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Fabrication of a smart suspension structure of micro tactile probing

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Abstract

In micro tactile probing a design trade off must be made between stiff and robust probes. Stiff probes are capable of overcoming surface attraction forces, while delicate flexible probes are capable of making contact with a sensitive part without causing damage. To address this need for both flexible and stiff sensors a novel micro tactile probe has been proposed that makes use of an active suspension structure to modulate probe stiffness as required. In this paper we focus on the initial manufacturing process development of such a sensor. While initial design concepts were created with high precision machining techniques in mind, these are shown to have some fundamental limitations with respect to this specific application. Therefore a design for manufacture strategy was adopted and the structure of the initial design was modified such that it may be manufactured using a chemical etching based process. This paper presents the process followed to successfully adapt an initial sensor design for a chemical etching based manufacturing. Surface 3D microscopy was used to analyse the resulting structure, to demonstrate a significant improvement in device flatness. In addition Finite Element Analysis (COMSOL) was used to estimate the vertical and torsional frequency for the suspension structure which is compared with experimental measurements using a laser vibrometer to show good agreement.

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Keywords: Micro-CMM, mechanical probe, chemical milling

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1. Introduction

In recent years, micro coordinate measuring machines (μCMMs) have received increasing attention in terms of development and commercial availability [1]. At the heart of these systems is a mechanical tactile-probe sensor used to signal contact with workpiece, which is the focus of this research. In general micro-mechanical probes consist of three main parts as can be seen in fig. 1. The suspension system is used to hold the stylus and determines the stiffness of the mechanical probe. The suspension system is used to hold the stylus and determines the stiffness of

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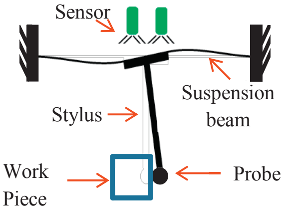

Fig 1: the main components of tactile microprobe

the mechanical probe. The stylus is the second part which transmits the contact force between the probe tip and workpiece to suspension system. The detection system is third part that is used to detect the position of the suspension system, and it may be achieved in a range of ways for example capacitive, optical, or piezo-resitive methods are all possible. When measuring sensitive micro parts using contact metrology systems, a successful micro-probe sensor is required to have a small contact force to avoid damaging the work piece. This leads to desired probe sensor stiffness that is less than 200 N/m [2]. However, as the flexibility of the probing system is increased one of the obstacles that must be overcome is the effect of surface attractive force experienced when the probe tip retracts from the surface of the work piece. This must be done after taking the measurement when the probe has made contact with the surface when surface forces may result in the probe becoming stuck to the surface [3]. This paper presents the initial fabrication and basic characterisation of a new form of smart suspension structure that may be used as part of future micro tactile probe sensors. The suspension structure in question has been specifically designed to allow dynamic modulation of stiffness during probing. This is to reflect the need of the probe to be both very flexible as well as stiff during different phases of probing. Also, in this paper we introduce the basic design of the proposed sensor and describe the manufacturing process that has been developed to generate suitable devices.

2. Suspension structure design

The working principle of the device is based on a beam that is subjected to a compressive load which is used to reduce the lateral stiffness of the centre point of the beam. Theoretically it should be possible to reduce stiffness in this way to zero which occurs at the buckling load for the beam. To make it possible to reduce stiffness to close to this point in a controlled way requires a precisely manufactured miniature mechanical structure. For example, load applied to the beam must be constrained such that the load vector is coincident with the axis of the beam. In addition the structure must be symmetrical and free from any bias effects that may tend to predispose the beam to bend as a result of an axial load. To allow load to be applied to a suspension beam in a controlled way there are two main features of the proposed design as can be seen in fig. 3b. These are the delicate inner suspension structure, and the outer bulkier frame and compliant guide mechanisms. The inner suspension system consists of a central platform, three suspension beams and three sensor paddles. The probe stylus is rigidly fixed to the central platform that is supported by three suspension beams. When the stylus tip is deflected from its neutral position it exerts a moment on the central platform and changes its orientation. The changes in orientation are also experienced by the paddles and sensors (capacitive or optical) located above them sense the change and signal to the computer that specimen surface has been contacted. The main function of the compliant mechanism is to hold the suspension system and transmit the force that is provided by actuators to the 3 beams as can be seen in fig. 3b. However, to predict the stiffness of the probe in all degrees of freedom, the vertical and torsional frequency of suspension structure may be calculated using finite element analysis. The first three mode shapes for suspension structure have been estimated to identify the expected measuring frequencies, as can be seen in fig. 2. The suspension structure designs have been modelled using spring steel AISI 1095 the properties of which can be seen in Table 1.

