Investigation of nonlinear effects for contact-type interfaces in vibro-acoustic modulation test.

A. Klepka*, K. Dziedziech*, J. Mrówka*, J. Górski*

* Department of Robotics and Mechatronics, AGH University of Science and Technology
email: klepka@agh.edu.pl;

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ABSTRACT

The paper presents experimental investigation of nonlinear effects in vibro-acoustic modulation test, generated due to contact-type nonlinearity. The two samples with prepared contact surfaces were tested in experimental works. Two excitation types: low and high frequencies are introduced into the structure via electromagnetic shaker and piezoelectric transducer respectively, to produce contact-related nonlinear effects. The contact surfaces are driven to move relative to each other in two types of motion: micro slip and stick and slip. The motion types are classified according to displacement values using laser vibrometer. For given scenario the analysis of nonlinearities is performed based on signal response. The paper focus on investigation of both sidebands distribution around carrier frequency and higher harmonics of low frequency excitation.

1. Introduction

Recently, non-linear techniques of damage detection and localization have become more and more popular. The possibility of selective excitation of structures together with improved measurement methods cause that effects associated with non-linear behaviour of damage can be observed for very early stage of failure. This is one of the main reasons why non-linear techniques are still attractive for both structural health monitoring and non-destructive testing. Additionally the methods can be apply for complex composite structures and anisotropic materials as well as metallic structures and isotropic materials. Non-destructive damage detection methods are constantly evolving. The reason for that is that demand of increasingly complicated engineering structures still growing. The use of advanced materials causes that the quality control process requires more and more accurate techniques to detect material imperfections. An example can be composite materials. The number of composites structures used as responsible structural elements has considerably increased over recent years. Unfortunately, despite the mechanical properties (often better than metallic equivalents), corrosion and aging resistance, composites also have some drawbacks. The first main problem is the production process due to ensure repeatability of mechanical parameters of the composite structures. Very often, composites contains delaminations or structural discontinuities already at the production stage. The second main problem is poor resistance of composite structures to Low Velocity Impacts (LVI). In both cases, the signs of damage does not have to be visible with the naked eye. Usually have the form of intra-structured delamination but the outer layer remains intact. This types of defects are very difficult to detect. The specialized techniques have to be used to assess the structure. For metallic structures the similar difficulties occur. In metal, damage develops in a visible way. It is possible to observe the damage propagation process (e.g. fatigue damage) but in many cases this is difficult due to the lack of access to

* Corresponding author. This is useful to know for communication with the appropriate person in cases with more than one author.
structural elements. Examples are riveted joints, which in many cases the fatigue crack is initiated under the surface of the rivet head.

Common feature of metallic and composite materials, in the case of damage (delamination or fatigue crack), is possibility of use non-linear methods for damage detection and localization. For both cases, the damage can be assumed as contact type damage. Delamination and fatigue crack have a contact interface. It is formed as a result of loss of material consistency. When the contact interfaces are forced to vibration, then surfaces starts to interact with each other and produce nonlinear effects. The effects can be produced various mechanisms. Many hypotheses about the origin of these effects can be found in the literature. One of them is non-linear stiffness characteristic of damaged structure\[^1,2\]. This characteristic depends on relative motion type of contact surfaces and changes over contact conditions. There are two motion types between the contact surfaces is predicted: in-plane and out of plane. Figure 1 presents predicted cases of motion type\[^3\].

The following stiffness characteristics for the relative displacements shown above are assumed. When the out-of-plane movement occurs the closing/opening action of delamination or fatigue crack (“clapping mechanism”) is predicted. It is mean that stiffness is different for tension and compression phase and bi-modular stiffness causes pulse-type modulation of material stiffness. In this case the frequency domain representation of the signal response contains the fundamental frequency of excitation (movement) equal to frequency of closing/opening action and sets harmonics of fundamental frequency. The second case is related to tangential relative motion of damage surfaces (in-plane motion). In this case the stiffness characteristic is changed twice per cycle because the effect is independent from direction of motion. For this reason the symmetrical stiffness characteristic can be assumed. In the signal spectra only odd harmonics of fundamental frequency appears. For In-plane motion the two phases of movement can be recognized. The firs is micro-slip and occurs when the excitation amplitude is low. Then the static friction forces can be broken and the movement take place between neighbouring asperities. The stiffness characteristic for micro-slip mode can be assumed as piecewise linear. When the static friction forces are broken the surfaces starts to slide relatively to each other in stick and slip mode. In this case the cyclic changes for stick and slip phase. This turns the characteristics into hysteresis. When the hysteresis is symmetrical only odd harmonics of excitation frequency are visible in the spectra of the response signal\[^4\]. The examples of stiffness characteristics for different motion type presents Figure 2.

