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Electroacoustic Transducers in Air and Water.

SANDWICH TRANSDUCERS

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When it was first decided to try and build piezoelectric transducers at frequencies below 100 kHz certain electrical driving problems arose. It was clear to the early experimenters that a quartz crystal transducer at these relatively low frequencies would have to be more than about 3 cm thick at resonance, and this thickness would necessitate excessively high driving voltages in order to obtain sufficient field strength for the desired sound intensity. Even with a water load, the impedance was likely to be several megohms.

Langevin, in a British patent of 1921, suggested a way in which the impedance could be reduced and more sensible driving voltages employed. He showed that if a sandwich construction was use with a thin quartz wafer held between steel plates, then the impedance would be markedly reduced. In fact by adjusting the dimensions of the various parts he felt that it might be possible to tailor the electrical impedance for any given acoustic load impedance and frequency by treating the sections as part of a transmission line. He showed that the power factor would be optimal if the front plate was a quarter wavelength thick and the quartz layer and back plate had the relationship

$$\tan \frac{2\pi \ell_q}{\lambda_q} \qquad \tan \frac{2\pi \ell_b}{\lambda_b} = \rho_q c_q / \rho_b c_b ,$$

where ℓ_q and ℓ_b are the thickness of the quartz wafer and back plate respectively. This ensured that the quartz wafer and back plate provided a composite 1/4 wavelength section.

The advantage of such a system of sandwich construction becomes apparent when we consider an equivalent circuit for a crystal being driven near its fundamental resonance or overtones. The transformation factor, coupling the mechanical side of the circuit to the electrical is α for a symmetrical load and 2α with one surface backed by air. Now

$$\alpha = e_{hj} S/\ell ,$$

where e_{hj} is the piezoelectric stress constant relating a given field strength vector j to a particular stress component h, S is the cross sectional area and ℓ is the length or thickness of the crystal. So that a reduction in ℓ increases α and radically decreases the equivalent sensitive part of the load, since

$$\text{Electrical Resistance } (R_E) = \frac{\text{Mechanical Resistance } (R_M)}{4\alpha^2}.$$

If the crystal was simply thinned down to start with and operated at the required frequency it would be stiffness controlled and have a large capacitative reactance. A useful physical interpretation of the Langevin sandwich is that the backing plate provides the required mass reactance to cancel the crystall capacitative reactance.

Another type of sandwich element designed to achieve the same end is one where a middle section of low impedance material is used. As an example the front plate might be steel, backed by an aluminium alloy section, forming together a composite $\lambda/2$ bar. This might be driven by a crystal $\lambda/2$ thick attached to the rear of the aluminium alloy section. Such a device would have an electrical resistance at resonance given approximately by

$$R_E \approx \frac{R_M}{4\alpha^2} \left(\rho_A c_A / \rho_S c_S \right)^2 ,$$

where the subscripts refer to the steel and aluminium sections. Since a normal $\lambda/2$ resonant crystal is used to drive this assembly, there is no reduction in ℓ_q and so no increase in α compared to a single crystal transducer. The improvement in impedance is solely obtained due to the factor containing the ratio of the specific resistance of aluminium to that of steel in the above equation.

Obviously there are variations on the above themes, producing more complex sandwiches which are designed to have optimum electrical impedances, optimum mechanical Qs and good power handling characteristics. In these cases it is possible to extend the Langevin analysis to cover transducers with a variety of materials and a large number of sections. In order to determine the dimensions of each section for overall resonance, the best plan is to divide the transducer into $\lambda/4$ lengths and apply the resonance conditions:

$$\frac{Z_2 A_2}{Z_1 A_1} \cdot t_1 t_2 = 1$$ for a 2-section $\lambda/4$ length, (same as Langevin equation).

or

$$\frac{Z_3 A_3}{Z_2 A_2} \cdot t_2 t_3 + \frac{Z_3 A_3}{Z_1 A_1} \cdot t_1 t_3 + \frac{Z_2 A_2}{Z_1 A_1} \cdot t_1 t_2 = 1$$ for a 3-section $\lambda/4$ length.

Where Z_1, Z_2, Z_3 are the specific acoustic resistances, A_1, A_2, A_3 are the cross-sectional areas, and t_1, t_2, t_3 are the functions $\tan(2\pi \ell_3/\lambda_2)$ etc., for each section.

The calculation of the electrical impedance which will be seen at the terminals of a modern sandwich transducer, under certain loading conditions, is rather more difficult to evaluate accurately due to the number of different materials and sections involved, through which the load impedance of the medium is reflected. By solving the wave equation for the specified boundary conditions and piezoelectric and mechanical constants involved, it is possible to derive an equivalent circuit in terms of transmission line functions representing each section of the composite transducer. The circuit can usually be simplified for the particular frequency used, and the functions approximated by ladder networks or lumped elements. The equivalent circuit can then be used to gain some insight into the impedance which will be presented to the generator, and also the electrical and mechanical Qs. However such an analysis is lengthy and usually yields only approximate values for a reasonably complex transducer. It is nevertheless of value as it gives the designer an idea of the factors affecting the most important operating parameters and so allows him to 'trim' the design.

One problem with sandwich transducers - which because of their advantages are invariably used for high powers - is that the high stress regions usually come at interfaces between the sections. So for this reason, and also to inhibit the crystal or ceramic from going into tension, transducers are usually prestressed by an internal bolt or outer sheath. In the author's experience a good adhesive is still required between the various sections but this no longer acts so much as a glue as a good acoustic coupler, and in that sense is vital to provide low mechanical loss.

In terms of power handling capability a modern sandwich transducer may be limited by

internal strain,
dielectric loss,
or mechanical loss.

With the excellent modern piezoelectric ceramics available, like lead zirconate titanate with a Curie temperature of about 300°C and very low tan δ values at high field, dielectric loss is rarely a limitation, particularly as most transducers are run at a low duty cycle. A well designed and well made unit should have low mechanical loss, so it is more likely that even with prestressing internal strain may provide the limitation, since there is always a practical limit to the amount of compression which can sensibly be applied. One of the National Institute of Oceanography's G.L.O.R.I.A. transducer elements used in a long range side scan sonar has been run at depth at a duty cycle of 1 : 6 for 48 hours, radiating 1000 acoustic watts at 7 kHz into water through a diaphragm 15 cm in diameter. During this trial the internal temperature of the lead zirconate titanate stack, which is 5 cm in diameter and 10 cm long, rose only 30°C above the ambient temperature. Proof of the remarkable high field properties of the latest ceramics available to the designer.

Sandwich transducers of all shapes and sizes are in use in science and industry today. They are used to radiate high powers into water, or to drill through rock, and they can be found in many mechanical engineering applications such as extrusion processes and welding. They find use in numerous medical applications at high frequencies, and even in the most modern forms of bubble chambers designed to detect the presence of atomic nuclei as they pass through liquid hidrogen.