel cap for high-g PZT ceramic under a pre-stress of 67 N, by which the output voltage of a cymbal shows the highest sinusoidal wave. The output voltage increases with the thickness of PZT ceramic element as shown in Fig. 4(a), but the



(a) (b)

(c) (d)

Fig. 4. Output voltage waveform and harvested power of the cymbal transducer under a pre-stress of 67 N. (a) fixed steel cap thickness and different ceramic thicknesses, (b) fixed steel cap thickness and different ceramic thicknesses, (c) fixed ceramic thickness and different steel cap thicknesses, and (d) fixed ceramic thickness and different steel cap thicknesses.

output power after rectification as a function of resistive load decreased with the ceramic thickness as shown in Fig. 4(b). This trend can be explained as follows: with increasing the PZT thickness and increasing the rigidity, the deformation of the PZT disk is drastically decreased under the same force from the metal endcap. Even through the PZT ceramic volume increases, the tangential force will not be penetrated into the middle of the PZT thickness.

On the other hand, Fig. 4(c) and (d) show the data for various thicknesses of the endcaps. The thinnest steel cap of thickness 0.3 mm showed the highest voltage and power for the same level of applied force and ceramic thickness. Even under the higher force level of 55 N the thinner endcap sample showed the higher output power. This is probably due to a similar with increasing the metal thickness and increasing the rigidity, the deformation of the endcap along the tangential direction is reduced under the same force from shaker, leading to a lower strain generation on the PZT disk. It can be seen from Fig. 4(d) that an output power of 42 mW can be realized across the 400 kΩ resistive load on applying cyclic force of 40 N at 100 Hz.

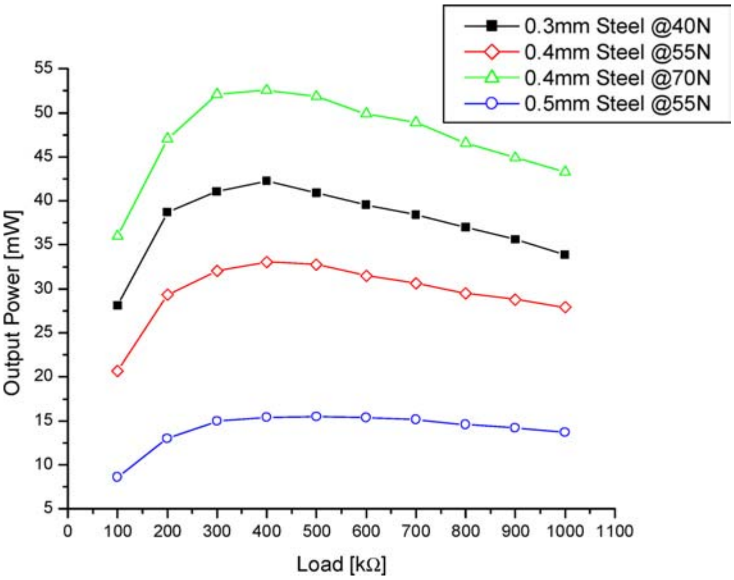


Fig. 5. Output power of the cymbal under high force condition 70 N and a pre-stress of 67 N.

The enhancement in the magnitude of the output power is small compared to an increase in the force level. However, it was found that the efficiency of the charging circuit improved significantly with increasing force level and it was possible to harvest more power. Further investigations were done under even higher force levels. In order to apply the high magnitude force the thickness of the steel caps was increased. Note that the 0.3 mm steel sample cannot endure a force higher than 50 N. Figure 5 shows the variation of the maximum output power as a function of the resistive load for various steel cap thickness and force level. Maximum power of 52 mW was obtained for the cymbal having steel cap thickness of 0.4 mm under 70 N force. The cymbal showed no degradation in structural integrity under such high force level showing its high tolerance for the vibration stresses. The results of this section provide the optimum dimensions for the cymbal transducer under high force conditions given as: $\phi 29 \times 1.8$ mm, where steel cap has the thickness of 0.4 mm.

