Session 2 - Unsteady Pressure Measurements

INVESTIGATING THE PERFORMANCE OF MINIATURE SEMICONDUCTOR PRESSURE TRANSDUCERS FOR USE IN FAST RESPONSE AERODYNAMIC PROBES

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Summary

Over the last two decades, there has been an increasing body of work on fast response aerodynamic probes (greater than 1KHz bandwidth) based on some form of semi-conductor pressure sensor mounted close to the measurement point. These are seen as competitors to the hot-wire probe and to laser anemometry, in some, but not all, applications. The last decade has seen a move to probes with surface mounted sensors, thus increasing the available bandwidth. The present paper examines the dynamic response of a typical semi-conductor sensor diaphragm, and presents the results of some shock tube experiments in which typical diaphragm configurations were tested.

Introduction

There is currently much research work focussed on measuring, predicting and understanding the unsteady processes occurring within turbomachines and elsewhere. Traditionally, unsteady aerodynamic measurements have been made using hot-wire or optical (LDA or L2F) anemometry techniques. The advantage of the hot-wire sensor lies in its low cost, but it is susceptible to damage by dirt particles, and its sensitivity can change with the impact of particles on the wire itself. Laser anemometry, on the other hand, is expensive and relatively difficult to set up, though is a truely non-intrusive technique. Two decades in time have seen considerable progress towards the use of fast response aerodynamic probes based on silicon semi-conductor pressure transducers as an alternative approach to these other techniques for a robust and versatile measurement tool. This paper outlines some design issues which have to be addressed in considering the frequency response of these probes.

Most of the work in developing fast response probes in the 1970s concentrated on using semi-conductor pressure sensors mounted in the stem of the probe. Senoo,

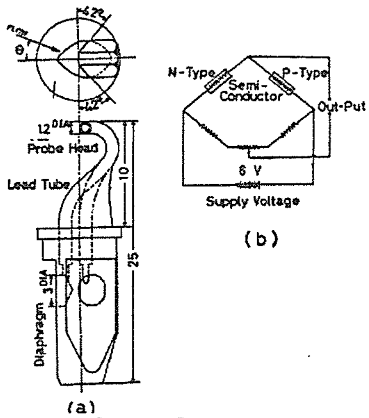

Fig.1: Probe of Senoo [1973

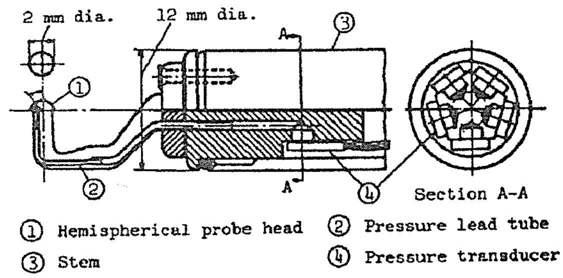

Fig.2: 'Fast' 3D probe of Matsunaga [1978]

Kita and Ookuma [1973], following these lines in 1973, developed a two-dimensional cobra probe, Figure 1, whilst the first three dimensional probe was the combined five hole probe (head diameter 2mm), Figure 2, of Matsunaga, Ishibashi and Nishi [1978], with semi-conductor sensors buried in quite a bulky stem (12mm diameter). This first generation of probes, albeit faster response than conventional pneumatic probes, were still limited in their bandwidth (typically 1kHz).

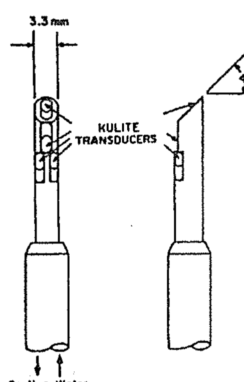

Fig.3: 'Cylindrical' probe of Epstein [1985]

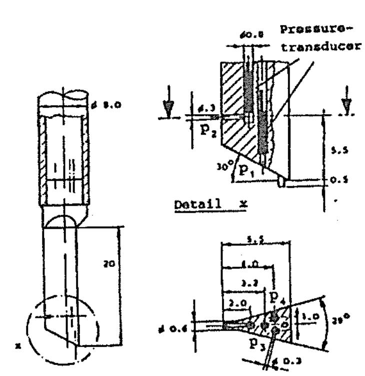

Fig.4: Wedge probe of Heneka [1983] also used by Ruck [1990]

