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FIBER-OPTIC COUPLED PRESSURE TRANSDUCER*

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ABSTRACT

A fiber-optic coupled pressure transducer was developed for measurement of pressure transients produced by fast electrical discharges in laser cavities. A detailed description of the design and performance will be given. Shock tube performance and measurements in direct electrical discharge regions will be presented.

INTRODUCTION

Dynamic pressure measurements in transverse discharge lasers are difficult to obtain. The acoustic energy developed in the laser cavity is produced by an electrical discharge between the laser electrodes. In a KrF laser the current peak in this discharge is 150 K amps lasting 40 ns delivering about 100 J to the gas. A large portion of this energy is in the form of heat, but a significant fraction does appear in the form of pressure shock waves. Aside from the transient over pressure of near 1.5 and its attendant stress considerations, we are concerned about the density gradients in the gas causing the laser beam to be diffracted, spoiling its focasibility. The electromagnetic noise (EMI) produced during this discharge often occurring at 70 kV, presents a severe electrical noise problem for the most standard transduction techniques i.e., strain gauge, variable reluctance, piezoelectric due to very large electric and magnetic fields produced and large ground currents. It is particularly difficult to obtain the peak dynamic pressure between the electrodes directly in these electrical discharge not only because of large currents flowing in the "ground", but any perturbation of the surface of the electrodes produces electric field enhancement which can cause arcing at the transducer which either can destroy the transducer or produce erroneous pressure information.

A fiber-optic coupled pressure transducer was developed, so that pressures could be measured directly in these high current discharges. First a prototype instrument was designed and tested for dynamic performance and then these techniques were applied to a laser discharge system designed for acoustic studies. We will describe both devices and their performance.

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DESIGN

From simple energy deposition calculations an estimate of the pressure magnitude can be made. Unfortunately, the uncertainty in the volume of the gas that receives this energy is not well known, nor is it valid to assume that the energy is uniformly deposited in the discharge volume. Probably a larger portion of the energy is deposited near the cathode. Nonetheless, as estimate of this pressure will at least allow the full scale range of the transducer to be selected. These will be cavity resonances excited which can create standing waves and without deliberate introduction of damping and acoustic attenuators, amplification of two or more can be expected. We choose to set the full scale pressure at 100 psia.

Since we also were interested in learning about resonant modes as well as the shock step produced, we needed a transducer of wide bandwidth in the order of 30 kHz.

Further, we wanted to keep the sensing diaphragm small so that a minimum perturbation would be made on the electric field. We choose to keep the diaphragm below 0.25 inches in diameter. This is all very well, but how do you convert the diaphragm displacement to a form which will ignore the electrical noise?

We elected to use the KD-100 Fotonic sensor made by Mechanical Technology Incorporated. This device consists of a 0.108-inch-diameter probe filled with fiber optics. About half of these fibers are connected to a light source and half to a photodetector. As the probe is brought near a reflecting surface, light from the emitting fibers is picked up by the receiving fibers. A small displacement of the reflecting surface results in a change in the received light and thus a change in output. Figure 1 shows the output in volts vs displacement in thousands of an inch. A location of the probe at 0.004 inches from the diaphragm produces a linear signal of sensitivity of over 4 V/mil. At that setting the peak-to-peak electrical noise (wide band) is equivalent to ± 5 μ inches displacement.

A prototype pressure transducer was then built as shown in Fig. 2. This crossection indicates how the fiber-optic displacement probe was secured. This modification of a conax fitting allowed the probe to be located at the optimum 0.004" away from the diaphragm using the probe to read out its precise location and then securing it by tightening the back nut.

The diaphragm was machined in a separate part as shown in the drawing. Given the desired outside diameter of 0.25 inches the inside diameter was 0.171 inches, therefore the inside radius = 0.0855 inches.

