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Use of a polymer film bridge to measure the contact force applied by instruments used in the measurement of surface texture

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ABSTRACT

ISO 3274 (1996) advocates that the static measuring force applied by the tip of a stylus-based surface texture measuring instrument should be 0.75 mN and should not vary during a measurement. This force is usually set by the manufacturer and is difficult for the user of the instrument to verify. This report details a procedure whereby the stylus tip is drawn across a thin polymer film that is rigidly supported at both ends. The deflection of the film, caused by the contact of the stylus tip with the film, is measured and the force being applied by the stylus is calculated. While results showed that this particular method would not be suitable for applications where high accuracy is required, it could be useful as a cheap and simple conformance test device to check whether the stylus force is compliant with ISO 3274 (1996).

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CONTENTS

FIGURE LEGENDS

TABLES

1. INTRODUCTION

The surface texture of a machined component is important in many industrial areas, including, medicine (for example the surface of hip replacement joints), the machining of optical surfaces and the effectiveness of an adhesive since the surfaces to be joined will dictate the type of adhesive required. The texture of a surface will affect the wear and serviceability of a component and hence its useful life. For example, the surface of a piston needs to be smooth enough to minimise friction, but if it is too smooth then it would not be able to retain a layer of lubricant and metal-to-metal contact would create rapid wear. However, a mirror manufactured for an optical telescope would need to have a very smooth surface to optimise specular reflection (Leach 2000[(1)]). Surface texture can be measured on scales ranging from millimetres to nanometres depending upon the application.

A variety of methods can be used to measure surface texture. The most common method adopted at present is that which involves physically dragging a diamond stylus across the surface. A pickup and transducer convert the vertical movement of the stylus into an electrical signal, which in turn, is connected to an electronic amplifier to boost the signal from the transducer to a useful level. The vertical displacement of the stylus is plotted as a function of the horizontal displacement to provide a representation of the profile of the surface. The shape and dimensions of the stylus will influence the information gathered during measurement. A typical stylus shape is that of a cone with a spherical tip. The tip radius is usually in the range 1 to 10 µm. Truncated pyramidal, or chisel, shaped 0.1 µm tips are available for specialised measurements. Damaged or worn stylus tips can lead to errors in measurement results – on a surface with narrow or deep valleys they may be unable to penetrate to the valley bottom. Therefore it is important that the condition of the tip is regularly checked (Leach & Hart 2001).

The force that the stylus exerts onto the surface is also important. International standard specification ISO 3274 (1996) advises that the static measuring force at the mean position of the stylus should be 0.75 mN and should not change during measurement (Leach 2001[(2)]). Excessive stylus force can damage delicate surfaces while on a hard surface this excessive force can lead to rapid stylus wear. A stylus force that is too low can affect the measurement of surface texture as the stylus fails to remain in contact with the surface. This loss of contact is caused by a lack of vertical inertia of the stylus and transducer system. Chetwynd (1998) reported the difficulty in measuring stylus forces and stated that there is the possibility that forces set on measuring equipment at the time of manufacture are subject to accidental disturbance.

The aim of this investigation was to produce an instrument capable of measuring the force exerted by a stylus on a surface. This force measuring device needed to be accurate, stable in a variety of working conditions, robust enough to be used in an industrial application, inexpensive, traceable and capable of measuring a range of stylus forces with magnitudes from micro-newtons to milli-newtons.

The work reported here is an investigation of the possibility of using a device based on the displacement of a thin polymer film as a method of measuring a contacting stylus force. The device used was a simple membrane, or bridge, system with a section of polymer film of 33 μm thickness forming the bridge, under which was placed a displacement sensor. A calibrated electro-static (capacitance) displacement sensor was then used to measure the displacement of the film due to the contacting force of a stylus. The displacement of the film due to an applied force was theoretically analysed. Different tensile loads were applied to one end of the film to investigate the relationship between tension and displacement.

2. SYSTEM DESIGN

To meet the design requirements highlighted in §1 a stainless steel block was used with the polymer film placed across it forming a bridge structure. Figures 1(a) and 1(b) are schematic diagrams of the block from two different viewing angles. Two clamps, each using two screws, as in figure 1(a), held the polymer film in place and at the required tension. The block had a hole in the bottom into which a Pioneer PDG 500 Series capacitance displacement sensor was located. This hole was positioned so as to place the centre of the sensor directly under the centre of the polymer film, *i.e.* where maximum deflection under the force of a stylus would result. Three small washers were affixed to the base of the block, in tripodal formation, to give a stable surface on which the block could stand and to act as a set of spacers to prevent the capacitance sensor from coming into contact with any surface on which the block was mounted.

