METHODS FOR NONLINEAR ULTRASONIC SPECTROSCOPY

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ABSTRACT

The nonlinear ultrasonic testing is quite prolific method but it has some limitations in practical testing, mainly for inhomogeneous materials. Materials with undamaged structure are essentially linear in their response, while the same material, when damaged, becomes highly nonlinear. In spectrograms is it represented by harmonics and sideband generation. The nonlinear ultrasonic spectroscopy is evolved as a new way to improving the NDT and it offers some new possibilities for the NDT. This is the basis for nonlinear wave diagnostics of damage, methods which are remarkably sensitive to the detection and progression of damage in materials. This paper offers analysis, principles and basic methods for nonlinear ultrasonic spectroscopy and also contains their limitations.

1 INTRODUCTION

Present ultrasonic non-destructive testing methods of material are based on analysis of elastic wave reflection, absorption and interference. Determination of inhomogeneous material properties using these methods is very difficult, if small cracks or defects are distributed in all sample volume, or if dimension of such defects is comparable with the wavelength. Samples with complicated shape are difficult to analyze too. In such samples we can use non-linear effects of wave propagation and creation of higher harmonic signals in the vicinity of defects. Defects are sources of anharmonic atom potential energy and due to this anharmonicity, second and third harmonic signal is produced.

Second way uses two different source frequencies and the intermodulation products are detected. Non-linear propagation, reflection and interaction of longitudinal waves have been investigated for a long time [3], [4]. Different asymptotic approaches have been used to describe velocity variation and profile distortion of non-linear waves during these processes. The non-linear propagation, reflection of sine waves was studied in detail [5], where analytical expressions describing simultaneous propagation of two sine waves are derived.

The basic peculiarities of this problem were clarified on the basis of numerical simulation data. In the considered case the interaction of the waves amplifies the non-linear effects, which give information on material characterization by non-destructive testing.

Theoretical basis to explain new effects denoted as Non-linear Elastic Wave Spectroscopy (NEWS) is based on the results of the elasticity theory, where instead of classical Lame's constants (elastic modulus of the second order) are considered elastic constants of the third order, Murnaghams's coefficients. In these equations the elastic wave attenuation is described by complex modulus.

This new group of materiology methods is based on employing the nonlinear properties of general-type defects and inhomogeneities from the viewpoint of elastic wave propagation. The theoretical basis for the explanation of nonlinear effects connected with the propagation of elastic waves is given in [2]. In practice, two basic methods, namely, the resonance method and the non-resonance method are in use.

2 OBJECTS SHOWING HIGHLY RESONANCE BEHAVIOUR – SIMONRU(A)S

The presence of damage in materials causes significant second order and nonlinear effects on the acoustic wave propagation characteristics. The method is termed SIngle MOde Nonlinear Resonance Acoustic Spectroscopy (SIMONRAS). The behavior of damaged materials is manifested by amplitude dependent resonance frequency shifts, harmonic generation and nonlinear attenuation. The sensitivity of this method to discern material damage is far greater than that of linear acoustic methods. This approach may be applied in two ways. First, the mechanical excitement effect is enhanced. Second and last but not least, the resonance frequency shift versus the exciting signal magnitude behaviour is employed.

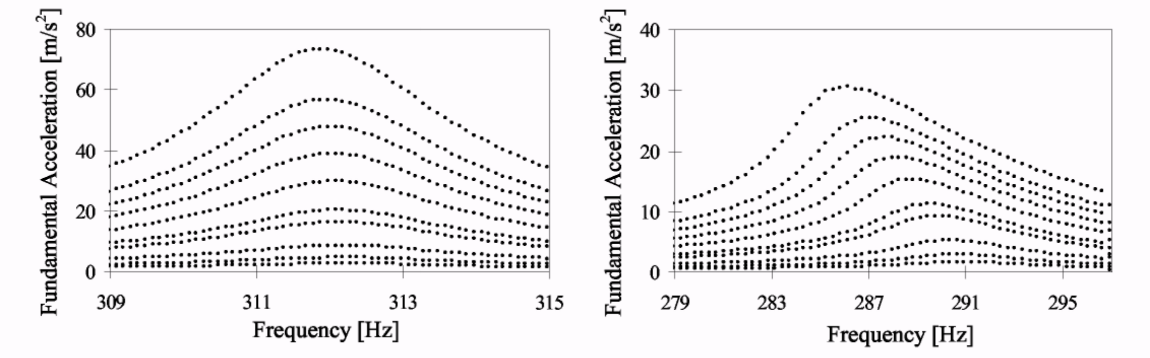


Fig. 1: *Example of frequency shift in a) undamaged sample b) damaged sample (SIMONRAS method)*

