Detectability of kissing bonds using the non-linear high frequency transmission technique

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Abstract

Kissing bonds are adhesive bonding defects and are thought to arise from either contamination of the surfaces during manufacture or various forms of environmental attack. . When adhesives are used for safety critical applications the current method is to undertake extremely careful process control. None-the-less premature failure of adhesive joints still occurs and kissing bonds are often the most likely cause. Despite the need of detection of kissing bonds, they are difficult to be detected using conventional non-destructive testing techniques such as ultrasonics since the thickness of kissing bonds is many orders of magnitude less than an ultrasonic wavelength. However, kissing bonds can exhibit a strongly non-linear ultrasonic response when a high amplitude of ultrasonic wave propagates through the kissing bonds area. This paper concerns a study of the detectability of kissing bonds in adhesive joints using the non-linear high frequency transmission technique (NHFTT). Three specimens with perfect and imperfect bondings were tested using the NHFTT and non-linear parameters of them were measured to judge the conditions of the adhesive joint.

Keywords: Non-linear ultrasound; Kissing bonds; Adhesives; Non-linear parameter

1. Introduction

In this study, kissing bonds are defined as adhesive bonding defects in which the adhesive and the substrate are in some way contacted or coupled through a very thin layer which is defined as region which exhibits lower normal or shear stiffness due to bonding imperfection. They are typically caused by either surface contamination during the manufacture processing or environmental degradation. It is difficult to detect kissing bonds using conventional non-destructive testing techniques such as ultrasonics [1] because the thickness of the kissing bond is many orders of magnitude less than an ultrasonic wavelength.. Nonetheless, it is thought that when a large amplitude ultrasonic wave propagates through the kissing bond area, the system will behave non-linearly and harmonic will be generated in the non-linear system which is shown in figure 1. It can be seen that the input signal with the single excitation frequency (ω, named fundamental frequency) propagates through the non-linear system and then on the receiving side the output signal contains the energy not only at ω but also at integral times of ω (named harmonics) which makes the detection of kissing bonds possible. In this paper, the output amplitude at the excitation frequency

(ω) is defined as A_0 and the output amplitudes of harmonics of the excitation frequency, 2ω, 3ω, 4ω, …, are defined as A_1, A_2, A_3, … respectively.

In this paper, the effect of loading on the ability to detect kissing bonds using a non-linear ultrasonic technique that is called the non-linear high frequency transmission technique (NHFTT) is investigated. The method is such that it can be used, with high amplitude incident wave, appropriate signal processing and over a range of the compressive loading. Under low compressive loading, "clapping" type behaviour is expected and hence high-level non-linearity. Conversely, high-level loading is expected to cause kissing bond surfaces into contact increasing contact stiffness and reducing non-linear behaviour.

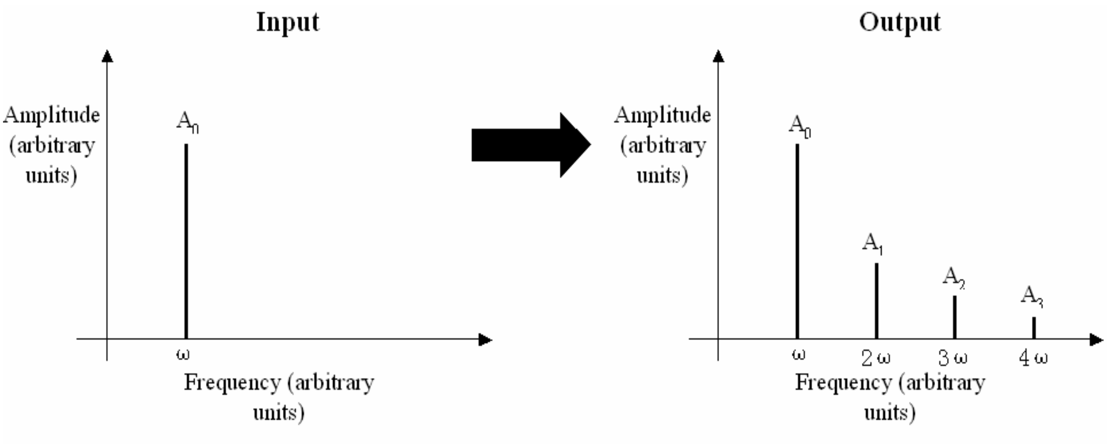


Figure 1. The non-linear behaviour of kissing bonds at the frequency spectrum.