Kerrebrock, Thompkins and Epstein of MIT started the move towards surface mounted technology with their five way spherical probe [1980], and their later cylindrical combined probe [1985], Figure 3. European work has produced some surface mounted wedge probes and some wedge probes with sensors mounted within the probe head (Broichhausen, Kauke and Shi [1983], and Elmendorf [1988], [1989], of Aachen; Heneka [1983], Bubeck [1987] and Ruck and Stetter [1989,1990] of the University of Stuttgart, Figure 4; and Cooke [1989] at Rolls-Royce, Derby. Semi-conductor pressure sensors are well known for their characteristic temperature dependency as well as their pressure sensitivity. In some of the work outlined above, these stability problems in the past have dictated the use of conventional pneumatic tappings for the measurement of absolute or DC components, with the silicon sensors being used only for the "fast" or AC component.

Recent work in Oxford and at Kulite has focussed on the mounting of the sensing element itself directly on the component on which a measurement of pressure is to be made (removing the necessity of the usual mounting shim and signal conditioning electronic components from the sensor location), and on the development of a new approach to the signal processing which is consequently required (Ainsworth, Allen and Dietz [1989], and Ainsworth, Dietz and Nunn [1990]), Figure 5.

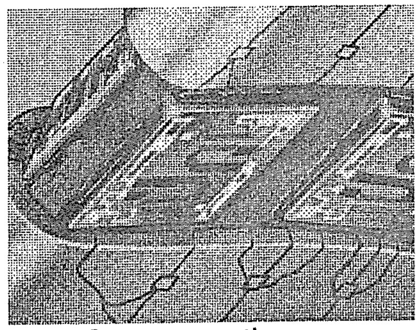

Fig.5: Sensor mounting on component, Ainsworth [1989]

This offers the potential, for fast response probe work, of better thermal stability and more compact design. In the chosen method of sensor mounting, the silicon diaphragm is finally coated with a layer of silastomer (RTV 511), which has the dual role of protecting the diaphragm to some extent from mechanical damage caused by the impact of debris, and of also presenting an aerodynamically smooth surface to the flow. A natural question which consequently arises relates to the effect on the sensor frequency response of this silastomer coating: can it be optimised in any way?

Dynamic Testing of Pressure Transducers

Testing the frequency response of any system is usually achieved by applying an input signal to the system and analysing the resulting system response. The input signal may be sinusoidal, a step (which contains all frequencies) or an impulse (the system output response to an impulsive input signal is equal to the system frequency response). Many methods have been tried over the years for applying sinusoidal input signals to pressure transducers by such means as acoustic loudspeakers, and hydrophonic wave generators but these are usually limited to relatively low values (in terms of the input signal) of amplitude and frequency.

Because of the interest here in values up to 500 kHz or so, methods of dynamic testing in shock tubes have been employed, which have the combined advantages of yielding information to these high frequencies together with possessing input step signals of significant amplitudes, in turn stimulating a significant amplitude in the output signal of the transducer under test for measurement.

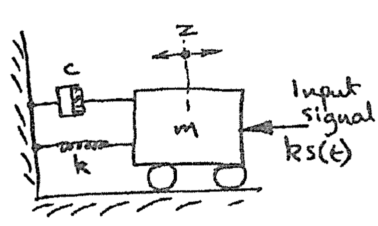

Fig. 6: Dynamic system

The semi-conductor pressure transducers under consideration here have a silicon diaphragm some 1mm square, with a minimum thickness of order .01 mm, on which a Wheatstone bridge network of strain sensitive resistors is deposited. Deflection of the bridge yields corespondingly an electrical signal proportional to the applied pressure, and the mechanical dynamic response (displacement versus time, for instance) of the diaphragm may be treated as a second order system, with a mass, spring and damping. Analysis of the system indicated in the diagram in Figure 6 yields a complex system transfer function of the form:

$$F(j\,\omega) = \frac{1 - (\frac{\omega}{\omega_0})^2 - j\;2h\;(\frac{\omega}{\omega_0})}{[\,(\,1 - (\frac{\omega}{\omega_0})^2\,)\,]^2 + 4\,h^2\,(\frac{\omega}{\omega_0})^2},$$

where ω_o ($= \sqrt{k/m}$) is the undamped natural frequency and h ($=c\,/\,2\sqrt{m\,k}$) is the damping ratio. Using Laplace transforms, the system response to a step excitation for h <1 may be characterised as $T\ (\,t\,) = 1 - \frac{e^{-h\,\omega_0\,t}}{\sqrt{1-h^2}}\ [cos\left\{\sqrt{1-h^2}\ \ \omega_0\,t\ \ - \sin^{-1}h\right\}]$. The classic Bode plots