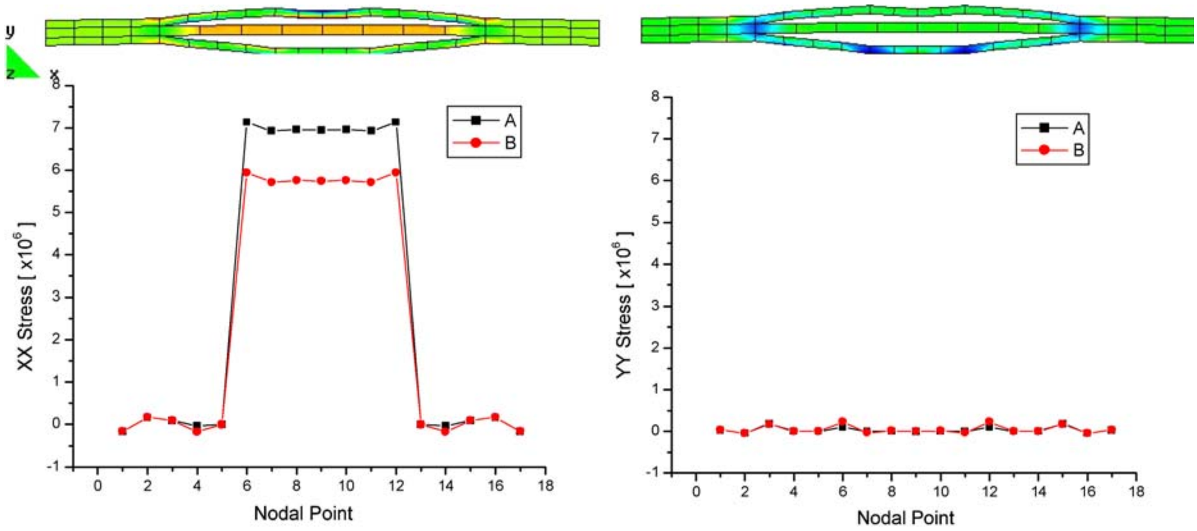
4. FEM Analysis of the Cymbal Transducer

A detailed FEM analysis was performed on the cymbal transducer using the ATILA software to investigate the interrelation between the generated charge and applied stress for different ceramic thicknesses without taking into account a bias compressive stress (radial direction) in the PZT disk, due to the thermal expansion difference between the metal and PZT. Figure 6 shows the stress distributions in the x-y plane (x: radial direction, y: normal direction) when the mechanical force of 70 N at 100 Hz is applied along the y direction on the high-g PZT ceramic of thickness 0.5 mm and steel cap thickness of 0.4 mm. As is evident from this calculation, most of the input mechanical energy is converted to the PZT deformation along the x (i.e., radial) direction, as the magnitude of the XX tensile stress (X_{11}) is significantly higher than compressive YY stress. Along the cavity diameter the magnitude of the tensile stress was of the order of 6 MPa while the compressive stress is almost negligible. Note again that if we consider the thermal mismatch between the metal and PZT ceramic, this tensile stress is almost cancelled. The points A and B in Fig. 6(a) and (b) correspond to nodal lines corresponding to the top and bottom surfaces of the ceramic. Hence, the generated electrical energy from the cymbal transducer can be expressed as [8]:

$$U_e = \frac{1}{2} \cdot \left(k_{31}^{\mathrm{eff}}\right)^2 \cdot s_{11}^D \cdot X_{11}^2 \cdot Vol \tag{3}$$

where Vol is the volume of the PZT element. Differentation of the Eq. (3) yields the expression for the electrical output power given as:

$$P_{\mathrm{Out}} \propto d_{31}^{\mathrm{eff}} \cdot g_{31}^{\mathrm{eff}} \cdot X_{11}^2 \cdot t \tag{4}$$



