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Piezo Film: Form and Function

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Abstract

Many excellent mathematical models exist for predicting the high-frequency response of piezoelectric transducers. Most of these, however, are designed to describe the behaviour of thickness-mode devices. With the advent of piezoelectric polymer material and, in particular, large-scale producion of the piezo form of polyvinylidene fluoride (PVDF), a new class of very useful transducers has arisen. These are more closely allied to strain gauges, but demonstrate very high voltage sensitivity to strain. In many circumstances low-frequency response is of more concern than the upper limits and a simple resistor/capacitor model suffices. But the unique properties of 'piezo film' allow operation into frequency ranges far beyond those possible using foil resistance gauges.

The object of this paper is to demonstrate how the high-frequency response of planar piezoelectric strain sensors may be derived quite simply from inspection of the surface geometry of the elements themselves. The standard tools of signal theory are applied in an abstract manner, and the general form of the results allows prediction and construction of complex signal-processing elements using standard film patterning techniques.

The author has worked with the applications engineering group of Pennwalt Corporation's Piezo Film Department since 1984, and has seen the development of PVDF from a laboratory curiosity into its current position of major importance as an electromechanical and pyroelectric transducer component.

1. Introduction

The effects which govern the frequency response of piezoelectric transducers are, generally speaking, well defined and understood. At the low-frequency end of the spectrum a simple R–C model adequately describes device behaviour (see Fig. 1). For higher frequencies more complex models have been developed and refined [1]. Such models were originally designed for highly resonant materials such as quartz and PZT. Polymer materials such as polyvinylidene fluoride (PVDF) show much higher damping factors, but the mathematical models can be modified to reflect this. With the current expansion in the scope of piezoelectric polymer transducer applications, however, a different set of considerations may arise. In perhaps their simplest mode, piezo-film transducers (in the 'receiver' mode) act as distributed 'dynamic strain gauges', where the sensing area can be virtually unlimited. Here the transducer consists simply of an active area of film defined by a region of overlapping metallized electrodes on upper and lower surfaces, and a connection arrangement. The device is then bonded, like a strain gauge, to the substrate under test. In this case the effective damping factor for the polymer is intuitively higher than for an unsupported element operating in the 'thickness' mode. The extremely thin cross section would not be expected to support resonant modes between its ends (assuming that the lateral dimensions are orders of magnitude greater than the thickness). In fact, the properties of the substrate are assumed to govern all aspects of resultant signals.

The object of this paper is to investigate the relationship between the geometry of such transducers and their function as signal-processing elements in an abstract manner, by considering their response to a hypothetical mechanical impulse. A technique, rather than a model, is proposed to describe the high-frequency behaviour of piezoelectric polymer strain transducers using the standard tools of signal theory.

To avoid duplication, the piezo-film devices are assumed to be mechanical-to-electrical energy convertors, although the governing principles apply equally well in reverse.

2. Discussion of Mechanical Unit Impulse

In electronic circuit analysis, the frequency response of a system can be described equally well by a graph in the frequency domain or by the amplitude/time plot of the impulse response. By the duality property of the Fourier transform, the

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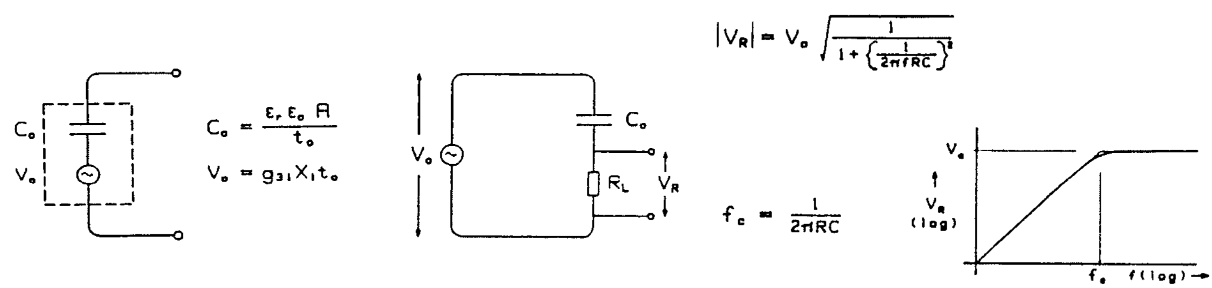


