Experimental investigations of contact-type damage nonlinearity

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Abstract. The problem of identification of non-linear phenomena associated with contact-type non-linearity is the subject of many research papers. The number of theoretical models describing the non-linear phenomena is constantly increasing. New capabilities of experimental verification and observation of these non-linear effects provide opportunities for a more accurate mathematical description of the non-linear behavior of contact interfaces. Better understanding of the non-linear related contact mechanisms can lead to more accurate numerical models of structures with contact-types defects, damage propagation and prediction algorithms and development of new methods for damage detection. This paper presents research on the non-linear acoustic phenomena in the presence of contact-type damage. Two test samples in contact are subject to vibro-acoustic modulation test. Non-linear spectral components were analysed and compared to the temperature changes generated as a results of the frictional forces.

1. Introduction
Damage detection methods based on structural dynamics are increasingly being used. Among those techniques the nonlinear acoustics is becoming more attractive for contact-type damage. The reasons for this are: high sensitivity, easy of testing and in some cases possibility of damage localization. Problems that until now have not been resolved are: interpretation of the results and the lack of full knowledge about the mechanisms responsible for the nonlinear behavior of the damaged structures. Nonlinear acoustical phenomena can be related to many defects like imperfections of atomic lattices (intrinsic or material nonlinearity) and/or thermo-elastic behaviour of interfaces (e.g. cracks or contacts) and many others [1,2,3]. The first are related to material nonlinearity and they have been intensively investigated for sixty years [4,5]. The second group are local nonlinearities. Work on the explanation of the phenomena responsible for the local nonlinear effects associated with contact-type damage has been underway for 20 years but in many cases the results allow only for formulating hypotheses related to these phenomena. The reason for that is a variety of proposed contact related nonlinear mechanisms and fact that the similar nonlinear effects can be manifested by different mechanism and vice versa. Additionally it is very difficult or impossible to separate an assigned specific nonlinear mechanism to specific nonlinear effect. As a result, the nonlinear characteristics allow in easy way to determine damage existence when the baseline methods are applied. Due to the lack knowledge of the phenomena occurring in the structures with contact-type damage, it is extremely hard to interpret the results obtained without the knowledge about the states before failure. Physical understanding of nonlinear mechanisms involved is thus very important for implementation and real engineering applications.
The major objective of the paper is to investigate the nonlinear effect related to the contact phenomena during vibro-acoustic modulation test. The case related to friction mode of damage is investigated. The structure of the paper is as follows. Section 2 presents the general information about nonlinear acoustics. In Section 3 the experimental setup and procedures are described. Section 4 concerns on result discussion. Finally, the article is concluded.

2. Nonlinear mechanisms of contact.

The contact nonlinearity phenomenon is investigated for many years. Classically the two main mechanisms caused signal distortion are “clapping” mechanism and nonlinear friction mechanism. The first one comes from asymmetry of stress-strain relation when the two surfaces are driven by acoustic wave [6,7]. The wave has to produce enough stress to move surface interface. During compression phase the stiffness is higher than during tensile phase when the surface are in partial contact or without the contact. This phenomenon can be approximated by a piece-wise/bilinear stress-strain relation. The characteristic is presents in Figure 1.

\[
\sigma = K \left[ 1 - H(\varepsilon) \frac{\Delta K}{K} \right] \varepsilon
\]

(1)

where \(H(\varepsilon)\) is Heaviside function and \(\Delta K = K - \frac{\partial \sigma}{\partial \varepsilon}\) for \(\varepsilon > 0\). The bi-linear contact caused by a harmonic acoustic wave results in pulse-type modulation of material stiffness and wave deformation. As a result of wave distortion the higher harmonics (even and odd) of the fundamental acoustic wave appear in the response signal spectra.

