

NON-LINEAR ULTRASONIC SPECTROSCOPY AS A TOOL TO EVALUATE BUILDING MATERIAL STRUCTURE DAMAGE

Marta KORENSKA¹, Michal MATSIK¹, Monika MANYCHOVA²

¹Department of Physics, ²Department of Building Structures
Faculty of Civil Engineering, Brno University of Technology, Czech Republic

Abstract

The non-linear ultrasonic spectroscopy provides new prospects in the non-destructive acoustic testing of material degradation. Detailed studies of dynamic non-linearities and hysteresis in inhomogeneous media have shown that the occurrence of mesoscopic elements in the material structure gives rise to strongly non-linear dynamic phenomena accompanying the elastic wave propagation. These non-linear effects are observed in the course of the degradation process much sooner than any degradation-induced variations of linear parameters (propagation velocity, attenuation, elastic moduli, rigidity etc.). These non-linear wave methods thus open new horizons to the acoustic non-destructive testing: they provide high sensitivities, application speed and easy interpretation that have never been achieved before. Intensive research in the field of non-linear spectroscopy of elastic waves (NEWS) has proved recently that the methods, which are based on the occurrence of non-linear effects in the spectral response, can serve as a highly sensitive tool to detect material defects. The present paper deals with a study and a research of these novel methods from the viewpoint of their applicability in the field of detecting reinforced concrete structure defects.

Key words: Reinforced concrete, corrosion cycles, structure defect, nonlinear ultrasonic spectroscopy, ultrasound harmonic signal, elastic waves, transfer characteristics, high harmonic amplitudes, nonlinear effects,

1. Introduction

Stability of building structures is one of very important issues in the field of non-destructive defectoscopy. Thanks to the stormy development of concrete and reinforced concrete buildings taking place in the last century, the condition of concrete and reinforced concrete became a hot topic in the last decade. Concrete proved to be a durable construction material in the recent years, however, concrete structures often experience degradation after years of service. Structure rehabilitation techniques have reached a high standard recently. However, the absence of an acceptable, relatively fast and cheap monitoring method, which would be capable of detecting bridge faults at an early stage, thus making a simple and cost-effective maintenance possible, is still persisting. Therefore, elaboration of new and simple defectoscopic methods, capable of determining the integrity of a given structure or a building element is of sign importance. It is also essential to develop and/or refine the methods designed to estimate the lifetime of building structures.

The reinforced concrete integrity is impaired frequently in consequence of the reinforcing steel corrosion (Korenska et al., 2005). The condition of the reinforcing steel makes an important element determining the reinforced concrete structure quality, reliability and applicability. However, the steel reinforcement corrosion deteriorates substantially the reinforced concrete structure technological properties and, consequently, reliability and service life. The reinforced concrete condition monitoring methods, which are currently most frequently used, consist mainly in visual checks supplemented with simple carbonation degree or concrete strength tests, cannot be

considered sufficient if an estimate of the structure exploitation period is required. Electromagnetic or ultrasonic methods to determine the reinforcement profile or shielding require a great amount of knowledge about the structure, thus being virtually unavailable. X-ray tests are expensive and locally limited. New non-linear acoustic spectroscopy methods appear to be very promising just in the field of non-destructive testing in the building industry.

2. Nonlinear Ultrasonic Spectroscopy

New promising non-destructive testing methods are based on the non-linear behaviour of current defects and inhomogeneities regarding the elastic wave propagation process (Abeele et al. 2000, Litwiller, 2002).

There are two groups of methods available for application: resonance and non-resonance. Non-resonance methods are used to study suppressed resonance specimens. These methods analyse the effect of non-linearities on acoustic signals propagating through them. These methods can be split into two groups.

In the first group, a single ultrasound harmonic signal is employed. The non-linearity gives rise to additional signals featuring different frequencies according to Fourier expansion. In general, the amplitudes of these additional components decrease with the natural number n :

$$f_n = n f_1 \quad | \quad n = 0, 1, 2, \dots, \quad (1)$$

Nevertheless, among the emerged signals, the third harmonic appears to be most pronounced, see Fig. 1. This is why the third harmonic amplitude is pursued by most researchers, especially in electronics (Hajek et. al., 2003).