2. Background

In 2004 Biwa et al. [2] measured the non-linearity of the solid-solid contact interface with applied pressure using the ratio between the harmonic amplitude (A_1) and the square of the fundamental frequency amplitude (A_0) as:

$$A_1/A_0^2 = \frac{m\rho c\omega}{2P_a\sqrt{1+C^2P_a^{2m}/(\rho c\omega)^2}} \qquad (1)$$

Where m and C are positive constants extracted from a suitable contact model, c is wave velocity, ω is angular frequency, $\rho$is mass density and P_a is interface contact pressure. The ratio of A_1/A_0^2 depends on the frequency of incident wave and the interface contact pressure.

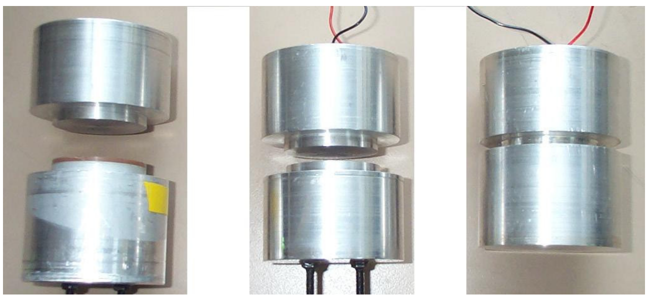
It can be seen from eq. (1) that the contributions to A_1 from interface is proportional to A_0^2. Moreover, the interface non-linearity has been shown to generate much greater harmonics than the bulk material non-linearity [3, 4]. There are a number of authors [2, 5, 6] using A_1/A_0 as a non-linear parameter, but that parameter is not independent of the amplitude of incident wave [2]. Therefore in this paper, the parameter of A_1/A_0^2 is used to qualify the non-linearity of kissing bonds in adhesive joints.

3. Experiment apparatus

Three specimens were tested. The first consists of two aluminium blocks, one with an adhesive layer as shown in figure 2(a). A 2 mm thick adhesive layer (3M EC3448) was cast onto the 20 mm diameter of lower aluminium cylinder. It is assumed that the adhesive layer is perfectly bonded on one side and purely separated on the other side. This specimen will be referred to as the kissing bond (KB) specimen. The second one consists of two aluminium cylinders both of which have the same dimension and material as the the KB specimen as shown in figure 2(b) and this specimen will be referred to as the two aluminium-cylinder specimen (Al-Al). The third specimen was a solid aluminium cylinder that is exactly the same dimension and material as the Al-Al specimen. This specimen will be referred to as the reference specimen which is the aluminium specimen (Al) as shown in figure 2(c). The only difference between the KB specimen and the other two is the extra adhesive layer. The system of the KB and Al-Al specimen is expected to behave more linear under high compressive loading than under around zero loading due to the less variation of stiffness in high loading level.

In the experiment, a 15-cycle tone-burst signal was generated by the arbitrary function generator (AFG), amplified by the power amplifier and sent into the specimen. The specimen was then loaded against the bottom cylinder from 0.1 kN (average contact pressure, P_a, across the interface is 0.08 MPa) to 14 kN ($P_a = 11.2$ MPa) in a hydraulic loading machine. Note that the technique, in which an undamped piezoelectric disc which is glued on the aluminium cylinder is used to send a signal in the frequency range of 1 to 5 MHz into a specimen and the output signal is received by an damped ultrasonic transducer, is also termed the high frequency non-linear ultrasonic technique and is suggested by a number of authors [7, 8].