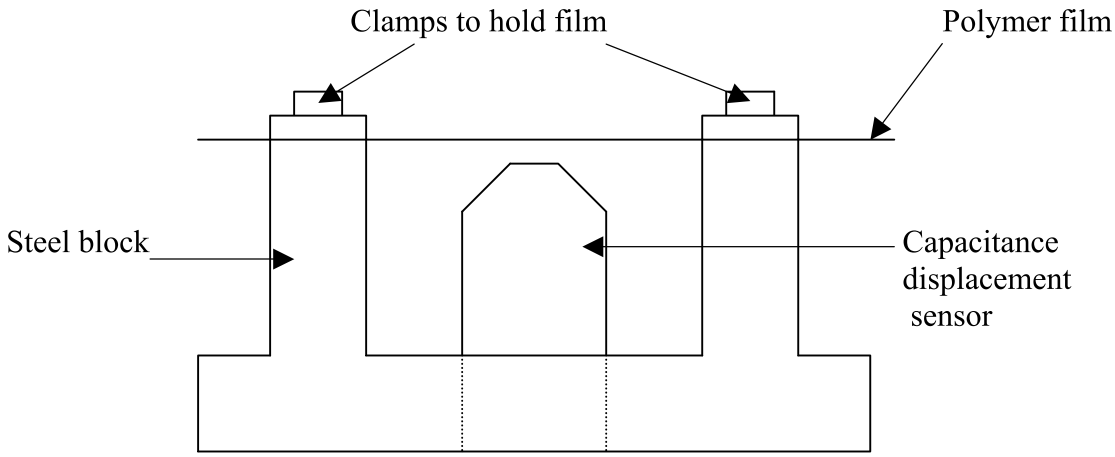


Figure 1(a) Schematic diagram of block (side elevation)

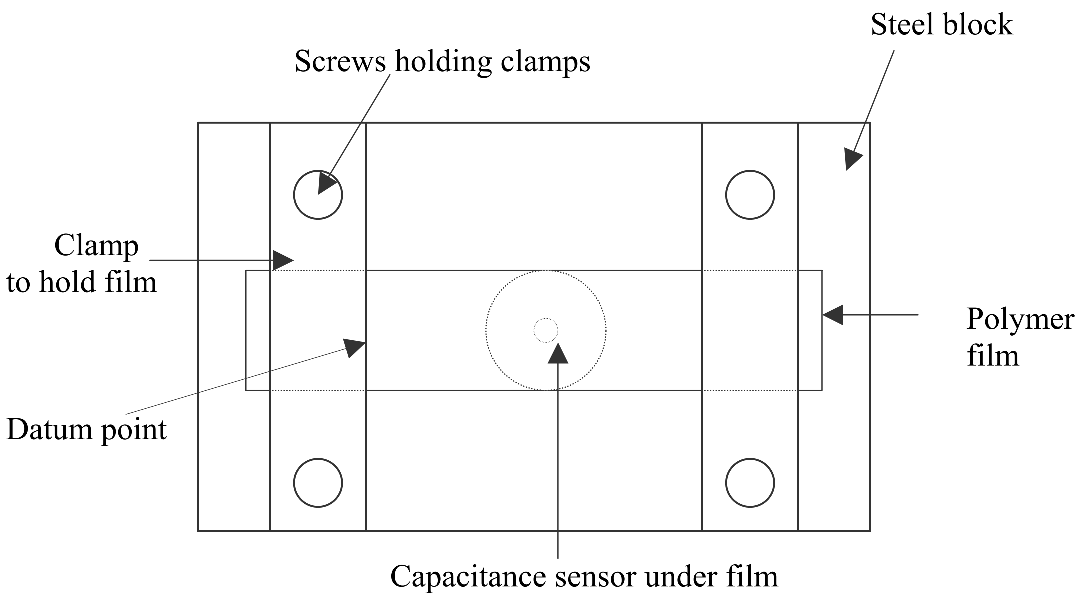


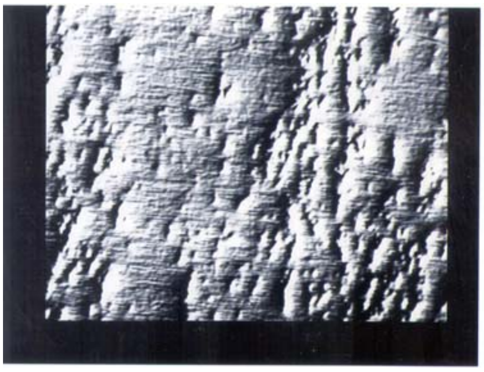
Figure 1(b) Schematic diagram of block as viewed from the top

The sensor was a parallel-plate capacitance sensor with measurement ranges of 0 ± 0.025 µm to 0 ± 254 µm (the least sensitive range being 254 µm and the most sensitive 0.025 µm) with an accuracy of 98% of the full-scale deflection. The standoff distance of the sensor from the polymer film was 190.5 µm. The film (Solef®) was aluminium-coated on both sides and had a total measured thickness of 33 µm.