Fig. 1. Low-frequency electrical model.

information displayed in either form is equivalent. An analog circuit is excited by a high amplitude pulse of extremely short duration whose 'area' (product of amplitude and duration) is unity. This input signal contains equal energy over a very wide bandwidth and can thus elicit all of the circuit behaviour. The resulting output or impulse response can then be processed by the Fourier transform to reveal the circuit frequency response.

In the mechanical world, severe practical problems underlie the generation of anything resembling a unit impulse, and so the normal procedure is to apply an input of known Fourier transform, obtain the transform of the output signal and, by division, extract the system frequency response. For piezo-film strain transducers the problem is to apply an input of sufficiently high bandwidth, since the frequency response may extend to many megahertz.

It is proposed that an entirely conceptual analysis can, in this case, be performed by considering a hypothetical planar impulse which arrives from a given direction as a parallel wavefront oriented perpendicular to the direction of propagation. This signal is carried by the substrate, not by the film itself, *and its velocity reflects this*. At any instant, the film output is then determined by the 'area' of intersection of the wavefront with the transducer area. By the 'sifting' property of the Dirac function, this overlap is simply the width of the piezo-element at that instant (Fig. 2). Thus there is a

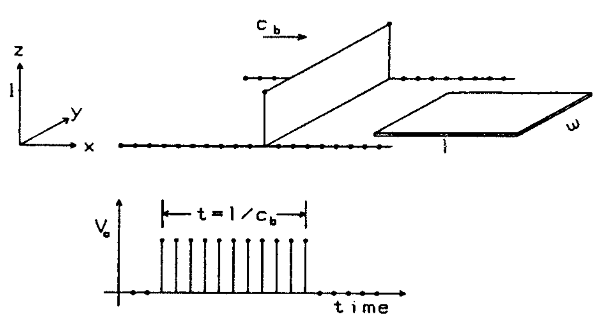


Fig. 2. Unit sample method.

very direct relationship between the active area and the system impulse response and the response can, in fact, be written down by inspection. By changing the angle of incidence of the planar impulse it is possible to build up a polar response pattern. Symmetry in the geometry of the transducer is obviously carried through to the polar frequency response.

3. Piezo Film as a Signal Processor

The effect of different transducer shapes can now be considered. By direct consequence of the properties of the Fourier transform, a rectangular element displays a frequency response curve of the form $\sin x/x$ with the main lobe centered on zero frequency and a series of nulls spaced equally in frequency (Fig. 3). (It is worth noting that this response would be predicted for film operating in the thickness mode if the level of damping was critical. The nulls would represent the frequencies at which the wavelength of incident energy corresponded to the thickness of the sensing element. If the Q of the thickness-mode device was higher, then there would also exist a series of peaks at the multiples of $\lambda/2$. It is assumed that the effective level of damping will not support resonances in the planar mode.) A circular element shows similar form, but with a wider main lobe and faster roll-off of minor lobes. Care must be taken when comparing circular and square elements, since for unit areas the diameter of the circle is longer than the width of the square. Hence the width of the main lobe in the frequency response is reduced to just fractionally wider than the square. The upper frequency roll-off is perhaps the most interesting area of difference. If a tangent is drawn to the peaks of the minor lobes, it is found that the rectangle shows -20 dB/decade slope, while the circle gives -32 db/decade.

