7th ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2015
A.L. Araújo, C.A. Mota Soares, et al. (Editors)

Kissing bonds monitoring using nonlinear vibro-acoustic wave modulations

Wieslaw J. Staszewski*, Karol Świercz*, Lukasz Pieczonka* Dariusz Broda* and Andrzej Klepka*

*Department of Robotics and Mechatronics, AGH University of Science and Technology
Al. A. Mickiewicza 30, 30-059 Krakow, Poland
w.j.staszewski@agh.edu.pl

Key words: kissing bonds, structural health monitoring, nonlinear acoustics, nonlinear vibro-acoustic modulations

Summary: *The paper reports an application of nonlinear acoustics for kissing bond monitoring in composite samples. Low-frequency modal excitation and high-frequency ultrasonic excitation are used to produce nonlinear modulations in bonded carbon fiber reinforced polymer samples. Low-profile piezoceramic transducers are used for ultrasonic excitation and for measurement of acoustical responses. The work presented focuses on the analysis of damage-related nonlinearities manifested in power spectra as sidebands around carrier high-frequency components. The paper demonstrates that the method can be used for kissing bond detection in composites.*

1 INTRODUCTION

Adhesive bonding is a material joining process in which an adhesive, placed between structural members (adherends), solidifies to produce an adhesive bond [1]. Adhesive bonding is used in many engineering applications as an alternative to mechanical joints, like riveting and screwing. With the development of more advanced structural adhesives this type of joints becomes a viable alternative to mechanical joints also in the responsible load-bearing connections. Adhesive bonding provides many advantages over conventional mechanical fasteners including lower structural weight (no additional mass of fasteners), lower fabrication cost, and improved damage tolerance [2]. The use of adhesive joints is especially important in structural components made of fiber reinforced composites, where use of mechanical fasteners usually results in the cutting of fibers and introduces stress concentrations that reduce structural integrity. Adhesive joints on the other hand provide more uniform stress distribution, better strength-to-weight ratio and have greater design flexibility. For these reasons adhesive bonding has found numerous applications in almost every branch of engineering. One of the problems with use of adhesive bonding is the occurrence of “kissing bonds”. This type of defect occurs when joined surfaces are in contact but with very little bonding. Kissing bonds are especially dangerous because they are very difficult to detect by the conventional ultrasonic techniques [3][4]. This is due to the fact that there is no noticeable separation between the bonded surfaces and hence there is no significant impedance contrast that alters the linear features of propagating ultrasonic waves.

Taking this in consideration some authors applied the classical nonlinear acoustics, that analyzes wave distortion and the appearance of higher harmonics, to diagnose kissing bonds [5][6]. The conclusion from that investigations was that only a combination of two or more testing techniques could provide an enhanced information about the kissing bond.

This work is therefore focused on a different measurement approach. Instead of looking at the linear features of propagating ultrasonic waves, or a distortion of a single traveling wave, we focus on nonlinear interaction between two waves that are introduced into the test sample. The following sections describe the details of the considered measurement technique, provide the description of composite test samples and finally report the results that have been obtained.

2 MEASUREMENT TECHNIQUE

Diagnostic technique considered in this study is the Vibro-Acoustic Modulation (VAM) technique [7][8], also referred to as the Nonlinear Wave Modulation Spectroscopy (NWMS) [9]. The technique falls under a broad category of 'pump-probe' techniques that have been long used in nonlinear acoustics. The idea is to apply two dynamic fields – an intensive high amplitude field to perturb the material elasticity (pump wave) and a weak field to measure the induced elastic changes (probe wave). Typically, one uses a High-Frequency (HF) ultrasonic wave as the probe and a Low-Frequency (LF) modal/vibration excitation as the pump. These two excitations are introduced to a test sample simultaneously, as illustrated in Figure 1.

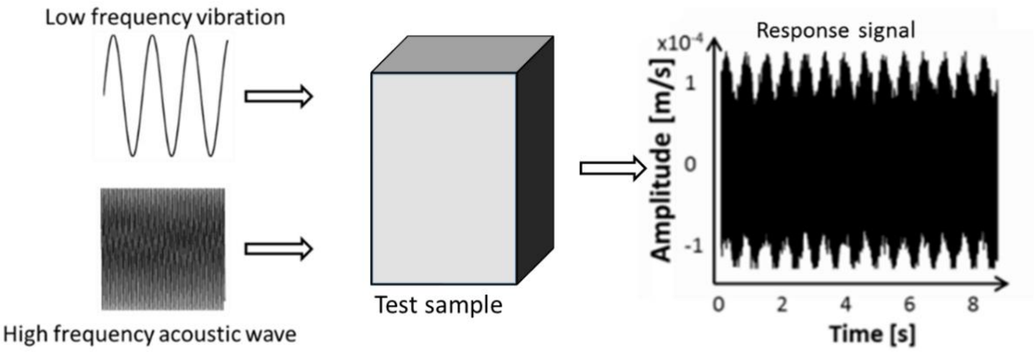

Figure 1: The principle of vibro–acoustic modulation (VAM) technique.