(a) XX Stress distribution

(b) YY Stress distribution

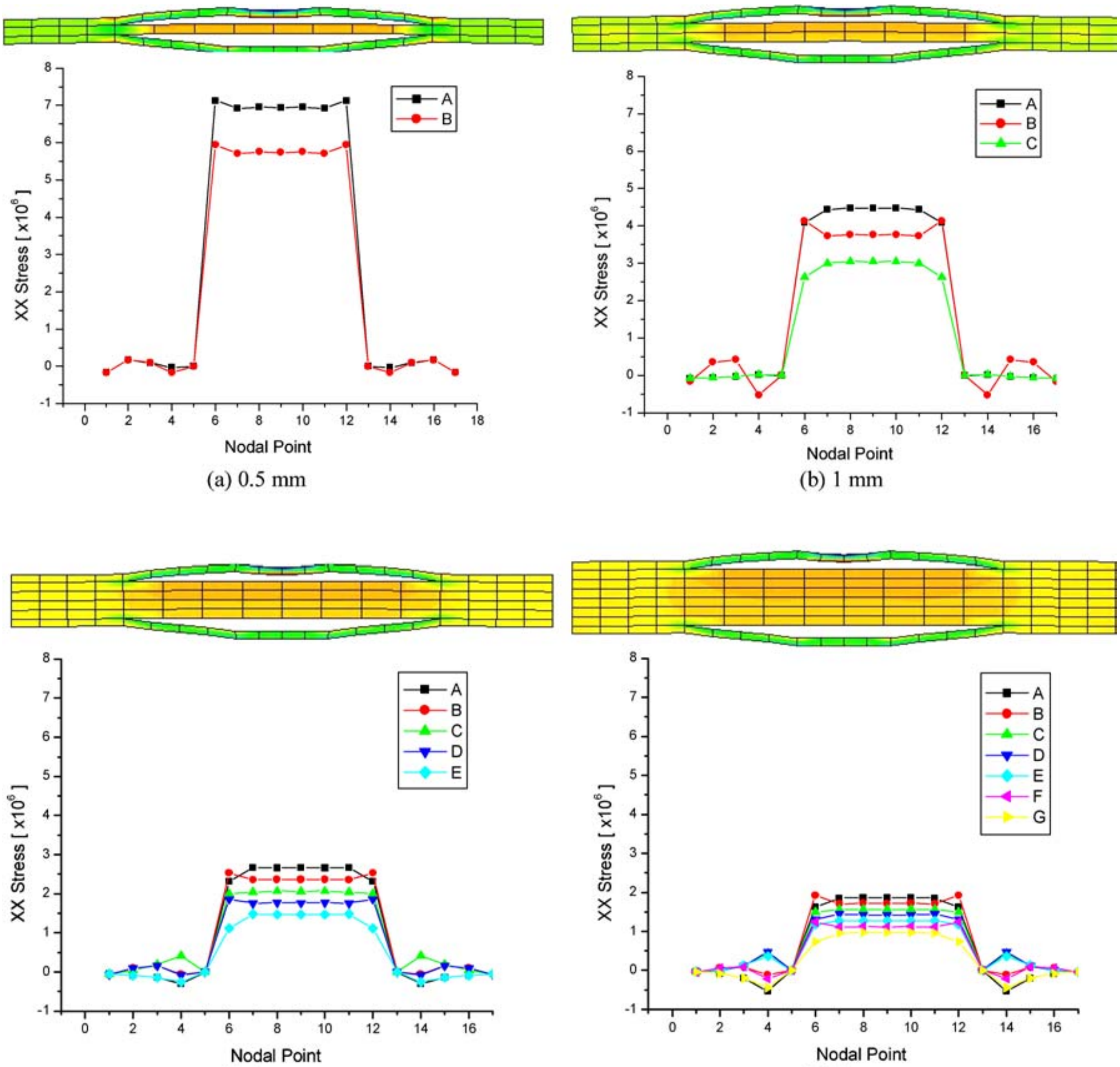
Fig. 6. Stress distribution in the PZT ceramic under 70 N and 100 Hz force: (a) XX-direction and (b) YY direction.

It can be seen from the above equation that the transducer with higher magnitude of the resultant tensile stress along with higher piezoelectric coefficients will provide higher power. Figure 7 (a)–(d) shows the tensile stress on the nodes of the ceramic under 70 N force for various ceramic thicknesses. The nodes were chosen at every 0.5 mm depth from the top along the thickness of the ceramic. Thus, a ceramic with thickness of 0.5 mm has 2 nodal lines while the ceramic with thickness of 1 mm has 3 nodal lines. The induced tensile stress decreases rapidly with increasing thickness of the ceramic for a fixed ceramic diameter and steel cap thickness. The output power factor given by Eq. (4) was computed by FEM analysis and is listed in Table 2. The power factor shows a maximum at ceramic thickness of 1 mm. The maximum in the power factor occurs due to the compensating effect of the piezoelectric constants and generated stress. These results clearly demonstrate that for a fixed ceramic diameter and endcap thickness the optimal thickness of the PZT ceramic which provides enhanced power harvesting can be calculated depending on applied force level. This trend is similar to that obtained in previous section but the magnitude of the ceramic thickness is not so significant. This may be due to the variation of effective elastic compliance depending on the metal and PZT ceramic thicknesses.