When increasing the loading on the specimen more surface asperities on the interface will come into contact and each asperity tends to be flattened [2]. The changes of the contact asperities can cause the variation of the contact pressure P_a of the interface which can be the reason of the variation of the non-linear parameter A_1/A_0^2. The non-linearity of solid-solid contact interface dependent of the interface contact pressure P_a is shown in eq. (1).



(a) (b) (c)

Figure 2. Experiment specimens: (a) Kissing bonds (KB) specimen. (b) Two aluminium-cylinder (Al-Al) specimen. (c) Aluminium (Al) specimen

4. Transmitter natural filtering technique

In the non-linear system, not only the specimen can generate harmonic the equipment (the power amplifier and the AFG) also are possible harmonic sources. To reduce the effect of the non-linearity from the power amplifier and AFG, the transmitter is used as a natural filter. Figure 3 shows the transfer function of the undamped piezoelectric disc (i.e. transmitter). Ideally the excitation frequency would be selected at a resonant peak and the corresponding first harmonic of the excitation frequency would at a minimum of the transfer function, which can cause a large ratio between the amplitude of the fundamental frequency and that of the first harmonic. Therefore the piezoelectric disc would act as a natural filter which would significantly reduce the first harmonic of the signal. Since the input signal contains the instrument-induced harmonics and after it is driven by the piezoelectric disc, the effect of the instrument non-linearity can be minimised. Frequencies of 1.2 MHz and 3.5 MHz can both satisfy the requirements to minimise the instrument-induce non-linearity.

It is found that the ratio between the amplitude at 7 MHz and that at the 3.5 MHz at the transfer function of the piezoelectric disc is much smaller than the ratio at the wide band ultrasonic transducer, which means the harmonics eliminated by the undamped piezoelectric disc in the system is much more than the harmonics enhanced by the wide band ultrasonic transducer. The influence of the wide band ultrasonic transducer on the system non-linearity is small. In this paper, 3.5 MHz is selected as excitation frequency.

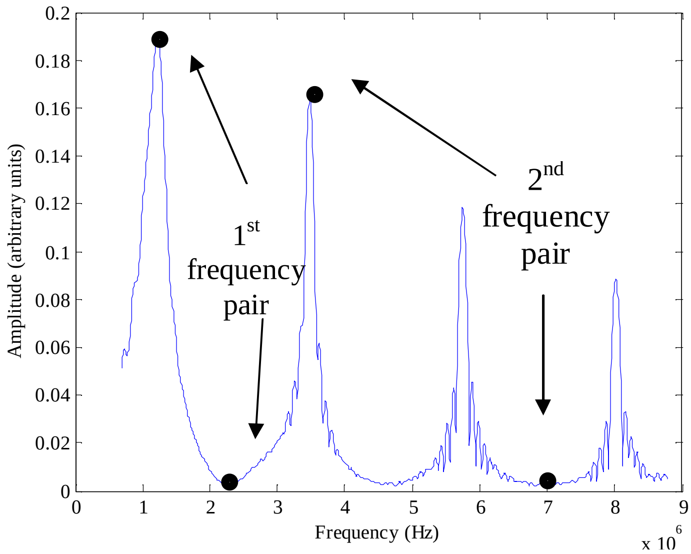
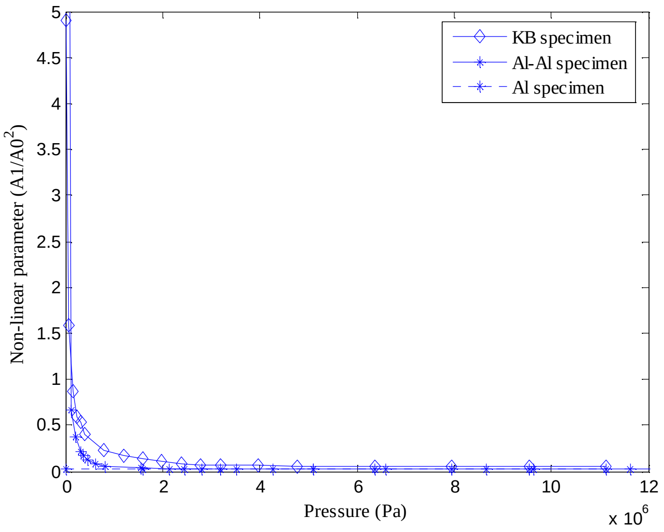


