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Vibration analysis of stylus instrument for random surface measurement

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ABSTRACT

This paper presents dynamic modeling and vibration analysis methodologies for investigating surface profile fidelity in stylus instruments, using a novel dynamic model that takes account of Hertzian contact stiffness between the stylus tip and surface. It briefly describes generation methods for modelling random surfaces and finite tips, which provide input for this nonlinear dynamic system. The influence of the damping ratio on the dynamic performance of the stylus instrument is examined and tends to confirm other recent work. The best combinations of signal fidelity and measurement speed occur with damping ratios considerably higher than conventionally used, mainly because the damping can suppress or delay tip flight. Residual vibrations associated with start-up transients are shown to have potentially serious effects on the signal fidelity. Hence, the responses of the stylus system to three typical velocity control signals are investigated. The normally used step control signal can generate relatively large residual vibration, while slope control and, even better, cycloidal control signal can suppress the residual vibration and guarantee the signal fidelity.

1. Introduction

The stylus instrument is one of the key enabling techniques for surface metrology and characterisation. Its advantages include convenient utilization, low sensitivity to surface contaminants and vibration, and direct recording of the mechanical surface relevant to many tribological applications. In modern engineering and scientific fields, high scanning speed is always desirable to reduce the environmental effects and to improve the efficiency of surface metrology. Thus, dynamic characteristics of such instruments are an increasingly important factor for signal fidelity in surface characterisation. In order to guarantee measurement accuracy and signal fidelity, vibration within such devices is one of the key issues needing to be systematically explored to avoid the signal distortion, which may be due to the tip flight, residual vibration, impact and collision.

Two ways in which the dynamic performance of stylus instruments affects signal fidelity are tip flight and surface damage due to inertial and damping forces. Tip flight refers to cases when the stylus tip fails to follow the profile of the measured surface during scanning process: the measured signal does not represent the actual profile of the real surface. This problem is reduced by using a stylus assembly with high natural frequency to enhance the tracking capability of its tip. Generally, the square of angular natural frequency is proportional to the stiffness and to the reciprocal of mass. For stylus instruments, the reduction of mass is limited by the geometric and functional requirements. For instance, the length of a probe lever arm might relate to workspace requirements and it must remain adequately rigid. Thus, the common method to improve the natural frequency of stylus instruments is to increase support stiffness. On the other hand, increased stiffness will increase the contact force at the measured surface, which might possibly damage the surface, distort the measured signal and reduce measurement accuracy. Thus, these two aspects must be traded off for signal fidelity improvement.

A few studies, mainly simulation, have been directed towards the signal fidelity of stylus surface measurement in recent years. Damir [1] presented the effects of stylus kinematics for several deterministic surfaces without considering the stylus tip radius. The point of separation of the stylus tip from the measured surface, maximum lift and path of the stylus after separation were established. McCool [2] assessed the combined effects of stylus tip radius and flight on the surface topography measurement. Simulations showed the magnitude of the distortion and the effects of the sample length and frequency on traced profiles. Song and Vorburger [3] described theoretical and experimental work on stylus flight and introduced different models of stylus flight in the profiling of sinusoidal, rectangular, triangular, and random surfaces. Pawlus and Smieszek [4] developed a model for predicting the flight distortion on a measured surface topography. Whitehouse [5,6] made a

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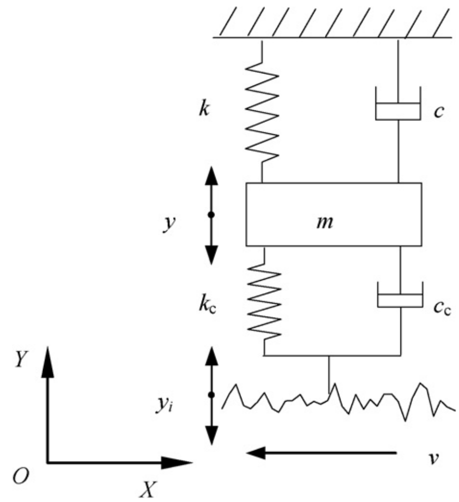

Fig. 1. Dynamic model of the stylus pick-up system.

major theoretical contribution to the dynamic aspects of scanning surface instruments. In terms of best measurement fidelity, he proposed that the optimal damping ratio for the mechanical pick-up of a stylus instrument be $\xi = 0.59$. This was confirmed experimentally by Liu et al. [7] using a modified stylus instrument to show that the minimal distortion on typical surfaces occurred with a damping ratio between 0.5 and 0.7. Tian et al. [8] established a dynamic model for random surface measurement using a stylus instrument. The effects of the design parameters of the instrument on the signal fidelity and critical scanning speed were systematically investigated. The finite tip size effects on dynamic performance were also investigated.

