Evaluation of the dynamic performance of a glass cantilever style constant force probe for the measurement of surface texture

Derek Chetwynd and Gavin Howell
School of Engineering, University of Warwick

Richard Leach
Centre for Basic, Thermal and Length Metrology,
National Physical Laboratory

ABSTRACT

A prototype surface topography contact probe based on a glass cantilever with capacitive micrometry to detect displacement has been evaluated under relatively extreme dynamic conditions. The probe is designed principally for low contact force measurement on sub-micrometre surface structures and to be scanned at speeds well below 1 mm s^{-1}. Its behaviour at higher speeds might be predicted by modelling it as a second-order system, but the complexity of interaction between a tip and surface casts doubts on how such models should be used. Hence a high-precision air-bearing table has been used to scan nickel replica sinusoidal surface profiles under the tip. This has allowed experimental verification of behaviour at speeds beyond 1 m s^{-1} and at profile signal frequencies to above the probe natural frequency (about 280 Hz). An extremely consistent output is reported under all test conditions with the frequency response flat to within 1 dB up to around 250 Hz. It is concluded that the probe technology may be used satisfactorily for measurements at speeds higher than are used on conventional surface metrology instruments.

ISSN 1469-4921

National Physical Laboratory
Queens Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of the Managing Director, NPL
by Dr David Robinson, Head, Centre for Basic, Thermal & Length Metrology

CONTENTS

1. INTRODUCTION **1**
2. DESIGN OF THE TEST SYSTEM **4**
3. BRIEF EVALUATION OF THE ORIGINAL PROBE **8**
4. DYNAMIC EVALUATION OF THE REBUILT PROBE **11**
4.1 CALIBRATION AND INITIAL INVESTIGATIONS 11
4.2 HIGH SPEED TESTING 12
5. CONCLUSIONS **16**
6. ACKNOWLEDGMENTS **16**
7. REFERENCES **16**

FIGURE LEGENDS

Figure 1 Schematic view of the glass cantilever probe 2
Figure 2 Photographs of the test system (left) and probe and sample stage (right) 5
Figure 3 Nanostep measurement of the 50 μm test piece 6
Figure 4 Log-linear frequency response of the original probe, determined by a shaker test 8
Figure 5a Profile by the original probe of the 50 μm wavelength sample at 0.25 mm s-1 traverse speed 9
Figure 5b Profile by the original probe of the 50 μm wavelength sample at 8 mm s^{-1} traverse speed 9
Figure 5c Profile by the original probe of the 50 μm wavelength sample at 14 mm s^{-1} traverse speed 10
Figure 6 Calibration curve for the rebuilt probe 11
Figure 7 Frequency response of the rebuilt probe by the shaker method 12
Figure 8 Typical forward traces from the 50 μm sine wave at speeds of 1 mm s^{-1}, 6 mm s^{-1} and 16.7 mm s^{-1}. The vertical offset is generated computationally for clarity 13
Figure 9 r.m.s. amplitude recorded from the 100 μm sine wave artefact at various frequencies (traverse speeds – see table 1) 14
Figure 10 log-log frequency response from scans on the sine waves: diamond – 100 μm forward, square – 100 μm reverse, triangle – 50 μm forward, circle – 50 μm reverse (for scan speeds, see table 1) 15
Figure 11 log-log frequency response from a transverse scan on the 50 μm sine wave (for scan speeds, see table 1) 15

TABLES

Table 1 Traverse speeds used indicated by their equivalent signal frequencies 14

1. INTRODUCTION

The measurement of surface texture is currently widely applied in manufacturing industry and is of growing importance in a wide range of technologies. Historically, surface texture has been used principally as a means of process control monitoring on machined metal and other relatively hard materials. Improved understanding of the behaviour of surfaces is leading to more sophisticated notions of designed surfaces, with a consequental need for improved metrology. There is also a growing desire to exploit, and so need to control, surface structure on softer materials at amplitudes of only a few nanometres. In both cases the 'traditional' stylus instrument may exert too much pressure onto the surface and other, preferably non-contact, methods are needed. A fuller discussion of recent thinking is provided in the literature (for example, Whitehouse 1994, Griffiths 2001, Whitehouse 2002). From the point of view of Standards Organizations, the need for methods of rigorously comparing different measurement techniques is becoming increasingly pressing. The study described here concerns the behaviour of one candidate probing technology that might be applied to master calibration instruments for inter-comparison trials.

In this context, there is no need here to review the variety of methods that can be used to measure surface texture. Neither are the relative merits and disadvantages of contact and, say, optical methods relevant – both must be part of the investigation into method divergence. At present the most common method of surface measurement involves physically dragging a diamond stylus across the surface. A displacement sensor converts the vertical movement of the stylus into an electrical signal, which, taken as a function of the horizontal displacement, provides a representation of a profile of the (cross-section 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, with a radius usually in the range 1 to 10 μm. Such a tip acts as a low-pass filter, removing detail of the small-scale structure of the surface in a highly non-linear manner. To obtain improved lateral resolution, a sharper tip is needed. Also needed is a lower contact force in order to keep pressures at a level where there is no serious damage to either surface or tip. The atomic force microscope (AFM) is the ultimate step in this progression. It uses a micro-fabricated cantilever beam with an integral tip as a force and displacement-sensing element. In the most common configuration, a laser and position sensitive detector monitors the deflection of the cantilever. The tip is scanned over the surface, while its height is continuously and automatically adjusted to maintain a constant deflection of the cantilever. The tip is then exerting a constant force on the surface, while the vertical drive signal directly represents the surface height variation.

The AFM has become established with remarkable rapidity as a major technique for surface topography and integrity measurements where nanometre sensitivity is essential. However, instruments of reasonable cost tend to have insufficient range for many applications, the tip and cantilever are inevitably delicate, and the sensitivity increases the vulnerability to environmental disturbances. Thus, AFM is unattractive for routine industrial inspection tasks, even of high-specification surfaces. Howard and Smith (1992) proposed and demonstrated a compromise between the AFM and conventional stylus probes. It was intended to be used in a mode similar to that of an AFM, but to be more robust and controllable at the cost of some sensitivity. The probe tip was a Berkovich cleaved diamond with typically a tip radius of less than 100 nm. It was bonded to a glass cantilever, of the order of 10 mm long and 100 μm thick. The rear face of the cantilever was metal coated to form a capacitive micrometer with an electrode on the base of the probe. The capacitor gap would be typically 10 – 20 μm, giving sub-nm displacement sensitivity. The linear gauging allowed more controlled setting of the contact force than on a typical AFM. The probe was scanned over a surface at constant cantilever deflection with the surface height being recorded as the vertical movement of the probe necessary to maintain that deflection.