The second non-linear mechanism which causes changes in stiffness characteristic is related to friction forces between the surfaces. If the amplitude of share wave is low, the damage interfaces are displaced in micro-slip mode between the neighboring roughness areas. This effect is independent of the direction of motion and additionally changes the stiffness characteristics twice (symmetrical non-linearity). In this case only odd harmonics are generated in spectra of the system response. When the amplitude of the acoustic wave increases enough, the contact static friction forces become broken. Then the surfaces of the crack starts sliding relatively to each other in stick and slip mode. This means that first, the asperities coupled by adhesion force deform elastically and then plastically (slip) [10,11]. It causes a cyclic change between static and kinematic friction phase which turns strain–stress characteristic into hysteretic [12,13]. As in the case of micro-slip mode, changes are independent of the direction of displacement and change stiffness twice per one cycle of loading, causing generation of only odd harmonics. Figure 2 presents stress–strain characteristics for micro-slip as well as stick and slip mode.

Figure 1. Stiffness characteristic (a) and wave deformation for “clapping” mechanisms.

Figure 2 presents stress–strain characteristics for micro-slip as well as stick and slip mode.
Besides the classic mechanisms associated with the interaction of the acoustic wave and the surfaces in contact, there are other sources that are not fully explained. Although bilinear stiffness effects a modulation in case of vibro-acoustic modulation test the experimental evidence that the cyclic contact is not the only mechanism involved his effect. Studies have shown that in the case of the wave amplitude is incapable of moving surfaces (cause opening / closing action) of the fatigue crack, the modulation still occurs. Tests have shown that this has to do with the temperature field generated in the contact area [1]. Another neoclassical phenomenon observed for contact type damage is modulation transfer. When the structure is excited by pumping and probing wave, the modulation is transferred from pumping to probing frequency [14]. This phenomenon is compared with Luxembourg-Gorky effect, observed for the first time for radio waves. In work [15] authors concluded that the reason of modulation transfer are dissipative mechanism and strong thermoelectric losses at the defect. Additionally the effect like frequency shift[16], memory effect [17], DC component [18] or hysteretic behavior can be observed for contact-type damage.

3. Experimental setup and procedures.

The experimental work performed focused on the friction forces in case of contact between two surfaces excited simultaneously by low frequency and high frequency acoustic wave. Classical vibro-modulation technique uses these two excitations to induce nonlinear effect in case contact-type damage. It is very important to select the low frequency properly. The most common approach is to select it as a one of the natural frequency of the structure. The natural frequency is related to mode shape. This causes determined moves of surfaces and produce different nonlinear effect. Classically the three crack mode can be defined [1]:

- Crack mode-I – crack faces move directly apart from each other (opening–closing mode);
- Crack mode-II – crack faces slide on each other in the direction perpendicular to the leading edge of the crack (sliding mode);
- Crack mode-III – crack faces move relative to each other and parallel to the leading edge of the crack (tearing mode).

Specified modes are presented in Figure 3.
To find the mode shapes of the investigated structure the modal test is performed. Then after selection proper low frequency excitation, the vibro-acoustic modulation experiment can be carried out. Two excitations are simultaneously used to excite the structure. One is the low/modal frequency and the second is high frequency acoustic wave. Schematically, the experiment steps are shown in Figure 4.

As a result of interactions low and high frequency excitations and contact interfaces the response signal can contain a lot of nonlinear components such as higher and subharmonics and modulation. Classical approach assumes that the nonlinear effects are related to closing/opening action caused by low frequency excitation, schematically presented in Figure 5.
On the other hand, there are experimental evidence that, besides the classical modulation mechanism, there are others, causing modulation despite the lack of relative displacement between the contact surfaces. In the experiment the frictional nonlinear mechanisms are investigated. Two samples were made from C45 steel. Overall dimensions of the test sample were 40x40x45 mm, with the contact surface of size 10x10 mm. The contact surfaces were grinded with sand paper with the grit size P1500 to obtain smooth surface and remove the trace of milling tool. After sanding, surfaces were cleaned and degreased. The one of the samples was fixed to ground. The second one has been set that the relative motion between contact surfaces occurred in one axis only. The second block was also attached to the electromagnetic shaker. The bottom sample was equipped with piezoelectric transducer for high frequency excitation. The top sample was loaded by extenders with mass from 0 to 500g. The experimental setup is shown in Figure 6.