None of these previous dynamic models has considered the Hertzian contact stiffness and damping effects between the stylus tip and the measured surface. The interaction between the tip and surface is only modelled as kinematic pairs. Such models cannot provide full information for the actual reaction of the surface acting at the stylus tip and the collision and impact forces on the surface at the end of tip flight. A new dynamic model is needed to accurately predict the dynamic behavior of the stylus instrument.

The novel dynamic model of stylus contact and fidelity introduced here takes account of Hertzian contact stiffness and damping forces. It is used to investigate the effects of tip flight on signal fidelity for severe cases of random and periodic surfaces. The method and procedure for generating a random surface profile are briefly described, with cubic spline interpolation used to smooth the generated profiles. The influences of the inherent parameters of a stylus instrument and the parameters of the measurement process on the signal fidelity are explored. The slope and cycloidal signals are investigated in order to reduce residual vibration at the beginning of each scanning process.

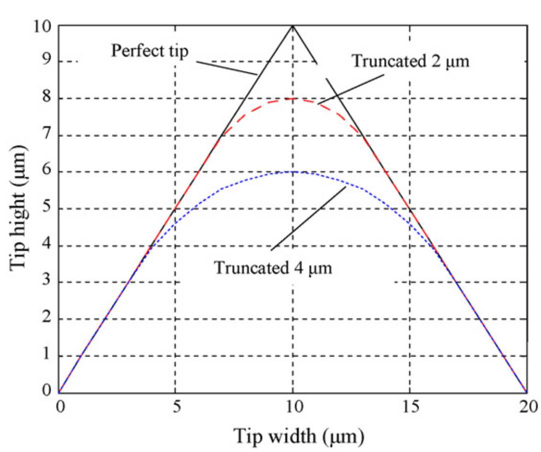

Fig. 2. Tip shapes.

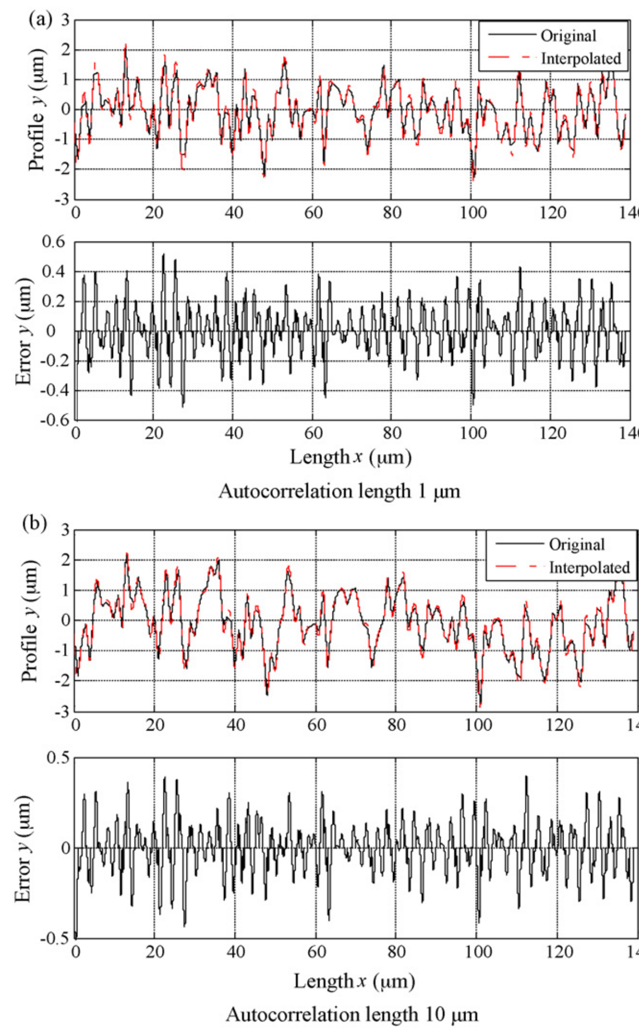

Fig. 3. Generated profiles with different autocorrelation.

2. Dynamic model

Fig. 1 illustrates the dynamic model of the stylus instrument and surface, and the coordinate system. The equivalent mass m of moving parts is supported by a spring with stiffness k and damper with damping coefficient c. The Hertzian contact between the tip and the measure surface is described by a Hertzian stiffness k_c and a damping coefficient c_c. The measured surface moves from right to left with a velocity v. The effective surface roughness that is swept through the contact region during scanning forms the dynamic input to the stylus system. The dynamics of such a stylus instrument can be modelled as a second-order damped mass-spring system. Thus, the displacement of the stylus tip during contact conditions is given by

$$m\ddot{y} + c\dot{y} + k(y + \delta) = k_c(y_i - y) + c_c(\dot{y}_i - \dot{y}) \quad (1)$$

where y and y_i are the vertical displacement of the stylus tip and random surface, respectively. δ is the initial static displacement. The adhesive forces (e.g., from adsorbed water films) at the contact between the tip and the surface are normally negligible for conven-