![Figure 1. Different type of motion for damage: out-of-plane (a) and in-plane (b).](image-url)
Figure 2. Stiffness characteristics for different motion type: clapping mechanism (out-of-plane motion) (a), micro-slip (b) and stick and slip (c).

2. Vibro-acoustic modulation

There are a lot of nonlinear acoustics methods allow to damage detection and localisation. All of them based on damage related non-linear effects generated as result damage and excitation interaction. Many application of these methods can be found in literature. This include methods based on higher harmonics\(^5,6\) and sub-harmonics analysis\(^2,7\), modulation transfer\(^8–10\), Local Defect Resonance phenomena\(^11,12\), frequency mixing and shifting\(^13\) and vibro-acoustic modulation\(^14–17\). The last technique is widely used for damage detection and localisation for structures with contact type damages. In this method the two types of excitation (introduced simultaneously) are used to force the structure to vibration. In general the frequency of these excitations can be selected arbitrary with assumption that the difference between them should be significant. The first excitation is low frequency (modal) excitation. In practice the low frequency is selected as one of the modal frequencies (related to mode shapes). This allows to obtain much higher response amplitudes with the same level of excitation signal. This excitation forced the contact surfaces to move. When the mode shapes are known then the relative direction of motion for contact interference can be assigned. The second excitation type is acoustic wave (high frequency excitation). This wave propagates through the structure (and contact area with variable stiffness). Due to non-linear stiffness characteristic the wave is distorted. This result in response signal modulation. This is manifested by the appearance of sidebands in the vicinity of high frequency acoustic wave peak. Additionally, due to nonlinearities the higher harmonics of the fundamental (low frequency) excitation can be found at the response signal spectra. In many applications the modulation intensity can be assumed as the damage index. The most common approach is to calculate it in the following way

\[
R = \frac{A_1 + A_2}{A_0}
\]
where $A_1$ and $A_2$ are the amplitude of first left and first right sidebands respectively and $A_0$ is the amplitude of high frequency excitation. The diagram of the methods presents Figure 3.

![Figure 3. The principle of vibro-acoustic modulation technique.](image)

Although the determination of this coefficient is relatively easy, its interpretation sometimes causes many problems. This is the case when the nature of nonlinearity changes with the increase of excitation or damage size. Then some harmonics or sidebands can disappear and the value of modulation intensity coefficient can be interpreted incorrectly. An example of one such case is illustrated in Figure 4 where the characteristic represents dependency between fundamental frequency amplitude vs amplitude of following harmonics is presented. It can be noticed that in the vicinity of 32dB there is a sudden change in the slope of the characteristic for the 2nd and 3rd harmonics. This means that the type of non-linearity changes and thus the harmonics and sidebands distribution is different. This change was caused by the beginning of closing / opening action of fatigue crack. For more details, see at [3].

![Figure 4. Fundamental frequency amplitude vs amplitude of 2nd and 3rd harmonics for cracked aluminium plate.](image)

The level of excitation amplitude also influence sidebands distribution. Figure 5 present the spectra zoomed around high frequency excitation peak. The structure was damaged by impact with energy 2J. Both spectra are calculated for the same parameters: low frequency excitation – 233Hz, high frequency excitation – 60kHz. The difference is only in amplitude of low frequency. For first experiment (Figure 5a) it was significantly lower.
It can be seen that in the case of a low excitation amplitude level all sidebands (even and odd) associated with the excitation frequency are visible. It suggests the non-symmetrical stiffness characteristics. For higher amplitude level (Figure 5b) only even sidebands are visible. For such distribution the symmetrical stiffness characteristics (piecewise or hysteresis) are predicted. For more details, see at [12]. The above examples indicate that there is a dependence between the amplitude of excitation and the type of nonlinearity activated as a result of damage.

The focus of the paper is on investigation of sidebands and harmonics distribution in vibro-acoustic modulation test for different excitation amplitude. The experimental work are related to in-plane motion of damage interfaces.

3. Experimental setup and procedures.

For experimental testing two C45 steel test samples with contact surface area 10x10 mm were prepared. The contact surfaces are grounded with a sand paper with the grit size P40 to obtain a rough surface. The samples have been compiled as shown in Figure 6. Modal shaker K2007E01 was attached to the upper sample. The lower has been attached to the base plate and equipped with a piezoelectric transducer. Next the transducer has been connected to high voltage amplifier. The top sample was loaded by an additional mass 200 g. The data measurement was acquired using impedance head PCB 288D01 to obtain force values and acceleration of vibration. To measure displacement data the Doppler laser vibrometer was used. The excitation signals were generated by Agilent 33500B Series generator. The sampling frequency was set at 51.2 kHz and total acquisition time was 10 sec. The experimental test rig presents Figure 6.

