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SCIENCE DIRECT
Journal of the European Ceramic Society 25 (2005) 2457–2461
www.elsevier.com/locate/jeurceramsoc

Mechanical stress and electric potential in cymbal piezoceramics by FEA

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Available online 11 April 2005

Abstract

A study of the electric potential and mechanical stress distributions by finite element analysis (FEA) of the cymbal piezocomposites was attempted for both the resonant and the off-resonant modes.

The stress concentration has been proved to reduce the performance of the cymbals and is on the origin of the further degradation issues. It is possible to eliminate some part of the stress concentration by removing a portion of the ceramic where the maximum stress concentration is observed or by the modification of the bonding layer. Several FEA ATILA® models were generated to analyse the stress distribution behaviour of cymbals with different grooves. Unexpected high electric field concentration is observed associated to the mechanical stress of the resonant modes. These analyses invalidate resonant applications of cymbals.

Keywords: Composites; Piezoelectric properties; PZT; Actuators; Finite element analysis

1. Introduction

The cymbal transducer is a small Class V flextensional transducer that originated from the successful “moonie” patent.[1] The cymbal piezoceramic consists of a lead zirconate titanate type (PZT) disk (fully electroded on both faces) sandwiched between two “cymbal” shaped metal endcaps with shallow cavities. The presence of the cavities allows the metal caps to serve as mechanical transformers of the axial stress into radial stress of opposite sign. Thus, the d_{33} and d_{31} contributions of the PZT now add together rather than subtracting. The cymbal design was a result of eliminating stress concentration on the moonie caps. This design, further improved the displacement characteristics. In addition, the transducer is simpler and cost effective.

The composite structure is an attractive feature of the cymbal design to tailor its performance. Thus, the properties as resonance frequency, blocking force, displacement and response times of the cymbal could be adjusted through the cap and ceramic materials selection in conjunction with the geometry and overall dimensions. The versatility of the design is well known and has been the topic of many publications.[2]

In this paper, the electric potential and mechanical stress distributions of the cymbal transducer was modelled using the finite element analysis (FEA). As actuators, cymbal piezoceramics need to reduce their stress concentration in order to attain higher generative force and reliability. In order to minimise these effects new strategies were investigated by FEA: by removing a portion of the ceramic, just below the point where the maximum stress concentration is observed, or by variations in the thickness and distribution of the bonding layer. In addition, the electric potential distribution in the ceramic has been analyzed.

Up to now, FEA of the cymbal piezocomposite are focussed on the impedance frequency response and their characterization as underwater transducer and sound emitters.[3,4] The distribution of electrical and mechanics fields have never been discussed and studied for this kind of metal-ceramic composites. Therefore, the development of some cymbal applications has been limited.

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0955-2219/$ – see front matter
doi:10.1016/j.jeurceramsoc.2005.03.082

Table 1
Comparison between experimental and FEA calculated values

	Resonance frequency (kHz)		d_{33}^{eff} (pC/N)	
	FEA: ATILA	Experimental	FEA: ATILA	Experimental
Symmetric cymbal	31	26 ± 6	9599	11000 ± 1000
Asymmetric cymbal	30	27 ± 4	5300	4500 ± 650
PZT disk	156	160 ± 5	370	374 ± 60

2. Finite element analysis

A commercially available finite element analysis, 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 1 mm thickness, 12.7 mm diameter, 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. Because the geometry, boundary conditions and material properties are axisymmetric, an axisymmetric FEA was developed. Mesh with quadrilateral-shaped elements of four nodal points was employed. This model is suitable for the calculation of mechanical and electrical load cases. In this work, a 1 kV of electrical excitation was applied to the model.

Both the modal and the harmonic analysis for resonant and off-resonant modes were studied. A frequency of 100 Hz was chosen for the off-resonant simulations. In resonance and anti-resonance analysis (modal analysis), the electrical potential, the displacement and the stress distribution have to be normalised for comparison purposes. However, the modal analysis does not taken into account the voltage amplitude. Then, to compare the stress or electrical potential of two different designs by mean of modal analysis, the ratio stress/maximal displacement or voltage/maximal displacement has to be calculated. In this work the attention is focused on the cavity resonance mode. Since the modal analysis results are relative values, an harmonic analysis was performed in the vicinity of the cavity resonant frequency for the asymmetric cymbal.