A glass cantilever probe, based on the principles just discussed, had been designed and built by the University of Warwick Precision Engineering Research Group for use at the National Physical Laboratory (NPL). It was intended for use in constant force mode at slow lateral traverse speeds on calibration standard and other comparison artefacts. Typically, it would be used as a sensor on super-precise, bespoke instruments such as the NPL NanoSurf series (see, for example, Leach and Cross 2002). Figure 1 illustrates the basic device. The cantilever is nominally 10 mm in active length, 3 mm wide and 100 μm thick, machined from rolled glass. The actual beam is 15 mm long with 5 mm cemented to a nominal 10 μm step on the body. The overlapping areas of gold metal coating on the cantilever and on the body provide a capacitor of 10 pF at mid-range. Since the principal mode of operation was to be at constant deflection (constant capacitance), guard electrodes were not used and nor was there any correction for linearity errors associated with end-rotation of the cantilever. The measured properties of the device when used with a Queensgate Instruments Nanosensor electronics unit were: range >3.5 μm, sensitivity 0.66 V μm^{-1}, first resonance of free beam 263 Hz and beam stiffness 40 N m^{-1}.

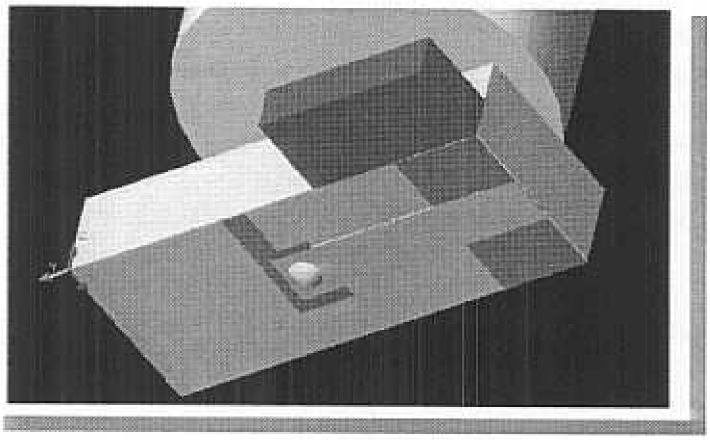

Figure 1 Schematic view of the glass cantilever probe

The work reported here studies the response of the probe at high frequencies and at high lateral scan speeds (compared to those typical of precision surface metrology). Such work was not included in the original characterization of the probe since its application required only a response from zero to a few hertz and a resonance of above 250 Hz was accepted as a sufficient specification for this purpose. Subsequently, a direct experimental evaluation was required to establish the potential of the technology for other applications.

The tip, cantilever and narrow air-gap together form a classic second-order dynamic system. The original evaluation of the probe confirmed this pattern of behaviour by means of 'hammer tests' and showed the critical damping factor to be around 0.025. There are two textbook frequency response curves for second-order systems, one where the free sprung mass is excited by an oscillatory displacement of the base and the other where the free sprung mass is excited directly by an oscillatory force without positional constraint. The similarity of these forms at frequencies well below the resonance justifies the simple criterion applied earlier. However, the actual operation of the probe does not comply with either of the schemes so it is unsafe to assume that they can still be used to predict behaviour at higher frequencies (still below resonance). The probe tip is driven by, in effect, the vertical displacement of a surface below it and in contact with it. A reaction force at the surface arises to move the tip against inertial, spring and damping resistances. Providing that this force remains positive, the tip should follow the surface motion (to the limits of secondary effects such as elastic indentation). The expected response will therefore be of the 'stylus bounce' type well known in conventional stylus topography instruments. In practice, the small cantilever may exhibit several modes of deflection – it has, for example, relatively low torsional stiffness compared to conventionally pivoted stylus systems. There may be additional damping imposed by friction at the tip-surface contact, which could be dependent on lateral speed as well as surface properties. Thus modelling becomes more complex and is vulnerable to poor parameter estimation. Experimental investigation under conditions typical of normal use is therefore preferred.

2. DESIGN OF THE TEST SYSTEM

Although the probe is intended primarily for operation in constant force mode, its capacitive micrometry gauging placed directly in line with the tip offers a reasonably linear measurement of tip displacement over a range of a few micrometres. It is, therefore, capable of operation in the equivalent of constant height mode, as used less commonly on AFMs. Here the surface height is measured directly as the deflection relative to the probe base, with the force of contact varying with displacement (surface height). In constant force mode the response of the height control servo is an intimate part of the overall response. Thus, as a matter of policy, the dynamics of the probe were studied in constant height mode. The major advantage of this approach is that a direct measure of the probe response is obtained. It is very difficult to obtain a precise characteristic for the servo alone under displacement amplitudes and input noise levels representative of typical operation, so there are objections beyond those of computational stability to the idea of deconvolving the closed loop response to find that of the probe. Generally, within its own bandwidth, the servo will reduce the displacement at the tip and so it is expected that the probe response in constant height mode will be a somewhat poorer than that in constant force mode. The scheme adopted is a conservative one. The variation of force during measurement will have negligible effect with the hard surfaces used in the tests. Measurement linearity is likely to be poorer than in closed-loop operation but this is acceptable price for the other advantages. Absolute, traceable accuracy is not important to the tests being undertaken since they involve comparisons between measurements made only on the one test system. The test-rig is adjusted to ensure that each measurement uses the same part of the sensor range.

The main sequence of tests was conceptually very simple. Surfaces with sinusoidal height profiles were moved horizontally below the probe to provide output height signals over the same track at a range of traverse speeds. Figure 2 illustrates the experimental set-up used. A linear slide and a heavy angle block carrying the probe. Both rest on a granite surface table in a metrology research laboratory (not, therefore, held to Standards Room conditions). The masses are so high compared to the forces induced by motion that friction maintains more than adequate stability over periods much longer than needed for the tests. At the same time, the block may be moved readily to different positions around the slide carriage in order to perform different measurements without the need to demount either the probe or the test piece.

The probe was directly mounted to a vertically-acting precision piezoelectric positioning device (Queensgate Instruments, DPT) as it would be in typical use, although in most of the present work it was switched off in order to minimize possible cross-talk between capacitive gauging carrier signals. This positioning device was cantilevered from the angle plate (about 150 mm to allow it to overhang various points on the slide) via a single axis translation stage driven by a micrometer thread manual screw (Newport Inc.). The stage was oriented with its axis vertical and such that the screw was placed in compression by the weight of the probe mounts. Manual adjustment of probe height could readily achieve 0.1 μm precision given visual feedback of the probe signal.

