Nonlinear Ultrasonic Damage Response to Excitation Strength and Position

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Abstract A laminated carbon-fibre reinforced divinycell plate is tested by a nonlinear ultrasonic technique for damage positioning. A high-frequency air-coupled transducer plate is placed above the plate surface, and a low-frequency contact source is fixed at one end. The high-frequency wave field fulfills the open resonator criteria making it localized inside the plate. The nonlinear damage response position is obtained by moving the high-frequency source on either side, having fixed sensors on both plate sides. Further, the nonlinear damage response is measured to change approximately linear with increase in high-frequency, or low-frequency, amplitude.

Keywords Nonlinear nondestructive testing, Acoustic open resonator, Air-coupled transducers, Non-contact transducers, Nonlinear acoustic imaging.

1. Introduction

The use of composites is rapidly increasing and is strongly competing with the use of metals since composites can be very strong while having comparatively low weight. Even in critical structures like airplane wings, ship hulls etc. the use of composites is great and desirable. Therefore there is a demand of understanding the damage process for composites and how nondestructive testing techniques can be used. Using ultrasound inspection like pitch-catch methods can be difficult since the transmission for many frequencies is very low [1]. Another problem is the waves being trapped in wave guides in the different layers, allowing only one layer to be inspected. New more promising methods has been developed using nonlinearity parameter evaluation. The advantage to study the nonlinearity is that defects like cracks and delaminations are strongly coupled to nonlinearity and is a measure of the health status of the tested object.

The nonlinear acoustic methods are sensitive to material damage such as micro-cracks and fatigue [2], [3], [4]. The damage response is often obtained as a nonlinear response to a mix of two input signals - a continuous single high-frequency sinusoidal, and a broadband low-frequency transient [5].

When damage like a crack or delamination is present, the high frequency, \( \Omega \), in the output spectrum is found to be modulated by some of the test objects model low frequency resonant, \( \omega_1, \omega_2, \omega_3, \ldots \). This modulation shows up as sidebands, \( \pm \omega_1, \pm \omega_2, \pm \omega_3, \ldots \), and indicates the presence of damage. The basic property of this method is that it interrogates the complete object at once, which is many times an advantage. On the other hand, for complicated structures it may be impossible to test the complete object in one test. Additionally, the position of the damage may be a necessary output parameter when dealing with structures like buildings, airplanes and ships.

The work in this paper deals with aspects of the localization techniques with non-contact transducers described earlier [6], [7], [8]. Other air-coupled techniques have been described in for example [9], [10], [11].

2. Experimental methods and test object

An estimation of the nonlinear parameter from the modulation spectroscopy is determined by the area of the sidebands in the frequency spectrum of a measured signal - the shaded area in Figure 1. When no damage is present the amplitudes of the sidebands are low or not present at all, and the sideband amplitudes increase with damage. To generate the low frequency waves that interact with the high frequency in the defect region, the test object is excited at some of its modal frequencies. In this work an electrodynamic shaker (LDS V-406) was used to sweep sine waves 30-3000 Hz in 20 ms. The high frequency acoustic wave is introduced into the test object by a transducer, which is non-contact in order to be easy to move above the structure. The transducer is fed a continuous sine wave amplified by a Krümm-Hite 7500 amplifier to the range of 25 to 200 volts. The response measurement is made by an acoustical response standard piezo ceramics, pzt27, which is glued to a fix position on the structure. During the test of transducer wave field a Stanford Research Systems 844 lock-in amplifier recorded the signal. For the analyzes and quantification of the nonlinear parameter a LeCroy6050M digital oscilloscope was used.
The test object is a laminate of carbon fibre 5.5 mm reinforced divinylcëll core of 60.0 mm in a sheet of 1.5 times 1.5 meter. Between the core and one of the carbon reinforcements intentional delaminations were introduced at the manufacturing. The high-frequency excitation is taking place through an air-coupled transducer set at a distance of approximately 10 mm from the object surface - see Figure 2.

