PIEZO FILM VIBRATION SENSORS

NEW TECHNIQUES FOR MODAL ANALYSIS

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ABSTRACT

This paper discusses the application of thin film piezoelectric polymer transducers for experimental modal analysis. An overview of the operating characteristics of poly(vinylidene fluoride) is presented, followed by descriptions of a brief comparison experiment with conventional transducers, a machinery vibration experiment, and two systems which use basic analysis to develop secondary transducers. The results appear to be entirely consistent and of some significance where conventional devices apply limitations of dynamic range, bandwidth, format or economics.

1. INTRODUCTION

System design for experimental modal analysis currently shows a trend towards modularity and flexibility. The number of data acquisition channels available per unit cost is rising, while self-contained equipment demonstrates increased signal generating and processing power. It is appropriate that recent advances in transducer technology may act to reduce further the complexity of instrumentation required, with obvious benefits of reduced set-up time and system cost.

One fluoropolymer in particular has proved to be of special interest, since it may be processed to achieve a very high degree of piezoelectric activity. This is poly-(vinylidene fluoride) or PVDF, which is well established in non-piezo form as a durable engineering plastic with excellent environmental properties.

Fully finished vibration sensors and exciters have recently become available, demonstrating the industrial demand for low-cost transducers in an increasing field of applications ranging from simple switches to complex biomedical monitoring [1]. Tzou has demonstrated use of PVDF as the active element of a lightweight accelerometer [2]. This paper focusses on the implications of the thin film format itself and the use of sensors and exciters exploiting the longitudinal or surface strain mode of operation.

2. SUMMARY OF PROPERTIES

A comparison of the fundamental properties of PVDF with other piezoelectric materials is shown in Table I. The net effect of the low film thickness, low permittivity and moderate charge sensitivity is to yield devices of "useful" capacitance (typically several nanofarads) with very high voltage sensitivity to strain. Low film thickness also plays a major role in determining the operating sensitivity in the longitudinal axis, since extremely high stress may be generated by quite modest applied force or strain. This feature forms the basis of many piezo film applications.

2.1 ELECTRICAL TO MECHANICAL CONVERSION

When an electrical field is applied across the thickness of a simple piezo film element, it causes primarily a change in length. Changes in width and thickness also occur but these are usually less apparent. Ultrasonic devices, however, exploit the thickness mode. Bimorph configurations allow small differential strain in two reverse polarity elements to be translated into substantial flexural motion.

Although the induced strain may be small, the low mechanical Q-factor of the film allows wide bandwidth performance. If the receiving transducer is also piezo film, then measurements are possible over a very high dynamic range.

In an effort to investigate the transfer characteristics of the film, a reciprocal technique was used where a 9um transmitter was bonded to a 28um receiver element and the assembly lightly clamped to a rigid substrate. The resultant magnitude and phase plots are shown in Fig 1.

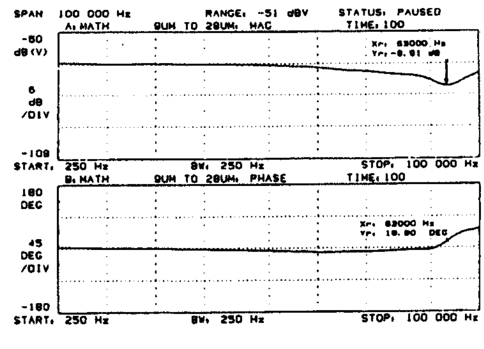


Fig 1. Reciprocal Calibration of Piezo Film

The 9 dB drop in amplitude at 63250 Hz was found to be an effect of the connecting leads. The care necessary when mounting any strain sensor should be doubled for these truly dynamic measurements. The overall characteristic of this Tx/Rx pair is remarkable, particularly throughout the audio band. When such pairs are applied to resonant structures, the "insertion loss" in voltage terms may be as low as 40 dB. Very modest drive signals can be used. The periodic noise output of an HP 3561A Dynamic Signal Analyser at about 70 mV r.m.s. provided sufficient direct excitation for almost all of the experiments described in this paper.

