# Influence of Asperity Deformation on Linear and Nonlinear Interfacial Stiffness in Dry Rough Surface Contact

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**Abstract.** Many studies have successfully used ultrasound to measure the interfacial stiffness of dry and lubricated contacts in tribological applications. These have been performed with low power, elastic ultrasonics waves. Only a few works studied the nonlinear effects that arise when high power waves reflected and transmitted at an imperfect contact. Little experimental work is available. The aim of the present study is to show how the elastoplastic deformation of asperities in a rough surface contact affect the nonlinear behaviour and compare this to similar bahaviour in a continuum solid. It is seen that initial loading is plastic and after several cycles of loading/unloading, both reflected and transmitted nonlinear parameters are fully elastic. These parameters from a dry contact also give the same result as a continuum media.

## 1. Introduction

The stress-strain relationship of a nonlinear material is defined by a nonlinear version of Hooke's law:

$$\sigma = C_{11}\varepsilon - C_{11}\,\beta\,\varepsilon^2 \tag{1}$$

$$\beta = -\frac{3C_{11} + C_{111}}{C_{11}} \tag{2}$$

where $\sigma$ normal stress, $C_{11}$ and $C_{111}$ are the 2nd and 3rd order elastic constants, $\varepsilon$ is the strain and $\beta$ is the nonlinear parameter. When a high-power longitudinal ultrasonic wave propagates in a continuum medium, it is distorted and higher order harmonics are generated in the ultrasonic wave. Several studies have related this nonlinearity to the 2nd and 3rd order elastic constants [1,2]:

$$\beta = \frac{8}{kx^2}\frac{A_2}{{A_1}^2} \tag{3}$$

where $k$ is wavenumber, $x$ distance between transducers (emitter and receiver), $A_1$ and $A_2$ are the amplitude of the fundamental frequency and 2nd order harmonic.

Nonlinearity is also generated when a high-amplitude ultrasonic wave is incident at rough surface (i.e. imperfect) contact; this is known as Contact Acoustic Nonlinearity (CAN) [3]. When two rough surfaces are loaded together contact occurs at asperity peaks. The interface consists of solid contact regions and air gaps and is less stiff than the bulk material. As the distance between the transducers (emitter and receiver) in an imperfect contact configuration is constant, Eq.3 can be reformulated, and the reflected and transmitted nonlinear parameters are given [4]:

$$\begin{cases} \gamma' = \dfrac{A_{2R}}{{A_{1R}}^2} \\ \beta' = \dfrac{A_{2T}}{{A_{1T}}^2} \end{cases} \tag{4}$$

where $A_1$ and $A_2$ are the amplitude of the fundamental frequency and 2nd harmonic, and subscripts R and T denote reflection and transmission.

The present work aims to study the effect of elastoplastic deformation of a dry rough contact on the nonlinear ultrasonic parameters both for reflected and transmitted longitudinal ultrasonic waves. These parameters are then used to determine the nonlinear interfacial stiffnesses.

## 2. Methods

Fig. 1 shows the experimental set-up for measuring ultrasonic propagation in **(a)** a continuum medium and **(b)** a dry rough contact. A series of single aluminium 6082 blocks with the thicknesses in range $10\ mm$ to $75\ mm$ was considered for measuring the material nonlinearity (see Fig.1a). Two aluminium blocks (shown in Fig.1b) were machined, and the contacting surfaces were polished to create a dry frictional joint. Three piezoelectric transducers with centre frequency $2\ MHz$ and $5\ MHz$ were coupled to the blocks as shown in the figures. The transducer with centre frequency $2\ MHz$ generated the incident wave, the other two transducers with centre frequency $5\ MHz$ received the signals reflected and transmitted in the continuum block and from the interface. A power amplifier (RITEC RAM-5000) was used to generated high power emitted signals. The signals then stored by a digital oscilloscope. In the continuum media (Fig.1a) the reflected and transmitted signals for different thickness were captured. While for the contact set-up (Fig.1b) the interface was subjected to nominal contact pressure from 0 to $5.5\ MPa$. The reflected and transmitted pulses were captured in the time domain, processed using a window function, zero padding and Fast Fourier Transform (FFT), to present results in frequency domain in order to distinguish the amplitude of fundamental and 2nd harmonics.

