Three-dimensional characterisation of a novel vibrating tactile probe for miniature CMMs

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Abstract

This paper presents the characterisation of a novel three dimensional vibrating tactile probe for miniature co-ordinate measuring machines (CMMs). This novel vibrating probe has been developed to address the main issues associated with tactile probing on the micro-scale. The vibrating probe is designed to act isotropically, with low probing forces (near zero), and experience minimal effects from the surface interaction forces. In this paper the tests completed to verify the precision of the contact sensing ability of the probe in three dimensions will be described, along with quantification of the isotropy of the probe. The results will be presented and discussed. Several operational differences between classical static probes for miniature CMMs and the novel vibrating probe developed by NPL will be highlighted. These differences include tip diameter calibration techniques, strategies for use, environmental considerations and logistics. Finally, the future plans for the development of the probe will be discussed, especially initial tests to be completed with the probe deployed on a suitable precision CMM for miniature parts.

1 Introduction

The use of CMMs designed specifically for the measurement of high precision miniature parts is well documented [1], [2], [3]. These miniature CMMs are ideal for high accuracy tactile measurements of sub-millimetre scale features on centimetre and millimetre-sized objects to sub-micrometre accuracy.

Current efforts to enhance the capability of miniature CMMs are focused on the development of new probing systems [4]. These developments aim to address several requirements for miniature CMMs that relate to physical issues that affect the accuracy of tactile probing at this scale. These issues include, but are not limited to, unwanted adhesion of the probe to the measurement surface; inertia or surface interaction forces causing false triggering of the probe and “snap-in” of the probe to the measurement surface; and plastic deformation of the surface under high contact forces during measurement. An additional issue facing micro-CMM probe design is the lack of suitable styli with effective working lengths with respect to their tip diameter (aspect ratio) that are sufficient to contact currently manufactured high aspect ratio features.

A micro-scale CMM probe (or micro-probe) has been developed at the National Physical Laboratory that was designed to operate in a vibrating mode [5]. The micro-probe consists of a triskelion (three-legged) MEMS device and a micro-stylus, fabricated by electro-discharge machining. The vibration of the probe is controlled so that the stylus tip is always vibrating normal to the measurement surface. This is an essential characteristic of the probe, and has been considered when developing the probe concept, design and all modelling [6], especially that of the surface interaction forces [7].

The vibration of the probe is controlled so that the acceleration of the stylus tip is sufficient to counteract the surface interaction forces between the stylus tip and the measurement surface during contact measurement. The probe is also designed to operate isotropically, such that it acts equally in every probing direction. To be specific, the micro-probe is considered to act isotropically if its tip is able to vibrate at the same amplitude and frequency in any chosen vibration vector.

The micro-probe is made to vibrate by using six piezoelectric actuators, two on each flexure. Interaction with the measurement surface produces a change in vibration characteristic, which is determined by a piezoelectric sensor on either end of each flexure. The micro-probe is fully described elsewhere [5] and the basic design is shown in figure 1.

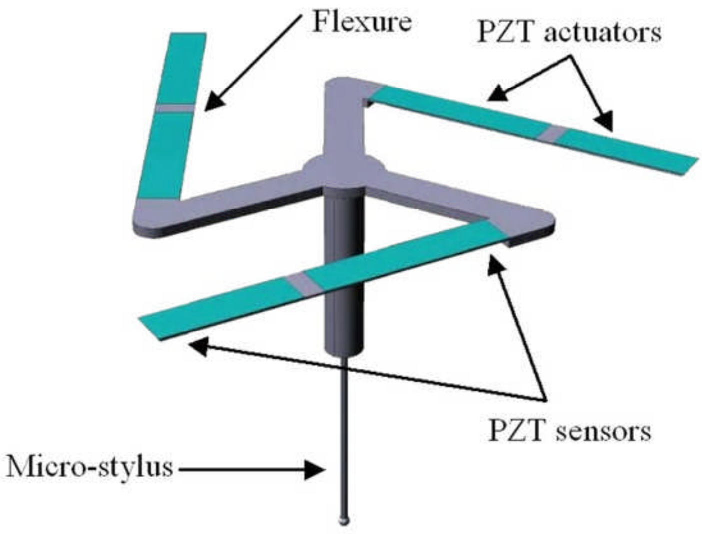

Figure 1: Schema of the NPL micro-CMM probe.

