Precision Engineering 37 (2013) 711–720

Contents lists available at SciVerse ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Nonlinear viscoelastic modelling of stylus probing for surface metrology

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ARTICLE INFO

Article history:
Received 16 September 2012
Received in revised form
24 November 2012
Accepted 6 February 2013
Available online 18 February 2013

Keywords:
Nonlinear viscoelastic model
Signal fidelity
Contact stiffness
Stylus instrument

ABSTRACT

This paper presents a nonlinear viscoelastic methodology for modelling probe–surface interactions and so explores the signal fidelity in stylus based surface metrology. A novel model is introduced to simulate the nonlinear contact behaviour between the stylus tip and the measured surface. After briefly describing existing models of contact between solid bodies, a modified nonlinear viscoelastic contact model is introduced into the dynamic modelling of the stylus instrument. Based on this model, two scanning modes, i.e., raster scanning and spiral scanning, have been examined for high-speed measurement of a circular sinusoidal *XY* grid. The tip flight and residual vibrations associated with start-up transients are shown to have potentially serious effects on the signal fidelity during fast surface scanning. The effects of the scanning speed and direction have been investigated to show the influences of the scanning methodologies on the measurement. It is demonstrated that the spiral scanning methodology has inherent advantages for fast scanning with acceptable measurement accuracy.

1. Introduction

Surface metrology and characterisation is one of the key enabling techniques in modern industrial production control and research ranging from conventional manufacturing, through automotive, aerospace, semiconductor, nanotechnology, bio-medical engineering, to smart materials and coatings [1,2]. Although a number of surface metrology and characterisation methodologies and instruments have been developed and are commercially available, stylus based contact profilometry and metrology is still considered as one of the most important techniques for reliably measuring surface 2D profiles or 3D topography, it is convenient to use, has low sensitivity to surface contaminants and vibration, and directly records the mechanical surface relevant to many tribological applications. Also most ISO surface standards are still based on stylus type instruments. However, stylus profilometers suffer a slow scanning speed and a risk of damaging, or at least leaving slight marks on the surface being measured, despite regular efforts to tackle these issues [3–6]. The contact force of some newer instruments can be reduced dramatically (perhaps to less than a μN) but this is at the cost of measurement speed. The question of best balance between performance criteria remains open, not least because of the growth in demands to measure softer surfaces, including biological ones.

It is generally assumed that a high scanning speed is always desirable, because it increases measurement efficiency and also reduces thermal effects. Therefore, the dynamic performance of such instruments has been studied extensively over the past decades on issues of tip contact, tip flight, residual vibration, impact and collision [7–11]. Tip flight (temporary loss of contact) and surface impact damage (plastic deformation) arising from inertial and damping forces are considered to be two major ways in which the dynamic characteristics of the stylus instruments affect signal fidelity [8,12,13]. The tip flight can be generally reduced (ideally, eliminated) by increasing the natural frequency of the stylus assembly. However, this method of enhancing the tracking capability of the tip is limited by the surface impact damage from the large contact force, it implies for faster scanning. Previous investigations further revealed that the optimal damping ratio for the classical mechanical pick-up of a stylus instrument should be around 0.5, considerably higher than that of most commercial stylus instruments [6,10].

Our previous study [14] discussed a critical measurement speed that is dependent on contact force, tip size, and spring stiffness. In addition, it suggested that starting transients could affect the contact stability. Thus the use of pre-shaped control signals for driving the stylus scanning could potentially reduce, or even avoid, the effects of the residual vibrations [14]. Also, some recent studies have proposed that replacing the conventional raster scanning by a spiral scanning method could improve scanning speed and signal fidelity [15,16]. By providing a continuous measurement track with very constrained regions of acceleration, spiral scanning introduces

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0141-6359/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.precisioneng.2013.02.004

fewer transients and can significantly improve the scanning speed without causing severe signal distortion, thus being a good methodology for fast/video-speed scanning.

Dynamic modelling and simulation is one important technique for investigating the performance of stylus instruments, and so providing guidelines for stylus instrument design and scanning parameter selection. Damir [5] 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 [7] 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 [8] 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 [9] developed a model for predicting the flight distortion on a measured surface topography. Tian et al. [10] 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 effects of finite tip size on dynamic performance were also investigated. Recently, the Hertzian contact model has been introduced to model dynamic aspects of the contact behaviour between the tip and measured surface [14]. Based on the established model, the effects of the physical characteristics of the stylus instrument and scanning parameters on the signal fidelity were investigated.