The maximum stress for an edge clamped diaphragm is:

$$\sigma_m = \frac{0.75\ P\ a^2}{t^2} \quad \text{or} \quad t = a\sqrt{\frac{0.75\ P}{\sigma_m}}$$

where P = pressure in psi
a = radius in inches
t - thickness in inches

for 304 SS to keep well within the elastic limit, we chose σ_m to be 30,000 psi or less

thus

$$t = a\sqrt{\frac{0.75\ P}{\sigma_m}}$$

t = 0.005 inches for σ_m = 20,000 and if t = 0.0035 inches, σ_m becomes 45,000 psi

The natural frequency of an edge clamped diaphragm is:

$$fn = \frac{10.21}{2\pi}\sqrt{\frac{Et^2 g}{12(1 - V^2)\rho\omega a^4}}$$

where

E =	Youngs Modulus of	28×10^6 for 304 SS
V =	Poisson's ratio	0.3
$\rho\omega$ =	weight density	0.283 lb/in'
a =	radius	0.0855 inches
t =	thickness	0.005 inches
g =	gravity	386 in/sec^2

This gives fn = 66 kHz for an 0.005 inch thick diaphragm and 39.6 kHz for an 0.0003 inch diaphragm which is above our 30 kHz goal. The 3 db roll-off frequency of the fiber optics transducer electronics is 60 kHz so this will not limit the response. Finally, the displacement of a diaphragm is given as:

$$Zm = \frac{3(1 - V^2)a^4\ P}{16E\ t^3}$$

where Zm is the maixmum deflection of the center. This gives a maximum deflection of 0.26 mil for a thickness of 0.0005 inches at 100 psi and 1.2 mil for a thickness of 0.0003 inches at 100 psi.

Two diaphragms were machined, one a thickness of 0.0005 inches, and a second with a thickness of 0.0035 inches. The 0.0003-inch diaphragm could be considered a 50 psir pressure range diaphragm if 30,000 psi max stress is held as the upper limit.

$$Pm = \frac{\sigma m\ t^2}{0.75\ a^2} = 50 \text{ psi}$$

CALIBRATION

Static calibration was made as shown in Fig. 3, indicating the 0.005-inch-thick diaphragm performed quite well to 150 psi (33,000 psi stress load). Hysteresis was less than 2% and linearity less than 5%. Although this is not outstanding, it is quite sufficient for the dynamic data to be measured in our laser application. Figure 4 shows the output vs pressure for a 0.0035 inch diaphragm transducer. This transducer exhibited only 1.4% nonlinearity and 1.3% hysteresis for 100 psi range.

A shock tube was used to determine the dynamic performance of this transducer. The fiber optic coupled pressure transducer was mounted at the end of the shock tube and adjacent to it, a piezoelectric transducer was also mounted for reference.

Figure 5 shows the step response of the 0.005 inch diaphragm fiber-optic coupled transducer and the piezoelectric reference transducer. The transducer shows a 30% overshot and a rise time 10-90% of ∿ 20 μs with a ring frequency of near 30 kHz. This result is satisfactory.

LASER EXPERIMENT

The pressure transducer was installed directly in the laser electrode as shown in Fig. 6. With careful machining, the diaphragm was located within 0.001 inches of the electrode surface and the gap around the diaphragm was also held within 0.0005 inches. This was important to minimize the electrical field enhancement, and it was observed that no arcing occurred at the transducer. A series of experiments were made using a dummy transducer connected electrically and mechanically to the electrode but not exposed to pressure to verify that the signals were not electrical noise or vibration induced. After considerable effort including the use of torroids on the output coax, filtering and use of a 50 Ω line driver amplifier a signal/noise of 14:1 was achieved. A typical pressure trace is shown in Fig. 7. This signal was also analyzed with a spectrum analyzer which clearly indicated three dominant cavity resonances at 10.125, 12, and 18.75 kHz. Analysis of the time trace shown the cavity longitudinal reflection at 850 μs. The calculated reflection time was 885 μs for this gas mix of 90% He, 10% Ar. We verified that indeed these signals were pressure by changing the gas. Experiments with He gave a reflection time of 640 μs. The cavity resonant frequencies also shifted by the ratio of the velocity of sound in the two gas medias. Experiments are now in progress to correlate the pressure magnitudes with the electrical energy deposited in the discharge and to evaluate the effectiveness of acoustic attenuators.

CONCLUSION

A fiber-optic coupled pressure transducer designed for measurement directly in an electrical discharge did work well. Peak pressures, dominant cavity resonances and damping characteristics were obtained.

My suggestion to other experimenters is to place the electronic readout circuitry in a screen room if at all possible and to incorporate a low impedance line driver in the output circuit. These two procedures will reduce the EMI-induced noise.