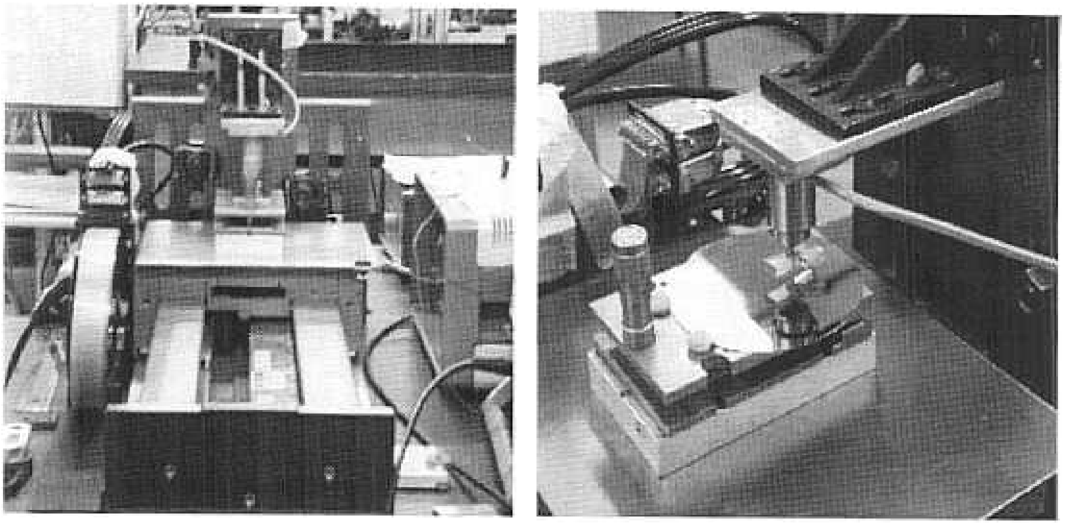

Figure 2 Photographs of the test system (left) and probe and sample stage (right)

The horizontal slide was a high precision air bearing single axis movement with direct drive from integral linear motors (Aerotec Inc.). A sheet-steel screen was clamped to the carriage by an aluminium block that carried grooves to kinematically locate the ball-feet of a micrometer tilting stage (Newport Inc.). The 600 mm movement was much greater than needed here, but the large carriage gives good static loading onto the air bearings and its large inertia smooths motion irregularities in the manner of a flywheel. The drive is a computer controlled closed loop system based on an integral 20 nm resolution optical grating. Both position and speed are controlled, with in-built acceleration phases used when step changes of speed are demanded. The slide has minor disadvantages. There is a discernable lift in carriage height between its stationary and moving states, but it was demonstrated to be consistent and so of no consequence for the comparative trials being undertaken. The excitation of the linear motors induced some electrical noise in the high sensitivity probe, a few percent of the amplitude of the typical test signal, but the effect on the r.m.s. value used for the comparisons was negligible. In compensation, the slide allowed all traverse speeds needed in the test sequence to be obtained within a single set-up, with no disturbance to the test piece.

While other samples were used to provide further evidence that the probe was operating satisfactorily, the test procedure used two test pieces. Both were hard-coated nickel replicas of fly-cut sinusoidal profiles, one of nominal wavelength 50 μm and nominal amplitude 0.5 μm, the other 100 μm and 1 μm Ra (Rubert Ltd). Figure 3 illustrates the typical surface topography. The replication introduces various imperfections into the topography, so a search was made for a region with good consistency of sine wave amplitude and minimal local form error. The test pieces were cleaned by gentle rubbing with acetone and lens tissue, followed by a dry rub to remove residue. Each in turn was set on the tilting stage on the carriage with the lay of the topography aligned by eye to be perpendicular to the traverse axis and the probe tip engaged with it. The levelling was then adjusted until the variation in the trend line of the profile was small compared to the amplitude of the sinusoid over a 4 mm track length. Measurements were recorded normally over a 4 mm or 2 mm section of this track, with the probe height set to keep the signal in the most linear part of its range.

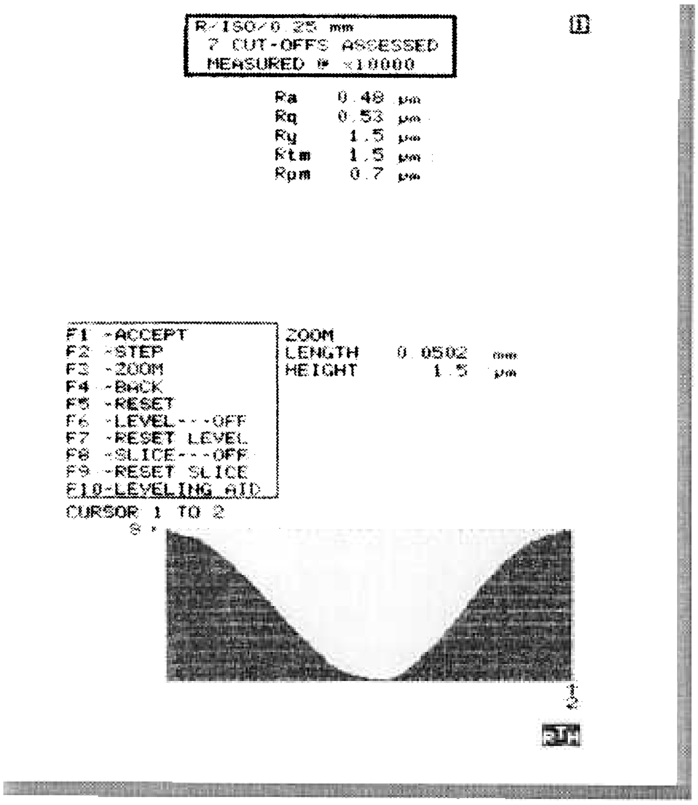

Figure 3 Nanostep measurement of the 50 μm test piece

Profile data was recorded by software written in LabVIEW (National Instruments Corp.) running on a separate computer to that used for motor control and data aquisition. A 16-bit analogue to digital converter with a 10 V range was used. Samples were taken at uniform time intervals. Data logging was started just before starting the drive and continued for a short while after the traverse stopped to ensure capture of any transients. For consistency of later analysis, the sampling interval for the main test sequences was always set to give (nominally) 20 points per cycle independent of speed or test piece wavelength. In all of these tests the nominal traverse was of 40 wavelengths (i.e. 800 points, plus leader and trailer). Data were exported to a spreadsheet, where unrequired leaders and trailers were manually removed from each profile. For the main sequence of frequency comparisons, ten cycles (200 points) were extracted, starting approximately at point 400 but always choosing a high point so that the remaining signal was essential in the cosine form. This minimises end-effect errors from the ensuing straight line removal by subtraction of the linear least-squares straight line. After removal of the straight line, the r.m.s. value of the 10-cycle section was computed by the internal function of the spreadsheet.