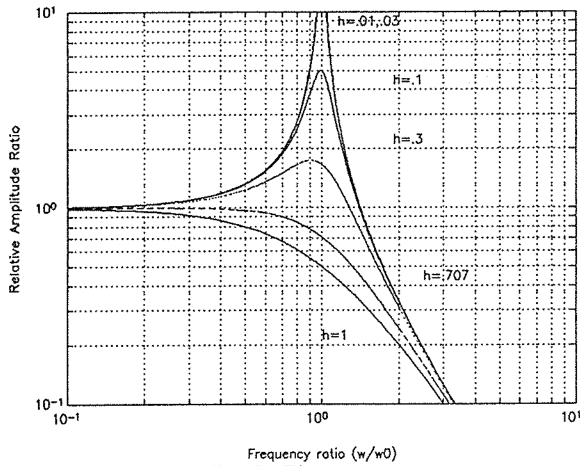

Fig.7: Bode Amplitude Plot

of amplitude ratio and phase angle against non-dimensionalised frequency (actual frequency divided by diaphragm natural frequency) arise from this expression of complex system transfer function. Here, they are plotted for values of interest arising in the pressure transducer application. In this nomogram form, the results clearly show that with relatively lightly damped diaphragms (h <0.3 ,say), deviations from unity amplitude ratio of order tens of percent occur even at frequencies of one half of the diaphragm natural frequency. In terms of phase angle (output phase minus input phase), low damping ratio results in approximately constant phase (relative to high damping ratios) until close to the natural frequency, where the phase of course changes by 180 degrees.

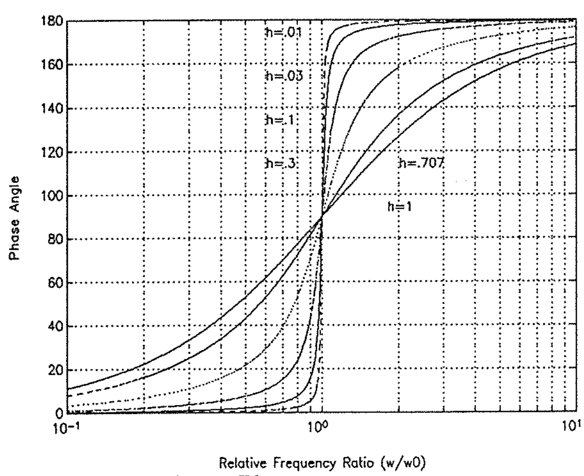

Fig.8: Bode Phase Plot

Bearing in mind the usual application in turbomachines of fast response sensors, a new plot is presented which is possibly more relevant. In Figure 9, a plot is given of the phase angle divided by the relative frequency ratio, against relative frequency ratio, again for values of interest in the pressure sensor application. In considering the use of a fast response total pressure probe downstream of a turbine, examining passage related losses, say, it will be important to know the effects of probe response on waveform distortion. Typically, the output from such a probe might be ensemble averaged, and the results interpreted in terms of passage position. If the system transfer function results in a phase angle variation with frequency, then it would be better if this phase angle variation were linear with frequency, so that any time delays introduced by the sensor were then constant (time delay = phase divided by frequency) with respect to frequency. All frequency components making up the waveform signature (as one blade passage moves past the probe, say) would then be delayed by the same amount, and no relative time