Unusual measurements may be performed using this technique as illustrated by the magnitude and phase response curves of a U.S. dime coin in Fig 2. Both elements measured 15mm x 4mm and were attached with double-coated adhesive tape.

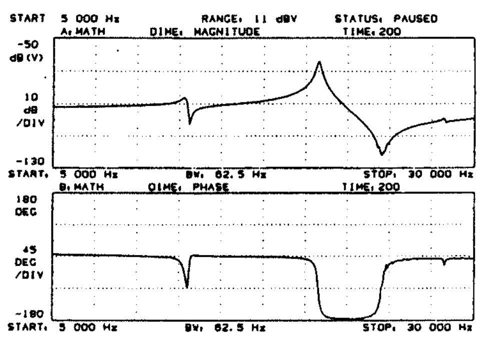


Fig 2. Resonances of a Dime

2.2 MECHANICAL TO ELECTRICAL CONVERSION

In its simplest mode of operation, piezo film acts as a piezoelectric strain gauge. The voltage output may be some four orders of magnitude higher than resistive wire or foil gauges, and two orders above semiconductor types. Linearity and frequency response appear to be excellent. The applications described here involve the use of quite large areas of film relative to the surface being measured and so record to average strain over the area. Point receivers are presumably possible but have not been investigated by the author. The "blanket coverage" technique may be considered useful to capture all vibrational modes. The transverse sensitivity is typically -14 to -20 dB relative to the longitudinal axis. Thus a degree of directionality is possible which may be further enhanced by the transducer shape. Any direct comparison with conventional strain gauges should be performed in a uniform strain field for meaningful results.

Low frequency limitation is caused only by the available electrical time constant or applied load. Simple high-impedance FET buffer circuits will extend operation down to fractions of Hz, but the typical roll-off frequency of a single element into a 10 Megohm input may be 10 or 20 Hz. Thus external electronics are not generally required, except for very low frequency work.

2.3 PYROELECTRIC CONVERSION

PVDF absorbs strongly in the near-infrared and in fact makes an excellent passive IR detector material [1]. Temperature transient sensitivity may thus be an issue in critical applications. Except at low frequencies, the effect is swamped by the high vibrational sensitivity of the film.

3. TRANSDUCER COMPARISON EXPERIMENT

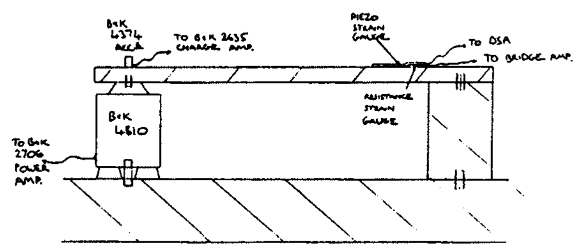


Fig 3. Transducer Comparison Experiment

A rectangular section steel beam was clamped at one end and vibrated in the vertical axis at the free end by a B&K Mini-Shaker Type 4810. Near to the clamping boundary a shielded piezo film sensor (Pennwalt Type SDT1-028K) was mounted directly over a standard foil resistance strain gauge connected in ¼ bridge configuration. A low-mass accelerometer B&K Type 4374 was mounted above the point of excitation (Fig 3.)

3.1 PIEZO vs RESISTANCE GAUGE

The foil sensor required the use of a

low noise bridge amplifier configured with a gain of 60 dB. The excitation voltage was kept low to avoid self-heating. The gain requirement limited the amplifier bandwidth to about 20 Hz. Fig 4. shows clearly the amplifier roll-off effect. Fig 5. compares the unity-gain piezo film signal with the +60 dB bridge amp output at 1 Hz. The piezo film signal is approximately 26 dB greater.