It has been demonstrated that the contact model between the stylus tip and the measured surface is one of the major factors significantly affecting the computational accuracy of the established models. Previous contact models only considered the interaction between the tip and surface as kinematic pairs, and thus cannot provide full information for the actual reaction force at the surface under the stylus tip, nor for the collision and impact forces on the surface caused by the tip flight. The latter involve seriously nonlinear dynamic behaviours during the impact period. Although [14] introduced the Hertzian contact stiffness and damping effects, it did not consider the nonlinear viscoelastic impact model necessary for high quality predictions of the dynamic behaviour of the stylus instrument.

This paper introduces and explores the use of refinements made to incorporate Hertzian contact and non-linear damping forces into the dynamic model of a stylus based pick-up mechanism. The novel nonlinear viscoelastic model is used to investigate the signal fidelity for a circular sinusoidal *XY* grid, which is a typical sample for the characterisation and calibration of planar surface measurements. Two scanning methodologies, raster scanning and spiral scanning, are employed to examine the signal fidelity at fast scanning rates. The influence of the direction of spiral scanning on the performance of the stylus instruments is also investigated.

2. Dynamic model of stylus instrument pick-up

There are many variant configurations of pick-up mechanisms in stylus based instruments, but they have many mechanical similarities, falling into broad categories based on how the stylus tip is supported: lever mechanism, flexure hinge mechanism, and air-bearing mechanism. For simplicity and without loss generality, all these configurations of the pick-up can be simplified with reasonable accuracy into a second order damped mass spring mechanism as shown in Fig. 1. The *O-xyz* reference coordinate frame for the dynamic model of the pick-up mechanism is fixed to the instrument with its *x*-axis aligned to the linear profiling (or fast axis) direction.

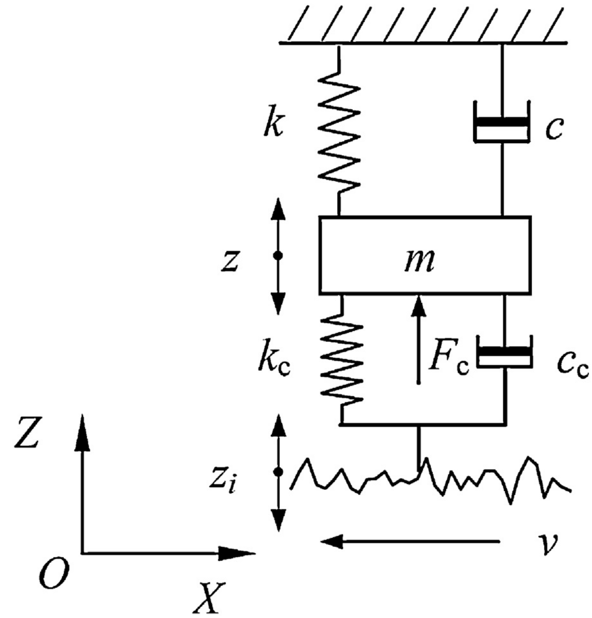

Fig. 1. Dynamic model of the stylus pick-up system.

The sample has a body-fixed frame *O-XYZ*, with *Z* always parallel to *z* and the other axes commonly, but not necessarily, aligned. The equivalent mass *m* of moving parts is supported by a spring with stiffness *k* and damper with damping coefficient *c*. Stylus motion is driven by a force F_c acting directly upon the mass. Early models considered only this upper section, with F_c being the reaction force due to the contact between the stylus tip and the surface. Here, F_c is generated by a contact spring with stiffness k_c and a damper with damping coefficient c_c, that couples to the kinematic (rigid) surface.

2.1. Displacement modelling

The instrument traverse is described by the measured surface moving in the negative *x*-direction (from right to left in Fig. 1) with a velocity *v*. The effective surface topography that is swept through the contact region during scanning forms the dynamic input to the stylus system. For all the explicit conditions addressed in this paper, the effective surface profile can be taken as the actual given one; surface features are large compared to typical tip dimensions. However, it is important to note that the effective surface is really that modified from the input by the finite dimensions of the tip. This is a highly non-linear process that strictly requires a great deal of intense computation between each step in the models discussed here. However, to a good approximation for engineering materials, the effective profile can be computed in advance by a kinematic stylus simulation or, equivalently, a spherical morphological filter [5].

Thus, the displacement of the stylus tip while it maintains a contact condition is given by

$$m\ddot{z}(t) + c\dot{z}(t) + k(z(t) + z_0) = F_c \quad (1)$$

where $z(t)$ is the vertical displacement of the stylus tip, z_0 is the initial static displacement. F_c depends on $z_e(vt)$ where $z_e(x)$ is the effective surface profile; early, rigid contact models forced the condition $z(t) = z_e(vt)$. The adhesive forces (e.g., from adsorbed water films) at the contact between the tip and the surface are normally negligible for conventional stylus instruments. Thus, the reaction force is assumed to never be negative.