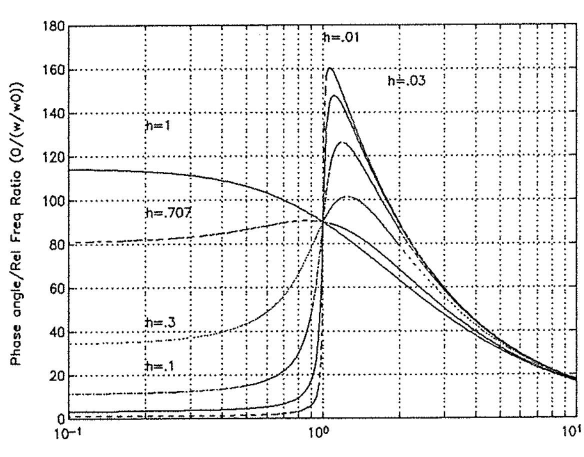

Fig.9: Time lag introduced

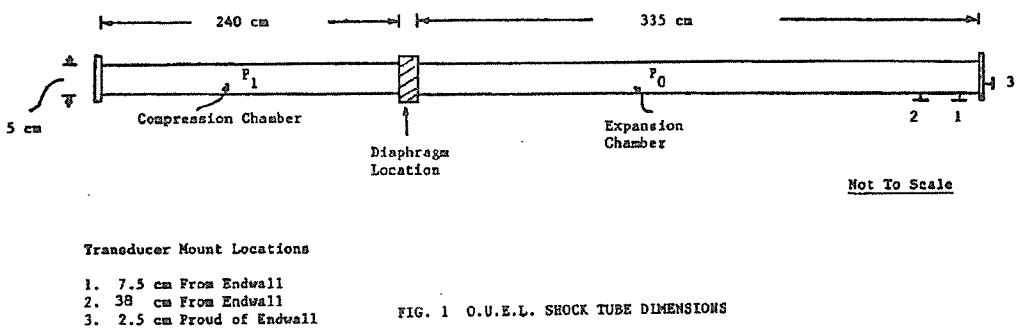

Fig.10: Layout of Oxford Shock Tube

distortion would be introduced. For the lightly damped diaphragms, it can be seen in Figure 9 that this time delay has changed by less than one per cent at frequencies up to eighty per cent of the natural frequency.

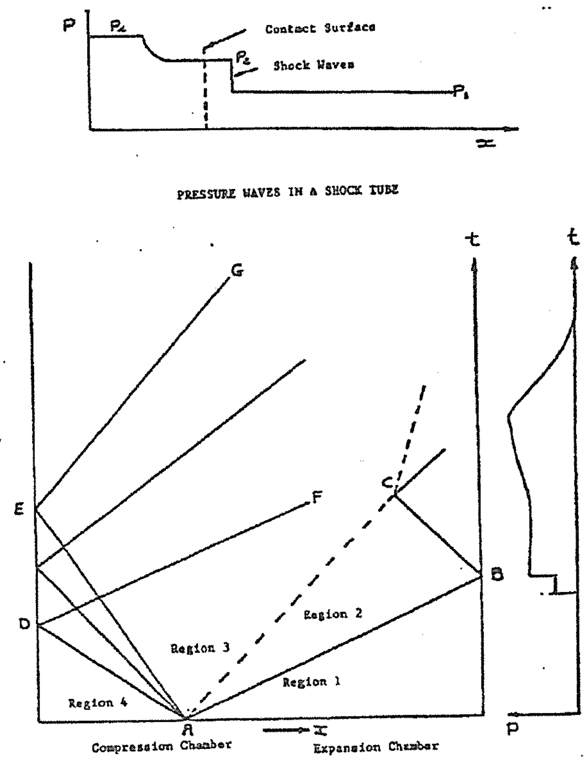

Fig. 11 Wave motion within Shock Tube

A method of testing diaphragm sensors in a shock tube was developed to gain experimental data on real responses. A diagram of the shock tube constructed and its dimensions are given in Figure 10, where it will be seen that various sensor mounting locations were used. The compresssion chamber is pressurised until a Mylar diaphragm, separating it from the expansion chamber, bursts at approximately 10 bar, and causes compression wave and expansion waves to propagate down the tube in both directions. Distance-time and pressure-time (for a location close to the end of the tube) diagrams are given in Figure 11. The end wall location had the advantage of true step-like input signal, though in terms of the frequencies of interest, the wave propogation time over the sensor diaphragm when mounted in