3. CALIBRATION OF THE SYSTEM

3.1 PRELIMINARY STUDY OF THE POLYMER FILM

A preliminary study was made to investigate whether the film already had scratches present on its surface, or whether it was possible to make scratches on its surface with a stylus operating under typical conditions. This test involved gluing a piece of the polymer film to a small metal block and viewing a predetermined area under a Nomarski microscope. Having found no discernable scratches, a set of experiments were carried out using the NPL NanoSurf IV stylus instrument (Leach 2000(2)) in order to deduce if scratches could be made on the surface of the film. Using a 0.2 μm radius truncated pyramidal (chisel) tip stylus with a nominal force set at 40 μN a series of five runs of 30 seconds duration each at a speed of 0.5 mm per minute were made over the selected and previewed area of the film. The sample was then viewed under the Nomarski microscope to check for any scratches that may have been made by the stylus. Figure 2 shows a 'before' and 'after' image of a selected area of the film; no scratches are discernable.



Before scratch testing

After scratch testing

Figure 2 Images taken before and after scratch testing

3.2 INITIAL SET-UP OF THE CAPACITANCE SENSOR AND THE POLYMER FILM

It is essential that the polymer film was not subject to axial elastic deformation. Therefore, it was clamped across the bridge with only sufficient tension to prevent the film from sagging under its own weight.

In order that the capacitance sensor could be positioned at the correct standoff distance from the underside of the film, the block was turned onto its side and clamped to the bench. A slideway with a small rod attachment could then be set up behind the capacitance sensor. The rod functioned as an adjuster to move the sensor towards the polymer film. The correct distance was achieved by a series of increasingly fine adjustments to the capacitance sensor settings and noting readings from the sensor. Once the sensor had been set at the correct standoff distance it was held in place with a nylon screw.

3.3 RESULTS OF THE SYSTEM CALIBRATION

3.3.1 SYSTEM CALIBRATION

Having set up the device, the variation of the deflection of the film with force was measured using a set of calibrated masses ranging from 1 mg to 120 mg, equivalent to forces of approximately 10 μN to 1.2 mN. Each mass was placed onto the centre of the polymer film bridge and the deflection of the film as indicated by the capacitance sensor was recorded. Ten measurements were made for each mass applied in order to calculate the average deflection of the film.

3.3.2 COMPARISON WITH THEORY

Theoretical values for the deflection, δ, of the film can be calculated based upon the dimensions of the film being used, the force applied to the surface of the film by the mass and the Young's modulus, E, of the film.

The deflection was calculated using equation (3.1) from Young (1989)

$$\delta = \frac{-2mg(l-a)^2 a^3}{3EI(l+2a)^2} \tag{3.1}$$

where I is the moment of area of the film's cross section given by

$$I = \frac{1}{12}\left(wt^3\right) \tag{3.2}$$

where E is 3200 MPa, the width of the film w is 0.010 m, the length of the film l is 0.010 m, the thickness of the film t is 3.3×10^{-5} m, a is the distance from the datum point to the central point of the film where the maximum deflection occurs (the datum point is illustrated in §2, figure 1(b)) and mg is the magnitude of force causing the deflection of the film. The negative sign on the right hand side of equation (3.1) indicates that the displacement is in a downward direction. The value of the acceleration due to gravity, g, has been taken as 9.81 m s^{-2}.

In theory, forces of 10 μN to 1.20 mN cause central deflection values of 0.37 μm to 42.13 μm. Figure 3 shows the theoretical results and the experimental results on the same graph. The experimental deflections on the graph range from 0.32 μm to 39.85 μm.

