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ANALYSES AND MEASUREMENTS OF ACOUSTICALLY MATCHED, AIR-COUPLED TONPILZ TRANSDUCERS

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Abstract – This talk examines an industrial, air-coupled tonpilz transducer used for acoustic ranging. The study is prompted by a situation common to long-standing industrial products: passive/active material supplies decline or disappear and replacements must be integrated into old designs. The conventional approach relies on 1D analyses and experimental prototypes. Today, new material integration is facilitated by 2D and 3D time-domain finite element models. These are used here to investigate overall modal characteristics, foam matching layer response, and device mounting issues.

INTRODUCTION

The tonpilz (sound mushroom) resonator is a time-tested design for relatively low frequency, high-power transducers. It has been used in naval sonar systems for over 50 years and is commonly found in industrial applications like ultrasonic cleaners and acoustic ranging devices. The concept can be traced back to Langevin, who sandwiched a quartz resonator between two massive plates to reduce resonant frequency. Detailed discussion of these longitudinal vibrators may be found in [1-5].

The transducer consists of a piezoceramic ring stack between massive ends, prestressed by a central bolt. Tail and head masses lower the device's resonance frequency well below that of the piezo stack. Prestress permits high intensity drive and output. The lighter head mass is flared for better mechanical impedance matching to the load and to size the radiating aperture for beam collimation. A foam matching layer increases coupling of sound energy to the very low impedance air load.

Some of the points considered here are coupling between the desired piston-like resonance and the flared head mass bending resonance, sensitivity of the air-coupled transducer to foam matching layer properties, edge constraints on the matching layer, and electromechanical coupling asymmetries in the piezoceramic rings. Model results are compared to measurements of electrical impedance, pressure, and surface displacement patterns.

Correlation between experiments and PZFlex time-domain finite element models [6] is generally good. In particular, response is quite sensitive to longitudinal and shear wave absorptions in the matching layer. This study reveals practical details of an air-coupled tonpilz's 3D modal response and sensitivity to mounting (boundary) conditions. Finite element modeling provides the physical insight missing from simple 1D models and helped interpret confusing experimental data.

DEVICE DESCRIPTION AND ISSUES

A cross-section of the 14 kHz tonpilz device studied is shown in Fig. 1, along with the simplest spring-mass idealization. The device consists of a stack of four PZT4 ring transducer elements connected electrically in parallel, a steel tail mass, a flared aluminum head mass, a steel compression bolt, and a foam matching layer bonded to the head mass. Sphere volume in the spring-mass model indicates relative lumped mass of the tail, head, and matching layer for the device.

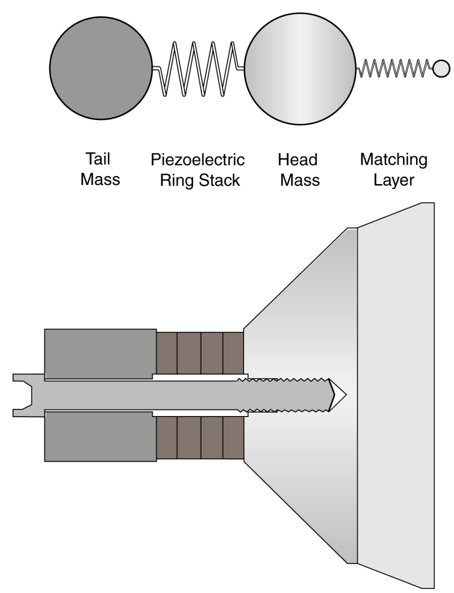

Figure 1. Tonpilz transducer cross-section and simple spring-mass model.

The tonpilz unit had been in production for many years, and design rules for the device died with the designer. This study was prompted by replacement of the original foam matching layer material, which had gone out of production, with a newer, more robust foam material. Prototype devices with the new foam gave considerably lower output than older devices. Empirical trials and 1D simulation had failed to improve device performance. Therefore, finite element modeling was employed to better understand performance issues and identify potential design improvements.

DATA AND 1D MODELS

A series of prototype devices was constructed and electrical impedance curves were generated at various stages to identify the vibration modes excited. Effects of varying the thickness of the new matching layer, its edge geometry, placement in the housing, softening of the housing, and potting material were also examined. These prototypes showed a clean resonance at 13.7 kHz without any matching or potting, and another surprising resonance at 23 kHz (see Figure 2).