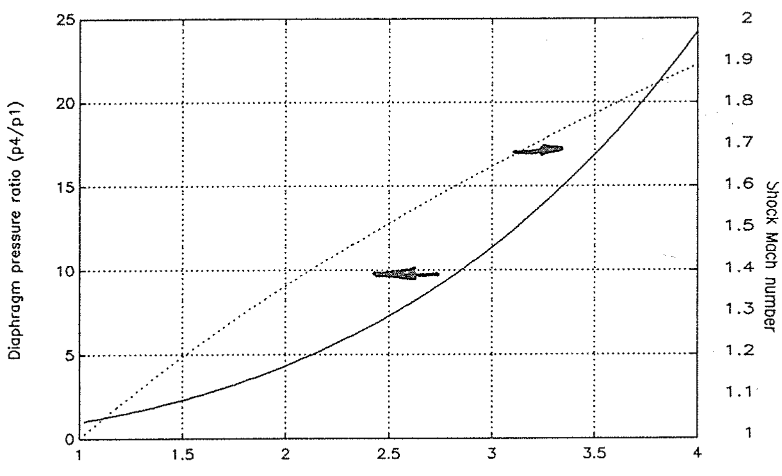

Fig. 12: Predicted Shock Tube Conditions

the side of the tube was sufficiently small to give a similar response. In practice, there is plenty of time to take data after the incident shock has passed the side wall location before the reflected shock appears, thus giving the step input, given the shock Mach number and the ability to take data at sampling rates up to 40 Mhz. The shock strength (pressure in front of the shock divided by that behind), and the shock Mach number are related to the diaphragm burst pressure ratio as follows, following solution of the Rankine Hugoniot relations:

$$\frac{p4}{p1} = \frac{p2}{p1}\left[1 - \frac{(\gamma-1)(\frac{p2}{p1}-1)}{\sqrt{2\gamma}\sqrt{2\gamma+(\gamma+1)(\frac{p2}{p1}-1)}}\right]^{\frac{-2\gamma}{(\gamma-1)}}, \text{ and } M = \left[\frac{\gamma-1}{2\gamma} + \frac{\gamma+1}{2\gamma}\frac{p2}{p1}\right]^{\frac{1}{2}}$$

Here $\frac{p4}{p1}$ is the diaphragm burst pressure ratio, $\frac{p2}{p1}$ is the shock strength and M is the shock Mach number. These are plotted graphically in Figure 12.

Amongst many other tests, a series of experiments was conducted on one silicon diaphragm mounted in the side arm of the shock tube, with differing amounts of

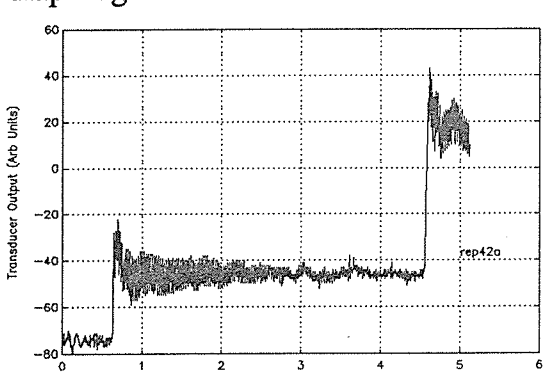

Fig. 13: Shock tube test - no RTV at 4 MHz

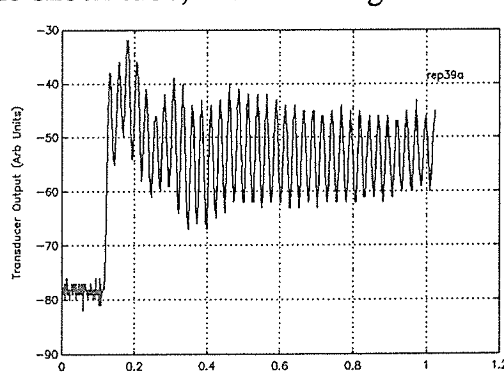

Fig. 14: Shock tube test - no RTV - 20 Mhz

silastomer covering the diaphragm, to test the effect of this covering on the transducer response. In the first instance, a bare diaphragm was tested, the electrical output from the diffused Wheatstone's bridge network being sampled at 4MHz. At this sampling rate (Figure 13) both the incident and reflected shocks can be observed and there appears to be little damping to oscillations introduced, which at such a low damping are virtually at the natural frequency. This is confirmed by data taken at a sampling rate of 20 MHz (Figure 14), whilst spectral analysis (Figure 15)