While traceable accuracy is not critical to the comparison process itself, it remains important to confirm that the probe is operating correctly in its design regime. The comparison is vulnerable to variations in sensitivity across the range of the probe and so its region of best linearity was used for the tests. Static calibration for these purposes was achieved by engaging the tip with the end face of a closed loop piezoelectric actuator (DPT – Queensgate Instruments) traceable *via* the manufacturer's certification to laser interferometry. The read-out precision was to 1 nm and the uncertainty to the internal reference no more than a few nm. Thermal drifts of the complete metrology loop and the measurement noise from the probe were the main sources of uncertainty. These varied according to specifics of particular measurements, with, for example, the noise-related uncertainty in a single reading of the probe typically below 10 nm (95% confidence) with the Aerotec slide switched off and exceptionally as high as 50 nm with the slide drives energized. The frequency response derivations involved signal averaging and the noise is then expected to contribute less that 1% of typical signal levels. It does not seem helpful to included explicit error bars on comparative measurements under these circumstances.

The cantilever of the original probe fractured during testing and a replacement device was built to the same nominal specification, although using a slightly different method of bonding the cantilever to the base. Evaluation of the replacement raised some doubts about the behaviour of the original. While impossible to verify from the broken device, it is strongly suspected that it was operating at excessive contact force. The spring rate was within specification but a cantilever fault may have shifted the zero point for setting forces. For completeness and reference, section 3 has a brief summary of the behaviour of the suspect device. Section 4 then details the results of the full study on the replacement, which was known to be operating in the intended manner.

3. BRIEF EVALUATION OF THE ORIGINAL PROBE

Repeating the concerns reported in section 2 that there may have been a fault on the original device so that the contact force was considerably higher than it appeared to be, a brief summary of its behaviour is nevertheless included. Before scanning the test pieces at various speeds, an estimate of the amplitude response in the absence of lateral sliding was made. The tip was engaged with the platform of a simple dynamic calibrator based on a magnetically driven elastic mechanism, Chetwynd and Honda, 2002 (see also Leach and Cross 2002). Driven by a constant amplitude sinewave voltage from a signal generator, this performs a standard 'shaker' test. The actuation was open loop and the mechanism known to have a small resonance at about 80 Hz, so this test is simply for providing a general summary of the probe dynamics. Figure 4 shows the response obtained, using a log-linear plot. The characteristic matches well the expectation for a lightly damped second-order system, with a resonance at around 280 Hz, consistent with the probe specification.

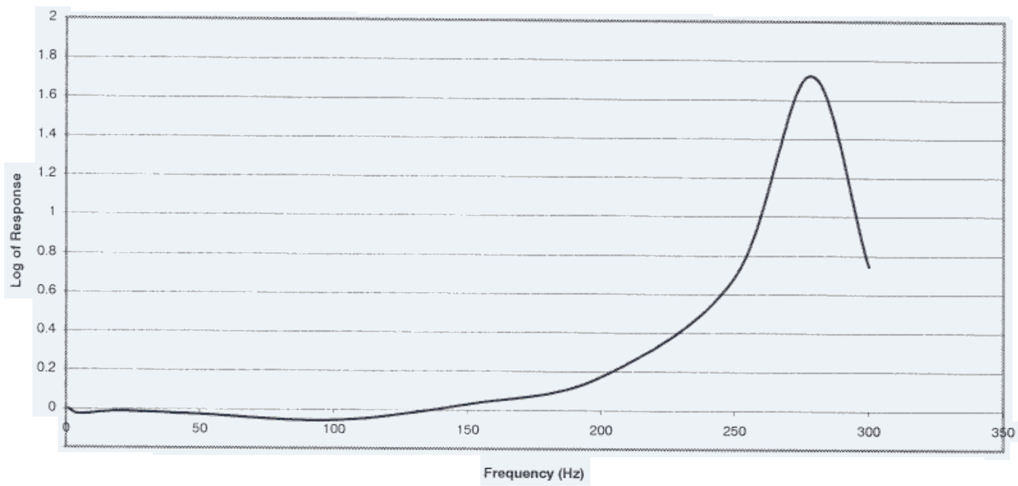

Figure 4 Log-linear frequency response of the original probe, determined by a shaker test

The preferred direction of traverse for the probe is in a line parallel to the length of the cantilever and with the tip at the trailing edge of the relative motion of the probe to the surface. Motion-related horizontal forces at the tip-surface interface then put the cantilever into slight tension, the most stable loading condition. Figure 5 shows typical traces from scans in this direction. Even the slowest of these scans is relatively fast compared to the normal operation of instruments such as the NPL NanoSurf series. Since the purpose here is merely to compare data, the amplitude axis has not been scaled but remains as the voltage recorded from the conditioning electronics. At slow speeds the profile is consistent within itself and with expectations. At higher speeds, there is evidence of transients (some directly attributable to the acceleration and deceleration phases of the stage motion). Eventually, a signal at the resonance of the system is imposed significantly on the 'true' profile. The frequencies corresponding to traversing over the test piece wavelength at the speeds of these profiles are respectively 5 Hz, 160 Hz and 280 Hz.

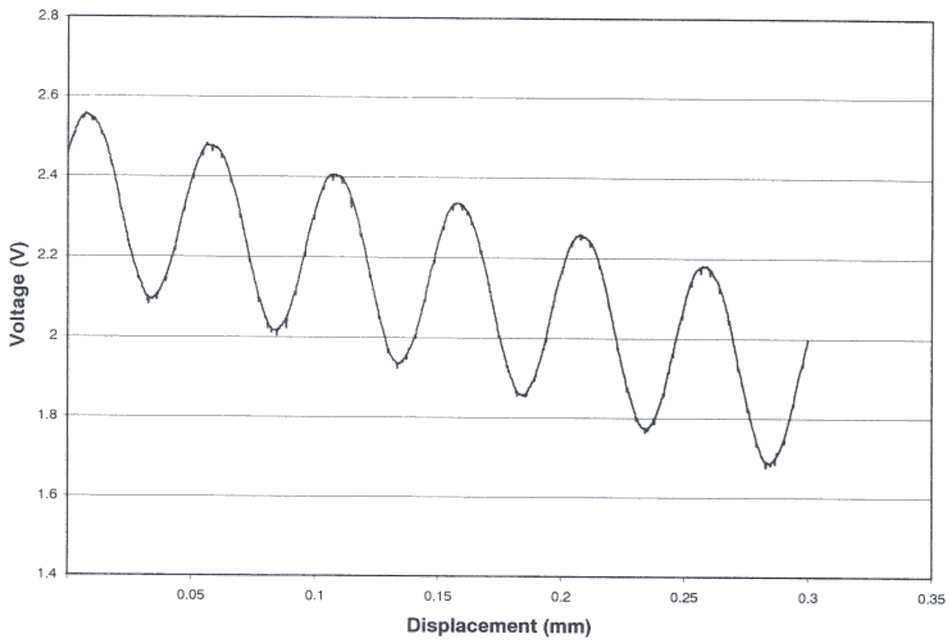

Figure 5a Profile by the original probe of the 50 μm wavelength sample at 0.25 mm s^{-1} traverse speed