Assembly of the flexure MEMS device and the spherical stylus tip was completed using a miniaturised assembly setup using a dedicated miniature robot. The full assembly process is described elsewhere [8]. A photograph of a completed micro-CMM probe is shown in figure 2.

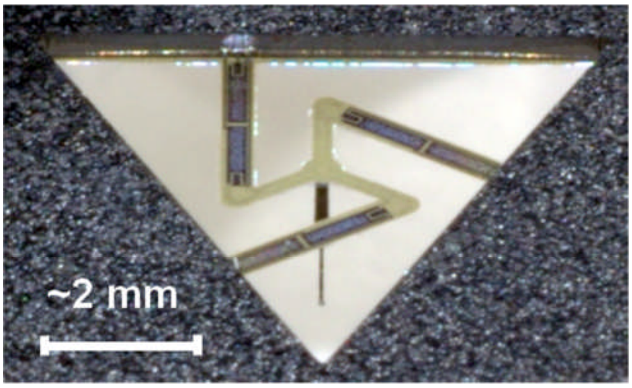

Figure 2: An assembled micro-CMM probe.

Following work focussed on the design, manufacture and assembly of the micro-probe, detailed testing is underway to ensure that it acts as designed: as a vibrating micro-CMM probe suitable for use on a minature CMM.

2 Characterisation in 3D

Initial experiments were designed to investigate the behaviour of the micro-probe when operating in a single direction while approaching, interacting with and directly contacting a surface. To complete these tests, the probe was activated and a test surface was manipulated such that it approached the probe normal to the direction of vibration. The movement of the surface was controlled to approach the probe in steps of less than 100 nm, and controlled such that the over-travel after contact was less than the amplitude of the vibration. A laser Doppler vibrometer was used to continually record the vibration signal, as a supplementary detection signal to the output of the piezoelectric sensors.

The ratio between the changes in vibration amplitude and the approach distance of the reference surface are calculated for each position of the test measurement surface. When there is no interaction between the probe and the surface, this ratio is nominally zero, and when the probe is making contact with the surface this ratio is nominally unity. Any intermediate ratios are the result of a non-contact interaction between the probe and the reference surface, where the amplitude of vibration change changes less than the change in surface approach distance. A further parameter investigated during probe interaction with the surface, in addition to amplitude, was the phase of the output mechanical vibration with respect to the input electric drive signal. The results of an interaction between a measurement surface and the micro-probe when vibrating vertically are shown in figure 3. The error bars indicate the experimental standard deviation of the mean. Negative distances from the surface describe the probe removed from the surface by that value, and positive distances describe the probe in contact with the surface and experiencing over-travel. The position of the surface is estimated to within one approach interval, through post-process analysis of the output data.

A similar experiment can also be conducted in the lateral direction, with the probe vibrating parallel to the surface-normal of a sideways facing test surface. These results are shown in figure 4.

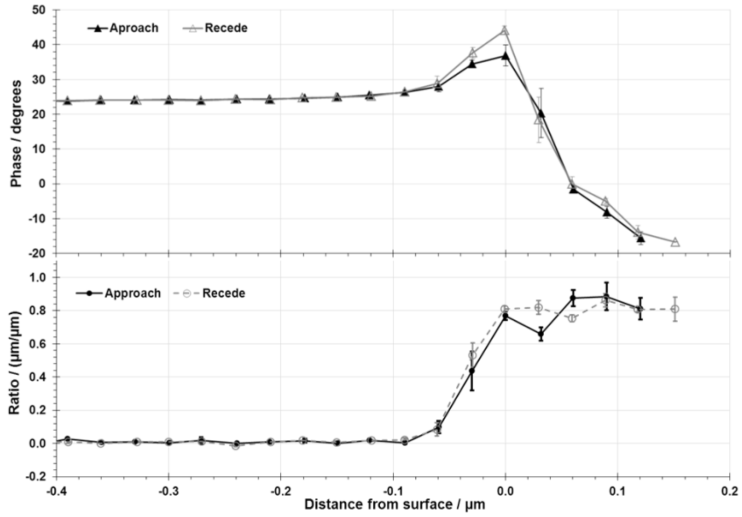

Figure 3: Vertical test results. Comparison of the two measured signals: phase of the output signal relative to the drive signal (top) and the amplitude measurement (bottom), plotted against distance from surface.