![Figure 1](image-url)

**FIGURE 1.** The nonlinearity estimation is done in the frequency domain by the sideband area determination.

3. Transducer wave field

The transducer used here is aimed at acting as an open resonator and some basic criteria for that is described in [6], [7]. The acoustic wave must have good transmission to be able to excite nonlinearities through the laminate to be detected on both sides of the test object. Several frequency sweeps over a large frequency region was used to determine an appropriate operating frequency for the high frequency transducer. It was found that 125 kHz satisfies all above described conditions and the transducer wave field is presented in Figure 3, where the wave field is assumed to be symmetrical for the center of the transducer.

The damage response is a nonlinear mix by two separate input signals: one high-frequency from the non-contact transducer (A in Figure 2), and one low-frequency. The low-frequency wave field is present everywhere in the object, while the high-frequency field is made to have much higher amplitude in the region under the transducer [7], [8]. It is this wave field that results in the localization of the response. Therefore the shape and extent of this field is important for the position accuracy estimation.

![Figure 2](image-url)

**FIGURE 2.** The transducer wave field response set-up.

In Figure 3 the amplitude response of the high-frequency amplitude is shown as a function of distance from the transducer center. The solid line is measured on the top surface of the plate (the same side as the transducer). The dotted line is measured on the bottom surface of the plate (opposite side from the transducer). The frequency is 125 kHz which fulfills the conditions for an open resonator. The curves show that the wave field on the top layer is more uniform in radial direction than the wave field on the bottom layer. On the bottom layer the energy found inside the transducer radius is considerably higher, and the change in amplitude takes place at the transducer edges. Comparing the amplitude within the transducer radius at both layers the response amplitude is of the same order.
4. Damage response dependence on transducer position

Knowing the transducer wave field we can estimate how far from the center of the non-contact transducer that a non-linear damage response is expected. Now we may investigate the different positions of excitation and sensing in relation to the damage vertical position.

In the investigation of objects the position of damage are found by the use of a fixed position low-frequency source (B in Figure 4), a variable position high-frequency non-contact source (A<sub>d</sub> and A<sub>o</sub> in Figure 4), and fixed position sensors (C<sub>d</sub> and C<sub>o</sub> in Figure 4). The object under investigation has damage close to one of the surfaces - the top layer. The damage response will be recorded for the four different cases of the high-frequency transducer being on the damaged side and on the un-damaged, and for the sensor being on the damaged side and on the un-damaged. The low-frequency source wave field from B is made to be independent of sides.

![Figure 4. The nonlinear damage response set-up](image)

The graphs in Figure 5 are nonlinear damage results from a test where a known calibrated delamination ranges from position 15 to 20 cm. In the graphs are seen also another un-intentional damage that range from position 4 to 6 cm. The plots of the damage response are shown in the following positions in Figure 5a: A<sub>d</sub>-C<sub>d</sub> solid line, diamond marks; A<sub>d</sub>-C<sub>o</sub> dash dotted line x marks; A<sub>o</sub>-C<sub>d</sub> dotted line plus marks; A<sub>o</sub>-C<sub>o</sub> dashed line, circular marks.

For the case A<sub>d</sub>-C<sub>d</sub> it is as expected since the nonlinear parameter increase as soon as the wave field reach the boundary of the delamination. Also, a new defect was found at about 5 cm.

The case A<sub>d</sub>-C<sub>o</sub> indicate the delamination boundaries. Since the transducer is on the same side as the delamination, the nonlinear parameter is of the same order as for the case A<sub>d</sub>-C<sub>d</sub>.

When putting the open resonator on the opposite side as the delamination, as cases A<sub>d</sub>-C<sub>d</sub> and A<sub>d</sub>-C<sub>o</sub>, the nonlinear amplitude is essentially decreased. The combination A<sub>d</sub>-C<sub>d</sub> indicates the same new defect and the known delamination. But it has much lower amplitude compared to the previous two cases.