Another shape of interest, although perhaps impractical from symmetry considerations, is a bilateral exponential (like a highly stylized Christmas star). This shape, when either axis is perpen-

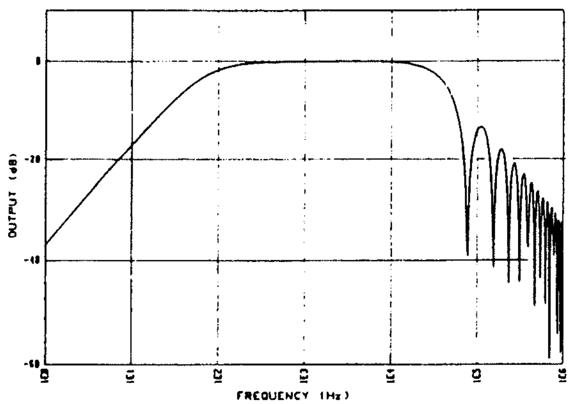


Fig. 3. Typical frequency response of element of piezo film.

dicular to the impulse wavefront, should show no nulls in the frequency response but simply an exponential decay with increasing frequency. Again, this results from the integration properties of the exponential function.

A simple experiment was designed to demonstrate the higher bandwidth of short elements versus long. Two narrow (6 mm) strips of film were prepared, one of length 50 mm, the other 350 mm. Both were bonded to the surface of a circular bar of brass. Impulses were applied to one face of the bar, and the resulting signals for each transducer were averaged and compared. Obviously, the bar did not transmit all frequencies equally well, and the narrow-band spectra only show a trend (Fig. 4). The spectra were reprocessed to obtain the band energies as a fixed bandwidth filter was stepped through the full spectra. The roll-off of the longer element's response was then clearly seen.

Before considering the derived polar frequency responses of various shapes, it is important to take into account the difference between the two commerically available forms of PVDF, namely uni- and biaxially oriented film. Uniaxial film will show higher piezo output for stress induced parallel to the machine direction of the film and reduced output in a direction perpendicular to the machine axis. Biaxial film shows more uniform activity at a 'compromise' output level. Both types can be programmed using weighting factors varying with incidence angle for polar response plots.

Circular elements are the simplest case by virtue of their symmetry. For biaxial film, the result becomes trivial with the polar response reflecting the symmetry of the element. With uniaxial film, only the main lobe is affected significantly. A dipole-like pattern is introduced near the origin, with the zero and 90° values showing the difference between the machine and transverse axes piezo coefficients (Fig. 5).

Square elements show that the main lobe describes an almost circular polar response until the amplitude has fallen considerably. Upper frequencies then tend towards a square polar pattern. This is interesting because the diagonal or 45° response shows the widest main-lobe bandwidth, although this angle presents the longest time-duration response from the element. The reason lies in the form: the impulse response in this case becomes triangular. An intuitive explanation is that the triangle more closely approximates an impulse by focusing more signal around the mid-

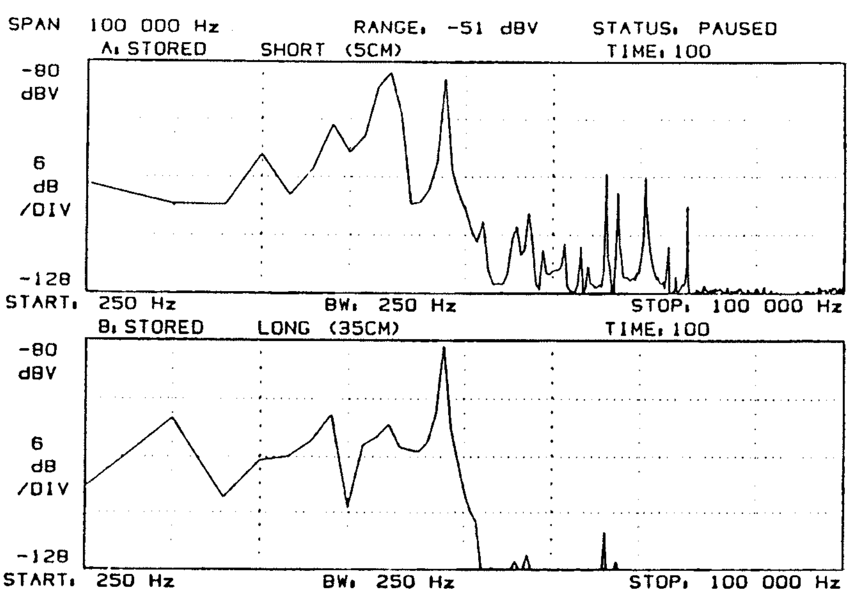
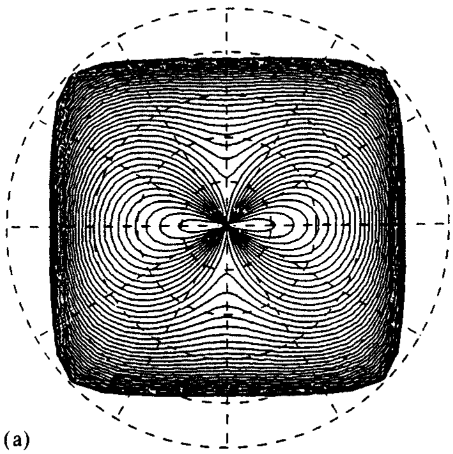
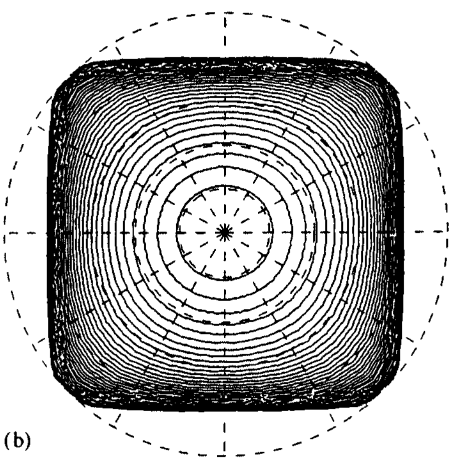


