Piezoelectric Pressure Transducer with Acoustic Absorbing Rod

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A piezoelectric pressure transducer has been designed, using readily available, inexpensive materials, which is capable of measuring sidewall pressures over a wide frequency range without serious distortion of the signal due to spurious elastic waves in the sensing element. The rise time is limited primarily by the transit time across the surface of the sensing element. The response of the gauge to a Mach 3.2 shock, gaseous detonations at pressure levels of 11 and 34 atm, respectively, is presented.

INTRODUCTION

MEASUREMENT of static sidewall pressures over a wideband frequency range from dc to above 1 MHz and for relatively long times continues to be an area where improvement is needed. Pressure transducers with piezoelectric sensing elements have been the most successful devices for this purpose. However, a faithful reproduction of the pressure in the high frequency range is difficult to achieve because of spurious elastic waves in the sensing element. Attempts to filter the output signal or to "compensate" for the oscillations leave much to be desired. The more fruitful approach is to eliminate the spurious elastic waves by appropriate design of the transducer. Two such designs which have appeared in the literature form the basis of the present work.

Edwards[1,2] successfully measured pressure as a function of time with a piezoelectric crystal by utilizing a quartz disk sandwiched between two Duralumin rods, one end of which is exposed to the pressure source. Longitudinal stress waves travelling along the bar traverse the disk and generate a charge. The acoustic impedances of the piezoelectric element and the elastic rods are matched, so that reflected waves off the interface are minimized and thus spurious signals associated with the longitudinal natural frequency are eliminated. In this method an elastic rod is placed ahead of the sensing element in order to eliminate distortion of the stress wave due to three dimensional effects. Edwards[2] concludes from experiments that the optimum position of the piezoelectric crystal is between 2 and 4 diameters behind the front surface. However, regardless of the position, the rod does not transmit a plane one-dimensional stress wave when a step increase in pressure is applied to the end of the rod; the rise time of the wave is a function of distance from the front face of the bar and the signal exhibits overshoot and damped oscillations. When $x/D \gg 1$ it can be shown that the rise time τ scales as follows[3]: $\tau \propto \nu^{2/3}(x/D)^{1/3}(D/C)$, where ν is Poisson's ratio, x is the distance between the front face of the bar and the axial strain sensing element, D is the diameter of the rod, and C is the velocity of a longitudinal wave ($C^2 = E/\rho$), where E is Young's modulus and ρ is the density. Baganoff[3] discusses this and various theoretical treatments of the problem. (Baganoff's gauge has been very successful for short time endwall pressure measurements, but is not suitable for sidewall measurements.) Jones[4] demonstrated that the bar method can be improved by using a beryllium-PZT combination, because of the extremely low value of Poisson's ratio for beryllium. For a 0.3 cm diam PZT-4 disk 0.05 cm thick located 10 cm from the stressed end, he obtained a rise time of 0.54 μsec and minimal overshoot in response to a reflected shock wave. Jones' total measuring time was limited to 15 μsec since he did not attempt to eliminate the reflected stress waves from the end of the beryllium rod.

A similar design which has achieved microsecond resolution was developed by Zaitsev,[5] as described by Soloukhin.[6,7] However, he placed the piezoelectric element directly on the front face of an acoustically matched backup rod. The Soviet design, which has been applied successfully to spinning detonations,[8] for example, utilizes a 1 mm diam barium titanate disk which is soldered with Woods' metal to a zinc rod and potted in beeswax. In the literature cited, the Soviet designers did not explicitly treat the problem of distortion of the stress wave in the sensing element due to three dimensional effects, but their results do not indicate that it is a serious problem.

Because many design and performance details concerning the Soviet design are not available and since new materials with improved properties are now available, the work at this Laboratory, which stems from Zaitsev's design, is presented.

DESIGN

A diagram of the pressure transducer as used in this Laboratory is shown in Fig. 1. The pressure sensing element is made of lead metaniobate ($PbNb_2O_6$). Tin was chosen as the material for the acoustic absorbing rod be-

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[1] D. H. Edwards, J. Sci. Instr. **35**, 346 (1958).

[2] D. H. Edwards, L. Davies, and T. R. Lawrence, J. Sci. Instr. **41**, 609 (1964).

[3] D. Baganoff, Rev. Sci. Instr. **35**, 288 (1964).

[4] I. R. Jones, Rev. Sci. Instr. **37**, 1059 (1966).

[5] S. G. Zaitsev, Pribory i Tekhn. Eksperim. **6**, 97 (1958).

[6] R. I. Soloukhin, Usp. Fiz. Nauk **68**, 513 (1959).

[7] R. I. Soloukhin, *Shock Waves and Detonations in Gases* (Mono Book Corp., Baltimore, 1966), pp. 145–150.