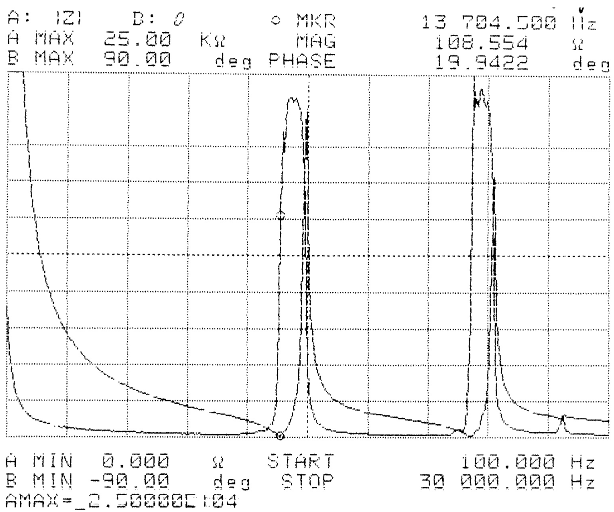

Figure 2: Electrical impedance of unmatched resonator.

Addition of the matching layer introduced not one, but two new modes, the lowest and weakest at 13.6 kHz. In practice, a teflon protective layer is added to the face of the foam matching layer. When this layer is applied, the mode structure shifts so that two weak modes are observed on the low frequency side of a large mode observed at 14.0 kHz. Application of the housing and potting shifts this frequency eventually to 14.6 kHz. The question became now: which was the best mode to use and how piston-like was it? It was also evident that device performance was particularly sensitive to edge effects and damping.

In order to gain a better physical understanding of device operation, simple 1D models were generated to study the main resonator and matching layer modes and their interaction. One made use of standard Mason/KLM transducer models using extensional material and downshifted matching layer properties. A second, much simpler, model used the analytical mass-spring oscillator representation illustrated in Figure 1. This provides a simple closed form solution to the 1D equations of motion [7]. For example, the resonant frequencies are given by

$$2\omega^2 = \left(\frac{k_1}{m_1} + \frac{k_2}{m_3} + \frac{(k_1+k_2)}{m_2}\right) \pm \sqrt{\left(\frac{k_1}{m_1} + \frac{k_2}{m_3} + \frac{(k_1+k_2)}{m_2}\right)^2 - 4k_1k_2\frac{m_1+m_2+m_3}{m_1m_2m_3}}$$

Spring constants k_1 and k_2 of the stack and matching layer follow from the unconstrained and constrained elastic moduli, respectively. Masses m_1, m_2, and m_3 are lumped contributions from the tail, head, and matching layer, respectively.

Both the KLM and oscillator models predicted a bare resonator frequency of 16.7-16.9 kHz, and no resonance at 23 kHz. The models including matching layer predicted a second resonance at 13.6 kHz, which was not strongly coupled to the tonpilz resonance. Clearly, however, more was going on in this device than predicted by these 1D models.

FINITE ELEMENT MODELING

2D and 3D finite element models were generated to gain additional insight into device operation, observe various mode shapes, identify the source of extraneous modes, and model some of the edge effects. The device is nominally axisymmetric so that 2D models should be quite sufficient; however, a 3D model was constructed as well to study the effects of asymmetries in the piezoelectric ring stack, and identify any asymmetric bending modes in the structure that might be affecting the overall device response.

Figure 3 shows the simulated mode shape of the bare tonpilz resonance at 14.35 kHz. The frequency is very close to the observed frequency at 13.7 kHz. However, the magnified mode shape in Fig. 3 makes

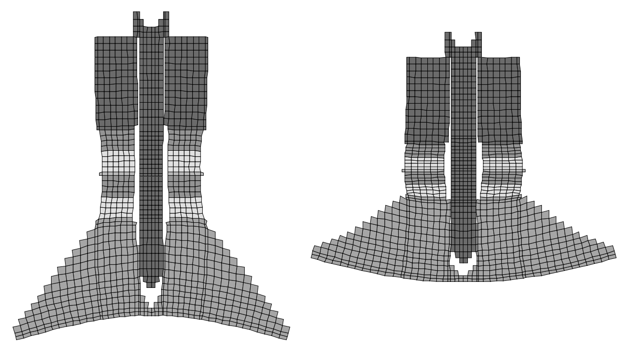

Figure 3: Magnified mode shape at 14.35 kHz of tonpilz resonator with no matching layer.