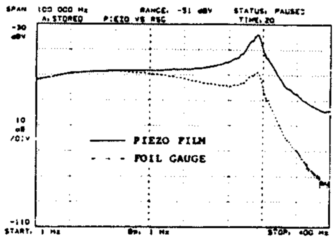


Fig 4. Bridge Amp Roll-off

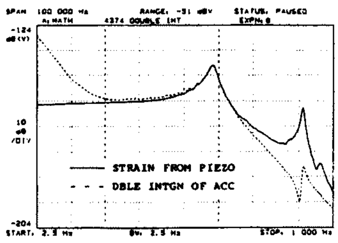
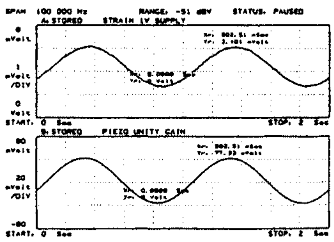


Fig 6. Accelerometer Comparisons



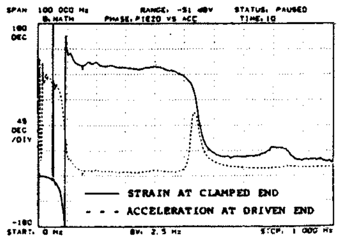


Fig 5. RSG vs PSG at 1 Hz

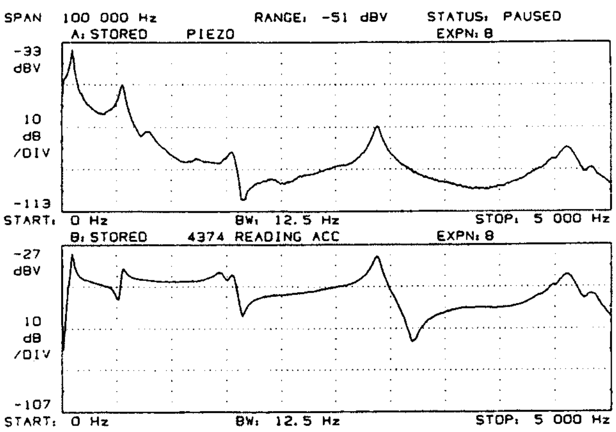


Fig 7. Strain and Acceleration at Higher Frequencies

3.2 PIEZO FILM/ACCELEROMETER COMPARISON

At slightly higher frequencies, it was found that the double integration of the accelerometer response matched the strain signal from the film transducer between two limits. Below 10 Hz the acceleration level was vanishingly small and the processed information cannot be considered valid. The second observable beam mode occurred at 525 Hz and here the driven-end displacement must be out of phase with the strain at the clamped end. Signals in the range of 10 Hz to beyond the first beam mode at 90 Hz are directly related. This situation is reflected in the magnitude and phase plots of Fig 6.

At still higher frequencies, the relationship between acceleration and strain at opposite ends of the beam becomes more complex. Correlation can still be seen, as in the traces of Fig 7.

4. MACHINERY VIBRATION

Diagnostic machinery vibration monitoring is becoming widespread, with the detectable symptoms well understood [3]. A basic experiment to determine the potential of dynamic strain transducers was configured on the lab bench.

A small but powerful DC brush motor with 11 poles was mounted on a sturdy plinth and fitted with a heavy flywheel on an extended shaft. An optical shaft encoder was used to supply synch pulses. Since the model was physically small, the plinth was the most convenient location for affixing transducers, although not considered optimal for analysis purposes.

A B&K Type 4371 accelerometer was bolted to the plinth in line with the shaft and just clear of the flywheel. A piezo film transducer Pennwalt Type SDT1-028K was bonded transverse to the shaft directly underneath the flywheel, extending from the edge of the plinth to the centreline.

The motor speed could be controlled coarsely but was maintained at nominally 5000rpm. An HP 3561A analyser was used in the external sampling mode since the motor speed fluctuated constantly.