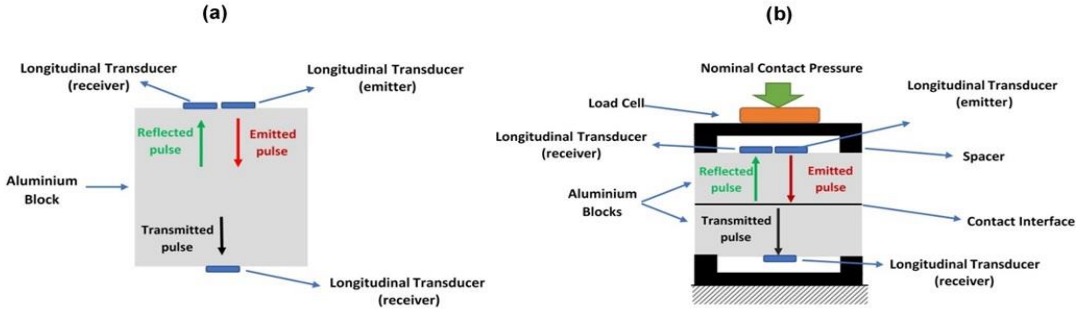


*Figure 1. Schematic diagram of the apparatus: (a) continuum aluminium block; (b) dry rough contact.*

The amplitude of the first, $A_1$ and second harmonic, $A_2$ were determined from the frequency domain signals and used in Eqs.(3) and (4) to obtain the nonlinear parameters for the continuum solid and rough surface interface.

## 3. Result and Discussion

Fig. 2a shows the hysteresis of the transmission coefficient for the 1st and 10th loading/unloading cycles. This hysteresis became negligible the ten cycles as the interface became elastic, more conformal, and hence stiffer. The same is seen for the reflected and transmitted nonlinear parameters ($\gamma'$ and $\beta'$). Increasing the nominal contact pressure results in the same value of nonlinear parameter in both the continuum aluminium blocks and the block containing the imperfect interface. Fig. 2c shows the relationship between the reflected and transmitted nonlinear parameters ($\gamma'$ and $\beta'$). It is seen that for the contact pressure higher than $3MPa$, both nonlinear parameters show similar values.

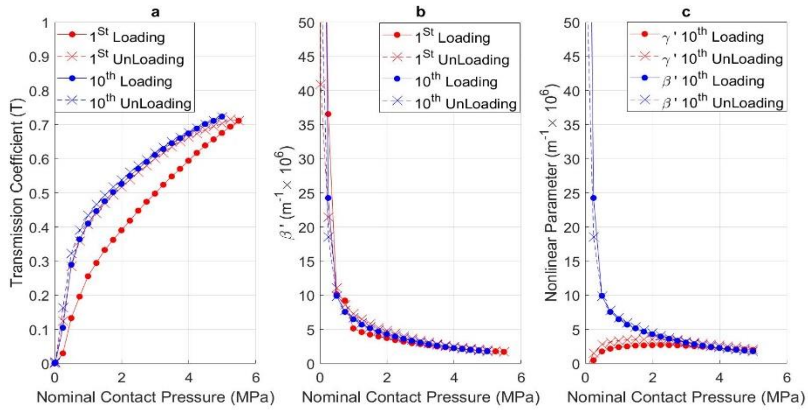


*Figure 2. Reflected and transmitted signal from/through a dry rough contact as nominal pressure increases for the 1st and 10th loading/unloading cycles: (a) transmission coefficient; (b) transmitted nonlinear parameter $\beta'$; (c) reflected and transmitted nonlinear parameters at the 10th loading/unloading cycle.*

## 4. Conclusion

Reflected and transmitted nonlinear parameters beyond 3MPa in a dry contact results in the same as those in a continuum medium. it is seen that as the number of loading/unloading cycles increases, the hysteresis in both reflected and transmitted nonlinear parameters decreases significantly. This indicates that the deformation of the asperities in contact turns to elastic deformation and subsequently a stiffer contact.

## References


[1] A. Hikata, B.B. Chick, C. Elbaum, Dislocation contribution to the second harmonic generation of ultrasonic waves, J. Appl. Phys. 36 (1965) 229–236. https://doi.org/10.1063/1.1713881.

[2] K.E. Van Den Abeele, Elastic pulsed wave propagation in media with second- or higher-order nonlinearity. Part I. Theoretical framework, J. Acoust. Soc. Am. 99 (1996) 3334–3345. https://doi.org/10.1121/1.414890.

[3] O. Buck, W.L. Morris, J.M. Richardson, Acoustic harmonic generation at unbonded interfaces and fatigue cracks, Appl. Phys. Lett. 33 (1978) 371–373.

[4] S. Biwa, S. Nakajima, N. Ohno, On the Acoustic Nonlinearity of Solid-Solid Contact With Pressure-Dependent Interface Stiffness, J. Appl. Mech. 71 (2004) 508–515.