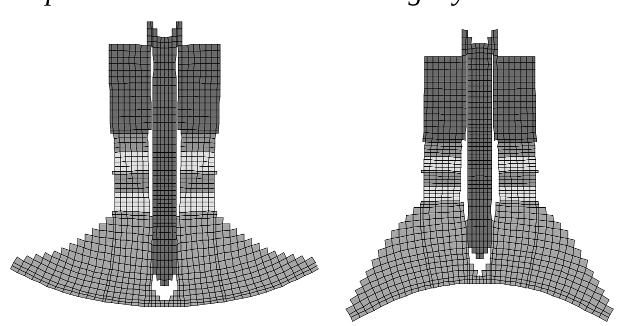

Figure 4: Magnified mode shape at 23.00 kHz of tonpilz resonator with no matching layer.

clear that the aluminum head mass is undergoing much more than a simple extensional vibration. The flared end of the head mass is also bending considerably in phase with the motion of the piezoelectric stack. This bending mode clearly is coupled to the tonpilz mode, and the combined coupled mode is reduced in frequency from that of the uncoupled tonpilz mode.

As seen in Fig. 4, the extra mode at 23 kHz not predicted by 1D models is the other branch of the coupled tonpilz/head bending modes. The bending mode is now 180° out-of-phase with the tonpilz mode. Either mode could probably be used successfully to radiate into air.

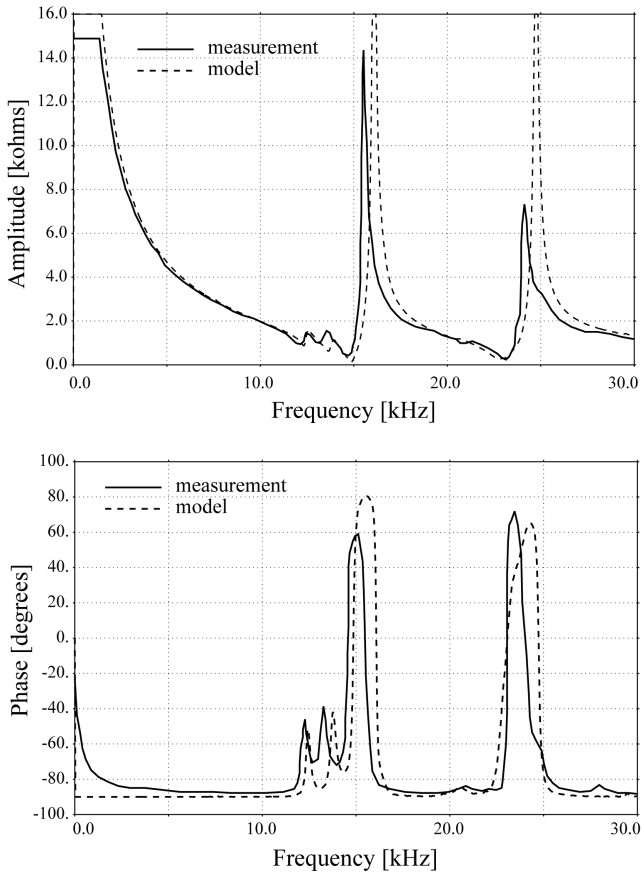

Figure 5. Comparison of 2D PZFlex simulation with experiment of tonpilz resonator with foam matching and teflon protective layer.

The foam matching layer was added to the 2D PZFlex model. This included the teflon protective layer as well. Note that no experimental characterization of materials was done. Instead, computer model iterations were used to estimate the foam's longitudinal and shear attenuation constants from the experimental impedance measurements. Reasonable correlations were obtained as shown in Figure 5. Here the simulated electrical input impedance is compared to that of a prototype device.

Since the desired frequency of operation was 14 kHz, the mode shapes in the neighborhood of that frequency were examined. Two of these mode shapes are shown in Figures 6 and 7. It is clear upon examination that the highest frequency mode is the most piston-like and should yield the highest output and most reproducible beam profile. That conclusion was supported in practice. The mode at 14.85 kHz (in simulation) shows a general piston-like shape with the least face plate ripple. In all cases, the edge of the matching layer shows considerable lateral and extensional deformation. This leads to the conclusion that edge clamping from housing and potting materials would have much influence on the final device output, and be a source of device-to-device variation if not carefully controlled.

The new matching layer's greater lateral deformation was caused by a higher Poisson ratio and longitudinal wave speed, hence, greater thickness, compared to the old foam. One change implemented in the final device that came from this analysis was tapering the foam matching layer so that only the forward edge was contacted by the housing. The housing was also slotted to reduce its stiffness. Both of these changes, also modeled, increased the output of the transducer.