The flywheel was tepped to accept small additional masses at 120° intervals around its circumference. Under initial conditions the system was found to have some inherent imbalance. This may be seen in Fig 8. as a high 1-order component. The contribution of the motor poles to the spectrum is substantial at 11 orders. The effect of adding a controlled imbalance at one location is also shown.

Phase information was then gathered from the addition of each extra mass individually and the effective location of the inherent imbalance deduced. Fig 9. shows phase diagrams of the results. The piezo film and accelerometer estimates differ in absolute phase (i.e. relative to synch pulse) but agree well about the relative location - very close to the "B" hole, slightly towards "C". The film signals also corresponded well to physical location of the holes relative to the encoder reference position.

It must be admitted that attempts to balance the system met with little success, suggesting that dynamic, rather than static, imbalance was the predominant factor.

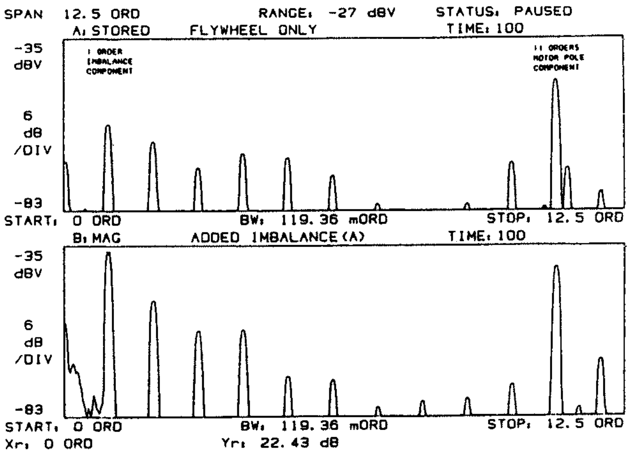


Fig 8. Inherent and Added Imbalance Signals

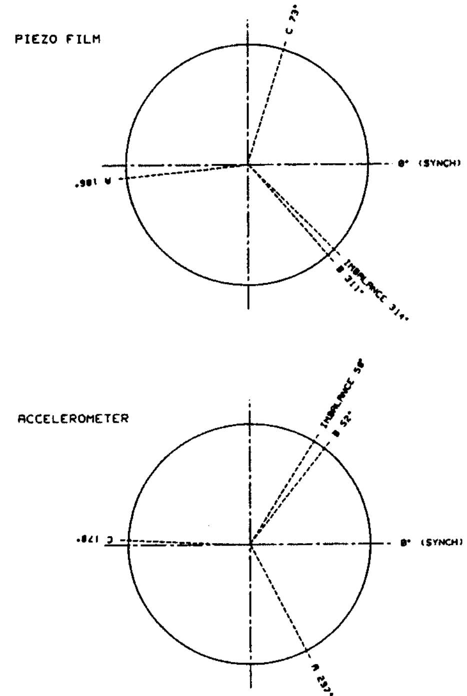


Fig 9. Imbalance Location using Phase

5. CLOSED-LOOP SYSTEMS

The low-mass, non-resonant characteristics of piezo film render it an excellent transducer material for observing and maintaining structures at resonance. Two devices incorporating this concept were examined [4],[5]. Once the transfer function of the structure under different conditions was known, gain stages were designed to sustain oscillation in one vibration mode and track the resonance as it shifted under the influence of external parameters.

A great advantage of this type of sensor is that the resultant output is normally a very clean squarewave signal, which is ideal for microprocessor interpretation as it involves primarily gating or counting operations. The behaviour of such devices is virtually independent of the piezo film transducers.

Pennwalt Corporation has adopted the generic title of "singing technology" for these systems, hence there are singing tubes, plates, switches, and so on. The techniques involved form excellent examples of piezo film applications.

5.1 SINGING TUBE

A brass tube 20 cm long with outer diameter 20 mm and nominal wall thickness .38 mm was equipped with solid brass end-caps and a piezo fim transmitter/receiver pair as depicted in Fig 10.