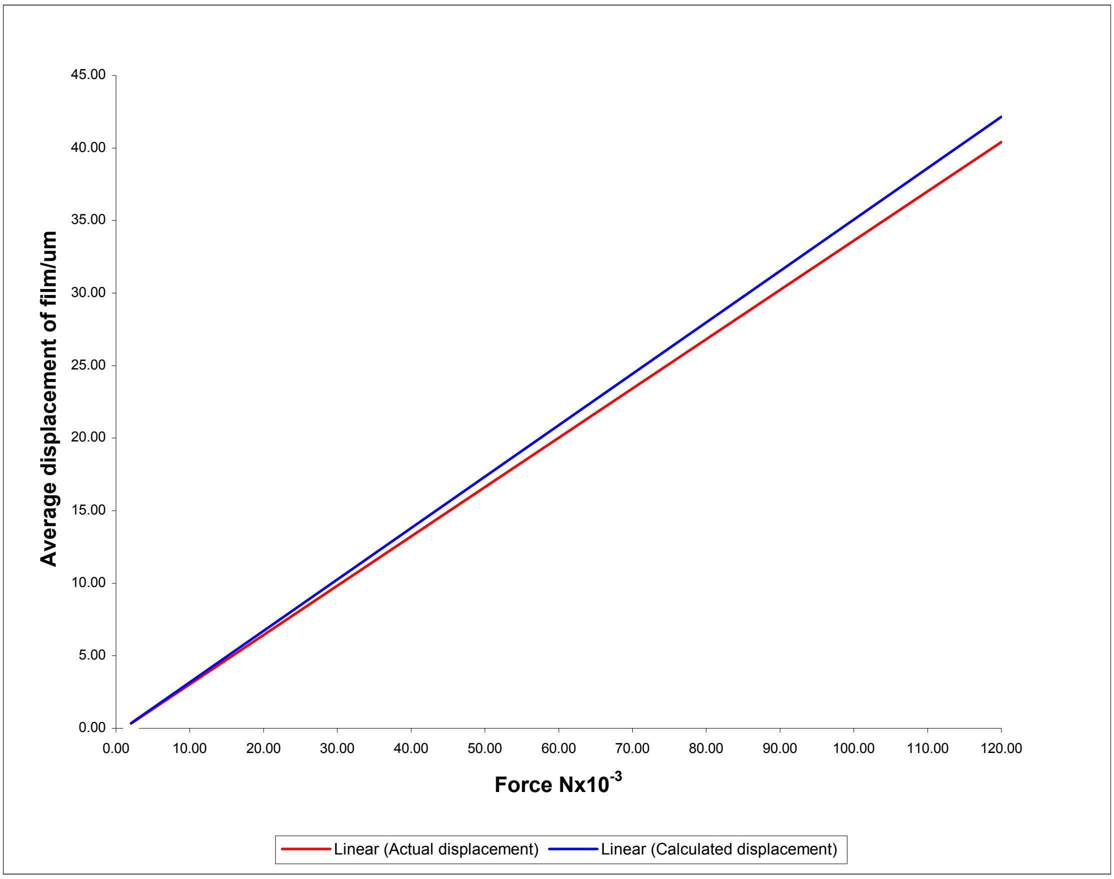


Figure 3 Actual displacement and calculated displacement

4. CALIBRATION OF A STYLUS FORCE

4.1 DEFLECTION OF THE FILM UNDER A STYLUS FORCE

The measurement of the deflection of the film under the force of a stylus was carried out using a Taylor-Hobson Form Talysurf instrument that was fitted with a 2 µm chisel tip stylus.

4.1.1 TENSION EFFECTS

The block was set-up to be level using a stage with angular adjustment in three orthogonal axes. Initially deflection measurements were made with the film tensile load adjusted by hand. The tension was subsequently adjusted using a small pan attached to the free end of the film with a calibrated mass placed on it. The masses used to adjust the tension of the film ranged from 1 g to 10 g in increments of one gram. Figure 4 is a graph of the effect the tensile load had on the displacement of the film. The most appropriate tensile load is 2×10^{-2} N since this lies in a linear region - this value was chosen as the tensile load while completing the measurements with the stylus.