These methods are called SIMONRUS or, for lower-range audio frequencies, SIMONRAS (Single Mode Nonlinear Resonant Ultrasound/Acoustic Spectroscopy). However, these resonance methods are relatively labour intensive, because they require many measurements to be taken (measurements of frequency response curves at different signal levels), so that they are not suited for fast operational measurements.

3 OBJECTS SHOWING WEAK OR SUPPRESSED RESONANCE BEHAVIOUR

Here are usually used other non-resonance methods, which use the effect of non-linearity on the propagating acoustic wave. These effects may be divided into two basic groups:

- measurements using a single-frequency harmonic ultrasonic signal (one frequency, f1)
- measurements using two or more harmonic ultrasonic signals (two and more frequencies, f1, f2 ..., fn)

3.1 MEASUREMENT WITH ONE HARMONIC ULTRASOUND SIGNAL

In the first case (see Fig. 2) the non-linearity gives rise to another harmonic signal of frequency f_v plus further additional frequency signals, according to Fourier series expansion.

$$f_v = n\, f_1 \qquad \big| n = 0, 1, 2..\infty , \tag{1}$$

In general, the amplitudes of these components decrease when the nonnegative integer, n, increases. Similarly, due to the relatively weak effect of the non-linearity non-symmetry, the amplitudes of the second and the next even-numbered harmonic components are lower than those of the odd-numbered ones. Therefore, the dominance of the third harmonic component over the other emerging signal components is typical. This is also why its magnitude is evaluated most frequently. Evaluation of other harmonic components can provide information about the non-linearity form in several cases, but it is not commonly used, because knowledge of the different harmonic component relative magnitudes may be supposed to be of little use in the crack materiology.

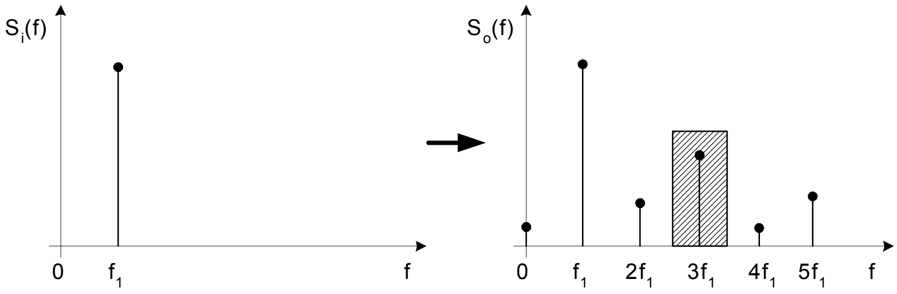


Fig. 2: *Growth of higher harmonic component magnitude in frequency spectra resulting from the propagation of a pure harmonic signal through a nonlinear environment, illustrating the selection of the dominant third harmonic component by a band-pass type frequency filter.*

3.2 MEASUREMENT WITH TWO HARMONIC ULTRASOUND SIGNALS

In the second case of two exciting frequencies f_1 and f_2 (which is most frequently used and simplest to handle), other harmonic signals of frequencies f_v arise, according to the following equation

$$f_v = \left| \pm m\, f_1 \pm n\, f_2 \right| \qquad \big| m, n = 0, 1, 2..\infty. \tag{2}$$