When the test sample is linear (undamaged), then the measured response signal transformed to the frequency domain exhibits only the two frequency components that were introduced i.e. the low frequency vibration and the high frequency acoustic wave. In contrast, if the test sample is nonlinear (damaged) the response spectrum exhibits additional frequency components, i.e. higher harmonics ($n \cdot LF$) and modulation sidebands around the high frequency component ($HF \pm n \cdot LF$). The latter is of major interest in the current work. The technique under consideration has been already applied for detecting damage in fiber reinforced composites [10][11].

3 TEST SAMPLES

Kissing bond test samples were prepared in the following way: a set of 130×25 mm test coupons was water cut from a unidirectional carbon fiber reinforced plastic (CFRP) plate with the nominal thickness of 1.5 mm. The individual test coupons were cleaned using the *Loctite 7063* cleaning agent and adhesively bonded to form a lap joint using the *Loctite 9497* two component structural bonding adhesive. The area of the lap joint was 25×25 mm. The geometry of the test samples is shown in Figure 2.

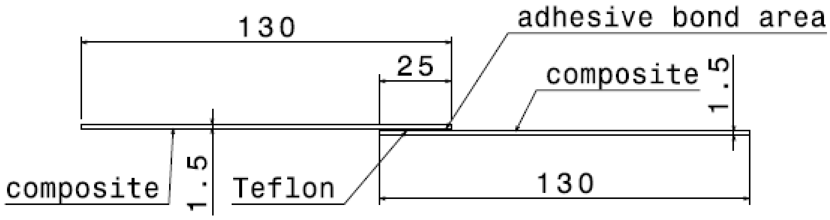

Figure 2: Geometry of the test samples

4 MEASUREMENT SETUP

Nonlinear acoustics tests were performed for both, i.e. the undamaged and damaged composite samples. Low-profile piezoceramic transducers were attached to the specimen sing two-component epoxy adhesive. A sine wave of HF = 30 kHz – was used for ultrasonic excitation. The peak-to-peak amplitude of the ultrasonic excitation was equal to 40V. Once the ultrasonic wave was propagating, the plates were vibrated using the second piezxoelectric transducer driven by a sinusoidal excitation. The excitation frequency was equal to LF = 500 Hz. The peak-to-peak amplitude of the LF excitation was equal to 40V also. The two specimen were investigated. The first with teflon insert and the second without the additional components between the bounded plies. Ultrasonic responses were measured using the *PSV Polytec* scanning laser vibrometer. Figure 3 illustrates the experimental arrangement used for the nonlinear acoustics tests.