REFERENCES

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3. Mechanical Technology, Inc., Latham, NY, 12110

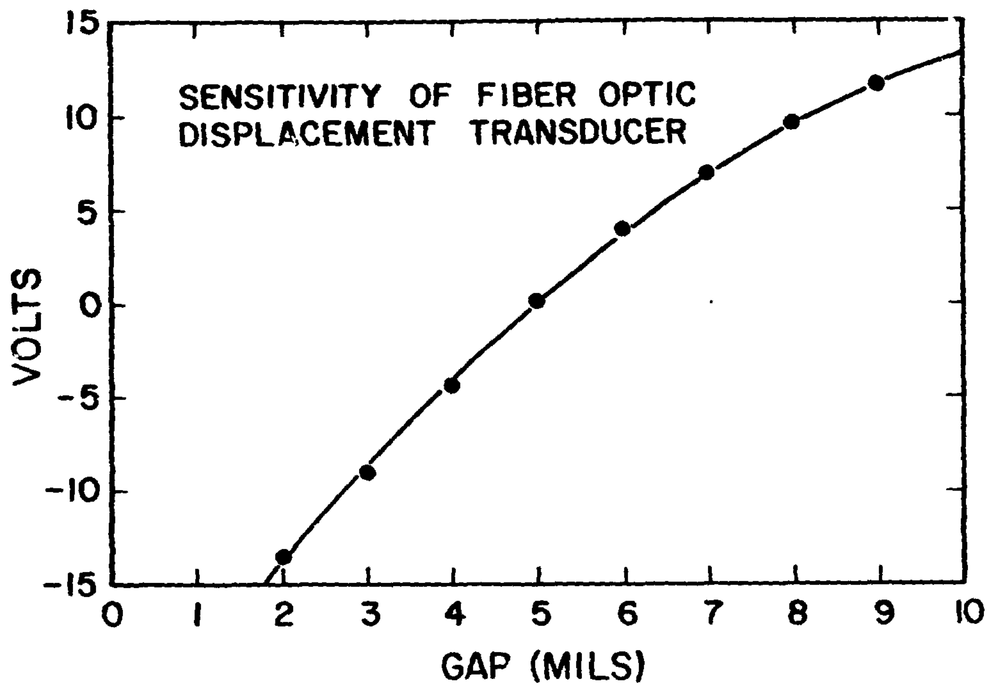
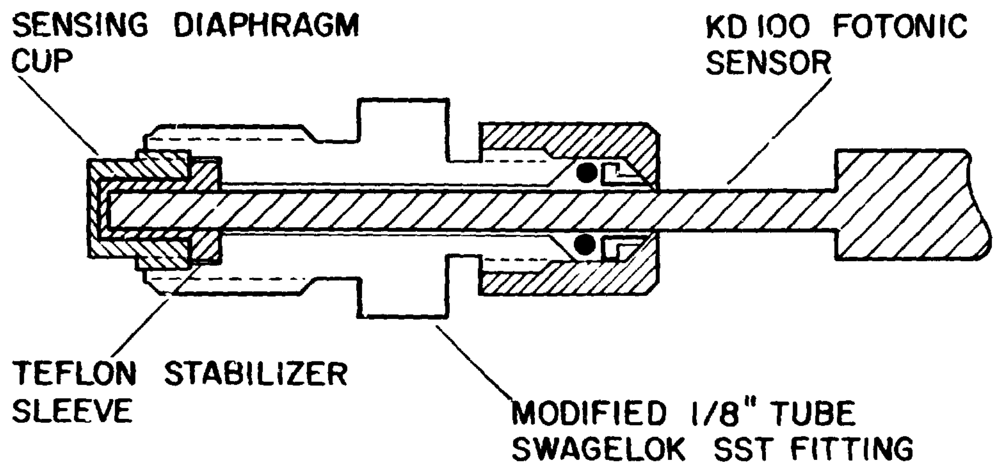

SENSITIVITY OF FIBER OPTIC
DISPLACEMENT TRANSDUCER
VOLTS
15
10
5
0
-5
-10
-15
0
1
2
3
4
5
6
7
8
9
10
GAP (MILS)