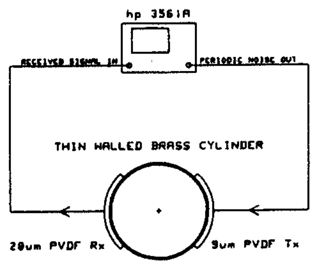


Fig 10. Analysis setup for Singing Tube

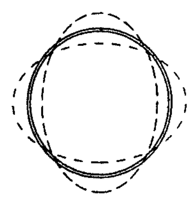


Fig 11. Primary Tube Mode

The expected primary mode shown in Fig 11. was found and verified in the following manner. Spectral response plots for empty and water-filled conditions wer obtained (Fig 12.). Sinusoidal excitation was then applied at the first resonance frequency and the node lines were literally drawn on the tube with a pencil point, observing the effect on the receiver amplitude. Zoom analysis with periodic noise excitation was then applied to note the phase characteristic at resonance. The gain stage thus required a quadrature output. The effect of simple non-inverting voltage gain can be seen in Fig 13., where oscillation occurred at a shifted frequency some 21.5 dB down on the magnitude curve, with obvious disadvantageous effect on gain requirements. The profile of frequency against volume of fluid or fluid height is shown in Fig 14. The mass-loading effect is related to the tube stiffness at any given point and good curve-fitting algorithms are currently in development.

The mechanical Q-factor of the tube was noted to fall slightly at about half-full condition, but rise again and in fact exceed the initial level when the tube was entirely filled with fluid. The self-oscillation was strong and stable throughout the frequency range.

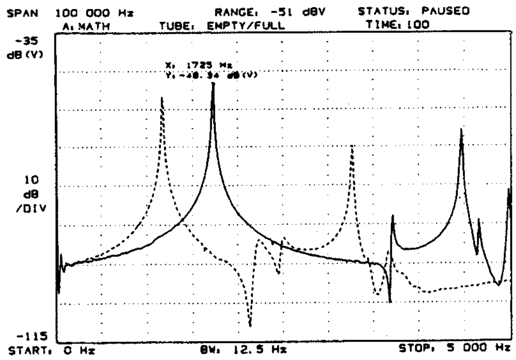


Fig 12. Effect of Fluid on Spectrum

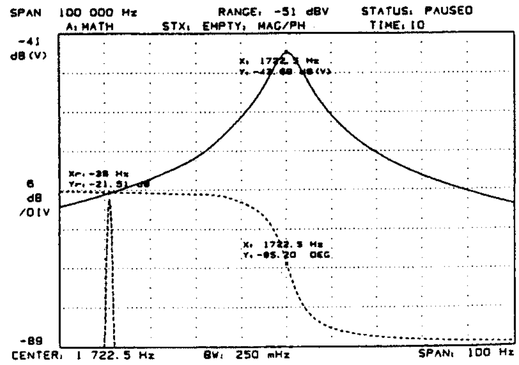


Fig 13. Expansion of Primary Resonance Frequency

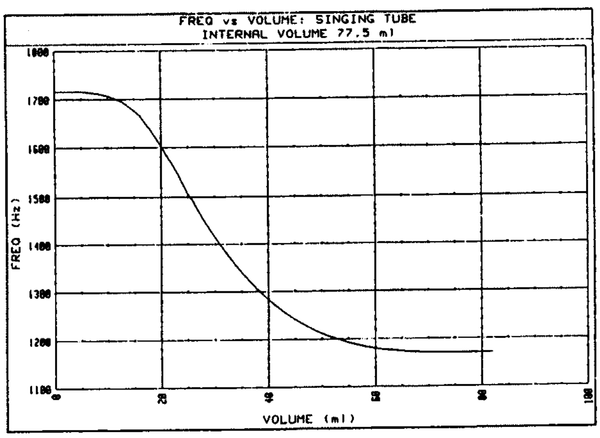


Fig 14. Frequency vs Fluid level/Volume

5.2 SINGING PLATE

A section of a spiral steel spring was cut to the outline shown in Fig 15. The exact shape arose out of external design considerations. A 9 um transmitter/28 um receiver pair of piezo film transducers was bonded to the plate. Both transducers were of the same area and covered a substantial proportion of the plate area. Orientation of the film was longitudinal in both cases. The analysis system was identical to that used for the singing tube i.e. no receiver pre-amplification or transmitter power amplification was required.