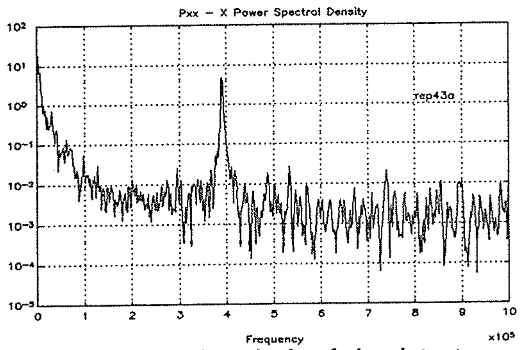

Fig. 15: Spectral analysis of shock test

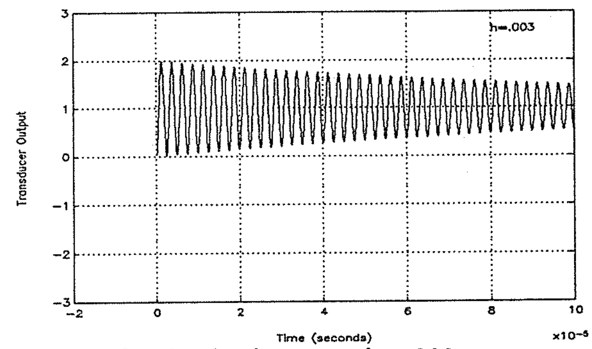

Fig. 16: Synthesised output - h = .003

indicates a frequency of oscillation of order 400kHz. A synthesised output in response to a step input from a second order system with a spring constant, mass, and damping (Figure 16) indicates that the damping ratio h is of order 0.003. For completion, the spectral analysis of synthesised outputs with differing damping ratios is included as Figure 17, showing the expected decrease in period of oscillation as damping is increased.

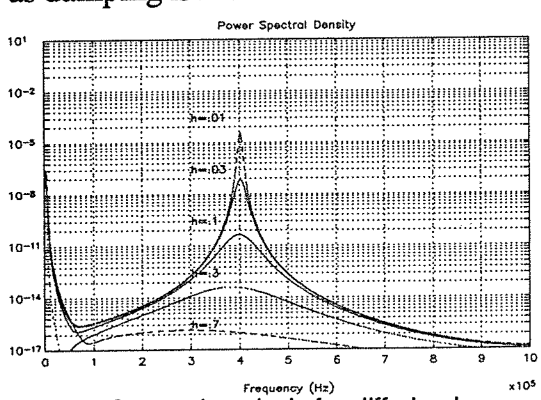

Fig. 17: Spectral analysis for differing h

Similar tests were conducted with firstly 0.125mm and then 0.25mm of silastomer added to the front of the diaphragm, perhaps representative of the order of covering which would be added to a diaphragm when mounted in a probe. Again, the test at 4MHz sampling rate (Figure 18) showed both the incident and reflected shock, but oscillations were more rapidly damped out, confirmed by the test at 20MHz sampling rate (Figure 19), and damping ratios of order 0.05 (0.125mm silastomer) and 0.3 (0.25mm silastomer) were measured.

