13th Australasian Fluid Mechanics Conference
Monash University, Melbourne, Australia
13-18 December 1998

THE DEVELOPMENT OF A MICROMACHINED HOTFILM SENSOR

Jon GORMAN[†], Fahad HUSSAIN[‡] and Mike GASTER[†]

[†]Department of Engineering, Queen Mary and Westfield College,
Mile End Road, London E1 4NS, ENGLAND
[‡]Sowerby Research Centre, British Aerospace PLC, Filton,
Bristol BS12 7QW, ENGLAND

ABSTRACT

This paper describes the development of a micromachined surface mounted hotfilm sensor on an insulating diaphragm. The initial design exhibited unexpectedly poor frequency response, this is explained using a simple thermal model. A greatly improved sensor has been developed and tested.

INTRODUCTION

The objective is to develop a system for the active control of transition using micromachined sensors and actuators. The intention is to sense wavepackets in the boundary layer on a flat plate and then to actuate to generate 'equal and opposite' canceling disturbances before nonlinearity occurs. One of the prerequisites of this system is the development of a sensitive hotfilm sensor using microfabrication technologies, this is described here.

Huang *et al.* (1996) describe the development of a hotfilm on a diaphragm for use in a turbulent drag reduction scheme. Their aim in placing the hotfilm on a diaphragm was to increase the sensitivity of the device, although it was also found to reduce sensor frequency response to around 9kHz; an order of magnitude higher than our requirements.

Following the work of Huang *et al.* it was decided to manufacture a hotfilm on a diaphragm as our sensor.

PRELIMINARY SENSOR DESIGN

The sensors were designed and fabricated at BAe's Sowerby Research Centre. The hotfilm itself is a 0.5 micron titanium film 400 microns long and 50 microns wide, as shown in Figure 1. The hotfilm is located on a polyimide diaphragm 20 microns thick and 660 microns square. Electrical connections to the sensor are made using gold tracks which lead through the polyimide layer to etched cavities on the wafer underside. This arrangement allows connection of the films to the bridge electronics without any flow side obstructions.

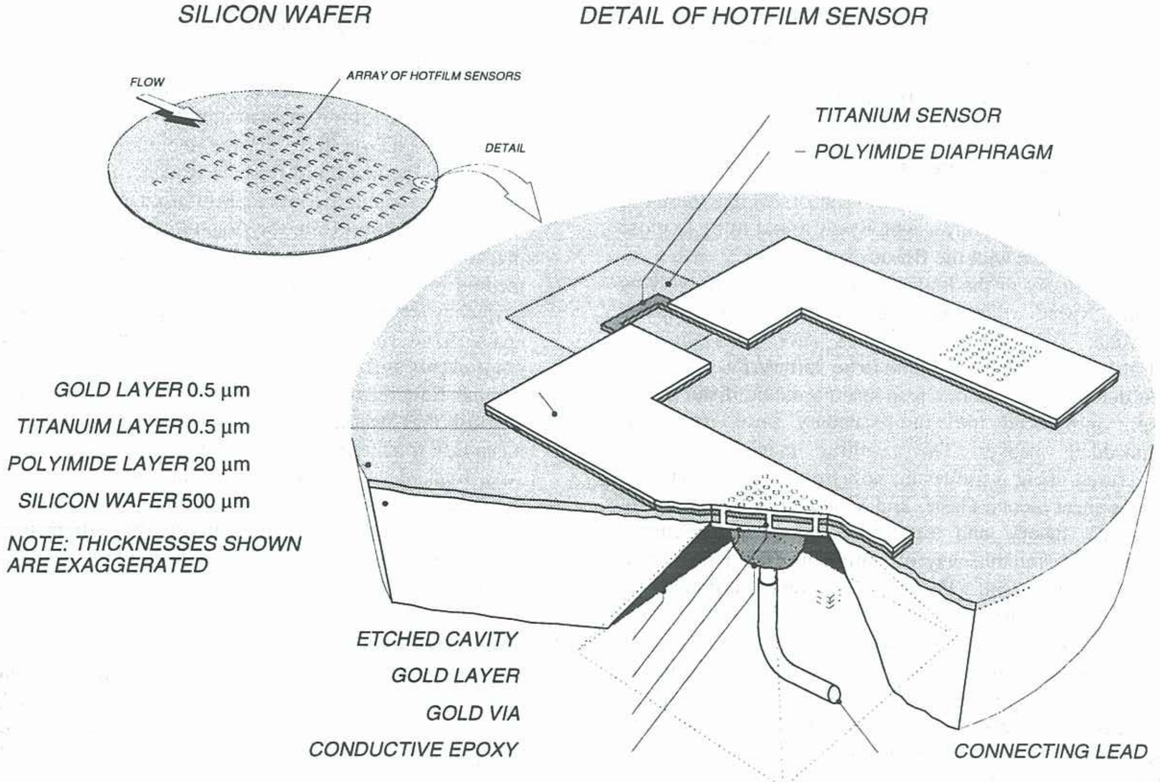

Figure 1 : Diagram of Preliminary Sensor Design.