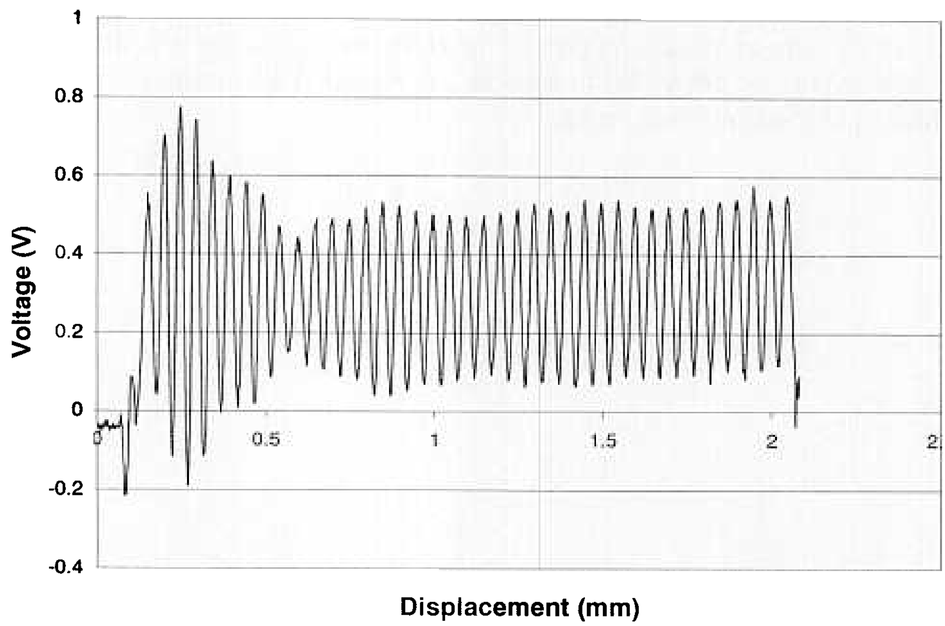

Figure 5b Profile by the original probe of the 50 μm wavelength sample at 8 mm s^{-1} traverse speed

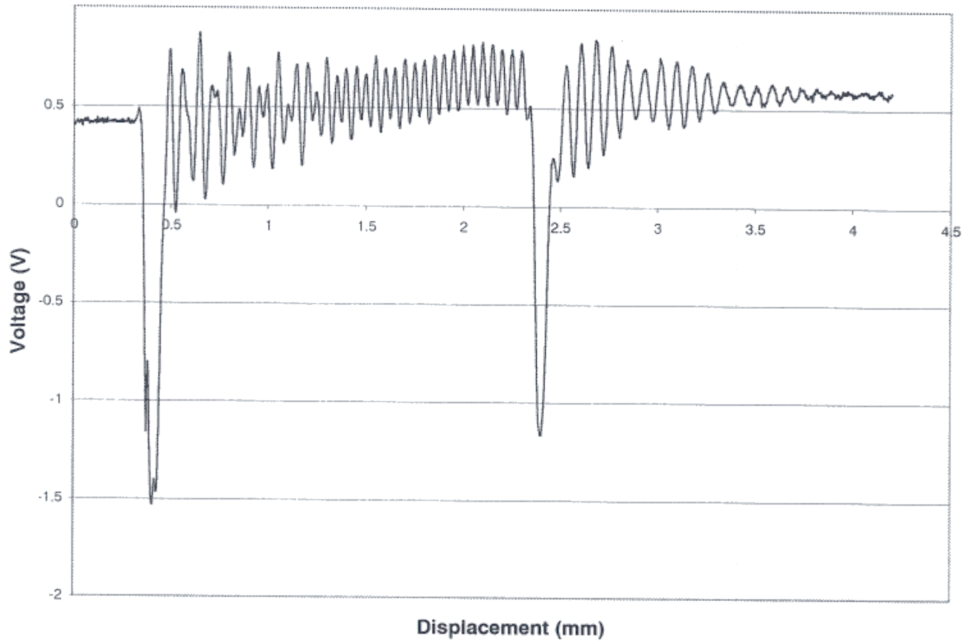

Figure 5c Profile by the original probe of the 50 μm wavelength sample at 14 mm s^{-1} traverse speed

The general dynamic behaviour illustrated by figure 5 was repeatable and consistent with the test pieces of different wavelengths. Chetwynd and Leach (2002) give an overview of the test results. However, given the doubts about this particular device, a summary of them in terms of a plot of the frequency response is deliberately withheld here. The data to be presented in section 4 is regarded as a more reliable guide to the application of the cantilever probes.

4. DYNAMIC EVALUATION OF THE REBUILT PROBE

4. CALIBRATION AND INITIAL INVESTIGATIONS

Following the collapse of the cantilever on the original probe, a new version was constructed to the same design, but using a different procedure for mounting the beam and gluing it. Initial testing indicated a spring rate of 64.3 N m^{-1} and a 'hammer test' on the free-hanging beam showed the resonant frequency to be 270-280 Hz. These values are consistent with the specification and similar to those of the original device. A psuedo-static amplitude calibration was performed by driving the tip with a Digital Piezo Translator as previously described. Figure 6 shows a typical result. Note that with the phasing of connections used in these tests an upward movement of the tip (as would be caused by a high point on a test surface) relates to a reduction in output voltage. The non-linearity associated with the cantilever end rotation and with manufacturing imperfections is clearly detectable but not too severe over a range much greater than the specification (3 μm). Best linearity is with the output level around 1 to 2 V, where the sensitivity is approximately 1.48 μm V^{-1}.