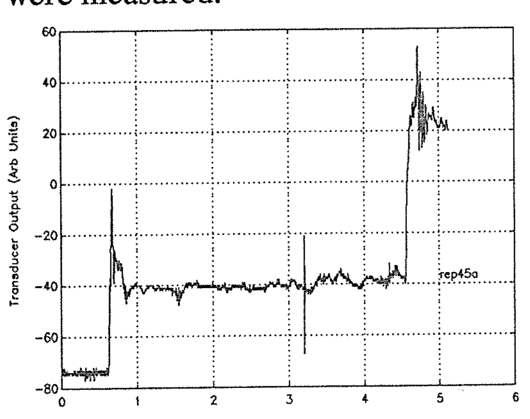

Fig. 18: Shock test - 0.25mm RTV - 4MHz

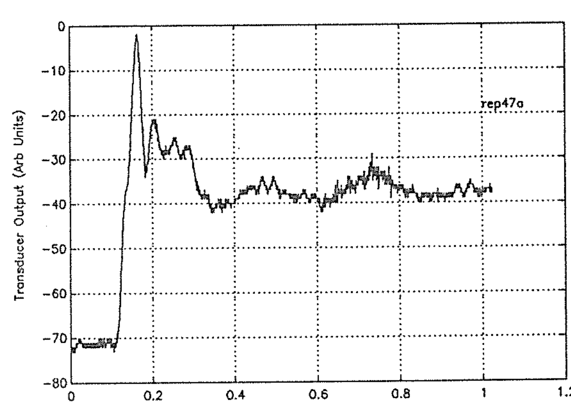

Fig. 19: Shock test - 0.25mm RTV -20MHz

These experiments show that it is relatively easy to produce a significant alteration in system damping ratio by the simple addition of silastomer to the diaphragm of a pressure transducer. Given the Bode and other plots presented earlier, this has important implications in the design of sensor configurations. It is possible and feasible to change the amplitude response and the phase response (and hence time delay as a function of frequency) in a prescribed way. Use of this information will allow the experimenter to establish whether he need determine the frequency response of each sensor in his probe, or whether, for his application, the deviation from unity amplitude ratio and zero phase shift is sufficiently small in his case to be neglected. During these shock tube tests, no failures of sensors were encountered, confirming the premise that the semi-conductor probe should prove more robust in service than the equivalent hot-wire probe.

Conclusions

The major conclusions from this work are as follows:

- It is plausible to represent the dynamic response of the diaphragm of a silicon semi-conductor pressure transducer as a second order system with spring constant, mass, and damping.
- It is possible to use a shock tube to establish experimentally what this response is in a quantifiable way.
- In designing fast response aerodynamic probes using surface mounted sensors, the addition of silastomer, in creating an aerodynamically smooth surface after manufacture, is likely to alter the dynamic response.
- Consideration of the classic Bode plots, and a plot of time delay against normalised frequency, are important to determining the optimum silastomer layer for a particular application.

References

Ainsworth, R.W., Allen, J.L., and Dietz, A.J., "Methods for Making Unsteady Aerodynamic Pressure Measurements in a Rotating Turbine Stage", Paper 22, Agard CPP 468, Luxembourg, 1989

Ainsworth, R.W., Dietz, A.J., and Nunn, T., " The Use of Semi-Conductor Sensors for Blade Surface Pressure Measurement in a Model Turbine Stage", ASME 90-GT-346, Brussels, 1990

Broichhausen, K-D., Kauke, G., and Shi, Zhi-da., "Some aspects of Semi-conductor Probe Development", Proc. 7th Symposium on Measuring Techniques for Transonic and Supersoic Flows, Aachen, 1983

Bubeck, H., and Wachter, J., "Development and Application of a High Frequency Wedge Probe", ASME 87-GT-216, Anaheim, 1987

Cooke, S.C., "Development of a High Response Aerodynamic Wedge Probe and Use in a High Speed Research Compressor", Proc. 9th Int. Symp. on Air Breathing Engines, Athens, 1989

Elmendorf, W., and Kauke, G., "Semi-Conductor Wedge Probes for Unsteady Flow Measurements", Proc. 9th Symposium on Measuring Techniques for Transonic and Supersonic Flow in Cascades and Turbomachines, Oxford, 1988

Elmendorf, W., Kauke, G.K., and Broichhausen, K.D., "Experiments on the Unsteady Flow in a Supersonic Compressor Stage", Paper 17, Agard CPP 468, Luxembourg, 1989

Epstein, A.L., "High Frequency Response Measurements in Turbomachinery", VKI Lecture Series 1985-03, Brussels, 1985

Heneka, A., "Instantaneous Three Dimensional Flow Measurements with a Four Hole Wedge Probe", Proc. 7th Symposium on Measuring Techniques for Transonic and Supersonic Flow in Cascades and Turbomachines, Aachen, 1983

Kerrebrock, J.L., Thomkins, W.T., and Epstein, A.H., "A Miniature High Frequency Sphere Probe," in Measurement Methods in Rotating Components of Turbomachinery, B. Lakshminarayana, Ed., ASME, New York, 1980

Matsunaga, S., Ishibashi, H., and Nishi, M., "Accurate Measurement of Non-Steady Three Dimensional Incompressible Flow by means of a Combined Five Hole Probe", in Non-Steady Fluid Dynamics, Winter ASME Meeting, San Francisco, December 1978

Ruck, G., and Stetter, H., "Unsteady Velocity and Turbulence Measurements with a Fast Response Pressure Probe", ASME 90-GT-232, Brussels, 1990

Senoo, Y., Kita, Y., Ookuma, K., "Measurement of Two Dimensional Periodic Flow with a Cobra Probe", ASME Journal of Fluids Engineering, p 295, June 1973