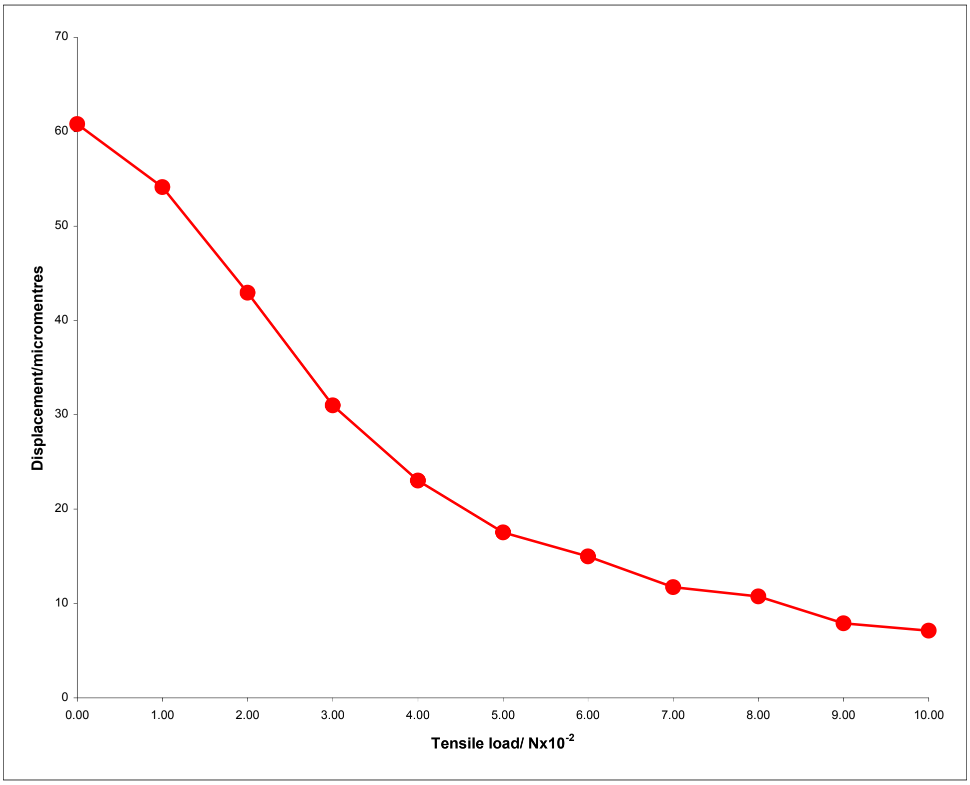


Figure 4 Tensile load against displacement

4.1.2 REPEATABILITY CONSIDERATIONS

The repeatability of deflections under the force of a stylus was the next major consideration. The deflections measured with the stylus in contact showed considerable variation. However, data from the Form Talysurf compared well with that recorded by the capacitance sensor. It was thought that air temperature and air-flow from the air conditioning units may be affecting the results and a small box was made to isolate the bridge as much as possible from all surrounding influences.

Approximate calculations were carried out in order to establish how much the air temperature could be contributing to the variation in deflection of the film. The expansion coefficient, α, of the film (obtained from the Solvay website) is quoted as being approximately 141 x 10^{-6} K^{-1}. The expansion coefficient of the aluminium coating on the film is small compared to the polymer film and was not considered to be a contributory factor. A change in the film's length, ΔL, calculated for a temperature change, ΔT, of 1 K, where the original length, L_0, is 10 mm, is given by

$$\Delta L = L_0 \alpha \Delta T \qquad (3.3).$$

By inserting the appropriate values into equation (3.3) the calculated change in length is 1.41 μm K^{-1}.

The sag, d, of the film due to a change in temperature may be calculated approximately by using Pythagoras' theorem for a right-angle triangle where L_1 is 10 mm and L_2 is the increased length of the film caused by a change in temperature. Figure 5 is a diagram of the relevant dimensions. The central sag, d, is given by

$$d^2 = \left(\frac{L_2}{2}\right)^2 - \left(\frac{L_1}{2}\right)^2 \qquad (3.4).$$

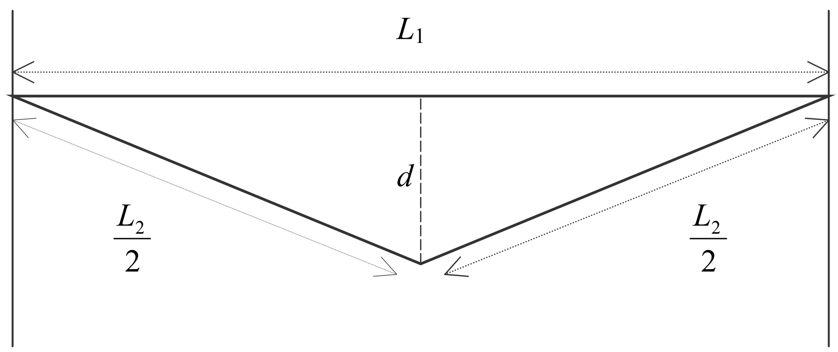


Figure 5 Approximate calculation of the film's sag due to a temperature change

The values obtained using equation (3.4) indicated a sag in the film of approximately 1.5 μm K^{-1}. This is a reasonable calculation since experimental deflections showed a 3 μm difference over a temperature range 19 - 21 °C.

A further calculation was also carried out (Kempe 1958) to test the validity of the approximate calculation and results in equation (3.4). This method was used to calculate the film's length in relation to its sag where the sag geometry is considered to be a quaternary, thus

$$L = a\left[\frac{1}{2}\sqrt{\left(1+\frac{16b^2}{a^2}\right)} + \frac{a}{8b}\ln\left(\frac{4b}{a} + \sqrt{\left\{1+\frac{16b}{a^2}\right\}}\right)\right] \qquad (3.5)$$

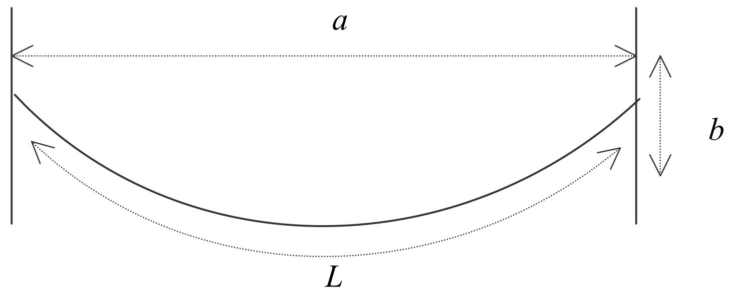


Figure 6 Calculation of the film's length in relation to its sag

where *a* is the distance between the two ends of the chord, *L* is the length of the deflected chord and *b* is the distance the chord is deflected by. The insertion of appropriate values into equation (3.5) gave results comparable to values calculated from figure 5 and equation (3.4).

Having discovered the problem of non-repeatable deflections, the block used for scratch testing mentioned in §3.1 was used to check that the film was not undergoing some other form of surface deformation. Ten measurements were taken using the Form Talysurf instrument with the results showing only an 84 nm spread in *Rz* [1]. This spread was extremely small compared to the spread in the deflections of the free-floating film. The resolution of the Form Talysurf is 10 nm, the apparent extra resolution is due to averaging.