Fig. 4. Short and long elements compared.



(a)



(b)

Fig. 5. Polar response plots, (a) uniax and (b) biax film.

point, whereas the square has evenly distributed output over time.

Rectangular shapes in general have rectangular polar responses, but the long axis of the shape results in a narrower bandwidth of frequency response, and vice versa. Thus a rotation of shape is implied in the transformation between surface geometry and polar response.

4. Exploiting Form: More Advanced Techniques

Electrode patterns may be formed on piezo film by sputtering or depositing through a mask, or by screen-printing with conductive ink. It is therefore very easy to form many discrete sensing elements on one continuous sheet, and also to interlink these elements. As an example of how the very abstract methods described above can be harnessed in a useful way, a device was constructed which resembled in many ways a conventional interdigital surface acoustic wave transducer. Two interlaced sets of 'fingers' were patterned on the upper surface of a sheet of film. The lower electrode was continuous and covered only the overlapping region of the fingers. Initially this rear electrode was made rectangular; later versions used one or several lobes of the $\sin x/x$ function.

The two interdigital electrodes only were electrically connected to measuring equipment. The device was bonded to sheets of glass, for reasons which will become apparent later.

With a rectangular rear electrode, the theoretical impulse response should consist of a series of

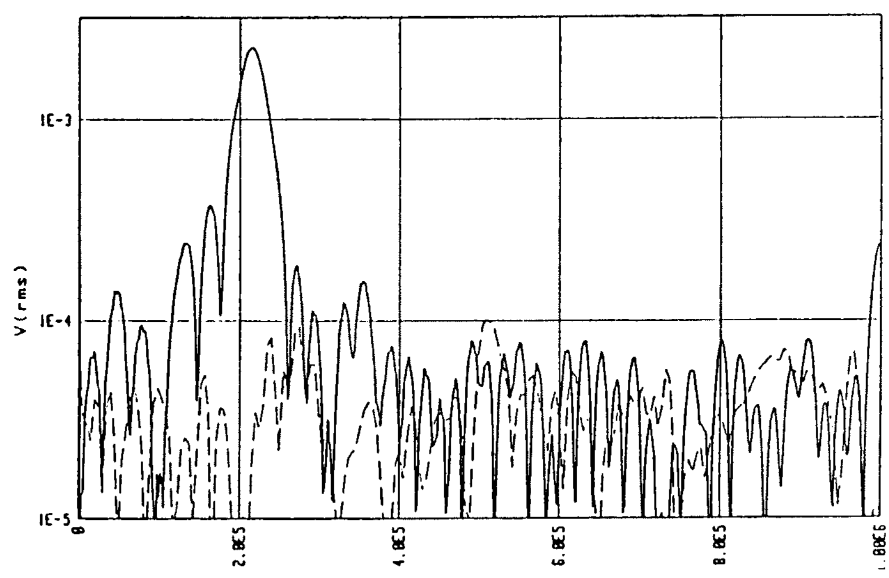


Fig. 6. Interdigital and circular elements, response to impulse on glass.