SENSOR PERFORMANCE

Sensor performance, both sensitivity and frequency response were determined directly in experiments.

Experimental Facility

Experiments were performed in the Low Turbulence Wind Tunnel in the Engineering Department of Queen Mary and Westfield College, London. The tunnel is of conventional recirculating layout with a 7:1 contraction. Working section flow is of exceptional quality, freestream turbulence is 0.01%, bandpass filtered between 4 and 4000 Hz.

The tunnel working section is spanned vertically by a flat plate with a super-elliptic leading edge. The silicon wafer under test was installed in a mounting disc which was then fitted into the plate, as shown in Figure 2. Great care was taken to ensure that the flow surface was smooth, all joints were carefully filled and lapped.

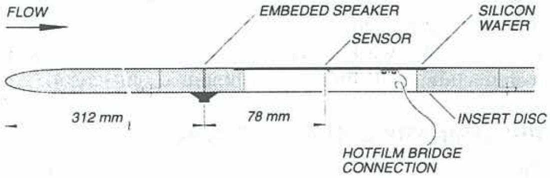

Figure 2 : Sectional view of the wafer mounted in the flat plate, showing the embedded speaker.

Flow over the plate was controlled using trailing edge flaps. On the working side the boundary layer was laminar with a minimal pressure gradient along the plate (this was monitored using 14 static pressure tappings). On the opposite side the boundary layer was tripped turbulent.

Hotwires and hotfilms were driven using Dantec 55M10 CTA Standard Bridge Units. In the experiments reported here the hotfilms were operated at a resistive overheat ratio of 1.4. Square wave and sine wave tests of the hotfilm units were performed at typical experimental velocities and indicated a frequency response of 50kHz.

Laminar Flow Experiments

In these experiments the hotfilm sensors were exposed to a laminar boundary layer which was found to be in close correspondence with the Blasius solution.

The sensitivity of the hotfilm was determined by varying tunnel speed while keeping the temperature closely constant, (this data is presented later, in Figure 10). Hotfilm sensitivity was found to be 250mV/Pa.

To determine frequency response harmonic disturbances were introduced into the boundary layer using the embedded speaker. The resulting modeshapes were measured using a traversing hotwire and also calculated using linear theory, Gaster and Shaikh (1996). Agreement between theory and experiment is good, Figure 3, providing a reliable way of estimating fluctuating shear stress at the wall. Disturbances were introduced at different frequencies and by scaling the linear calculations, fluctuating wall shear stress was inferred. This was then compared with (fluctuating) sensor voltage to infer the frequency response of the hotfilm.

Results of this analysis are shown in Figure 4. It can be seen that sensor frequency response rolls-off at very low frequencies; the -3dB point occurs at 10 Hz.

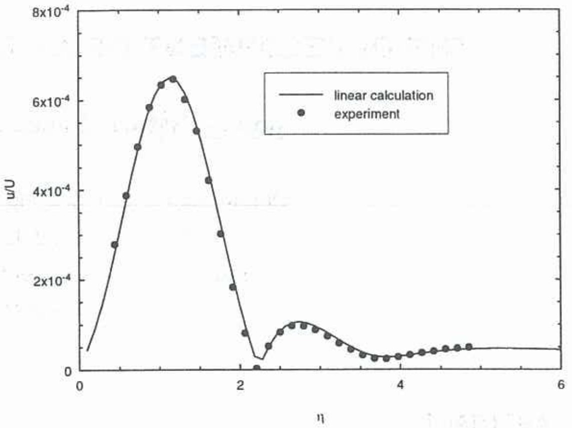

Figure 3 : Boundary layer u velocity fluctuations, measured and calculated for Re_{δ^*}: 887, F: 123×10^{-6}

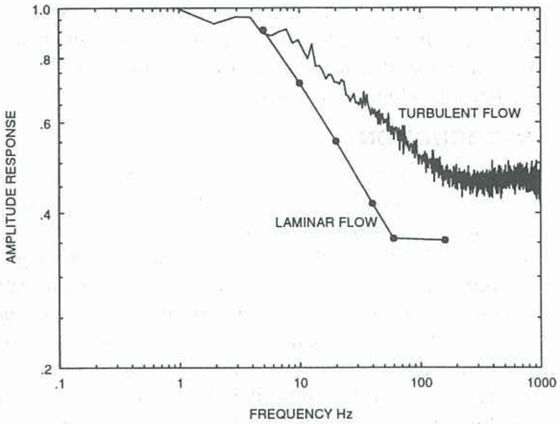

Figure 4 : Sensor frequency response, in laminar and turbulent flow.