2.1. Mechanical stress distribution

The consistency of the FEA calculations and experimental results were established in previous studies.[3,4] Table 1 shows calculated properties of cymbals as well as experimental results. The cavity resonance mode appears at 31 kHz. The resonance frequencies and the piezoelectric effective coefficients, experimental and calculated with FEA, for symmetric and asymmetric cymbals show the consistency of the FEA calculations and experimental results, indicating that

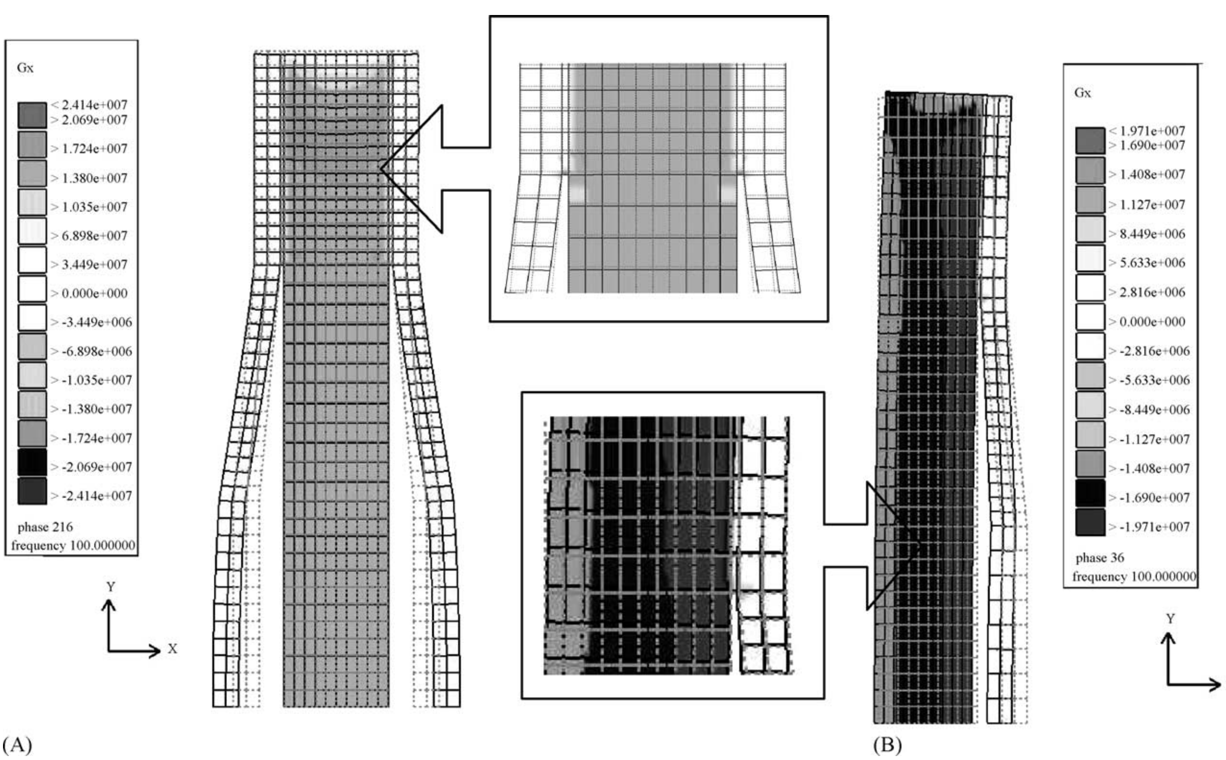

Fig. 1. Stress distribution of the baseline model in off-resonant cymbal actuators for symmetric (A) and asymmetric (B) design.

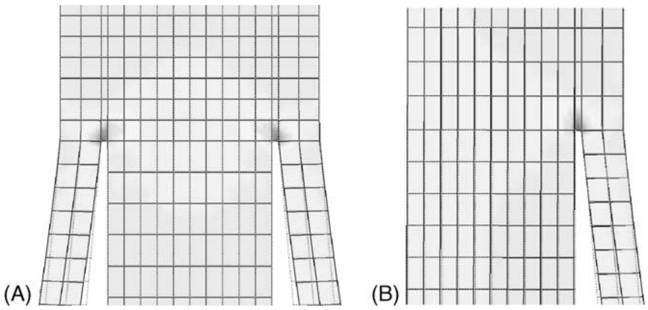

Fig. 2. Stress distribution at the resonance cymbal actuator for symmetric (A) and asymmetric (B) design.

ATILA codes can be used to model the behaviour of the cymbal.