Table 1: Structure parameters of the suspension structure (spring steel, AISI 1095)

Elastic modulus, E (Gpa)	Poisson's ration, ν	Density, ρ (kg/m^3)	Geometric parameters of the suspension structure (µm)					
			w_b	t_b	l_b	R	l_p	w_p
210	0.3	7850	700	100	4188.6	1111.3	4162.9	1420

Where w_b, t, l_b, R, l_p, and w_p denote the width , thickness and length of the suspantion beam, the distance between the centre of the platform and the end of the suspantion beam , the length and width of sensor paddles, respectively.

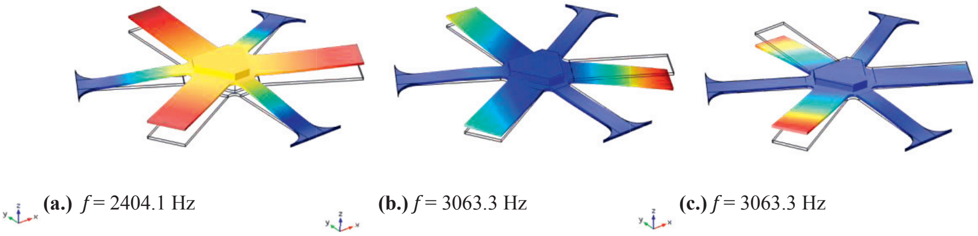
(a.) *f* = 2404.1 Hz **(b.)** *f* = 3063.3 Hz **(c.)** *f* = 3063.3 Hz

Fig 2: Estimated mode shape (a.) the first mode (the suspension structure vibrates vertically). (b. and c.) The second and third mode (torsional vibration of suspension structure)

3. Suspension structure manufacturing process

Initial prototype devices were manufactured using high precision micro manufacturing techniques, including conventional micro milling, and micro electro-discharge-machining. While these manufacturing techniques were able to provide valuable insight for device prototyping, they were subject to some limitations. They were found to be time consuming, costly, and also resulted in the development of unwanted residual stress in the structures. Previous prototypes of the suspension structure have been manufactured by two steps. Firstly, the micro milling machine has been used to mill the plate that has thickness 2mm from two sides to reduce thickness of sensor paddles down to 100 µm and the suspension beams, the center plate was reduced to 150 µm. Then three pinholes were made to insert the wire of the (EDM) to cut the plate into the required shape as can be seen in fig. 3a. Each hole was used to shape one third of the suspension structure and the process has been repeated three times in order to complete the final structure (see fig. 3.b.). This method has not been successful as the force and heat has deformed the structure and introduced residual stresses into the part where the center part deformed by around 220 µm in vertical direction as can be seen in fig. 4a**.**

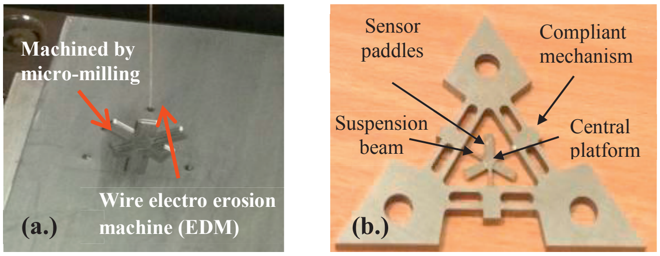

Fig 3: shows (a.) micro milling and erosion process to fabricate the suspension structure for the micro tactile probe. (b.) the first prototypes of the suspension structure.

To address these issues the design of the suspension structure was modified to make it suitable for manufacture using a commercially available chemical etching process. In this process, starting with 406 µm spring steel sheet, this was etched in a number of stages to produce the beams with a thickness of down to 100 µm, interconnected by a full thickness section as can be seen in fig. 5a. As the original design was 2mm thick the compliant mechanism had to be split into a number of layers due to limitations of the chemical etching process. This is because the variability of the etching process increases as the etch depth increases. Therefore to achieve good control of the thickness of the thin beams at the heart of the suspension structure, a start thickness of 406 µm material was chosen. To maintain structural robustness two were etched to sandwiched a thinner 406 µm layer. These did not contain the thin central beams, and were only required to support the sensitive central layer, the three layers can be seen in fig. 5b. The assembled prototype of the suspension structure is shown in fig. 5c.