4.2 INITIAL INVESTIGATIONS

As stated above temperature was considered a factor affecting the deflection of the film. Since the expansion coefficient of the film is relatively large even a small rise or fall in temperature could affect the overall dimensions of the film. The flow from the air-conditioning units in the laboratory was also another factor to consider since the air was turbulent in the area above the experiment. An Edale thermometer with two

[1] *Rz* is defined in ISO 4287: 1997 as the maximum height of the profile from the lowest valley to the highest peak

temperature probes was used, one attached to the bridge and the other positioned close to the film to measure air temperature.

Figure 7 shows results from deflections measured at different air temperatures and figure 8 is a graph with the theoretical effect of temperature change plotted against deflection of the film. According to figure 8, deflection should be proportional to the air temperature. However, in practice this was not evident although it is worth noting that these experiments were made without the protective box mentioned in §4.1.2. The results in figure 7 could be used as further confirmation that airflow and other movement around the experiment was affecting the deflection of the film.

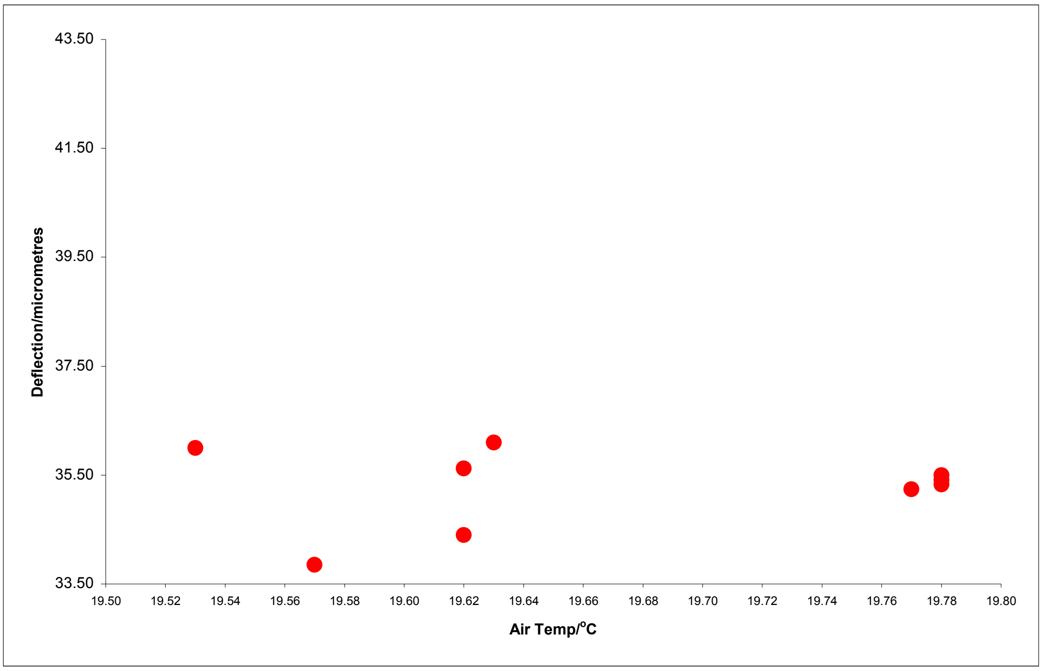


Figure 7 Air temperature against deflection (experimental results)