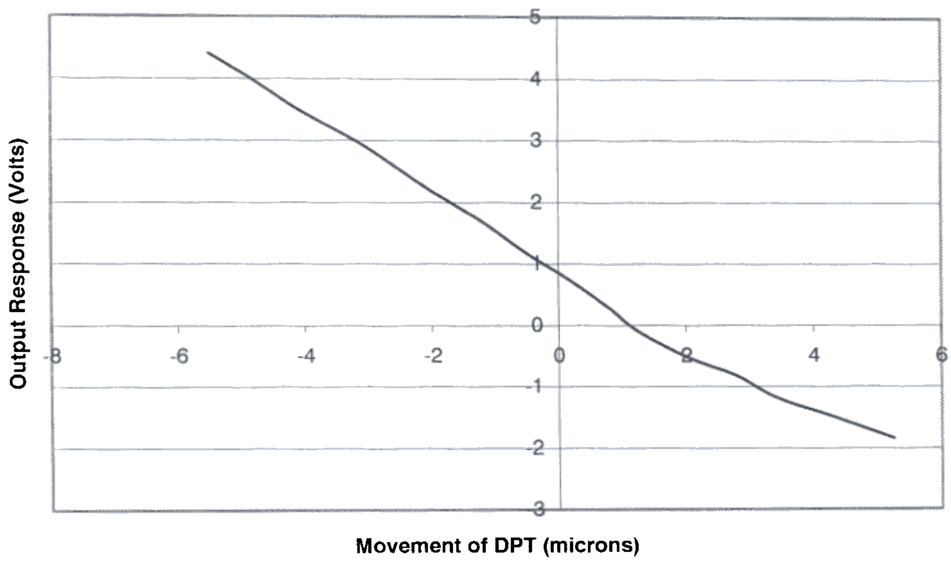

Figure 6 Calibration curve for the rebuilt probe.

Engaging the tip with a surface in the 'best' linearity region leads to a naturally imposed contact force of around 300 μN. This value is at the higher end of the range likely to be used for typical applications. There is a tendency to use higher forces on larger amplitude surfaces and at higher tracking speeds on the general grounds that it will beneficial to surface following. Since high speeds are the subject of this study, 300 μN was considered a reasonable force and all the subsequent dynamic tests were performed by lowering the tip onto the surface until a reading of about 1 V was obtained.

The piezo-translator drive electronics used here had a low-pass characteristic with a cut-off at about 20 Hz and so could not be used for proper dynamic characterization of the probe. It was used to excite the tip to above 300 Hz, based on around 1 μm amplitude at low frequency. This served to show that the probe was well behaved, recording a characteristic very close to that of the translator, as measured by an independent capacitive gauge (ADL Inc.), but with a slight increase in gain at above 200 Hz. The test with the simple dynamic calibrator (section 3) was repeated with the rebuilt probe, figure 7. The response at frequencies up to 5 Hz is very similar to that from the piezo-translator, showing consistent behaviour in the region for which it was expected. At higher frequencies the characteristic is significantly different from that for the original device, figure 4. The response is quite flat except for well-defined peaks. The one below 100 Hz can be attributed to the shaker. The source of the middle one appears to be the mounting structure for the probe, but a similar feature is not present in the earlier test with the same structure. The third peak is associated with the cantilever by comparison with the results of the hammer test. Note that the peaks are not large – less that 5 dB relative to the 1 Hz response. The variation between the results is taken as evidence that there may have been a fault in the original cantilever prior to its collapse.

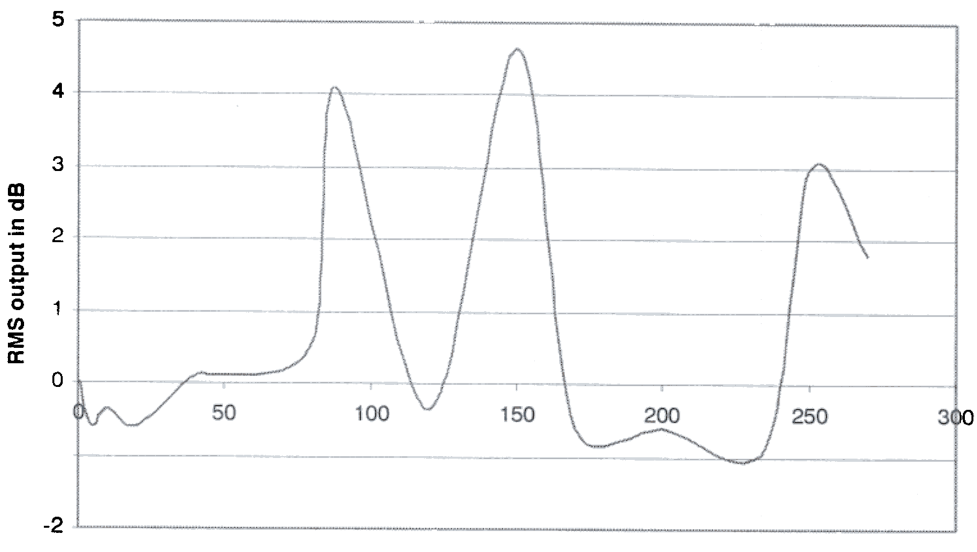

Figure 7 Frequency response of the rebuilt probe by the shaker method

4.2 HIGH-SPEED TESTING

The basic procedure for testing high-speed behaviour on the sine wave artefacts was described in section 2. Following the analysis of the data from section 4.1, that method was used with the extra constraint that the probe height was set such that the signal was generally between 1 V and 3 V during traversing. The primary operational mode for the probe is with the scanning direction such that drag forces on the tip put the beam into tension, here thought of as the 'forward' traverse. In 'reverse' direction stability might be expected to be a little poorer since there will be compressive forces along the beam and the potential for buckling-type deflections. The tests at each speed were actually performed by executing a forward traverse, pausing briefly and reversing at the same speed with profile data collected in both cases.

First, the operational noise levels were checked by scanning a good quality glass optical flat. Since the signal is broadband and subject to some spikes, the peak-to-peak amplitude was estimated from an oscilloscope instead of detecting an r.m.s. value. The static noise with the slide drive de-energized was around 5 mV. With the drive energized, the signal rose to about 40 mV but was of essentially constant amplitude at all speeds tested (up to 500 mm per min, in the units used by the controller, or about 8 mm s^{-1}). The noise is clearly derived mainly from interference from the drive but corresponds to only around 60 nm peak-to-peak and so contributes only a negligible 10 nm or so to the r.m.s. values recorded on the sine wave artefacts.