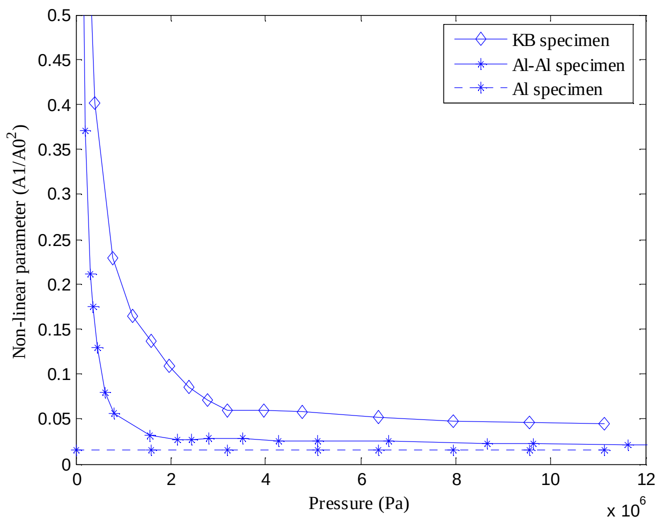
Figure 3. The transfer function of undamped piezoelectric disc

5. Experimental results

Three experiments with 3.5 MHz excitation frequency and 188 V input voltage were performed using the KB, Al-Al and Al specimens. The results in figure 4 (a)&(b) show how the non-linear parameter A_1/ A_0^2 varies over load from 0.1 kN (P_a = 0.08 Mpa) to 14 kN (P_a = 11.2 Mpa). It can be seen from figure 4(a)&(b) that the non-linearity of the Al specimen measurement is constant and is below the KB an Al-Al curves at all loads. The KB non-linearity quickly drops from 5 (at 0.08 Mpa pressure) to ratio of 0.06 (at 4 Mpa pressure), and above 4 Mpa the KB non-linearity decreases much more slowly. It is thought that below 4 Mpa, the contact non-linearity is the major effect, and above 4 Mpa the area of contact will increase until the contact is present across most of the interface, the adhesive non-linearity then dominates. Moreover, the Al-Al curve has a similar trend to the KB curve and as the loading increasing the non-linearity of the Al-Al specimen is closer to that of the Al specimen as expected. In addition, the Al (reference) line is not zero due to the non-linearity caused by bulk aluminium, coupling, transducers, etc. There is a constant gap between the KB and the Al curve after 4 Mpa which is believed to be a result of adhesive non-linearity.



(a)



(b)

Figure 4. High power ultrasonic response: (a) Non-linear parameter of A_1/ A_0^2 as a function of loading. (b) Zoom in graph of figure 4(a).

The non-linear parameter A_1/ A_0^2 of the KB and Al specimens as a function of pressure with different input voltages varying between 98 V to 188 V is shown in figure 5, from which it can be seen that although the input voltage is changing, the non-linear parameter of the Al specimen and KB specimen do not vary significantly. Above 4 Mpa, the KB non-linearities seem to be constant. This means even if the input voltages are changing this has only a small effect on the non-linear parameter.