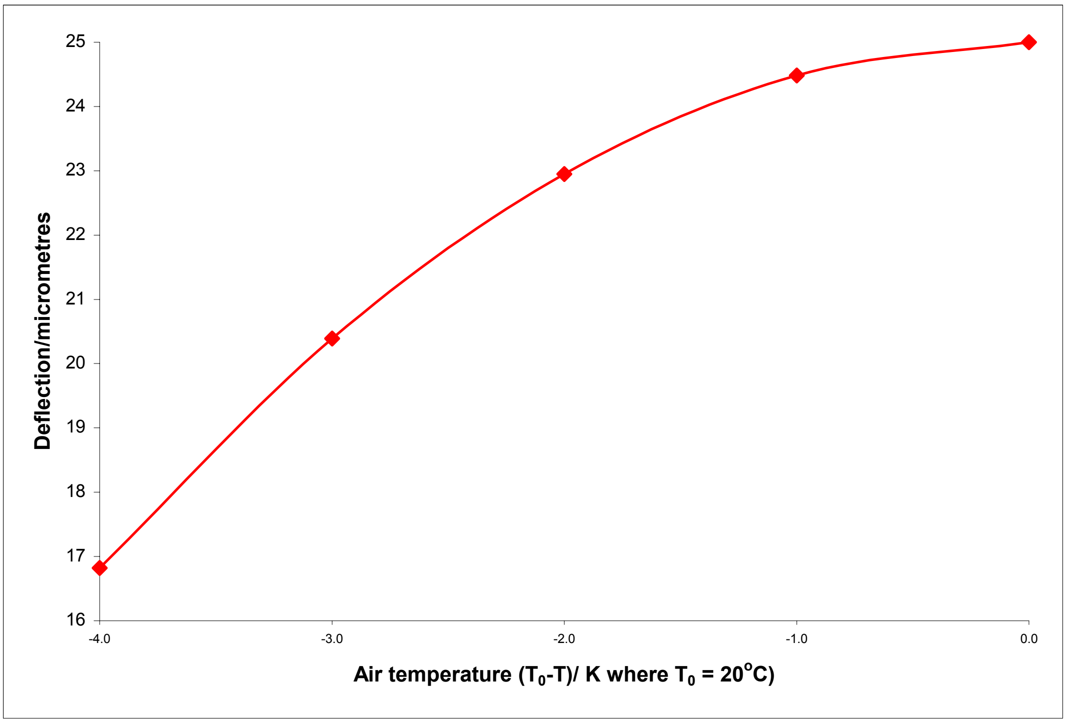


Figure 8 Air temperature against deflection (theoretical calculations)

It was found that the shielding box was most effective if the system was left to settle for around half an hour before taking any measurements. A temperature probe was fitted near to the film to measure air temperature inside the box. The purpose of this was to provide further evidence that air temperature and circulation were affecting the displacement of the film.

When deflections of the film were measured without the box, the measurements had a spread amounting to around 1 μm, but with the box in place the spread was reduced to 0.334 μm. A noticeable temperature difference was apparent between measurements taken with and without the box and this temperature difference affected the deflection values.

Figures 9 and 10 are examples of the difference in the film's deflection with and without the protective box placed over the experiment. The initial upward trend at the start of the measurements was due to a small recess having been cut in the clamp holding the film on the left-hand side of the bridge. The recess was cut so that measurements could start at a position that preceded the datum point. Peak to valley, *Rz*, values are in micrometres.

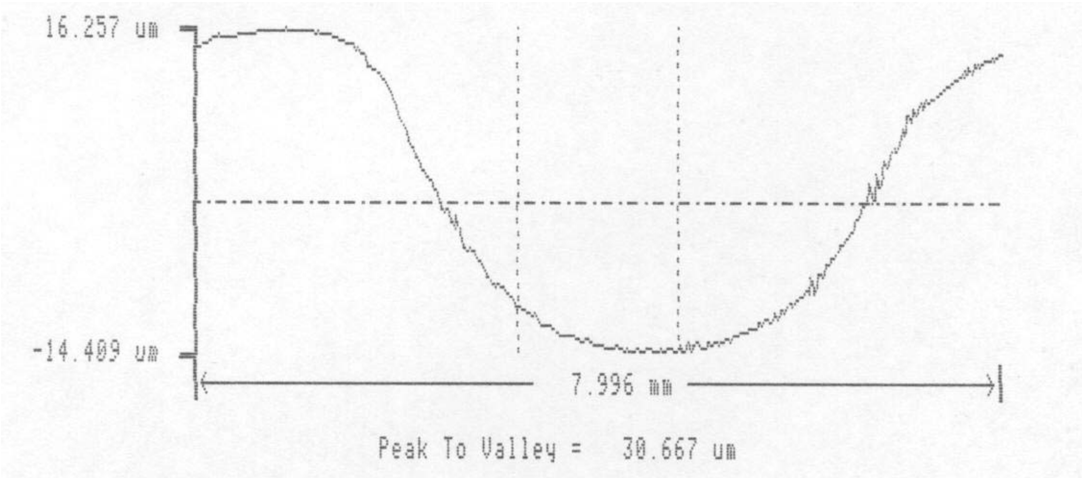


Figure 9 Example of a deflection measurement taken without the protective box

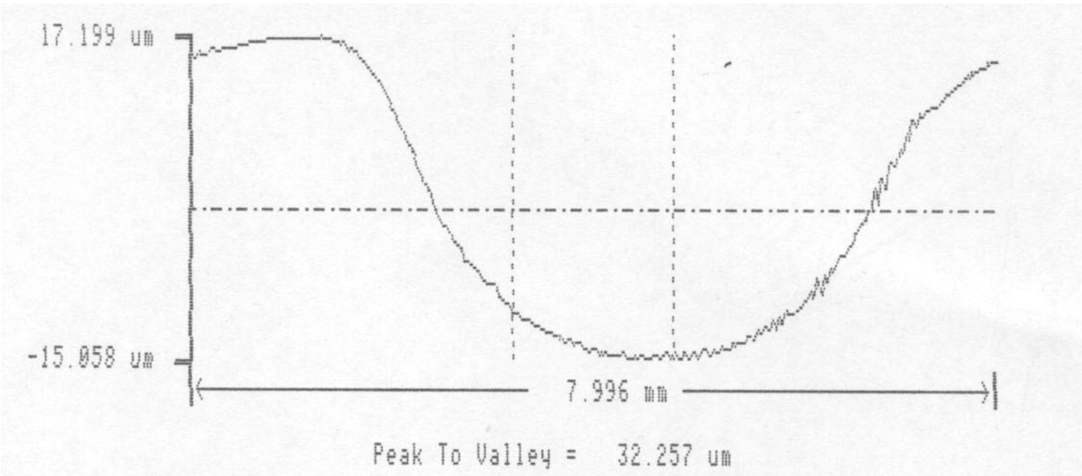


Figure 10 Example of a deflection measurement taken with the protective box in place