The general behaviour on all traces with the sinewave artefacts was very consistent. At slow speeds the scan appears to start and stop very cleanly. At higher speeds, transient behaviour can be seen, with some tendency for the absolute altitude to shift a little and the acceleration phases showing though broader cycles at each end of the trace. At the highest speeds, the transients include damped resonance signals corresponding to around 180 Hz. Figure 8 illustrates the pattern with forward traces (computationally offset from each other) at three speeds. All the transients can be attributed to the stage and other parts of the test-rig – the probe appears to be extremely well behaved. None of the transient patterns persists long enough to interfere with the signal analysis computation described in section 2.

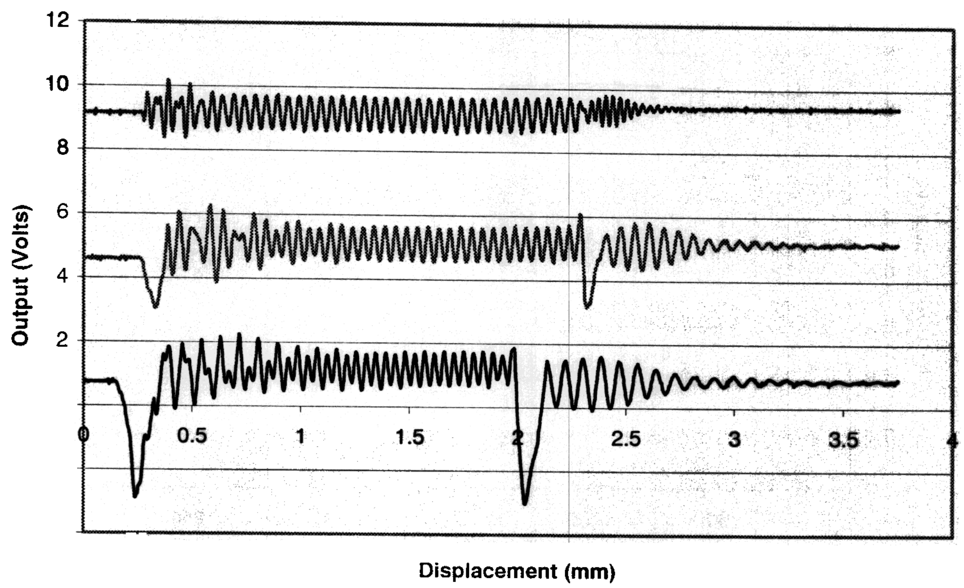

Figure 8 Typical forward traces from the 50 μm sine wave at speeds of 1 mm s^{-1}, 6 mm s^{-1} and 16.7 mm s^{-1}. The vertical offset is generated computationally for clarity.

Table 1 lists the speeds used for the main sequence of tests, together with the fundamental frequency of the resulting profile signal. Figure 9 shows a plot of the r.m.s. amplitude against this frequency for the 100 μm sine wave, using linear scales on both axes. Figure 10 compares on a log-log scale (as typically used in frequency analysis) the response from forward and reverse traverses on the 100 μm and 50 μm sine waves. Note that the whole vertical scale covers only a little more than 1 dB – the differences are very small and the response effectively flat up to around 200 Hz (traverse speed of up to around 12 mm s^{-1}). Although visibly separate on the plot, there is no evidence of faulty tracking in the reverse scans.

Speed /mm s^{-1}	Speed /mm min^{-1}	Frequency on 50 μm /Hz	Frequency on 100 μm /Hz
0.017	1	0.34	
0.05	3	1.0	
0.1	6		1.0
0.25	15	5.0	
0.5	30	10	5.0
1.0	60	20	10
2.0	120		20
3.0	180	60	
6.0	360	120	
9.0	540	180	
12.0	720	240	120
16.7	1000	334	
23.7	1420		237

Table 1 Traverse speeds used indicated by their equivalent signal frequencies

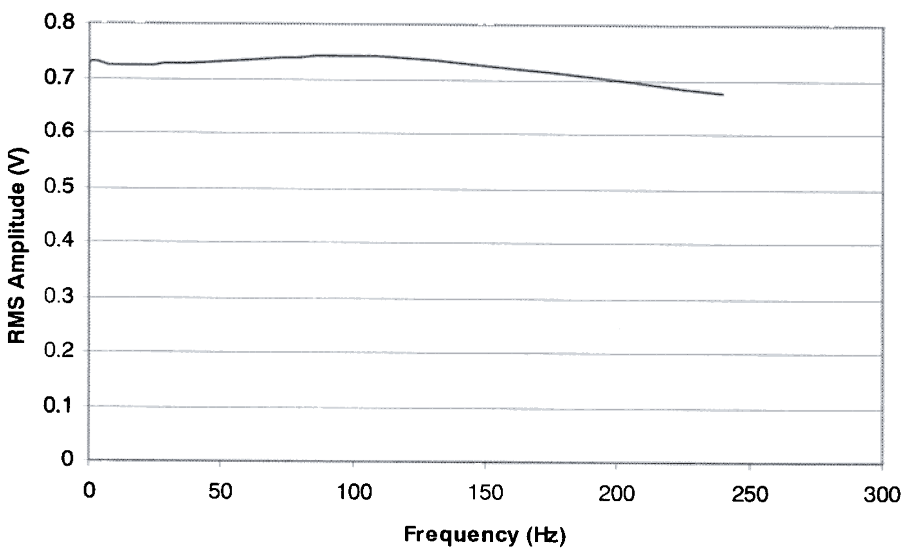

Figure 9 r.m.s. amplitude recorded from the 100 μm sine wave artefact at various frequencies (traverse speeds – see table 1)

