Monitoring of Contact Pressure of Solid-Solid Interface using Acoustic Nonlinearity

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Abstract

Contacting solid surfaces such as bearings and bolt threads is one of the critical sources of wear and failure in precision machinery. This paper presents an acoustic method to evaluate the contacting force of solid-solid contact surfaces using a special form of acoustic waves, which is a guided wave propagating between the joining boundaries with different wave velocity depending on the contact pressure. Mathematical formulation for acoustic wave propagation at contacting solids is made to obtain the dispersive relation between acoustic wave and contact pressure. Three different kinds of cubic steel blocks are machined and pressed together at various compression loads to form contact surface with different contact pressure. Acoustic wave is generated at the edge of the block and analyzed to determine the wave speed, which increases sensitively with the load. Theoretical and experimental results prove that contact force between two solid surfaces is linearly related to the acoustic wave speed of guided wave in the interface and may be monitored by it.

1 Introduction

The nonlinearity of contacting surfaces affects the acoustical features of ultrasound propagating along the interface of the solid-solid contact boundaries. Well-known acoustical manifestation of such nonlinear behavior is the change of wave velocity. As contact pressure increases and gives rise to higher interfacial stiffness of the boundary, the acoustic wave moves faster. The physical nature of this contact acoustic nonlinearity has been successfully explained by nonlinear spring model for contact-type interface[1,2]. In this model, the elasto-plastic behavior of contact surfaces is considered as a nonlinear spring whose stiffness is proportional to the contact area or external load. When two elastic bodies are brought into contact by force, it is expected that the contact area or contact pressure can be determined from nonlinear acoustic wave characteristic.

In this paper, cylinder-plane contact problem is investigated by using guided waves to show that contact force can be evaluated from acoustic wave speed. Approximate dispersion equation of interface wave is derived and used to calculate the wave velocity. In experiment, the wave speed is determined from time-of-flight measurement and shown to have a linear relationship with contact load.

2 Dispersion characteristics of guided wave in contact interface

The contact width *b* of a solid elastic cylinder held in contact with a plane elastic body by forces *F* along the cylinder length *l* in Fig. 1 can be determined with the Hertz theory as follow when deformation is much smaller than the radius of curvature of the asperity, R.

$$b = \sqrt{\frac{8RF}{\pi l}\frac{1-\nu^2}{E}} \tag{1}$$

Where, l is the thickness of contacting bodies, E and ν represent the Young's modulus and Poisson ratio, respectively.

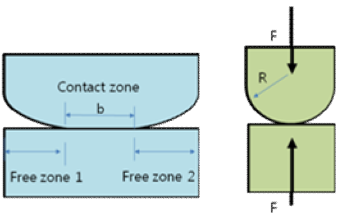


Figure 1: Contacting solids

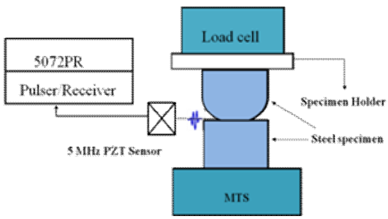


Figure 2: Acoustic measurement set-up

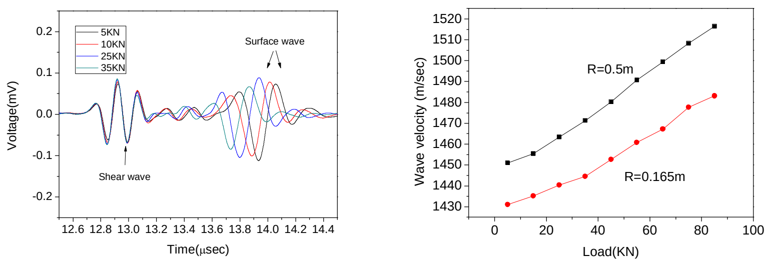
Apparently from Eq. (1), the contact area increases with the square root of the compressing force *F*. When an acoustic wave is applied to the contact interface at one side as shown in Fig. 2, it propagates first as Rayleigh surface wave along the free surface (free zone 1 in Fig. 1). Then it continues to move as interface wave along the contact zone of distance b in Fig. 1, and turns into Rayleigh wave again on the next free surface(free zone 2) and finally reflects at the rear side of the contact body. In this process, it propagates at Rayleigh wave speed c_R in free zones, but at different speed of c_I , the wave velocity of interface wave, on the contact zone. Therefore, once c_R and c_I are given, the contact width b or contact force F can be calculated easily from the time elapsed for the acoustic wave to take a round trip in the contacting body. Unlike the Rayleigh wave whose speed is non-dispersive and constant, the speed of interface wave, c_I is dispersive and dependent upon contact conditions, which is given by [3]

$$[4(\frac{c_s}{c_I})^2\sqrt{(\frac{c_s}{c_I})^2-1}\cdot\sqrt{(\frac{c_s}{c_I})^2-(\frac{c_s}{c_l})^2}-(1-2(\frac{c_s}{c_I})^2)^2]+2(\frac{K}{\omega\rho c_s})\sqrt{(\frac{c_s}{c_I})^2-1}=0 \qquad (2)$$

In Eq. (2), c_l and c_s are the longitudinal and shear wave speed, ω is wave frequency, ρ is the density and K is interfacial stiffness of contact area. Under the assumption that contact area is so small that the pressure of the contact zone is much higher than the rest of the elastic body, Eq. (2) leads to an asymptotic solution that interface wave speed c_I approaches the shear wave velocity c_s . This approximation enables us to estimate the size of contact area or contact force from the measurement of two acoustic wave velocities, c_s and c_R .

3 Experimenal Results

Two steel cubic blocks are machined and pressed together by tensile tester to construct a cylinder-plane contact interface in Fig. 1. Basically the steel cubes have a same dimension of 20mmx20mmx20mm. One steel block is a plane cube with flat surfaces, while the other has a cylindrical surface with a large radius of curvature as shown in Fig. 1. Three different curvatures are made to simulate a different deformation of contact, which are 0.165m, 0.5m and 1.0m. Compression load was applied to the steel blocks from 5kN to 90kN with the increment of 5kN. Ultrasonic transducer of 5MHz is mounted on the side of the specimen to generate acoustic wave along the contact surface. This configuration of experimental set-up is described in Fig. 2. Ultrasonic reflection signal is fetched from pulser/receiver to oscilloscope and computer for the measurement of time-of-flight of acoustic wave. An example of captured signal is shown in Fig. 3(a), where the peaks of the signal are detected and used to calculate the phase velocity of the wave. The overall wave velocity obtained from Fig. 3(a) is represented in Fig. 3(b), where the case of R=1m is omitted. In the figure, it is clearly seen that the wave velocity increase linearly with the load mainly because the contact area is expanded by the load. Fig. 3(b) also represents that the velocity of acoustic guided wave may indicate the state of contact condition including applied load or contact area. From experimental results, it is concluded that the acoustic wave velocity changes much according to the nonlinear deformation of contact solids with good sensitivity to monitor the contact load of cylinder-plane solid interface.



(a) (b)

Figure 3: Measurement results, (a) waveforms of acoustic signal, (b) variation of wave velocity due to applied load

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