Tribology International 73 (2014) 70–77

Contents lists available at ScienceDirect

Tribology International

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

An acoustic model for stiffness measurement of tribological interface using ultrasound

Fei Du, Jun Hong*, Ying Xu

State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, No. 99 Yanxiang Road, Xi'an, PR China

ARTICLE INFO

Article history:
Received 9 September 2013
Received in revised form
18 November 2013
Accepted 21 November 2013
Available online 1 December 2013

Keywords:
Ultrasound
Contact stiffness measurement
Reflection coefficient
Acoustic model

ABSTRACT

This paper proposed an acoustic model represented by spring–damper elements connected in series for ultrasonic reflection at tribological interface. Tribological interface was treated as a thin layer of Maxwell material, so that the effect of ultrasound attenuation at interface can be simulated accurately. Then the acoustic model was obtained using asymptotic expansion of an exact solution for this interface layer. Finally, the feasibility of the proposed model for contact stiffness measurement was validated experimentally. The results demonstrate that the proposed model can provide a quantitative measurement for both dry interface and interface with liquid film.

1. Introduction

Tribological interfaces like bolted joints and lubricated interface are indispensable in machine and mechanical device. Contact stiffness, which is an essential parameter for describing the tribological interface characteristics, has a great effect on the static and dynamic characteristics of the machine. The characteristics associated with these interfaces can frequently affect the performance of the machine. Therefore, it is important to measure the contact stiffness of real engineering interfaces for design and optimization of machine components.

Ultrasound is partly reflected from an interface between two solids. The amplitude ratio of reflected wave to incident wave, namely reflection coefficient, can be used for contact parameter estimation like contact stiffness [1–6]. Ultrasound method has been widely used since it can flexibly be performed to many real engineering materials and components such as bolted joints, interference fits, journal and rolling bearings [7]. Moreover, continuous improvements in ultrasonic technology make the measurement of contact parameter quite simple and quick to perform [1,8].

Ultrasonic reflection coefficient is related to contact stiffness by means of the acoustic model of interface. In the past few decades, several acoustic models [2,9–11] have been developed. Kendal and Tabor [9] proposed a spring model, which could be represented by a single spring, to describe the ultrasound reflection from stationary and sliding interfaces under the assumption of an elastic contact. Based on the spring model, Drinkwater et al. [3] measured the contact stiffness of an aluminum–aluminum interface under different pressures. Unfortunately, the measured stiffness is much higher than the predictions of theoretical contact models: at a nominal contact pressure of 100 MPa, ultrasound result is about 2.2 times stiffer than the prediction of the Greenwood–Williamson model (GW model) [12]. In contrast, the GW model agrees well with the experiment following the method of approach measurement within the range of elastic deformation [13]. Furthermore, Mulvihill [14] compared the stiffness of a pad-flat contact obtained from the spring model and that measured by the digital image correlation technique (DIC). The comparison results are similar: ultrasound result is about 2.4 times stiffer at the contact pressure of 100 MPa, and the ratio is greater at a lower pressure. Note that the DIC technique measured the relative displacement at the edges of contact surfaces. Nevertheless, at the contact pressure of 100 MPa, this relative displacement is a little different with that in the center of the contact surfaces according to the Finite Element Analysis (FEA) of the pad-flat contact. Hence, it can be deduced that the error of the DIC method owing to measuring region is not the main reason of the huge deviation between the measurement results of the two techniques. Mulvihill [14] pointed out that this deviation is probably due to the fact that ultrasound measurement always gives a local elastic unloading stiffness (even at a plastically deforming contact).

In the case of interface with liquid film, Dwyer-Joyce et al. [15] measured the stiffness of an interface with water film based on the spring model, and then calculated the thickness of the water film using interface stiffness. However, the measured film thickness is smaller than the real thickness of the film, indicating that the interface stiffness is correspondingly higher than the real value.

* Corresponding author. Tel.: +86 29 82668540.
E-mail addresses: jhong@mail.xjtu.edu.cn, dufeicsu2001@gmail.com (J. Hong).

0301-679X/$ - see front matter © 2014 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.triboint.2013.11.015

The spring model described above ignores the influence of mass. Baik and Thompson [10] presented a spring–mass model to consider the effects of interface mass (per unit area) for the interface with embedded pores or inclusions. Margatan et al. [16] verified the spring–mass model experimentally by measuring the reflection coefficient from interface with artificially introduced pores and inclusions. Their experimental results show that the role of mass becomes significant when the density of the inclusions is relatively high or the interface thickness is relatively large. For most tribological interfaces, the mass is lower than the surrounding media, so the results of the spring model and the spring–mass model are very similar [7].

The contact interface is regarded as ideally elastic in both the spring model and the spring–mass model. However, Krolikowski [11] and Biwa [17] pointed out that there is ultrasound attenuation at interface and the reason might be the friction or adhesion of contacting asperities. Therefore, Krolikowski [2,11] further developed a spring–damper model represented by a parallel connection of stiffness and damping elements to consider the effect of ultrasound attenuation in a simple way. The contact stiffness involved in the parallel spring–damper model is a complex, and its real part is the static contact stiffness which is independent of ultrasound frequency. Unfortunately, the contact stiffness calculated by the parallel spring–damper model is still much greater than that predicted by the statistical contact models: at the contact pressure of 100 MPa, ultrasound result is about 2.2 times stiffer than the prediction of the GW model [2].