[8] M. E. Topchiyan, Zh. Prikl. Mekhan. i Tekhn. Fiz. **4**, 94 (1962).

TABLE I. Properties of several piezoelectric disks normal to the direction of the applied force.

Piezoelectric material	Piezoelectric constant (pCb/N)	Dielectric constant (relative to air)	Mechanical Q	Curie point	Velocity of compressional wave	Density	Acoustic impedance
Quartz				550°C		2.65 g/cm^3	
longitudinal	2.3	4.5	10^6		5750 m/sec		1.52 g/cm^2 sec$\times10^6$
radial	2.3	4.5					
Barium titanate						5.7	
longitudinal	190	1700	300	115	4300		2.45
radial	−78	1700					
Lead zirconate titanate (PZT5A)[a]				365		7.75	
longitudinal	374	830	75		4350		3.36
radial	−171	830					
Lead metaniobate (278)[b]				550		6.0	
longitudinal	75	240	5		3200		1.92
radial	−12	240	10				

[a] Clevite Corp., 232 Forbes Road, Bedford, Ohio.
[b] General Electric Corp., 1501 Roanoke Boulevard, Salem, Virginia.

cause the acoustic impedance ($\rho C=1.99\times10^6$ gm/cm^2 sec) closely matches the acoustic impedance of the lead metaniobate ($\rho C=1.92\times10^6$ g/cm^2 sec). The rod was made 16.5 cm long to give a theoretical "ring free" time of 120 μsec. The rod was faced off on a lathe; no special lapping was done. Lead metaniobate was commercially available in 2.54 cm diam 1.27 mm thick, silvered on both sides. These disks were cut to size with an ultrasonic drill using a 1μ boron slurry, and with this technique a 3.18 mm diam was the minimum size that could be cut satisfactorily. Indium solder (Indalloy No. 1, Indium Corp. of America, Utica, N. Y.) which is a 50% indium, 50% tin alloy was used to join the lead metaniobate disk to the tin rod. No flux was used; however, it was found that a slight amount of precipitated silver powder on the surface of the disk greatly improved the solderability. The rod assembly was then positioned in a brass housing and potted in silicone rubber (Silastic 521, Dow Corning Corp., Midland, Mich.) to provide electrical and mechanical isolation. The clearance between the brass and the pressure sensing element was held to 0.38 mm to minimize longitudinal compression of the silicone rubber. One electrical connection is made at the end of the tin to a BNC connector and the other is made from the sensor to the case with silver doped epoxy and/or a thin wire soldered across the silicone rubber gap.

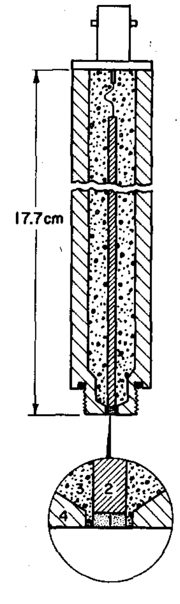

FIG. 1. Pressure transducer with acoustic absorbing rod which utilizes the following materials: (1) lead metaniobate 3.18 mm diam by 1.27 mm thick, (2) tin 3.18 mm diam by 16.5 cm long, (3) silicone rubber, (4) brass.

The choice of lead metaniobate requires some discussion. Quartz has been used extensively to date; however, it appears in general to have less desirable properties as a pressure transducer material than several ceramic piezoelectric materials such as lead titanate zirconate and lead metaniobate. Some of the pertinent properties are listed in Table I as obtained from manufacturer's data and Jaffe.[9] The charge generated by a single piezoelectric element is equal to the piezoelectric constant times the frontal area of the element times the pressure. The greater charge output of the ceramics is apparent, but of particular interest is the low cross-axes sensitivity of the lead metaniobate compared to the longitudinal mode. The voltage output is given by the charge generated divided by the

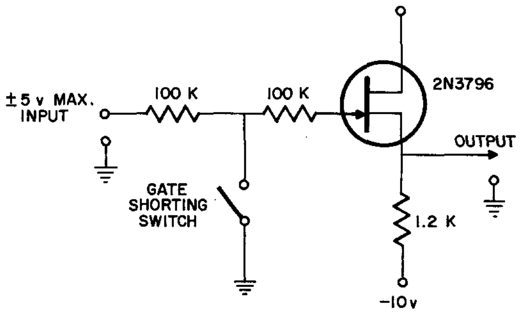

FIG. 2. High impedance circuit for the pressure transducer utilizing a field effect transistor.

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[9] H. Jaffe, *Encyclopaedia Britannica* (1965), Vol. 17, pp. 910–916.