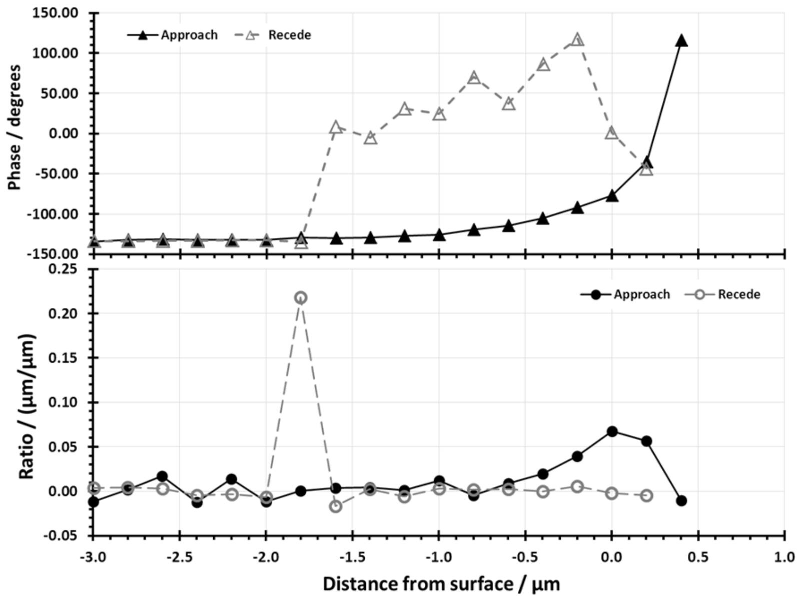

Figure 4: Lateral test results in one lateral vibration direction. Comparison of the two measured signals: phase of the output signal relative to the drive signal (top) and the amplitude measurement (bottom), plotted against distance from surface.

The data presented can be used to characterise the repeatability of the micro-probe. It can be seen that the probe operates as expected in the vertical direction. However, lateral interactions still exhibit snap-back. A more detailed description of these results is presented in [9].

Continuation of these experiments in all lateral directions, and in full 3D, will require control over the direction of the probe's vibration. This control is essential so that interaction with surfaces in any orientation can be realised. The control of the probe is governed by a set of vibration algorithms. These algorithms were developed by using the design knowledge of the probe, including its geometry and its dynamic response. Using these algorithms, the micro-probe will be able to vibrate in any chosen direction, in accordance with the previously decided definition for isotropy of vibrating probes. In order that testing of the micro-probe can continue in other lateral directions, and in 3D, the isotropy of the micro-probe needs to be confirmed.

3 Isotropy

A set of experiments was conducted to test the capability of the probe to act isotropically. These tests were designed to verify the capability of the vibration algorithm to control the probe.

The experimental procedure has the following steps. The micro-probe is activated, according to the control algorithm, to vibrate along a single vibration vector. A laser Doppler vibrometer is focussed onto each junction between the connecting arms of the central section and the three flexures in turn. After the data from each of the three junctions has been collected, the data is compiled and compared to the expected amplitude and phase to determine the isotropy of the micro-probe.

A graph of the ideal amplitude results, as calculated by the vibration algorithm, is shown in figure 5. These results show thirty-six lateral vibration vectors, with each data point representing a vibration vector every ten degrees, and not including any z axis component. Also, there is no appreciation of phase in these results.