![Figure 6. Experimental setup.](image)

4. Result and discussion.
In the first step the classical vibro-acoustic modulation test was performed. The structures were simultaneously excited by different low frequency excitation. In the same time the 45kHz acoustic wave was introduced to the structure. The temperature changes were monitored by high sensitive thermographic camera. Tests were conducted a number of times to check the repeatability of the responses. For different loading level and excitation frequency, the temperature changes were measured. The temperature profiles are presented in Figure 7.

![Figure 7. Temperature change profile for different frequencies and loading level.](image)

It can be noticed that temperature changes during test were dependent on loading level and excitation frequency. Their behavior was different for different loading levels. At higher loading levels very small
changes of temperatures were observed. Maximal temperature changes occur for loading level M1 and M2.

The examples of response spectra for low frequencies 6 and 16 Hz are presented in Figure 8.

![Figure 8](image)

**Figure 8.** Response spectra focused on vicinity of high and low frequency for 6Hz (a,b) and 16Hz (c,d) low frequency excitation.

Next the 1\(^{st}\) and 2\(^{nd}\) harmonics analysis was performed. The excitation amplitude was set to 0.4V. The low frequency was changed from 4 to 20Hz with step of 2Hz. The high frequency acoustic wave parameters were kept constant (45kHz@100V). The amplitude of the 1\(^{st}\) and 2\(^{nd}\) harmonics for different loading are presented in Figure 9.

![Figure 9](image)

**Figure 9.** 1\(^{st}\) (a) and 2\(^{nd}\) (b) harmonics of fundamental frequency for different loading level at different excitation frequency.
As can be noticed the amplitudes of harmonics changed with both excitation frequency and loading level. First the amplitudes increase with frequency values. For different loading levels they reach maximum values at different frequencies and start to decrease. For all cases of loading levels the shape of characteristics is similar.

The next analyses are related to sidebands level. The sidebands amplitude for different frequency excitation and loading level are presented in Figure 10.

![Figure 10. 2nd (a) and 3rd (b) sidebands amplitudes for different loading level at different excitation frequency.](image)

Sidebands levels for M0 and M1 are lowest. It is caused by weak contact between surfaces. Then the high frequency wave is attenuated. Curves related to 2nd sidebands shows different behaviour then 1st harmonics characteristics as shown in Figure 9a (except loading level M3). Regarding the 3rd sidebands for loading levels M2, M3 and M4, the characteristic shape resembles the 2nd harmonic.

In-depth analysis of above presented characteristics leads to conclusion that temperature changes for different loading levels in most cases are related to amplitude changes of given non-linear spectral components (harmonics and sidebands), this could confirm that there is a clear link between temperature generated as results of frictional force acting (temperature field) and non-linear effect related to contact phenomenon.

5. Conclusions.

The non-linear effects related to the contact phenomena in vibro-acoustic modulation test was investigated. Harmonic and sidebands amplitudes were analysed with respect to temperature changes related to friction in contact phenomena. Presented results confirms that temperature filed could correspond to generation of non-linear effects related to contact phenomena. The different behaviour of sidebands and harmonics can be observed for different loading but the shape of the characteristics match to the temperature profile in most cases. This could mean that the distribution of the temperature field generated due to the friction forces have a contribution to generate nonlinear effects observed in the response signal. Finding the relationship between these two phenomena could contribute to understanding of the contact related non-linear mechanisms.

Future works should consider analysis of roughness of the surfaces in contact, as well as different low and high frequency amplitudes of excitations.
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