The stress distribution response of the baseline model is shown in Fig. 1. A high stress concentration at the inner termination edge of the bonding layer is observed. For off-resonance mode, the harmonic analysis (100 Hz) shows that the higher stress is in the ceramic, but there is an important amount of stress located in the bonding layer (16.9 MPa). For the modal analysis (cavity resonance mode) this concentration is more evident. This can be seen in the detailed view of this region in Fig. 2. Fig. 3 shows the evolution of the stress concentration, at the inner termination edge of the bonding layer, in the vicinity of the cavity resonant frequency. It shows that the stress concentration at the bonding layer inner edge is 640 MPa near the resonant frequency. The bonding materials are not able to endure such stresses exerted in opposite directions (the tensile lap strength for the most usual epoxies is around 16 MPa), and micro-cracks may form. This could result in a local critical stress near the inner edge which leads to the complete composite fails by debonding before the global stress reaches a critical value for the rest of the structure. The tensile lap strength of the epoxy is comparable to the stress concentration for off-resonant applications. That fact could be overcome by reinforced epoxies, but for resonant actuator application this stress must be drastically minimised.

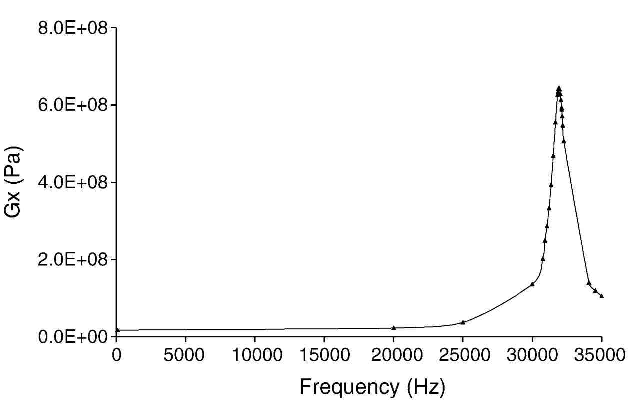

Fig. 3. Evolution of the stress concentration at the bonding layer inner edge in the vicinity of the cavity resonance frequency.

In order to reduce this stress at the resonant frequency the following modifications of the design were considered: (a) a groove in the ceramic just below the point where the maximum stress concentration appears; (b) an epoxy meniscus formed inside the cavity; and (c) a variation of the thickness of the epoxy layer. In order to simplify the calculations, the ATILA models were developed for an asymmetric cymbal due to its unique cavity resonance mode.[5]

Table 2 compares the reduction of the ratio stress/maximum displacement at resonance frequency for each assumption, as well as other variables, like the variation of the effective coupling factor (k_{eff}), cavity resonance frequency (f_r), stress concentration at the bonding layer at 100 Hz and maximum displacement of the cymbal at 100 Hz.

Firstly, a ring-shaped groove in the ceramic was modelled because it was found in former papers that the introduction of a groove in the moonies caps enhanced the displacement and reduces the stress concentration.[6] To determine the effect of the groove, both the locations and the dimensions (depth and width) of the groove were altered. The most effective position of the groove is centred, just above the edge of the inner cavity, with 0.05 mm of depth and 0.2 mm of width. A reduction of the ratio stress/maximal displacement at the resonant frequency of 19% was observed in this case (Table 2). But, at the same time for this geometry, a 40% increase in the stress concentration was obtained for the off-resonant model.

Because the cymbal with the ring-shaped groove has not been manufactured, the comparison between the FEA results and product testing data cannot be attempted.

A variation of the width of the meniscus was modelled, and the biggest reduction in the ratio stress/displacement, 23%, is obtained for a 0.5 mm meniscus epoxy width (Table 2). This new geometry has serious disadvantages: the distortion of the cavity resonance mode and the decrease of the displacement (24% less at 100 Hz).

Finally, a change in epoxy thickness was investigated. The best result was obtained for an epoxy thickness of 0.1 mm with a reduction of the ratio stress/displacement of 37%.

Table 2
Comparison between the three different strategies to reduce the stress concentration

	ΔStress/d at resonance frequency (%)	Δk_{eff} (%)	Δf_r (%)	ΔStress at 100 Hz (%)	Δd at 100 Hz (%)
Ring-shaped groove	−19	−4	−0.4	40	−2
Epoxy meniscus	−23	−8	15	1.2	−24
Epoxy thickness	−37	−3	−10	1.5	−9

This seems to be the best option but the epoxy was electrically insulating. This sometimes leads to a large voltage drop across the bonding layer that can reduce the receive sensitivity of a single element by 14 db at resonance.[3] However, this fact could be overcome by using an adequate electrically conductive epoxy, but the efficiency of the force transmission is anyhow reduced due to the increase of the damp in the bonding layer when the thickness increases.