For analysis and discrete load tests, the plate was suspended vertically with the light-weight connecting wires carefully dressed to avoid mechanical interference. The broadband frequency response obtained is shown in Fig 16. The predominant resonance at 9100 Hz was found to correspond with the highest acoustic output when driven with sine excitation, or impacted.

The first four resonances are shown in greater detail in Fig 17. It is obvious that even-numbered modes are almost entirely suppressed. When the frequencies of the first ten modes were recorded and analysed, a simple sequence was found which resembled those given for simple rectangular plates. A constant factor was calculated, and an index multiplier which yielded the various mode frequencies. The first three mode shapes were investigated using the same technique used for the tube and found to correspond with the same shapes as a free-free rectangular plate. The shapes and their index factors are shown in Fig 18, and the numerical results listed in Table III.

The reason for the suppression of even-numbered modes was then clear - the radius of the plate must discourage odd symmetry about the midpoint of the plate.

The strong resonance at 9100 Hz could have fallen in sequence as mode XI but the high amplitude suggested otherwise. It was found, again by drawing on the plate, that this frequency was the first transverse mode of the plate as shown in Fig 19.

When the plate was mounted in a micrometer drive arrangement (Fig 20.) to allow very fine adjustment of stress, this resonance was found to be much more susceptible to stress than the longitudinal modes. This "mode mobility" caused this resonance to shift right through other modes under load, giving rise to minor discontinuities in the otherwise smooth frequency vs. load profile when the system was connected in the self-oscillating mode. The interaction of two modes is shown in Fig 21.

Continuity was obtained over a reasonable range of frequency and the resulting curve is shown in Fig 22. The slight non-linearity shows that a small section of an inverse square root function is being magnified. The deviation of the measured curve from the linear regression line for the data is shown in Fig 23. The minor discrepancy at 100 grams load resulted from the joining of two data sets which were not recorded under identical environmental conditions. Temperature dependency for this material was rather pronounced.