Turbulent Flow Experiments

In the second series of experiments a trip wire was fixed to the plate surface to cause transition of the boundary layer. No artificial forcing was applied.

A Dantec glue-on hotfilm was mounted close to the diaphragm mounted hotfilms. The transfer function of the diaphragm mounted films was inferred by dividing the turbulent spectrum from the diaphragm mounted film by that from the glue-on, results are shown in Figure 4. This method implicitly assumes that the Dantec film has a flat frequency response. The diaphragm mounted hotfilm again shows roll off at very low frequencies; the -3dB point occurs at 20 Hz, in reasonable correspondence with laminar flow results. The difference between the laminar and turbulent results is accounted for by the difference in mean heat transfer from the sensor in each case.

As a final (destructive) test the underside of the sensor diaphragm was coated with conductive epoxy. This had the effect of reducing sensitivity but dramatically increasing sensor frequency response so that the -3dB point occurred at around 300 Hz.

Discussion

In both laminar and turbulent tests the frequency response of diaphragm mounted sensors was found to be poor. This is intuitively surprising since the thermal inertia of the system would appear to be reduced by placing the sensor on an insulating diaphragm.

THERMAL ANALYSIS

The principal difficulty in constructing a thermal model of the sensor is in estimating the heat transfer from the film. Thermal boundary layer theory cannot be used because the streamwise distances are so small. Estimates of heat transfer coefficient were made using theory due to Ma and Gerner (1993). A steady state thermal analysis suggests that just 1% of the total heat input is convected directly to the fluid from the hotfilm. Over 96% of the heat is lost to the substrate through the large gold electric tracks with the remainder lost through the polyimide diaphragm. These losses greatly reduce sensitivity, but do not explain the poor frequency response of the hotfilm.

Frequency Response

In order to model the sensor frequency response a two dimensional model of the diaphragm was first considered, before extending the analysis to a three dimensional sensor.

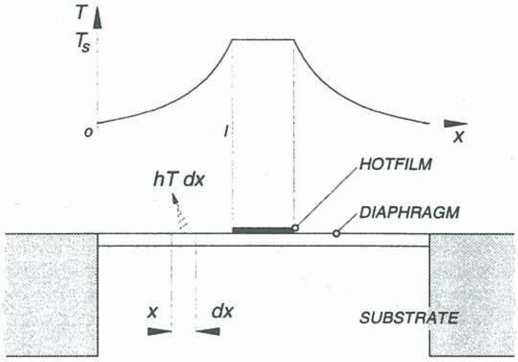

Figure 5 : Cross sectional slice of the sensor.

Two Dimensional Model.

Consider a two-dimensional slice through the sensor and diaphragm, as shown in Figure 5. If the diaphragm is thin enough to neglect temperature gradients across its thickness then the heat balance for a small element of diaphragm with convective heat loss is

$$-\mathrm{kd}\left.\frac{\partial T}{\partial x}\right|_{x}+\mathrm{kd}\left.\frac{\partial T}{\partial x}\right|_{x+dx}-\mathrm{hT}dx=\rho c d\frac{\partial T}{\partial t}dx$$

Where ρ, c and d are diaphragm density, specific heat capacity and thickness, respectively.

The silicon substrate will behave as a thermally massive sink at ambient temperature, giving boundary condition T=0 at x=0, for all t. If we assume that sensor temperature is maintained effectively constant by the feedback electronics then the boundary condition at the sensor–diaphragm junction is $T=T_S$, (a constant), at x=l, for all t.

