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Variable stiffness probing systems for micro-coordinate measuring machines

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ABSTRACT

Micro-scale probing systems are used on specialist micro-coordinate measuring machines to measure small, intricate and fragile components. Probe stiffness is a critical property of micro-scale probing systems; it influences contact force, robustness, ease of manufacture, accuracy and dynamic response. Selecting the optimum stiffness, therefore, represents a significant design challenge, and often leads to undesirable compromises. For example, when contacting fragile surfaces the probe stiffness should be low to prevent damage; however, for a more robust probing system the stiffness should be increased. This paper presents a novel concept for micro-scale probing systems with the ability to quickly and easily change and control probe stiffness during use. The intended strategy for using the proposed probe is first explained. Then the new concept is fully defined and explored through a combination of finite element analysis and experimental results. Two possible configurations of probe are described, and models for predicted performance for each are presented and compared. The models demonstrate significant stiffness reduction is possible with the proposed concept, and show it is theoretically possible to achieve a probing system with perfectly isotopic stiffness.

1. Introduction

The continued trends of product miniaturisation, increased part complexity, and the advancing capability of high-precision manufacturing technology, has resulted in the development of highly accurate micro-coordinate measuring machines (micro-CMMs). At the heart of many micro-CMMs is a specialised probing system that allows tactile measurement of small, delicate and intricate parts. The probing system is a critical part of the metrology loop, and the overall accuracy of a micro-CMM is heavily dependent on the performance of the probing system [1].

To support the needs of micro-CMMs a wide range of probing systems have been reported [2–4]. Conventional micro-scale probing systems typically consist of a stylus system, suspension structure and displacement transducer. A schematic representation of a conventional micro-scale probing system is shown in Fig. 1, with the key elements annotated. During a measurement, when the stylus tip makes contact with a surface it is deflected from an equilibrium position. The resulting suspension structure deflection is detected using displacement transducers, and by applying the appropriate transfer function the new position of the stylus tip is calculated. While the measurement principle is similar to conventional-scale probing systems, there are a number of special features and design requirements that are specific to micro-scale probing systems.

Typical micro-scale probing systems must impart low contact forces that are less than 1 mN, and ideally the contact forces should be isotropic [4]. For a given stylus tip deflection, achieving isotropic contact force requires the probe stiffness to be isotropic. Isotropic stiffness is beneficial as it reduces systematic errors during 3D measurements [5].

To allow intricate features to be measured, micro-scale probing systems are equipped with a slender stylus and small stylus tip. The stylus tip is typically around 100 μm in diameter; however, smaller tips are advantageous as they allow better access to intricate features [6]. A significant problem with small stylus tips is that they can result in large contact pressure. Even with contact forces of a few millinewtons, evidence of surface damage has been observed [7]. With the trend to further reduce the stylus tip diameters, this issue becomes increasingly problematic, as contact pressure is inversely proportional to the cube root of stylus tip radius squared [2,7].

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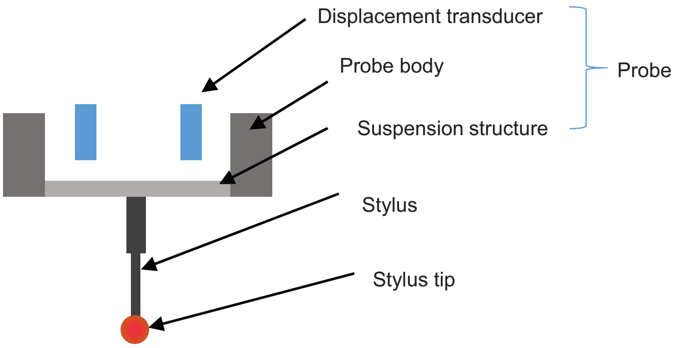

Fig. 1. Schematic diagram of the probing system.

To eliminate contact-induced surface damage, two options exist. The first option is to increase probe sensitivity, and reduce the probe tip velocity. This results in lower deflections of the stylus tip during a measurement, and consequently a lower contact force is developed. The second option is to decrease the probe stiffness, leading to less contact force for a given displacement [8]. In practice, reducing probe tip velocity and, therefore, increasing measurement time is rarely an attractive scenario; hence, the second option is favoured, and stiffness is reduced as much as possible.

A wide variety of low stiffness probing systems have been reported. For example, a flexure made from beryllium copper sheet, which has 50 μm thickness and 15 mm, length has been demonstrated with an isotropic stiffness of 10 N m^{-1} [9]. Another example is a probing system that makes use of a plate suspended by four 29 mm long, 180 μm diameter wires. This system has anisotropic stiffness, which in the vertical and lateral direction is 11 N m^{-1} and 118 N m^{-1}, respectively [10]. Probing systems that use silicon structures similar to commercial pressure sensors have also been developed [11,12].