Fig. 1



PRESSURE TRANSDUCER CROSSECTION

Fig. 2

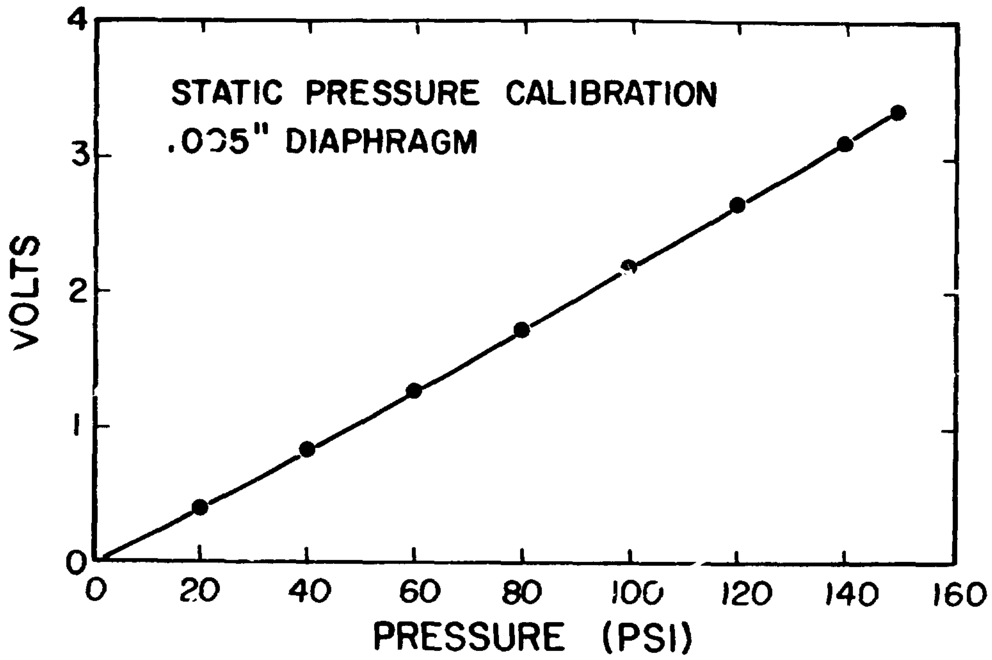


Fig. 3

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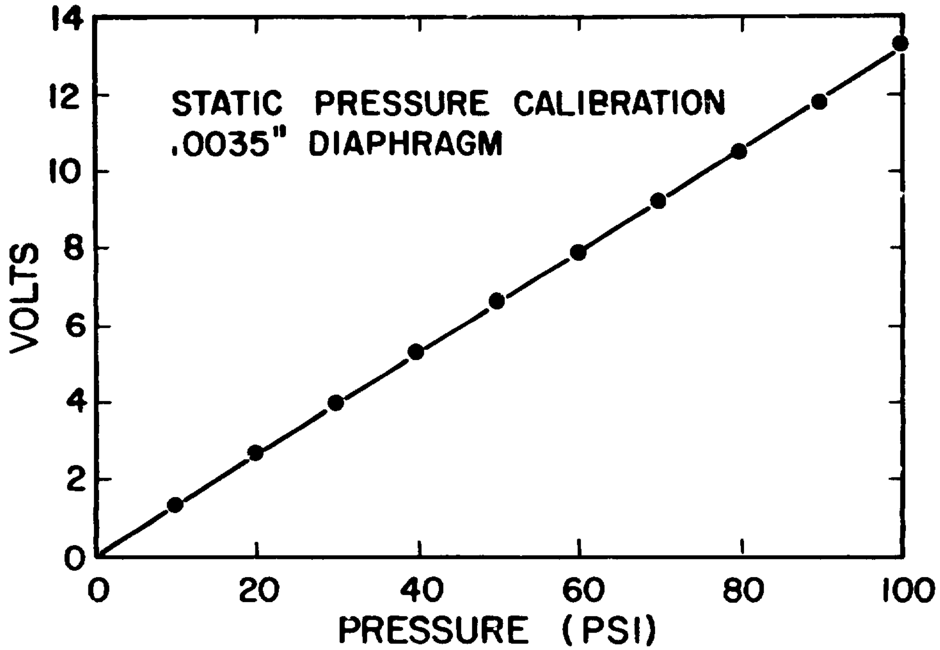