The acoustic models described above were constructed via a quasi-static approach. On the other hand, an interface between solids can be modeled as a layer of viscoelastic material, which could be used for describing ultrasound attenuation, with effective material properties [18,19]. Rokhlin and Wang [18] considered an adhesive interface to be a layer of Maxwell material and established an acoustic model using asymptotic expansion of exact solution for a multilayer system. Reflection coefficient from a thin epoxy layer between two steel substrates could be calculated accurately by the Rokhlin's model, when the complex modulus and Poisson's ratio of epoxy are already known. Actually, the material of the interface layer in Rokhlin's research is a generalized Maxwell material, the bulk modulus of which has three parameters. Therefore, it is difficult to apply the Rokhlin's model to contact stiffness measurement since there are excessive material parameters which are unknown in this case.

Based on the literature reviewed above, it can be stated that the existing acoustic models could not provide an accurate measurement of contact stiffness. Moreover, the measurement is only qualitative for dry interface. The main reason is that the previous acoustic models cannot accurately simulate the effect of ultrasound attenuation at interface probably owing to friction, adhesion or plastic deformation of the contacting asperities. Motivated by Ref. [18], we consider the tribological interface to be a thin layer filled with Maxwell material to incorporate the effect of ultrasonic energy dissipation, and then we propose and validate an acoustic model to provide an accurate measurement of contact stiffness.

The remainder of this paper is organized as follows. An acoustic model composed of spring–damper elements connected in series is constructed using asymptotic expansion of the exact solution of the interface layer in Section 2. Sections 3 and 4 verify the feasibility of the established spring–damper model for dry interface and interface with liquid film, respectively. Section 5 discusses the effect of an approximate relation used in the asymptotic expansion method on the stiffness measuring accuracy for dry interfaces. Section 6 presents all conclusions and summary.

2. A spring–damper model

2.1. Theoretical foundations

A tribological interface (see Fig. 1(a)) could be approximated as a thin layer of Maxwell material to simulate the effect of ultrasound attenuation, as shown in Fig. 1(b). In addition, both the upper and lower boundaries of the Maxwell layer were assumed to transmit continuous displacements and stresses.

When a longitudinal wave generated in substrate 2 (see Fig. 1(b)) is incident normally to the interface layer, the reflection coefficient is as follows according to the transfer matrix theory of multilayer system [20]:

$$R = \frac{\rho_0 v_0 \sin P + iZ_1 \cos P - iZ_2 \cos P - (Z_2 Z_1/\rho_0 v_0)\sin P}{\rho_0 v_0 \sin P + iZ_1 \cos P + iZ_2 \cos P + (Z_2 Z_1/\rho_0 v_0)\sin P} \tag{1}$$

where

$$P = \frac{\omega}{v_0} h$$
$$Z_1 = \rho_1 v_1$$
$$Z_2 = \rho_2 v_2 \tag{2}$$

In Eqs. (1) and (2), h is the layer thickness; ω is the angular frequency of ultrasound; v_0, v_1, and v_2, are the longitudinal velocities of the interface layer, substrate 1, and substrate 2; ρ_0, ρ_1, and ρ_2, are the densities of the interface layer, substrate 1, and substrate 2; Z_1 and Z_2 are the acoustic impedances of the substrate 1 and 2; and i is the imaginary unit. When the ratio of the layer thickness to wavelength is small, Eq. (1) can be asymptotically expanded [18]. With only the first-order terms retained, R takes

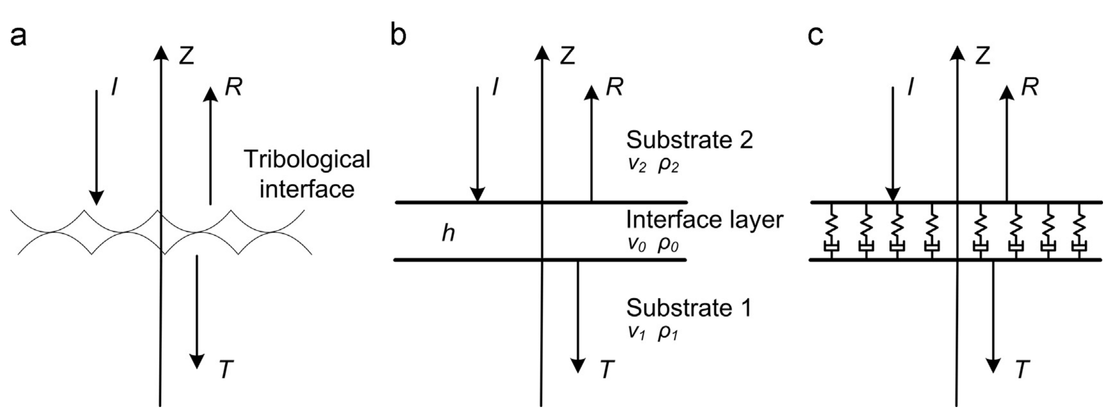

Fig. 1. Schematic diagram of ultrasonic reflection from tribological interface: (a) actual tribological interface, (b) interface layer of Maxwell material, and (c) a spring–damper model representation.