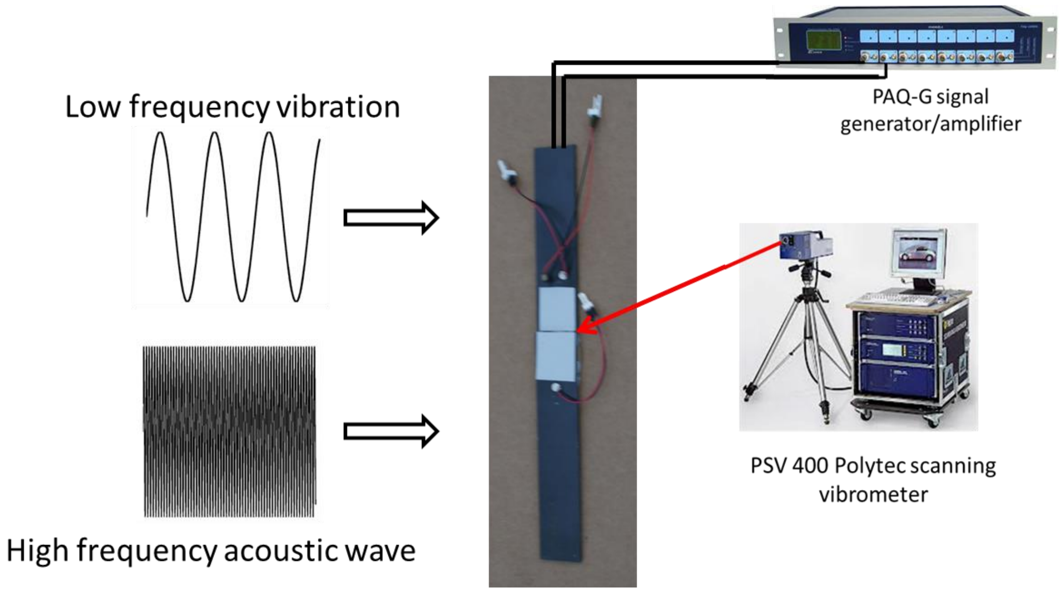

Figure 3: Experimental set-up used for the nonlinear vibro-acoustic tests.

The measurement grid consist of 207 measuring points (Figure 4). The spectra estimated for every point was averaged 7 times.

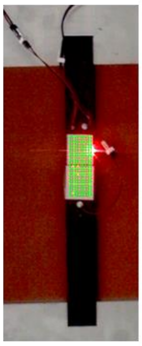

Figure 4: Measuring grid for tested sample.

For every averaged samples the modulation of intensity parameter was calculated according to formula

$$\mathrm{R} = \frac{A_1 + A_2}{A_0}$$

where A_1, and A_2 are amplitudes of the first right and left sidebands and A_0 is the amplitude of high frequency acoustic wave.

5 RESULTS AND DISCUSSION

Power spectra were calculated from the acoustic response signals. The spectra were zoomed around the fundamental acoustic harmonics in order to reveal possible modulation sidebands. The amplitude of these sidebands was analyzed. Figure 5 shows examples of zoomed power spectrum for the 300 kHz ultrasonic and 500Hz modal combined excitations.

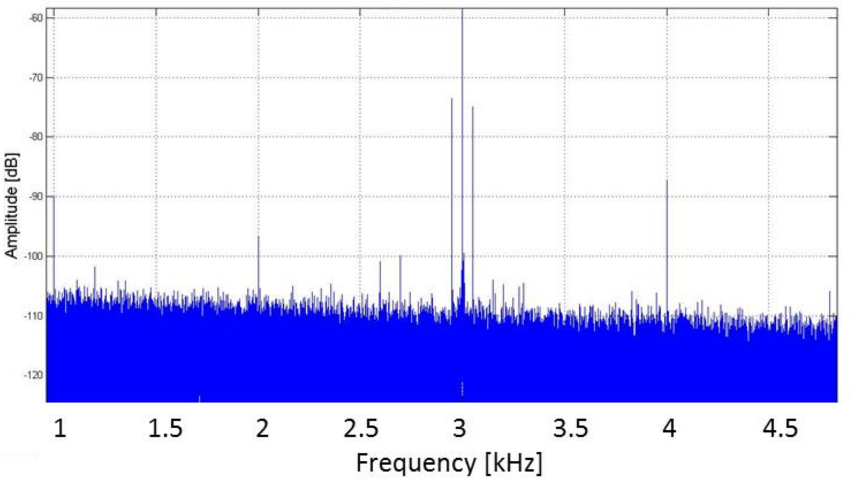

Figure 5. An example of ultrasonic response power spectrum for nonlinear acoustic test.

The modulation sidebands – corresponding to the frequency of the vibration/modal excitation – around the fundamental 30 kHz ultrasonic component can be clearly observed in Figure 5 for the samples with Teflon insertion. It is clear that these sidebands are exhibited by the nonlinear vibro-acoustic interaction due to the lack of bonding in the lap joint. To obtain the modulation intensity distribution on the specimen surfaces, the R parameter was calculated for all points form measurement grid. Figure 6 presents a modulation intensity distribution along *x* axis of the samples for specimen with good adhesion and Teflon insertion.