alternating polarity unit impulses, with the spacing of the impulses determined by the speed of sound in glass. This velocity is rather hard to define precisely, since the propagation of different types of wave under different conditions leads to a wide variety of numbers. At any rate, the Fourier transform of such an impulse response predicts a band-pass characteristic, with the width of the pass band being determined by the number of separate impulses in the complete response. The centre frequency is simply the inverse of the transit time between two positive (or negative) 'fingers'.

Experimental verification of this device proved predictably difficult, due to the impossibility of launching a unit mechanical impulse. However, the output resulting from breaking the glass sheet showed that frequencies around the predicted pass band were given preferential amplification. The glass-break event, in fact, offered a nearly random input signal for high frequencies when checked with a single broad-bandwidth transducer (Fig. 6).

Eventually, another similar interdigital transducer was used to launch a low-amplitude signal onto the glass, and the resulting output showed very clearly the characteristic of the combined transmit/receive system. The centre of the pass band was found to be affected by different thickness (or possibly composition) of glass.

The intended use for the devices was as glass-break detectors. The benefit of the pass-band limitation was to allow only certain frequencies that result exclusively from breakage to be detected and thus eliminate false alarms. In fact, it was found that minor breakage (as found with the impact of gravel) could generate almost as much high-frequency signal as total fracture. One significant advantage of the transducer was then that one side of the interdigital pattern could be monitored with reference to the rear plane, giving a low-pass characteristic. Thus the low frequencies resulting from the 'push' exerted on the glass could also be measured. Combining the low- and high-frequency signals with simple AND logic gave an extremely reliable decision on the event.

A possible development is the production of an interdigital device showing circular symmetry (a series of rings or arcs alternately wired). Such a device has been tried, with good preliminary results. Off-axis response was found to be better than for linear arrays.

These interdigital devices effectively supply gain at certain frequencies with very simple control over pass-band characteristics. The major differences over existing SAW filters are that the operating frequency is determined by the substrate material and not by the transducer alone, and that much lower frequencies can be achieved easily since very large area devices are possible and thus wider spacing of the 'fingers'. Finger width actually controls the amplitude of the upper harmonics of the filter response. Very narrow fingers, which themselves would show high bandwidth, allow multiple pass bands repeating through the frequency domain. Wide fingers superimpose a $\sin x/x$ characteristic on the upper harmonics.

It is interesting to note that this type of filter cannot be exactly represented by any analogue electronic network, but that it closely resembles a class of digital filter described by a simple polynomial expression in the z domain. The degree of the polynomial is determined by the number of fingers in the device, and the repeating property in the frequency domain is precisely analogous to any digital filter. If no 'spaces' are included in the impulse response, then the digital equivalent filter is actually a high-pass one, but the repetition in frequency of digital filters makes the classification of band-pass or high-pass in this comparison irrelevant. When one or more zero samples are included between the unit samples, then the digital filter is indeed a band-pass.

5. Conclusions

It has been shown that the high-frequency response of planar piezofilm elements can be derived very simply from analysis of their physical shape. Their properties are also affected by the substrate to which they are attached. In general, large planar dimensions imply low bandwidth, and vice versa. Frequency response can be altered by selection of shape to enhance or minimize high-frequency attenuation. More complex patterning can offer controlled band-pass and other characteristics.

Reference

1 W. P. Mason, *Electromechanical Transducers and Wave Filters*, Van Nostrand, New York, 2nd edn., 1948, pp. 185–224.

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General information about Piezo Film may be found in:

1 *Technical Manual*, Piezo Film Department, Pennwalt Corporation, 1987.
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