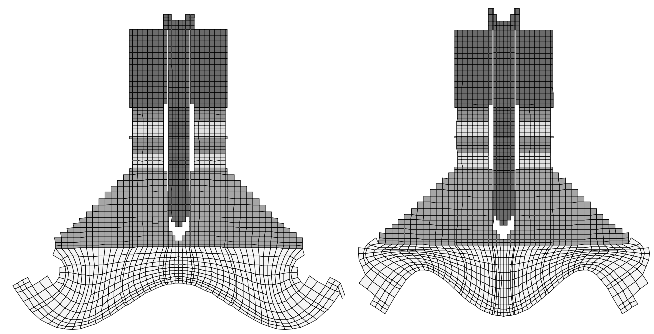

Figure 6: Mode shape at 12.3 khz of tonpilz resonator with matching layer.

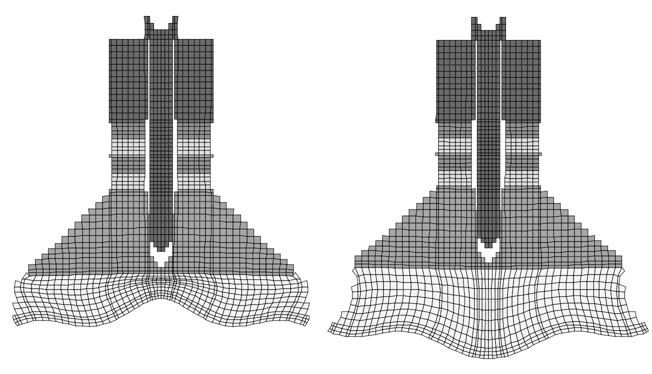

Figure 7: Mode shape at 14.85 kHz of tonpilz resonator with matching layer.

One inescapable fact regarding these air-coupled devices was that edge and damping effects due to the housing resulted in considerable performance degradation and variation. These effects could potentially be well modeled in PZFlex simulations, but required more effort than our budget allowed. As a result, optimizing the device performance remained a cut-and-try process surrounded with a "black art" aura.

Several other modes were examined as well as the ones reported above. Before the nature of the coupled tonpilz/bending modes was recognized, a 3D PZFlex model was implemented in order to see if the lower order mode was related to bending of the whole structure. Asymmetric piezoelectric layers were modeled to excite bending modes. The lowest order mode is shown in Figure 8. This mode is at 7 kHz, but was not observed in practice. Mode shapes around the higher 23 kHz coupled mode branch were also examined, and piston-like behavior was also observed. Consequently, one of these modes could also have been used for other applications.

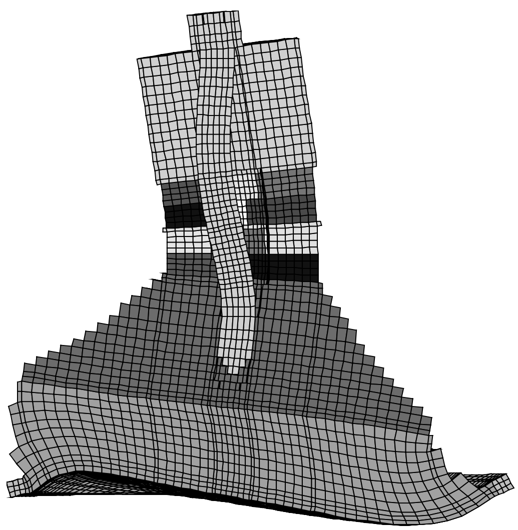

Figure 8: Bending mode shape at 7.0 kHz of tonpilz resonator with matching layer..

CONCLUSIONS

An acoustic ranging, air-coupled tonpliz transducer was modeled in order to optimize its output with a new foam matching layer material. Extensive 1D and 2D/3D finite element modeling was employed to understand the nature of the natural modes of vibration and to study the effects of housing and potting on overall device performance. The flared head mass provided a bending mode near the longitudinal vibration mode that coupled to it and lowered the operating frequency of the lower branch below that predicted by the 1D KLM and spring-mass models. This effect was well simulated in PZFlex models. The tapered head mass could have been redesigned to lessen the impact of the bending mode, but effort to do this was beyond the scope of project funding. It is not clear that doing so would have made the device more or less efficient; it probably would make the device design more robust to manufacturing process variation.

Several practical effects were studied involving the use of a teflon protective layer, matching layer edge effects, housing stiffness, and potting. While a loose protective layer gave a huge jump in output, it was not considered a practical design to manufacture. The edge of the matching layer was beveled, which provided less device variation and a bit more output. Reducing the housing stiffness had this effect as well. Potting tended to damp out the response as expected.

PZFlex modeling tools correctly simulated the device response quantitatively once reasonable attenuation parameters were used. Redesign of the device based on numerically modeling trials would potentially allow for a more robust design without extensive cut-and-try prototyping.

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