Even with the highest stress reduction (37% for 0.1 mm of epoxy thickness), the stress in the epoxy bonding layer is still too much high than the tensile lap strength of the epoxies. Then, the resonant actuator application of the cymbal devices is seriously jeopardize.

Because of the difficulty in the control of the width of the meniscus and the thickness of the epoxy bonding layer in laboratory conditions, the comparison between the FEA results and product testing data is a difficult task. The observation of cross sections of cymbals (not shown) demonstrated that inhomogeneities in bonding thickness generated by surface roughness as well the appearance of local meniscus allow the cymbal to overcome the critical tensile lap strength of the epoxy. Thus, it was demonstrate the reliability of the cymbal actuator with reported maximum loads up to 85 N[2]. On the other hand, the usual resonant frequency variations could be correlated with the bonding parameters at it is not a matter of this work.

2.2. Electric potential distribution

Due to the amplification of the stress and the displacement made for the metal caps, the effects between the electrical properties and the mechanical performance are more evident than in any other kind of piezoelectric actuators. The analysis of the distribution of the electric potential in cymbal has never been studied before.

Fig. 4 shows the electric potential distribution for the cavity resonance mode of the cymbal metal–ceramic composite. The electric potential field is inhomogeneous and is distorted and locally much higher at the inner ends of the bonding layer. This electric potential distribution is correlated with the mechanical stress distribution in the operating point, which is displayed in Fig. 4(C). Much higher stresses can be found at the points where the electric potential has its maximum too. Considering the intensity and distribution of electric potential, which have been shown in the figures, the non-uniform distribution of the electrical field in cymbal devices is obvious and cannot be ignored during the performance analysis. The distribution characteristic and trend of the electric potential, especially their high gradient near the inner edge of the bonding layer, have been shown clearly. As a result, the damage of piezoelectric material always would appear in this area.

For frequencies different of the resonance one, the electric potential distribution is a uniform gradient between the hot electrode and the ground.

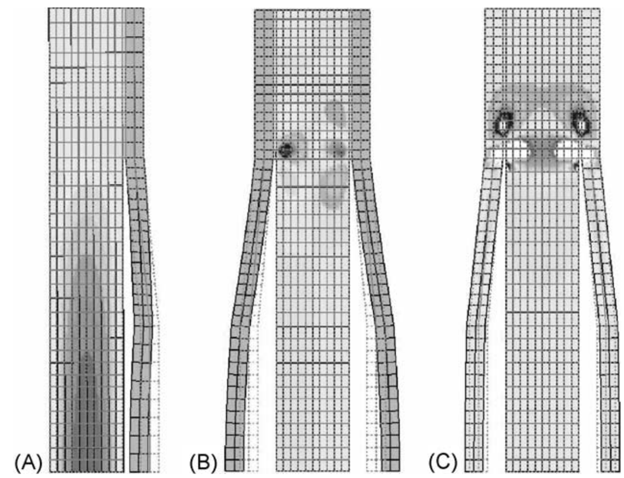

Fig. 4. Electric potential distribution for the cavity resonance mode for an asymmetric cymbal (A) and a symmetric cymbal (B). Stress distribution for the cavity resonance mode for symmetric cymbal (C).

This analysis is extensible for all the non-uniform load piezoelectric devices, like acoustic lens; therefore this analysis must be extended to this kind of transducer.

3. Conclusions

This work presents a modelling of the coupled electrical–mechanical characteristics of the cymbal ceramic–metal composites. The results allow a description of the performance for the cavity resonance and off-resonance modes of the cymbal device.

The developed model has been used to study their impact (ring-shaped groove, epoxy meniscus and thickness of the bonding layer) on the failure probability at the cavity resonance mode. The results of the analysis indicate that the stress concentration at the bonding layer leads to a failure of the device if it works at its cavity resonance mode because in the same way that the displacement is maximized at the resonance frequency, also the stress is maximized. This situation makes the cymbal device no apt for resonant applications.

Acknowledgements

This work has been financial supported by CICYT-DPI2002-0418-CO2-01. P. Ochoa was supported by a grant from FPI-CAM-FSE program.

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