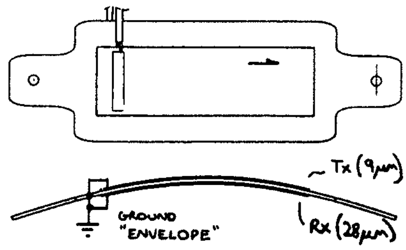


Fig 15. Singing Plate Format

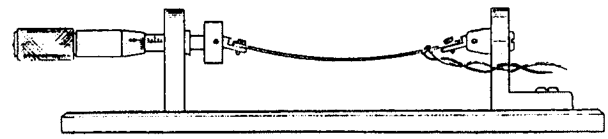


Fig 20. Micrometer Assembly for Plate Tests

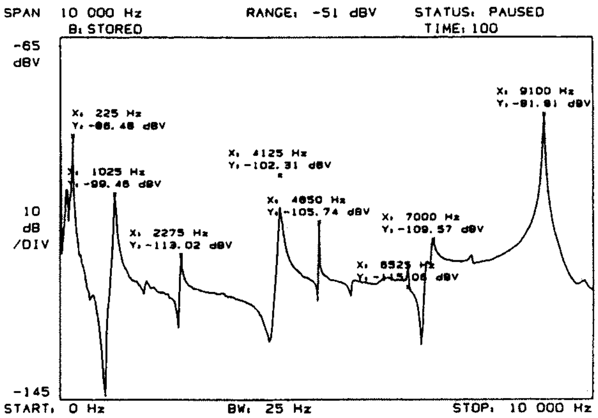


Fig 16. Plate Response:Broadband

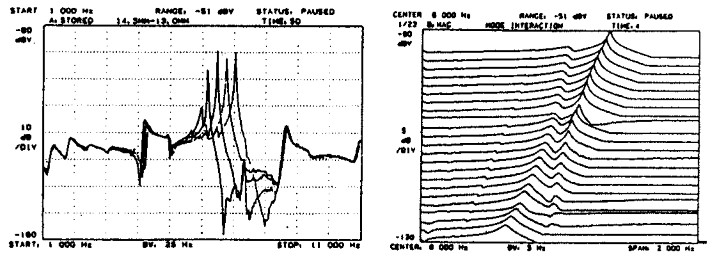


Fig 21. Transverse Mode Mobility and Interaction

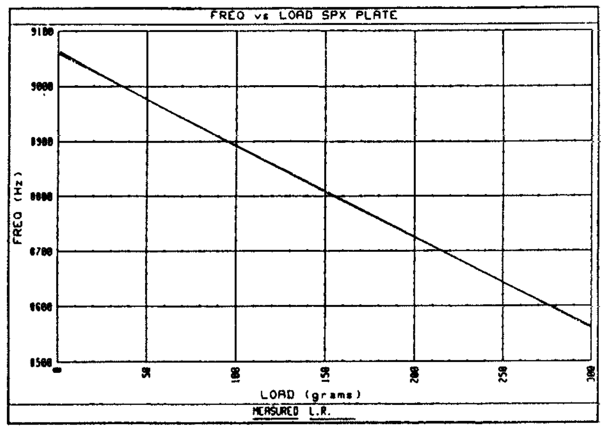


Fig 22. Frequency Variation with Load

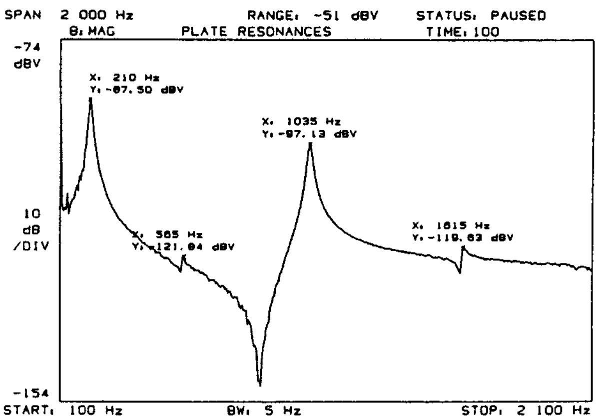


Fig 17. First 4 Modes: Singing Plate

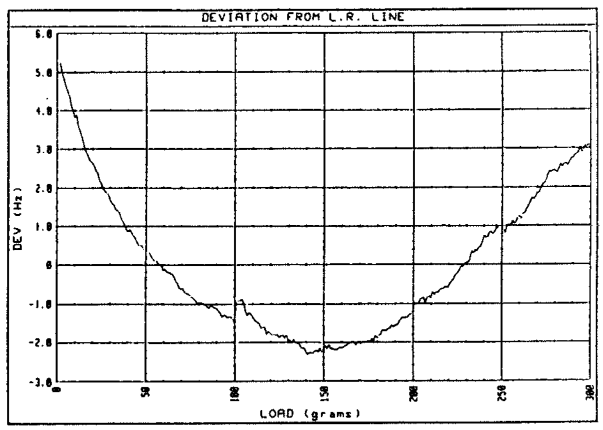


Fig 23. Deviation from Linear Regression Curve from Fig 22.