While low stiffness is beneficial as it reduces contact force, there are a number of negative effects that must be considered and overcome. First, low stiffness probes may be sensitive to small inertial loads generated as the probe is moved by the micro-CMM. These inertial loads must not result in stylus tip displacements that are mistaken for real surface contacts. Probes that exhibit this problem require the operating speed of the micro-CMM to be reduced and, as a result, there is an unwanted increase in measurement time [8]. Second, as the stylus tip makes contact with a surface, relatively strong surface attraction forces occur at the contact interface [5,8]. These surface forces may result in the probe becoming stuck to the surface (as illustrated in Fig. 2), which can lead to catastrophic failure of the probing system, and contamination of the workpiece. Thirdly, low stiffness structures are difficult to handle and manufacture, and can be easily damaged by shock loading.

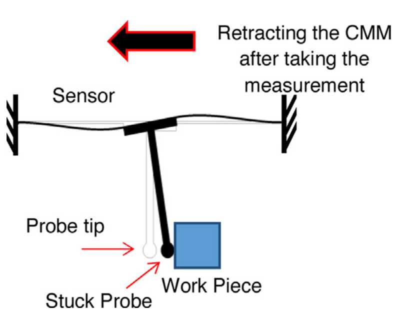

Fig. 2. Large probe deflections induced as the CMM retracts the probe from a surface following a measurement.

The most promising recent work that aims to overcome some of these problems has resulted in the development of a novel vibrating micro-scale probing system [8]. This probing system has been designed to counteract surface attraction force by using the dynamic inertia of the vibrating stylus system. However, the operation of this probing system requires a complex control strategy, and the exact nature of the interaction between the vibrating stylus tip and the surface has yet to be fully described.

In this paper, a completely new concept for probing systems with tuneable stiffness is presented. The new concept is fully defined and a description of the envisaged operating procedure for the probing system is presented. The proposed probing system uses a suspension structure that can be tuned to have either low or high stiffness as required. To illustrate this concept two examples of this kind of suspension structure are presented for comparison. The capabilities of each structure are carefully considered by using finite element analysis to model their potential performance.

To further demonstrate the feasibility of the proposed concept, a prototype probing system has been produced and results from initial testing are presented. The full capability of the variable stiffness probe is demonstrated by using a combination of the experimental data and finite element modelling, and the influence of critical geometric features that affect the performance are presented. The possible sources of error resulting from the approach have also been taken into account, and for each of the described potential issues, control methods are suggested to mitigate these errors.

2. Variable stiffness probing systems

Within a micro-scale probing system, the suspension structure (see Fig. 1) has the main effect on probe stiffness. To modify the stiffness of the suspension structure during use, three strategies can be adopted. The first strategy is to apply additional force to the structure to augment the action of external loads applied to the stylus tip [13,14]. The second strategy is to modify the effective geometry of the structure; for example, by moving the fixing points of the suspension structure to create either a shorter or longer beam [15]. The third strategy is to subject the suspension structure to an internal strain. This results in either strain stiffening for tensile loads, or reduced stiffness for compressive loads [16]. In previous work, the potential of each of these strategies was compared [17], and it was concluded that the use of compressive strain to reduce stiffness is the most suitable method for use with micro-scale probing systems.

To create a variable stiffness probing system, a novel suspension structure was designed to allow compressive force to be applied to the main spring elements within the structure. In general, as long as the spring elements are made of long slender beams onto which a compressive load can be applied, then a wide range of geometries is possible. Loads can be applied to the ends of each beam using a piezo-electric or other similar form of actuator. Using this type of structure, a probing system can be designed to operate in either a “stiff” or “flexible” mode. These modes may then be selected at suitable points within a measurement cycle by energising the actuator, as illustrated by Fig. 3. For example, when the stylus tip is being driven towards a workpiece, the probe will be in the stiff mode (Fig. 3a) to prevent false triggers caused by inertial loads generated when the probing system is moved by the micro-CMM. Immediately prior to making contact, when the probe enters a predetermined distance from the expected surface, it is set to the low stiffness condition (Fig. 3b) to ensure minimal contact force. After a measurement has been made, when the probe must be removed from the surface, it can be switched back to the stiff mode (see Fig. 3c). In this mode, it is possible to develop sufficient force at the stylus tip to overcome surface attraction forces, without overstraining, and potentially damaging, the suspension structure.

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