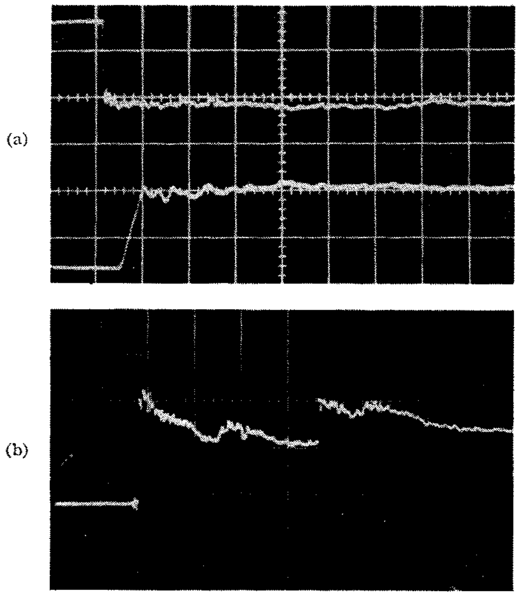

FIG. 3. Response of 3.18 mm diam lead metaniobate-tin pressure transducer direct to oscilloscope with 0.01 μF shunt: (a) Mach 3.2 normal shock in 1 atm air, 0.02 V/div., 50 μsec/div. (upper beam) and 5 μsec/div. (lower beam); (b) stoichiometric hydrogen–oxygen gaseous detonation initially at 2 atm, 0.05 V/div. and 50 μsec/div.

capacitance of the element, housing, and cable. The capacitance of the element equals the dielectric constant times the area divided by the thickness of the element. Since the capacitance of the housing and cable of this design is generally at least 100 pF, the relatively high dielectric constants of the ceramics are not a disadvantage in terms of output voltage level. Lead metaniobate is also of interest for pressure transducers because of its very low mechanical Q—a parameter which indicates the internal damping of the material. Quartz, on the other hand, has very little damping effect, and thus reflected elastic waves in the crystal continue for relatively long periods of time. The two ceramic materials have Curie temperatures comparable to quartz and the piezoelectric and dielectric constants vary little with temperature changes from 20 to 200°C or more. Finally, the velocity of a compressional wave, density, and acoustic impedance are given in Table I. Copper is a good acoustic match for PZT, while tin is an excellent match for lead metaniobate.

In recording a high frequency signal from the transducer, the output signal was shunted by 0.01 μF and connected directly to a Tektronix 555 oscilloscope, which has an input impedance of 10^6 Ω. This procedure results in an RC time constant of 10 msec and gives satisfactory results for sweep times less than 1 msec provided that the pressure jumps of interest are several hundred psi. In cases where the pressures are lower and/or the times of interest longer, it is desirable to increase the input impedance of the recorder. An insulated gate field effect transistor in a common source configuration, as shown in Fig. 2, was found to be a simple means of obtaining an input impedance of the order of 10^{14} Ω. The circuit used has a gain of 0.76 and an input current of less than 0.5 nA with 4 V input. This circuit was used for static calibration of the transducer. Over the investigated range of 7 to 70 kg cm^{-2} the output of the transducer was quite linear.

PERFORMANCE

The response of the pressure transducer flush mounted in the sidewall of a conventional 3.8×6.35 cm shock tube and in a 1.27×0.95 cm detonation tube is shown in Fig. 3. In Fig. 3(a) the response to a Mach 3.2 shock at a pressure level of 10.97 kg cm^{-2} gauge is presented. The rise time of the signal is 2.5 μsec which is associated primarily with the time for the shock to traverse the face of the sensing element. The spurious signals are quite small. The response to a 2 atm stoichiometric hydrogen–oxygen detonation at a peak pressure level of 35.2 kg cm^{-2} is given in Fig. 3(b). Here some precursor transverse vibration is evident (no attempt was made to shock mount the transducer case). Reflected shocks from a flanged joint and the end of the tube also are evident. In both cases it is rather remarkable that no significant signals due to reflected waves from the end of the tin appear. About 110 μsec after the initial shock a slight negative going pulse is apparent, which agrees with the predicted arrival of the primary elastic wave from the rear of the tin. Apparently the elastic waves in the tin are attenuated with the aid of the silicone rubber, and thus no further design features are needed for long duration operation.

While the detailed propagation of the elastic waves through the lead metaniobate-silicone rubber-tin is not understood, this combination of materials produced the best results compared to other materials tried. There appears to be no reason not to position the sensing element at the front surface of the transducer except possibly for protection against severe environments such as high heat flux, and electric and magnetic fields. Although this design has not been optimized, particularly with respect to the size of the sensing element, it is felt that this approach will lead to improved transient pressure measurements.

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