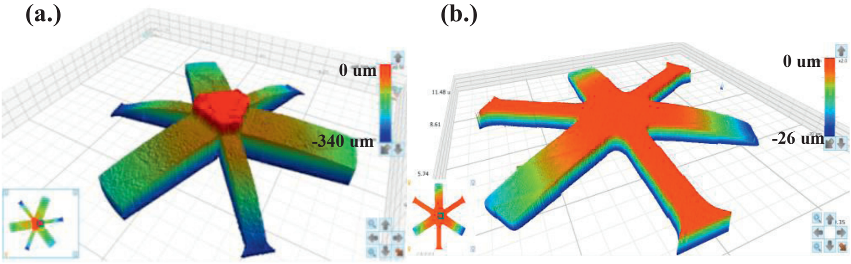

Fig 4: Measuring the flatness of the suspension structure that is manufactured based on (a.) conventional micro milling, and micro electro-discharge-machining and (b.) chemical etching.

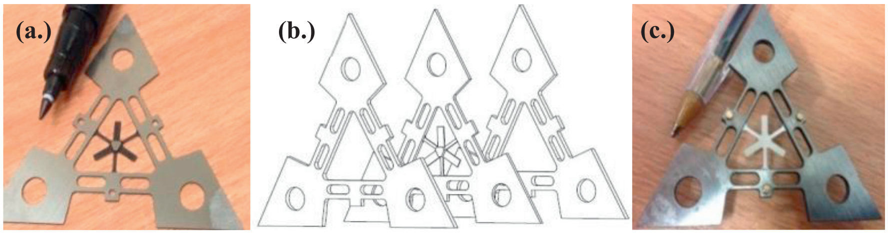

Fig 5: (a.) shows the thin layer of the suspension structure being etched from one side. (b.) shows thicker 800 µm layers sandwiched a thinner 406 µm layer. (c.) The assembled prototype of the smart suspension structure for 3D-probing system.

4. Initial testing of the suspension

The geometry and flatness of the suspension structure that has been manufactured by the chemical etching technique was measured using an optical microscope (Bruker Contour GT) as can be shown in fig. 4b. It is clear that the suspension beam has a good flatness compared with conventional machine. However, there is bending at the end of three sensor paddles where the maximum deviation in the paddles is around 16 µm in the vertical direction.

To find the resonant frequency of the structures, a laser vibrometer was used to measure the amplitude of the oscillations whilst the suspension system was excited from 2000Hz to 3000Hz as can be shown in fig. 6. The data could then be plotted in a graph and the natural frequencies identified as shown in fig. 7. The first peak at 2370Hz is the vertical natural frequency (f_V) and the second, smaller peak at 2645Hz is the torsional natural frequency (f_t). The measured vertical frequency has a good agreement with COMSOL results. However, it is clear that the COMSOL solution for the torsional frequency is greater than the measured frequency by 13.6%. This difference may as a result of the variance in the geometric dimension between the model and manufactured part.

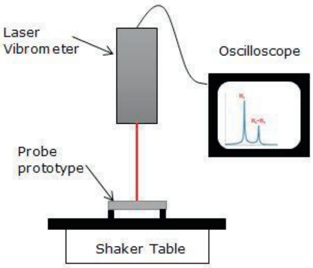

Fig 6: shows the Schematic of the setup used to find the natural frequency.

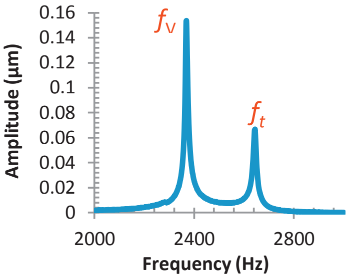

Fig 7: Sweep the frequency experimentally from the 2000 Hz to 3000 Hz to find beams resonant frequencies where the vertical and torsional natural frequency are 2370 Hz and 2645 Hz, respectively.

5. Conclusion and future work

The suspension structure was designed, fabricated, and tested. The design was shown a good agreement with numerical (COMSOL) solution. The new technique that can be possible to overcome the effect of the surface force for the tactile microprobe has been reviewed in this work. Tuning the stiffness in all direction by using a piezoelectric actuator and characterize probing system will be considered as future work.

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