4.3 RESULTS FOR CALIBRATION OF A STYLUS FORCE

Table 1 shows the complete set of deflection results obtained with and without the box. An air temperature measurement was also taken before and after each set of deflection measurements.

The results obtained while the protective box was placed over the experiment show good repeatability. The standard deviations in table 1 show the variation in displacement. There is a marked difference between the results obtained with and without the box.

It would be safe to assume that the increase in temperature within the protective box contributed to the increased deflection measurements. In addition, these results were more repeatable since the film was less affected by air turbulence.

Time of Reading	0945	1020	1150	1430	1445	1530
With/without box	Without	With	With	With	Without	With
Temp at start/°C	19.65	20.10	20.15	20.05	19.70	20.00
Temp at finish/°C	19.70	20.15	20.15	20.05	19.70	20.10
Deflection measurement from datum point/μm	31.493	34.057	33.112	33.111	31.349	32.827
	31.192	33.789	33.231	32.803	30.614	32.675
	31.636	33.649	33.190	32.864	30.379	32.232
	31.284	33.949	33.204	32.872	31.260	32.400
	31.559	33.866	33.241	32.820	31.209	32.330
	31.639	33.641	33.430	32.739	31.234	32.257
	31.397	33.963	33.446	32.798	31.047	32.289
	31.200	33.465	33.298	32.549	30.643	32.352
	30.457	33.868	33.396	32.651	30.433	32.328
	30.667	33.510	33.385	32.571	31.289	32.629
	30.912	33.618	33.281	32.445	31.242	32.501
	30.876	33.741	33.362	32.542	30.797	32.313
Approximate standard deviation (σ_{n-1})	0.390	0.188	0.106	0.187	0.361	0.188

Table 1 Deflection results

4.3 CALCULATION OF FORCE APPLIED

The deflection of the film can be calculated by re-arranging equation (3.1) from §3.3.2, where δ is the deflection of the film, F is the force applied to the film, E is the Young's modulus of the film, l is 10 mm and I is taken from equation (3.2).

A theoretical force, F, which has to be applied to obtain the resultant deflections, can be calculated by arranging equation (3.1) into the form of

$$F = \frac{192 EI\delta}{l^3} \qquad (4.5).$$

Displacement (μm)	Actual force (mN) derived from experimental data	Theoretical force (mN)
31	0.92	0.57
32	0.95	0.59
33	0.98	0.60
34	1.01	0.62

Table 2 Force applied for a deflection

Table 2 shows the displacement of the film and the actual force producing the deflection. Taylor-Hobson, the manufacturer of the Form Talysurf states that the approximate force generated by the stylus tip on a surface is 0.7 to 1 mN, depending on the position of the counter weight on the stylus arm. These results compare well with the results from the calibration with the masses in §3.3.2. A pan balance was also probed with the stylus. The results of this showed a force of 0.95 to 1.02 mN.

5. CONCLUSIONS

The design of the bridge was not inherently at fault, but it proved to be too delicate for the job it was intended to do. Temperature and airflow could have a detrimental effect on the results if the instrument was used in regions where there is a lot of movement from personnel, or used in conditions where there is no climatic control. Apart from the temperature and airflow considerations the film bridge would also be susceptible to dust and other foreign objects coming into contact with it. The initial problems with erratic results were overcome, but it must be remembered that even with the instrument in a stable environment there was still an overall standard deviation of 0.106 μm in the deflection measurement results, which is an approximate variation in force of 0.07 mN. This could increase considerably in an industrial application, so much so that the uncertainty of the deflection would become impractical to calculate due to constant fluctuations in the temperature and other environmental factors affecting the stability of the film.

To summarise, without the box, results obtained show an average of 0.92 mN with a repeatability of ± 0.024 mN. With the box the average is 0.98 mN with a repeatability of ± 0.030 mN.

While the method described here would not be suitable for applications where high accuracy is required, it would be useful as a cheap and simple conformance test device to check whether the stylus force is compliant with ISO 3274 (1996).

In order to measure forces of a lower magnitude it would appear that equipment with a higher sensitivity would be required. One possible solution to this might be found in an electrostatic device where very small forces and deflections of a cantilever could be amplified electronically to a useful level (Chetwynd 1998).

6. ACKNOWLEDGEMENTS

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