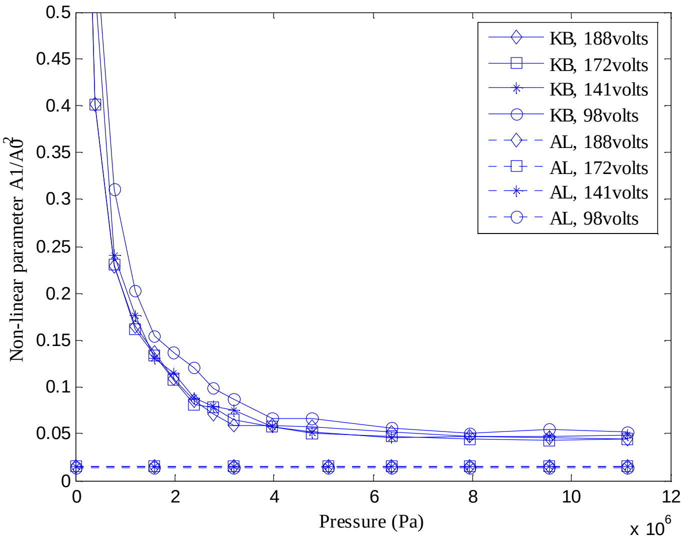


Figure 5. Non-linear parameter A_1/ A_0^2 as a function of loading with input voltages from 98 volts to 188 volts.

7. Conclusion

This paper describes the non-linear ultrasonic measurement of kissing bonds in adhesive joint using the non-linear high frequency transmission technique. Due to the fact that the harmonics are not only caused by the materials and kissing bonds but also by the instruments, a transmitter filtering technique is used to minimise the instrument-induced harmonics to improve the sensitive of the detection. Experiments were then performed to obtain the non-linear parameters of three aluminium specimens, one with and the other two without kissing bonds. At very low loading levels, the clapping non-linearity is the major effect which results in the non-linearities of the KB and Al-Al specimens being much larger than that of the reference sample. As the loading increased, all the non-linearities seem to be constant with load and the contact acoustic non-linearity is the major effect that results in the three samples of comparable non-linearities. But the non-linearity of adhesive sample is still larger than those of the Al-Al and the reference samples due to the extra adhesive, and as the loading increasing the non-linearity of Al-Al specimen is closer to but still larger than that of the reference sample due to the incomplete interface. When changing the voltage of the input signal the result shows the non-linearity is independent of the voltage. The non-linear high frequency transmission technique is a promising technique for detection of kissing bonds in adhesive joint at low loading level.

References:

[1]. Vine, K., P. Cawley, and A.J. Kinloch, The correlation of non-destructive measurements and toughness changes in adhesive joints during environmental attack. Journal of Adhesion, 2001. **77**(2): p. 125-161.
[2]. Biwa, S., S. Nakajima, and N. Ohno, On the acoustic nonlinearity of solid-solid contact with pressure-dependent interface stiffness. Journal of Applied Mechanics-Transactions of the Asme, 2004. **71**(4): p. 508-515.
[3]. Breazeale, M.A. and D.O. Thompson, Finite-Amplitude Ultrasonic Waves in Aluminum. Applied Physics Letters, 1963. **3**(5): p. 77-78.
[4]. Thompson, R.B., O. Buck, and D.O. Thompson, Higher Harmonics of Finite-Amplitude Ultrasonic-Waves in Solids. Journal of the Acoustical Society of America, 1976. **59**(5): p. 1087-1094.
[5]. Barnard, D.J., et al., Acoustic harmonic generation at diffusion bonds. Journal of Nondestructive Evaluation, 1997. **16**(2): p. 77-89.
[6]. Brotherhood, C.J., B.W. Drinkwater, and S. Dixon, The detectability of kissing bonds in adhesive joints using ultrasonic techniques. Ultrasonics, 2003. **41**(7): p. 521-529.
[7]. Fassbender, S.U., M. Kroning, and W. Arnold, Measurement of adhesion strength using nonlinear acoustics, in Nondestructive Characterization of Materials Vii, Pts 1 and 2. 1996. p. 783-790.
[8]. Rothenfusser, M., M. Mayr, and J. Baumann, Acoustic nonlinearities in adhesive joints. Ultrasonics, 2000. **38**(1-8): p. 322-326.