In the first experiment the amplitude of low frequency excitation (15Hz) has been linearly increased. High frequency excitation (15kHz) amplitude remained constant. For such signals the restoring force surface was calculated to find stiffness characteristics for different amplitude range. Based on restoring force method the displacement values for different motion type were determined. Next for amplitude level correspond to given stiffness characteristic, classical vibro-acoustic modulation test was performed. Two signals: mono-harmonic low frequency excitation (15Hz) and high frequency acoustic wave (15kHz) were introduced simultaneously to the structure with amplitudes related to identified motion types. The response signals were acquired as previously.
Figure 6. Experimental test rig.

4. Results and discussion.

F presents the time domain response signal for linearly increased amplitude. It is evident that although the amplitude of the excitation increases linearly, the amplitude of the structure response signal does not behave in this way. Two different ranges can be distinguish in time domain data: from 0 to 4 seconds and from 4 to 10 seconds.

Figure 7. Response of the structure for linearly increased amplitude.

Figure 8a presents the stiffness characteristics obtained for first part of the signal. The spectrum of the signal response for constant excitation amplitude from first range presents Figure 8b. The estimated stiffness characteristics can be assumed as piecewise linear. It suggest that the system is in micro-slip mode. The spectrum of the signal shows all harmonics of the fundamental frequency (instead odd harmonics). The reason for this may be the asymmetry of the stiffness characteristics. For non-symmetrical characteristics all harmonics of main component are predicted. Also all sidebands are visible when the spectra are zoomed around high frequency excitation peak (Figure 9). The amplitude of the sidebands decrease with the sidebands order up to order 4. For this order the amplitude is higher than for the order of 2 and 3.
Figure 8. Stiffness characteristic for first range of data (a), spectrum of response signal for constant amplitude from range 1.

Figure 9. The spectra of the response signal for vibro-modulation test zoomed at high frequency component (excitation amplitude from range 1).

The same analysis were performed for second range of the signal. Figure 10a presents the stiffness characteristics of response signal for range 4 to 10 second. This characteristics shows hysteresis character, typical for stick and slip relative movement of contact interface. Also spectra showed in Figure 10b show a typical distribution for hysteresis stiffness. The sinc modulated amplitude odd harmonics are dominant in this spectra. Only low amplitude even harmonics can be noticed. In case of sidebands around carrier frequency the odd sidebands are dominant (Figure 11). The amplitude of even sidebands are much lower than odd ones.

Figure 10. Stiffness characteristic for second range of data (a), spectrum of response signal for constant amplitude from range 2.
Figure 11. The spectra of the response signal for vibro-modulation test zoomed at high frequency component (excitation amplitude from range 2).

The analysis performed indicate that there is a relationship between the amplitude of the excitation (the type of relative motion of damage surface) and the non-linear effects observed in the response signal. Changing the type of relative motion triggers other mechanisms responsible for generating different non-linear effects. Different sidebands distribution suggest that in this case the reason for the change may be a different modulation type. The time domain signal for first range shows a typical amplitude modulation. To confirm the instantaneous frequency was calculated according to formula\(^{[18]}\)

\[
 f(t) = \frac{d\varphi}{dt}
\]  

where \(\varphi\) is phase of the signal. F and F present time domain signal and corresponding instantaneous frequency values. It is clearly visible that in the case of stick and slip movement, frequency and amplitude modulation occur while in the first phase of the movements there is only amplitude modulation.

Figure 12. Time domain signal (a) and corresponding instantaneous frequency (b) (excitation amplitude from range 1).
5. Conclusions.

The different motion types for contact type interfaces in vibro-acoustic modulation test was investigated. To steel samples with prepared contact surfaces were forced to sliding against each other with low frequency. At the same time the acoustic wave with frequency significantly higher than low frequency excitation was introduced to the structure using piezoelectric transducer. The restoring forces surface was used to find stiffness characteristics and identified the motion type. Base on that, it was possible to distinguish two dominant phases of movement: micro-slip and stick and slip. For the first motion type the piecewise characteristic was identified. For slip and stick the hysteresis stiffness was estimated. The instantaneous frequency for both motion type showed that two modulation types. For micro-slip the clear amplitude modulation exist while for stick and slip phase mixed amplitude and frequency modulations are visible.

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References and Footnotes

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