We assume a uniform heat transfer coefficient over the diaphragm surface with a mean and fluctuating part, (caused by fluctuating velocity), given by $\bar{h}+he^{i\omega t}$. By substituting into the differential equation and neglecting products of small terms we obtain the solution

$$\frac{T}{T_S}=\frac{\sinh\left(x\sqrt{\bar{h}/kd}\right)}{\sinh\left(l\sqrt{\bar{h}/kd}\right)}+\frac{ih}{\omega\rho cd}\left[\frac{\sinh\left(x\sqrt{\bar{h}/kd}\right)}{\sinh\left(l\sqrt{\bar{h}/kd}\right)}-\frac{\sinh(ax)}{\sinh(al)}\right]e^{i\omega t}, \qquad (1)$$

where

$$a^2=\frac{\bar{h}+i\omega\rho cd}{kd}.$$

The first term represents the steady temperature solution and the second the fluctuating part.

Using Equation 1 temperature fluctuations in the sensor diaphragm were calculated for small (1%) fluctuations in heat transfer coefficient. The magnitudes of temperature fluctuations are shown in Figure 6. No variation is seen between 0.01 and 0.1 Hz additionally there are no significant phase changes. At 1 Hz the fluctuations are seen to be attenuated and become more so with frequency. It can be seen that attenuation occurs at simmilar frequencies to that observed in the experiments on the hotfilm sensor shown earlier.

This analysis can be extended to the case of a diaphragm covered by a thin layer of highly conductive material, allowing analysis of gold covered parts of the diaphragm.

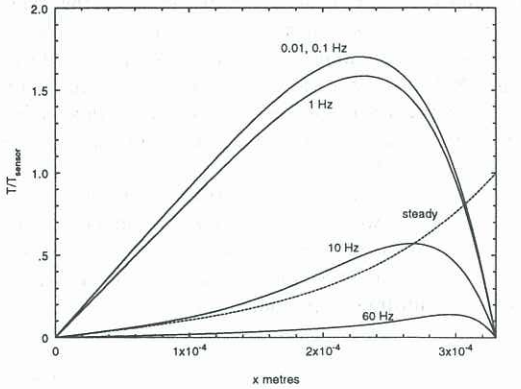

Figure 6 : Steady and Fluctuating temperature in the diaphragm. (Fluctuations are shown ×1000).

Modeling a Real Sensor

To model the sensor the previous two dimensional analysis was used to approximate the three dimensional conduction problem. Contributions from both the plated and unplated parts of the diaphragm were included as well as direct convection from the film.

A comparison of this theory and experiment is shown in Figure 7. Correspondence is quite good, the low frequency roll-off is captured by the analysis. Above approximately 120 Hz the model breaks down as the diaphragm ceases to be thermally thin.

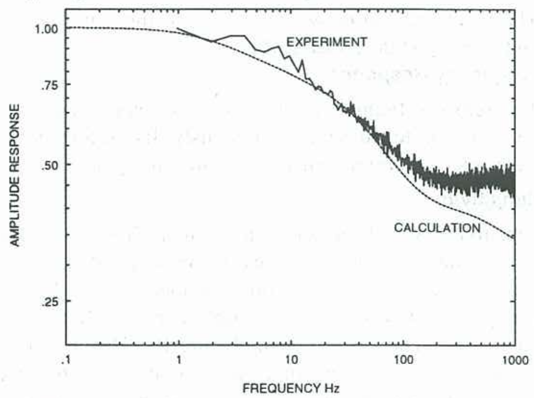

Figure 7 : Comparison of theory and Experiment.

Discussion

There is a clear physical interpretation for the behaviour of a hotfilm on an insulating diaphragm, based on the thermal model presented here. In the steady state the diaphragm is heated by the hotfilm. Convective heat transfer occurs from the heated diaphragm to the fluid. Perturbations to the heat transfer coefficient (due to velocity fluctuations) generate temperature fluctuations that propagate through the diaphragm back to the sensing element. At low frequency these waves are weakly attenuated and large areas of the insulating diaphragm generate waves which reach the hotfilm; the sensor area is effectively increased. At higher frequencies attenuation of the thermal waves becomes more pronounced and they produce less of an effect at the hotfilm. At this stage the effective area of the sensor is reduced to something more like it's geometric area.

IMPROVED SENSOR DESIGN

A number of improvements were made to the sensor design in order to improve sensitivity and frequency response. A diagram of the improved design is shown in Figure 8. Sensor area was greatly increased to cover a far larger proportion of the diaphragm area. Thus indirect convective heat transfer from the thermally sluggish diaphragm is reduced.

The gold tracks providing electrical connections to the titanium sensor were reduced in size and given a 'waist' in order to reduce conductive heat loss through them to the substrate. It is important to minimise conductive heat loss to the substrate as it reduces sensitivity.