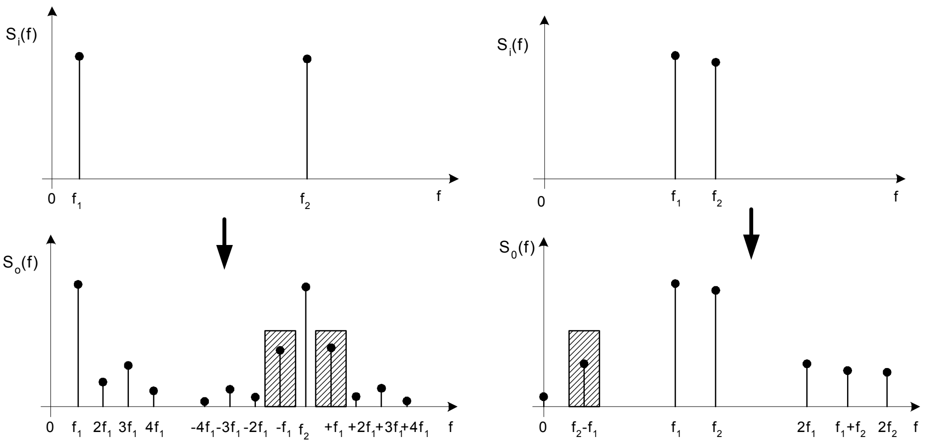
In this case, a substantially higher number of harmonic components are arising. In addition to the higher harmonics of the exciting signal, we obtain difference frequency harmonic components, which are more easily detectable. Two of the possible patterns are shown in Figure 2. For details, see the discussion below. Owing to the general amplitude decrease with increasing m and n, the most pronounced components are the first additive and difference components of frequencies

$$f_v = \left| \pm f_1 \pm f_2 \right| \qquad (3)$$

A variety of frequency ratios, f_1/f_2, may be chosen for the exciting signals. The mentioned principle is employed in the modulation ultrasonic spectroscopy (NWMS – Nonlinear Wave Modulation Spectroscopy).

Any higher number of exciting signal frequencies results accordingly in a higher number of the components to arise. However, this approach is very rarely used in view of its very low contribution to the non-linearity evaluation. From this point of view, a single-shot, i.e., wide-spectrum exciting signal may be considered a special case. Generation of the new harmonic components is hard to evaluate in this case.

Modulation ultrasonic spectroscopy (MUS) methods, which are also available, feature similarly two basic variants, which may be regarded as an analogy to AM modulation and mixing processes. In the first case, two harmonic signals whose frequencies differ from each other by order of magnitude, one of them being called the low-frequency, and the other, the high-frequency signal, are used. Their interaction with the defect gives rise to a narrowband AM signal, in which, in addition to the original frequency f_2, two sideband components, $f_2 \pm nf_1$, appear (see Figure 3a). To detect and measure the additive and difference components, either a rather sophisticated spectral analysis device may be used (providing extremely fine spectral component resolution, or lock-in detection with subsequent analysis of the audio-frequency signal. Both methods feature a limited measurement dynamic range of about 60 to 80 dB.



a) b)

Fig. 3: *Generation of new harmonic components in the frequency spectra caused by the propagation of two harmonic signals in a nonlinear medium, illustrating the selection of dominant components by means of a frequency filter: a) AM modulation (with high f_2/f_1 frequency ratio), b) AM mixing (for a low f_2/f_1 frequency ratio).*

In the second case, the mixing principle is used. The frequencies of the exciting signals are relatively close to each other and the first difference frequency component is rather low in magnitude. In this case, thanks to the relatively high difference between the exciting signal frequency and that of the difference components, direct detection of these difference components by means of a high-dynamic-range (about 120 dB or more) analog filter is an evident benefit.

3.3 MEASUREMENT WITH IMPULSE SIGNALS

The third case of the exciting signal operation comprises the measurements using an impulse signal (e.g., the so-called „instrument hammer"). This approach does not seem to be advisable because, as mentioned above, the sample is excited by a continuous spectrum signal (Dirac impulse) and the influence of nonlinear properties is difficult to detect. They are only used in the cases of an accentuated resonance response of the sample under investigation, where a wide-spectrum impulse excitation results in a narrowband harmonic response. Two examples known from everyday practice may be mentioned: (i) the sound spectral analysis carried out by human ear when a railway wagon wheel is test-knocked with a hammer, or, (ii) the change in the sound of a cracked bell.

4 CONCLUSION

The nonlinear ultrasound spectroscopy features some benefits against the classical ultrasound NDT. Lists following merits: speed, extremely high sensitivity: 10 to 1000 times as high as that of "normal" ultrasound, applicability to complicated shape samples, it is covering a large span of sample sizes (from microchips up to bridge structures), it is applicable to a wide spectrum of materials, and it is safe to apply.

Following production areas are typical for profitable application: continuous production tests for faults – car parts, bearings, machine parts, material for production process. First-line maintenance (replacement or repair is only carried out when really necessary, not earlier) – aerospace, nuclear power plants, structure (bridge) and building supporting elements.

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