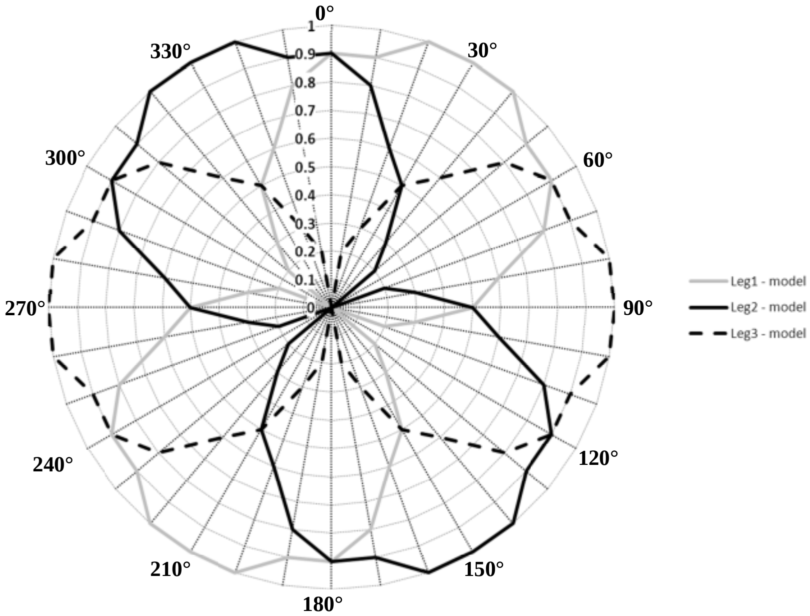

Figure 5: absolute values of vibration amplitude, as calculated by the vibration control algorithm. The radial axis indicates relative vibration amplitudes, and the azimuthal axis indicates vibration vector.

Data was collected from the micro-probe, as has been previously described, to determine the extent of the isotropy of the system. It is expected that the system will need to operate away from the resonance peak, so that the primary mode of vibration (*i.e.* vertical vibration) is not dominant. A set of tests were conducted at the frequencies corresponding to the approaching half maximum amplitude and the approaching quarter maximum amplitude. For a micro-probe with a resonant frequency of 1.506 kHz, these frequencies are 1.500 kHz and 1.493 kHz respectively. These tests were completed with input signals corresponding to vibration vectors every 30° to reduce the length of the experiments. Graphs displaying the results of these tests are shown in figure 6.

It can be seen that the observed anisotropic behavior of the system is currently inconsistent with the ideal situation derived from the model. However, the test completed at the frequency corresponding to the approaching quarter maximum amplitude displays a slight decoupling of the vibration of leg 1 and leg 2 with respect to leg 3 at 0°, 180°, 210°, 300° and 330°. This demonstrates that tests should continue at lower frequencies to ensure further decoupling of the three legs from vertical vibration mode, but that input signal amplitudes should be increased so that resulting vibration amplitudes remain large enough to counteract the surface interaction forces.