5. Discussion

A cymbal transducer is a Class V flextensional transducer capable of generating low frequency vibration in kilohertz range. The cymbal transducer has a compact, lightweight structure with a resonance frequency adjustable between 1 and 30 kHz, because the fundamental mode of vibration is caused by the up-down motion of the metal endcap. The overall displacement of the device is a combination of the axial motion of the disk plus the radial motion amplified by the endcaps. The effective piezoelectric constant, d_{33}^{eff} of the cymbal is much higher than the ceramic because of amplification by the steel endcaps. The measured d_{33}^{eff} for cymbals with different thickness of the ceramic and steel end cap used in this study are shown in Table 3. For a fixed ceramic thickness, the d_{33}^{eff} decreased with an increase in the steel end cap thickness. An increase of 0.2 mm in the steel cap thickness reduces the piezoelectric coefficient by approximately 50%. Further, for a given steel cap thickness, the d_{33}^{eff} decreased with an increase in the ceramic thickness. The decrease in the d_{33}^{eff} is rapid for the initial increase in the ceramic thickness but saturates for thickness higher than 2 mm. The results of this table further confirm the experimental results.

The output power for the cymbal transducer with dimensions $\phi 29$ mm × 1.8 mm (with 0.4 mm steel



(a) 0.5 mm (b) 1 mm

(c) 2 mm (d) 3 mm

Fig. 7. XX-stress distribution in the PZT ceramic for different thicknesses: (a) 0.5 mm, (b) 1 mm, (c) 2 mm and (d) 3 mm.

cap thickness) under stress of 55 N and 70 N was found to be 33 mW and 52 mW, respectively, across the load of 400 kΩ. For a steel cap thickness of 0.4 mm the force magnitude of 70 N is close to the maximum bearing capacity. In order to apply stress higher than this level and harvest power with high efficiency, there is just one option and that is to increase the diameter of the cymbal in a specific ratio. Increased dimensions will allow using thicker steel caps and ceramics.

6. Summary

This study reports the power harvesting under high force—low frequency conditions using cymbal transducers. A mechanical force of 70 N at 100 Hz applied on the cymbal transducer having dimensions $\phi 29 \times 1.8$ mm (steel cap thickness = 0.4 mm) resulted in electrical power generation of 52 mW across a 400 kΩ resistor. FEM analysis of the transducer showed that most of the applied stress is expended in deforming

Table 2. Output Power factors calculated by FEM.

	Thickness			
Factors	0.5 mm	1 mm	2 mm	3 mm
C (nf)	16.96	8.48	4.24	2.83
v_{out} (V)	30.5	36.5	40.9	43.1
X_{11} (MPa)	1.99	1.25	0.736	0.525
d_{33}^{eff} (pC/N)	7389	4421	2477	1742
d_{31}^{eff} (pC/N)	87	112.4	135.9	149
$d_{31}^{eff} \times g_{31}^{eff} \times X_{11}^{2} \times t$	**0.96E-3**	**1.26E-3**	**1.25E-3**	**1.19E-3**

Table 3. The effective piezoelectric strain coefficient d_{33}^{eff} of cymbal transducer.

	PZT			
Endcap	0.5 mm	1 mm	2 mm	3 mm
0.3 mm		**12,600**		
0.4 mm	**13,330**	**10,520**	**6,500**	**5,500**
0.5 mm		**6,330**		

*Unit is [pC/N].

the cymbal along the radial direction and the stress factor along the thickness direction is significantly small. Power factor analysis of the cymbal showed the ceramic thickness dependence of the output charge. Based on the results of this study it can be conjectured that the cymbal transducer can provide an alternative power source in automobile applications.

Acknowledgment

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