Fig. 4

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SHOCK TUBE DYNAMIC PRESSURE TEST

STEP RESPONSE

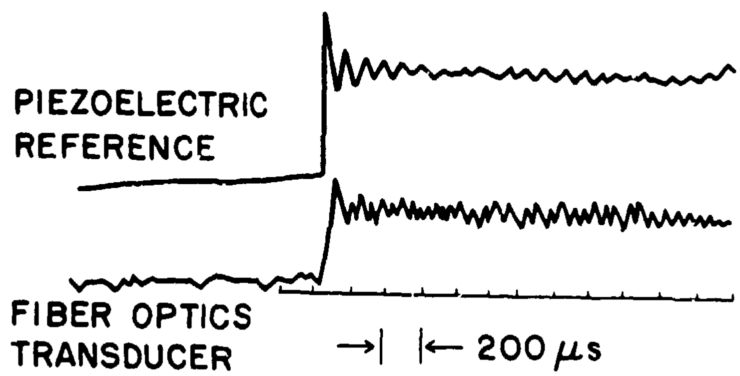
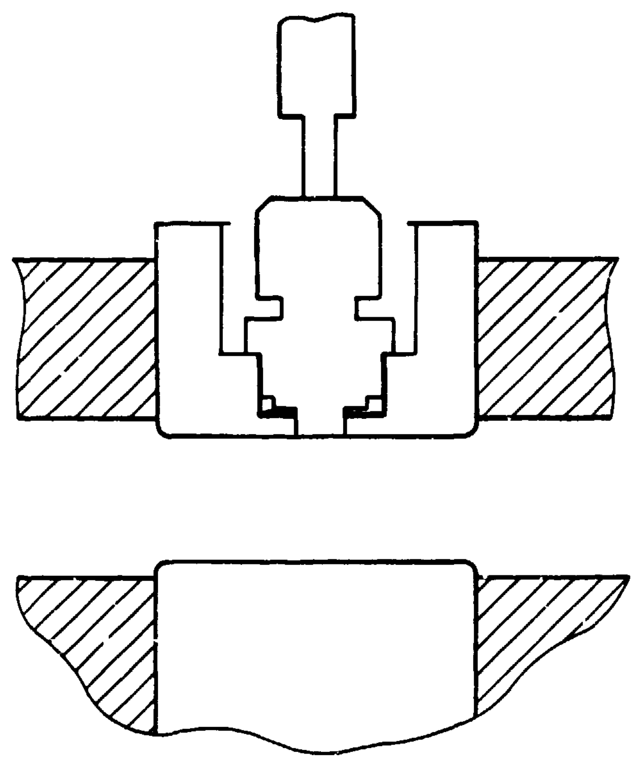


Fig. 5



INSTALLATION OF PRESSURE SENSOR IN LASER ELECTRODE

Fig. 6

PRESSURE MEASUREMENT IN LASER

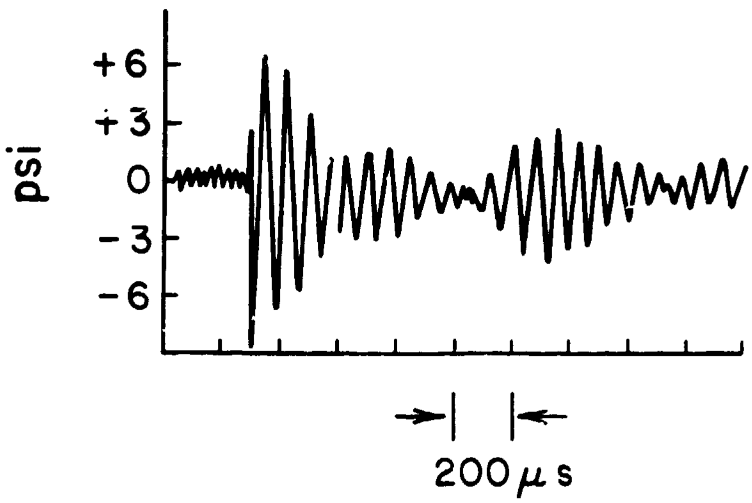


Fig. 7