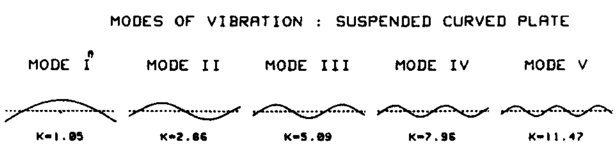


Fig 18. Longitudinal Vibration Modes

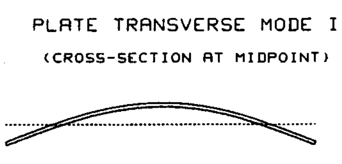


Fig 19. First Transverse Mode

6. CONCLUSIONS

Piezo Film vibration sensors have proved to be successful in performing many different vibration measurements over a wide range of frequencies. Used in conjunction with film exciters, a minimum I/O analysis system can be realised. The techniques involved are extremely simple to implement and allow dynamic analysis of complex structures. The interpretation of strain signals may require fresh consideration of analytic methods, and so an open invitation is extended to those skilled in the art to experiment in like manner and verify or confirm the true potential of this new and exciting material in the widening domain of modal analysis.

REFERENCES

[1] Technical Manual, Pennwalt Corporation Piezo Film Department (1987)

[2] Tzou, H.S. "Light-weight Transducer Development Using Piezoelectric Polymer" Proceedings of the Fifth International Modal Analysis Conference (1987)

[3] "Dynamic Signal Analyser Applications" Hewlett-Packard Application Note 243-1 (1983)

[4] Strachan, J.S. "Piezoelectric Apparatus For Measuring Bodily Fluid Pressure Within a Conduit", U.S. Patent No. 4600855 (1986)

[5] Strachan, J.S. "Force Transducer" U.K. Patent No. 2148504B

TABLE I : COMPARISON OF PIEZOELECTRIC MATERIALS

Property	Units	PVDF Film	PZT	$BaTiO_3$
Density	10^3 kg/m^3	1.78	7.5	5.7
Relative Permittivity	$\varepsilon/\varepsilon_0$	12	1,200	1,700
d_{31} Constant	(10^{-12})C/N	23	110	78
g_{31} Constant	(10^{-3})Vm/N	216	10	5
k_{31} Constant	% at 1 KHz	12	30	21
Acoustic Impedance	(10^6)kg/m^2-sec.	2.7	30	30

TABLE II : SUMMARY OF OPERATING PROPERTIES - DT1 ELEMENT

DT1 - 15mm x 40mm PVDF substrate, 12mm x 30mm active area printed with Ag ink. Thickness 28 μm (excluding electrodes).

1. Electrical to mechanical conversion :
   (1 direction) 25×10^{-9} m/V, 700×10^{-6} N/V
   (3 direction) 33×10^{-12} m/V

2. Mechanical to electrical conversion :
   (1 direction) 12×10^{-3} V/με, 400×10^{-3} V/μm
   14.4 V/N
   (3 direction) 13×10^{-3} V/N

3. Pyroelectric Conversion :
   8 V/K

4. Capacitance :
   1.36×10^{-9} F, D = 0.018 @ 10 kHz
   Impedance @ 10 kHz : 12 kohm

5. Maximum Operating Voltage :
   dc: 280 V (yields 7μm displacement (1 axis))
   ac: 840 V (yields 21μm displacement (1 axis))

6. Maximum Applied Force (at break, 1 direction)
   6 - 9 kgf (yields voltage output of 850 to 1275 V)

7. Mechanical Q-factor :
   approx. 1.6

TABLE III : SINGING PLATE MODE FREQUENCIES

Curved steel plate in suspension

MODE	K	CALC FREQ	MEAS FREQ	CONST
I	(1.05)	(210)	210	200
II	2.86	573	565	198
III	5.09	1020	1035	203
IV	7.96	1595	1615	203
V	11.47	2299	2280	199
VI	15.60	3126	3090	198
VII	20.37	4082	4130	202
VIII	25.78	5166	5020	195
IX	31.83	6379	6360	200
X	38.52	7719	7720	200

$$K = \frac{(i+1)^2}{\pi} \qquad i = 2,3,4 \ldots$$

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