For case A<sub>d</sub>-C<sub>d</sub>, the new defect and the previously known delamination are not indicated in agreement with the earlier combinations, and it seems that other nonlinear sources might be present on the side opposite the known delamination.

Detecting delamination on the same side as the delamination, C<sub>d</sub>, the nonlinear response is higher than if measuring on the opposite side as the delamination, C<sub>o</sub>.

![Figure 3. The wave field inside the object as a function of radius for the frequency 125 kHz.](image)
FIGURE 5. The nonlinear damage response for the four combinations of excitation and sensing placements.

Determination of the damage position is most clear when the excitation and the sensing are made on the same side as the delamination damage. As the position of the delamination often is unknown, a combination of cross transmission-receiving would be preferable. Most often it is for practical purposes, and sometimes demanded, that the excitation and sensing are on the same side, which means that the cases of $A_d-C_d$ to $A_o-C_o$ are of main interest. In Figure 5b those two curves from Figure 5a are compared on different amplitude scales and it is seen that both these cases are probably usable.

5. Damage response amplitude dependence on the signal strength

The damage response level is obtained from the nonlinear mixing of the low-frequency and the high-frequency waves, resulting for example in sidebands around the high-frequency in the frequency domain. The response amplitude dependence on the amplitudes of the two mixing waves is an important factor in the damage level assessment. This dependence will here be tested for different levels of amplitudes for both the high and the low frequency signals. In the first test, the high-frequency input amplitude to the open resonator transducer is held constant at 100V while varying the low-frequency input amplitude of the shaker. In the second test, the input amplitude to the shaker was held constant at index 6 while varying the high frequency input amplitude. The position of the high-frequency transducer is fixed (see A Figure 6), as is the low-frequency shaker source (B in Figure 6). In the fixed sensors $C_d$, $C_o$ and $C_u$ the nonlinear damage response is measured as well as the high-frequency amplitude.

FIGURE 6. Set-up for the high- and low-frequency dependence measurement.
The measurements showed a large variance, so there were five taken for every amplitude set. All of the individual points are shown in the graph in Figure 7. Making a linear curve fit of their average show the slope dependence of the nonlinear parameter in all measurement points for both the high amplitude and the low frequency amplitude. The results for the low frequency amplitude dependence: $A_{C_d}: 2.42^* \text{ LFamp}, A_{C_o}:-0.02^* \text{ LFamp}, A_{C_d}:-205^* \text{ LFamp}$ and for the high frequency dependence: $A_{C_d}: 7^* \text{ HFamp}, A_{C_o}:-0.8^* \text{ HFamp}, A_{C_d}:-11^* \text{ HFamp}$.

![Graph showing nonlinear parameter vs. amplitude](image1.png)

**FIGURE 7.** 7a: the nonlinear damage response with varying high-frequency signal amplitude and constant low-frequency amplitude. 7b: the nonlinear damage response with varying low-frequency signal amplitude and constant high-frequency amplitude. 7c: the amplitude of the high frequency wave transmitted from the open resonator.

The nonlinear damage response is dependent on the wave field from the open resonator. On the top of the laminate and directly under the open resonator, the nonlinear response have a linear dependence while on the bottom position outside the wave field the nonlinear response have no dependence on the excitation amplitude.

6. Discussion

We have shown the possibilities of using ultrasonic open resonator to be used for localization of damage delaminations for NDT purposes. The test was performed with an air-coupled transducer on a sample with a calibrated delamination damage close to one surface of a plate. First, these results show that the wave field is different in the top layer from the bottom layer, which is usable for damage localization. Secondly, by moving the transducer and for different top-bottom combinations of transducer and the receiver, indications of delaminations can be made more clear. In a practical NDT situation having the transducer and the receiver on the same side might be a demand. Excitation strength is shown as being an important parameter. Also here the results indicates the differences having the transducer and receiver on the same and on different sides of the laminate.

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References