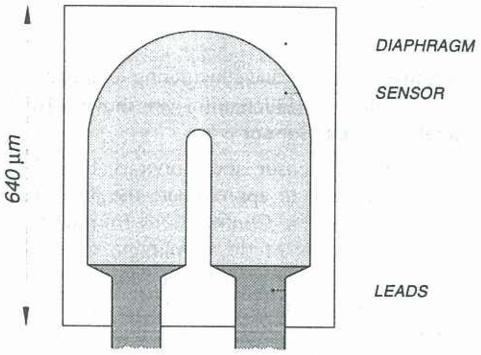

Figure 8 : Diagram of improved sensor design (plan).

SENSOR PERFORMANCE

The improved sensor was tested using the same facility and equipment described earlier.

Frequency Response

The sensor's frequency response was determined using the turbulent test described previously. Its perfomance is a considerable improvement, as shown in Figure 9.

Sensitivity

Sensitivity was determined in laminar flow tests. The sensor was located 0.4 metres downstream of the plate leading edge and the flow velocity varied. Air temperature was maintained closely constant. Results of this experiment are shown in Figure 10. The improved design has a sensitivity three times that of the original sensor. In terms of surface shear stress this corresponds to a sensitivity of 750mV/Pa, at an overheat ratio of 1.4. This compares very favourably with the sensors described by Huang *et al.* (1996) who report a sensitivity of 10mV/Pa at an overheat ratio of 1.12.

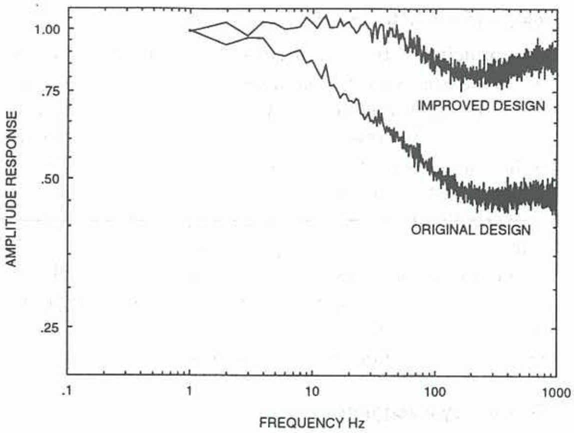

Figure 9 : Comparison between Frequency response of new and old designs.

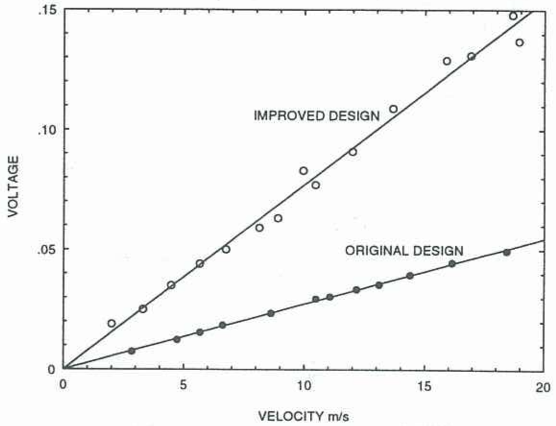

Figure 10 : Sensitivity of new devices.

DISCUSSION AND CONCLUSIONS

The results of the first part of this paper demonstrate the intuitively surprising result that placing a hotfilm on an insulating diaphragm can dramatically reduce its frequency response. Standard electrical tests of the hotfilm sensor fail to reveal this effect; indicting cut-off frequencies in the region of 50kHz when infact 20Hz is the figure obtained from more direct tests. This demonstrates the inadequacy of electrical tests in determining frequency response of a hotfilm on diaphragm system. A simple thermal model has been advanced which correctly predicts the attenuation above 20Hz, due to the polyimide diaphragm.

It appears that some roll off at low frequency is inevitable when a hotfilm is placed on an insulating diaphragm. This effect can be reduced by ensuring that convective heat transfer occurs principally by convection from the hotfilm rather than indirectly from the diaphragm. This requirement is met by ensuring that the diaphragm area is not too large in comparison with the hotfilm area.

REFERENCES

HUANG, J., TUNG, S., HO, C., CHANG, L. and TAI, Y. "Improved Micro Thermal Shear-Stress Sensor", *IEEE Trans. Instrum. and Meas.*, **45**(2), 570-574, 1996.

MA, S.W. and GERNER, F.M. "Forced Convection Heat Transfer From Microstructures", *Trans. ASME,* **115**, 872-880, 1993.

GASTER, M. and SHAIKH, F.N. "Receptivity to Free-Stream Disturbances", Report Dept. Engrng. Queen Mary and Westfield College, 1996.