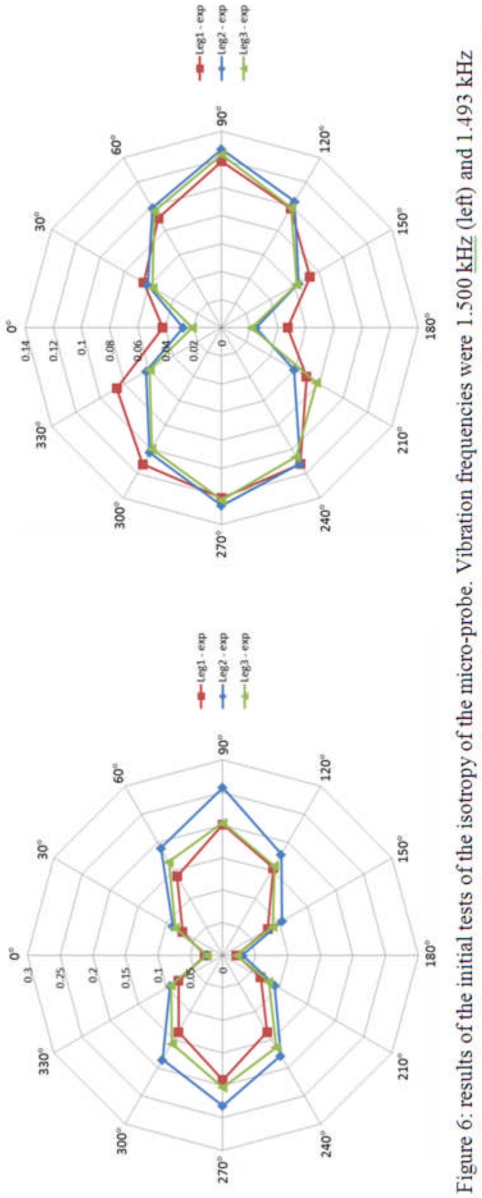

Figure 6: results of the initial tests of the isotropy of the micro-probe. Vibration frequencies were 1.500 kHz (left) and 1.493 kHz (right) for a probe with a resonant frequency of 1.506 kHz. The radial axis indicates relative vibratior [illegible] litudes, and the azimuthal axis indicates vibration vector.

4 Operational strategies

There are several operational issues that arise from the use of a vibrating micro-probe on a miniature CMM. These issues include the need for novel tip diameter calibration techniques, as well as accepted strategies for use and operation within the control loop of the miniature CMM. It is also essential that environmental considerations be addressed, and that any logistical challenges of using vibrating probes are identified and solutions developed. With respect to tip diameter verification, procedures similar to those described in ISO 10360-5 [10] would be suitable, with certain caveats in place. Firstly, the calibrated diameter will not be the diameter of the stylus tip, but rather the amplitude of the vibration in various vectors. This determination is analogous to the determination of the isotropy of the probe, through interactions with the probe tip rather than interrogation of the probe's flexures. The completed verification experiments, concerning the capability of the micro-probe to operate as a tactile probe for miniature CMMs, have demonstrated certain strategies for use that will be essential during operation. These include the need for short over-travel of the probe if surface forces need to be counteracted. It can also be noted that the expected signal outputs from the piezoelectric sensors could indicate impending contact. Certain environmental considerations must be addressed, especially when operating piezoelectric elements as actuators or sensors. It is essential that the probe operate in a stable environment, both in terms of temperature and humidity. To assist with the stable operation of the micro-probe, new prototypes have been designed that include polymer encapsulation of the flexures to guard against dynamic changes due to environmental driven changes in absorbed moisture, which is a common problem for piezoelectric materials [11]. Likewise, the operational environment should be free from high frequency vibrations that may couple to the vibrating micro-probe, and should also be free from air disturbances and turbulence, which has been detrimental to many experiments completed as part of this work. Finally, there are several logistical considerations for using the micro-probe developed at NPL. The most obvious of these is the delicate nature of the micro-probe. The compliant nature of the flexures has resulted in a micro-probe which can remain operational even after experiencing over-travel of greater than 1 mm. Likewise, these micro-probes and their disassembled components have already undergone transport testing by virtue of their transit to and from Asia and around Europe to facilitate production and assembly. However, the operation of these micro-probes does still depend upon the cleanliness of a 70 µm diameter stylus tip and a 1 mm long, 50 µm diameter stylus, which is a major consideration for operational logistics.

5 Conclusions and future plans

Completion of the interaction tests in the vertical (*z*) direction have confirmed that the probe can operate as a tactile micro-probe for miniature CMMs and that it successfully counteracts the problematic surface interaction forces. The results also suggest that the probe can operate in a non-contact mode. Initial tests on determining the isotropy of the system, which was a key feature included in the development of the mechanical design [6], have concluded that operation away from resonance is desirable. Currently, techniques used for isotropic operation of the micro-probe are resulting in a slight decoupling of the vibration modes of the three legs. Full decoupling is required for fully isotropic operation, and investigations are continuing to determine the ideal vibration parameters to achieve this. Continued use of the micro-probe during the testing phase is adding to the knowledge required to properly operate it on a miniature CMM. All developed strategies are being compiled and further developed to ensure efficient operation is obtained, comparable to that of a classical, static, miniature CMM probe. These strategies, and operational considerations, such a probe tip diameter verification, and programmed probing strategy for CMM operation, will be continually developed and reported during the next phase of testing. This final stage of testing will consist of true 3D interaction tests while the vibrating micro-probe is mounted on a high precision miniature CMM.

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