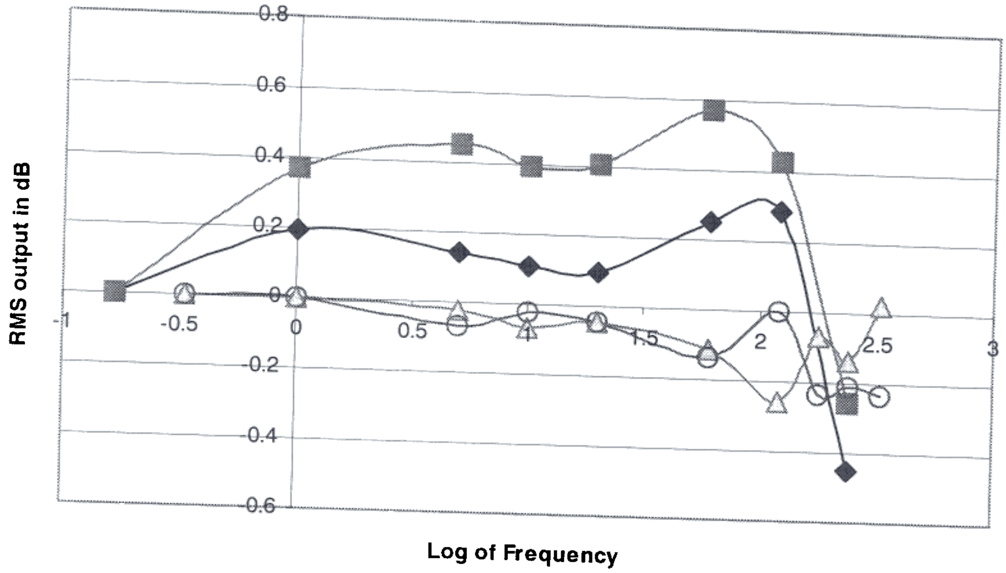

Figure 10 log-log frequency response from scans on the sine waves: diamond – 100 μm forward, square – 100 μm reverse, triangle – 50 μm forward, circle – 50 μm reverse (for scan speeds, see table 1)

A series of tests was also run on the 50 μm sine wave with the traverse direction perpendicular to the probe cantilever so that drag forces at the tip will impose torsion on the beam, figure 11. The gain was a little higher at low frequencies (speeds) compared to the forward traverse, but, again, the differences are of little practical significance.

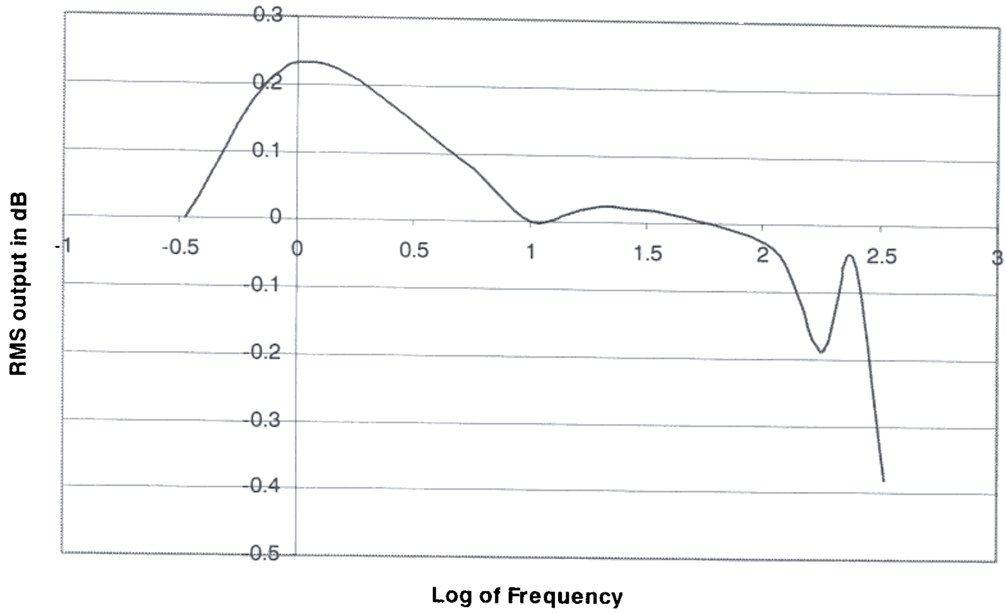

Figure 11 log-log frequency response from a transverse scan on the 50 μm sine wave (for scan speeds, see table 1)

5. CONCLUSIONS

A series of tests of the glass-cantilever probe has been undertaken, traversing it over nickel replica sinusoidal surfaces at speeds higher than are usually used for precision surface metrology with contact probes. The principal tests used profiles of 50 μm and 100 μm wavelength, with nominal amplitudes of 0.5 μm and 1 μm respectively. These values typify the larger sized surface structures for which the probe is intended to be used. Traverse speeds of more than 1400 mm per minute were used. At the highest test speeds the signal frequency generated by the profiles exceeded 300 Hz. Throughout this range of tests, there was no evidence of stylus bounce or other tracking defects in the steady state. Transients associated with accelerating the traverse increased greatly at higher speeds, but the settled signal held constant within 1 dB virtually up to 250 Hz. Subsequently, it appeared that there was a steady decrease in reported amplitude, with no evidence of peaking resonant behaviour. This observation remains provisional since the risk to the probe of testing at even higher speeds was judged to be too great for the value of the additional information that would be obtained.

The overall outcome of this programme of experiments is a practical confirmation that the glass-cantilever probes can be used satisfactorily for high-speed surface metrology. No undesirable effects generated from the interaction of, e.g., frictional forces and the elastic nature of the cantilever have been detected within a range of operational parameters considered to be wider than any sensible application of the technology would employ. Neither is there any significant difference associated with the orientation of the probe cantilever to the direction of traverse. As a general guideline to the application of this technology, the present tests indicate that glass-cantilever probes may be used at least up to within 10% of their beam natural frequency (even at micrometre amplitude signals) and at sliding speeds of up to at least 1 m per minute.

6. ACKNOWLEDGEMENTS

The authors wish to thank James Berriman, Keith Shaw and Gordon McKenzie for their help in commissioning the test equipment, and to Steve Wallace and David Robinson for technical support (all from University of Warwick). The work was funded by the National Measurement System Policy Unit Programme for Length 1999-2002 Project 5.2, milestone 5.3.5.

7. REFERENCES

Chetwynd D G, Honda S 2000 A low cost active calibrator for microdisplacement probes *Proc. Joint Warwick-Tokyo Nanotechnology Symp.* (extended abstract)

Chetwynd D G, Leach R K 2002 Dynamic performance of a cantilever-based topography probe, *in* FLM Delbressine *et al.* (eds) *Proc. 3rd **euspen** Int. Conference*, 769-772, Eindhoven May 2002

Griffiths B 2001 *Manufacturing Surface Technology* London: Penton Press

Howard L P, Smith S T 1992 Long range constant force profiling fo measurement of engineering surfaces *Rev. Sci. Instrum.* **63** 42894295

Leach R K 2000 Traceable measurement of surface texture at the National Physical Laboratory using NanoSurf IV *Meas. Sci. Technol.* **11** 1162-1172

Leach R K, Cross N 2002 Low-cost traceable dynamic calibration of surface texture measuring instruments *Meas. Sci. Technol.* **13** N1-N4

Whitehouse D J 1994 *Handbook of Surface Metrology* Bristol: Adam Hilger

Whitehouse D J 2002 *Surfaces and Their Measurement* London: Hermes Penton Science