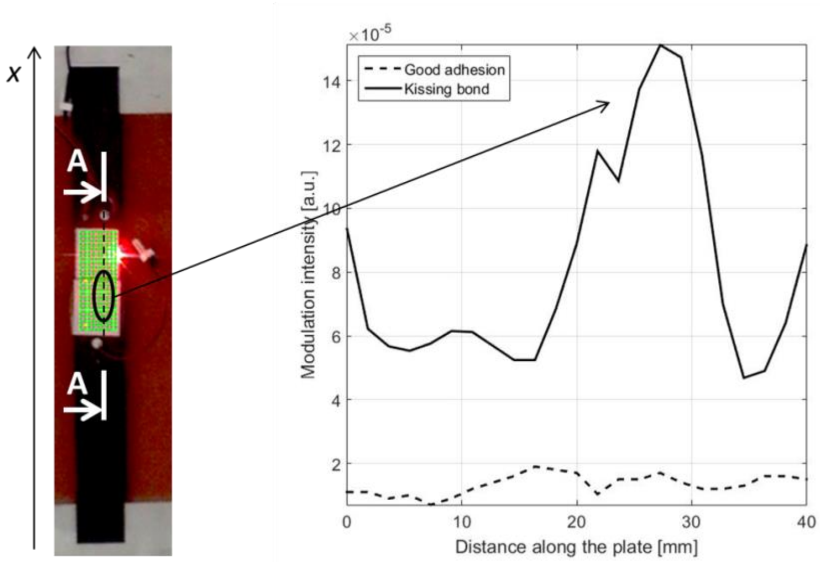

Figure 6. Modulation intensity distribution along tested sample.

As can be seen the maximum of modulation intensity R for sample with kissing bond coincides with the area of Teflon insert while only a small increase in the R parameter is observed for sample with good adhesion.

6 CONCLUSIONS

The paper presented a preliminary study on the application of the nonlinear vibro-acoustics modulation technique for kissing bonds monitoring. Nonlinearity in the system that was analyzed was represented by the intensity of modulation parameter R. The results demonstrate that it is possible to identify the imperfections of bonding using the proposed technique. The modulation intensity increases significantly when the Teflon patch was inserted between the adherends in the lap joint.. Despite the encouraging results of this preliminary study, further research with more accurate models of kissing bonds are required. Future work should also attempt to find the optimal parameters (i.e. low and high frequency of excitation) of vibro-acoustic modulation test.

ACKNOWLEDGMENT

The research was financed by the Foundation for Polish Science (FNP) within the scope of the WELCOME Programme - project no. 2010-3/2.

REFERENCES

[1] Adams RD, Comyn J and Wake WC (1997) Structural Adhesive Joints in Engineering. 2nd ed. London, UK: Chapman and Hall.

[2] Da Silva LFM, Dillard D a., Blackman B, et al. (2012) Testing Adhesive Joints, Best Practices. Testing Adhesive Joints, Best Practices, John Wiley & Sons.

[3] Nagy P (1991) Ultrasonic detection of kissing bonds ad adhesive interfaces. Journal of Adhesion Science and Technology, 5(8), 619–630.

[4] Brotherhood CJ, Drinkwater BW and Dixon S (2003) The detectability of kissing bonds in adhesive joints using ultrasonic techniques. Ultrasonics, 41(7), 521–529.

[5] Rothenfusser M, Mayr M and Baumann J (2000) Acoustic nonlinearities in adhesive joints. Ultrasonics, 38(1), 322–326.

[6] Yan D, Drinkwater BW and Neild S a. (2009) Measurement of the ultrasonic nonlinearity of kissing bonds in adhesive joints. NDT and E International, 42(5), 459–466.

[7] Donskoy, D. M. and Sutin, A. M., “Vibro-acoustic modulation nondestructive evaluation technique” Journal of Intelligent Materials Systems and Structures, 9, 765–775, (1999)

[8] Klepka, A., Pieczonka, L., Staszewski, W. J., and Aymerich, F., “Impact damage detection in laminated composites by non-linear vibro-acoustic wave modulations”, Composites Part B: Engineering, 65, 99-108, (2014)

[9] Van Den Abeele K, Johnson P A and Sutin A 2000 Nonlinear Elastic Wave Spectroscopy (NEWS) Techniques to Discern Material Damage, Part I : Nonlinear Wave Modulation Spectroscopy (NWMS), Res Nondestr Eval, 12 17–30.

[10] Klepka, A., Pieczonka, L., Staszewski, W. J., and Aymerich, F., “Impact damage detection in laminated composites by non-linear vibro-acoustic wave modulations”, Composites Part B: Engineering, 65, 99-108, (2014)

[11] Pieczonka, L., Ukowski, P., Klepka, A., Staszewski, W. J., Uhl, T. and Aymerich, F., “Impact damage detection in light composite sandwich panels using piezo-based nonlinear vibro-acoustic modulations”, Smart Materials and Structures, 23(10), 105021, (2014)