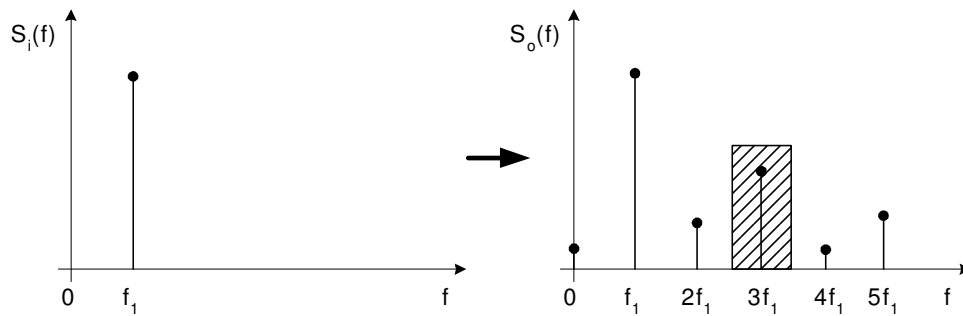


Fig. 1. Growth higher harmonic components in frequency spectra at transit pure harmonic signal through nonlinear environment with illustration of selection dominant third harmonic component by the frequency band-pass filter.

In the second case, several (usually two) ultrasound signals are applied to the specimen. The number of additional harmonic components generated is substantially higher. In addition to both exciting signals' harmonics, one gets also sum and difference frequency components.

$$f_v = | \pm m f_1 \pm n f_2 | \quad | \quad m, n = 0, 1, 2, \dots \quad (2)$$

Owing to the general harmonic amplitude versus frequency curve downward slope, the first sum and difference components are most pronounced. The application domain of the ultrasound modulation spectroscopy (usually referred to as NWMS – Nonlinear Wave Modulation

Spectroscopy) splits into two subgroups, which differ from each another by the exciting frequency ratio. Attention is paid to the second subgroup applied in experimental part. In this case, the frequency mixing principle is used. The signal frequencies are close to each other. The first difference component therefore falls into the low-frequency range as it shows Fig. 2.

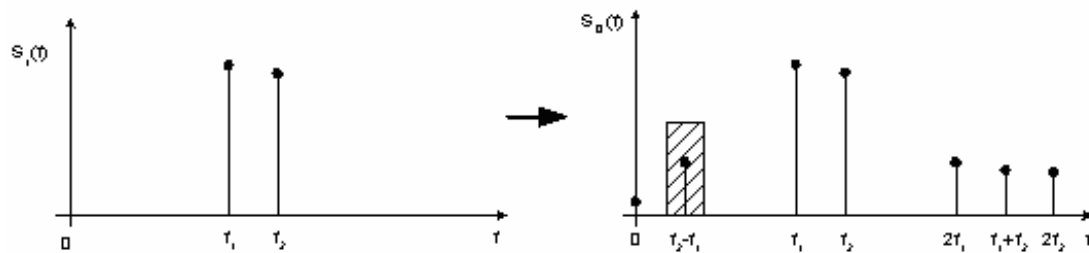


Fig. 2. Creation of new harmonic components in frequency spectra at transit two harmonic signal through nonlinear environment with demonstration of selection dominant components by frequency filter - event of mixing (with small rate of f_2/f_1).

Recently, various papers on both the theoretical and experimental examination of diverse methods and their applicability in some fields have been published. Most published papers as well as our experience show these methods to be highly promising for the defectoscopy and the material testing purposes in the near future.

One of the fields in which a wide application range of non-linear acoustic spectroscopy methods may be expected is civil engineering. Poor material homogeneity and, in some cases, shape complexity of some units used in the building industry, are heavily restricting the applicability of "classical" ultrasonic methods (Macecek, 2003). Precisely these non-linear acoustic defectoscopy methods are less susceptible to the mentioned restrictions and one may expect them to contribute to a great deal to further improvement of the defectoscopy and material testing in civil engineering (Korenska, Manychova, 2008).

3. Experimental Part

3.1. Tested Objects

Reinforced concrete joists of atypical dimensions of 50 mm x 50 mm x 360 mm, containing smooth steel bar of a diameter of 8 mm located in the joist longitudinal centre line, were studied in this experiment. Two mutual orientations of the ultrasonic transmitter – sensor connecting line with respect to the specimen longitudinal centre line were selected for the measurements, namely, the transversal orientation 1 and the longitudinal orientation 2, as is shown in Fig. 3. A set of six specimens in two degradation process stages plus a set of three reference specimens were tested.



Transversal orientation 1



Longitudinal orientation 2

Fig. 3. A location of the exciter and the sensor on the specimen under test

3.2. Experimental Arrangement

In the first measurement stage, a single harmonic ultrasonic signal method was applied. The experimental set-up and testing of its component units have been described in detail previously (Manychova, 2007) and will be only briefly described here - Fig. 4.

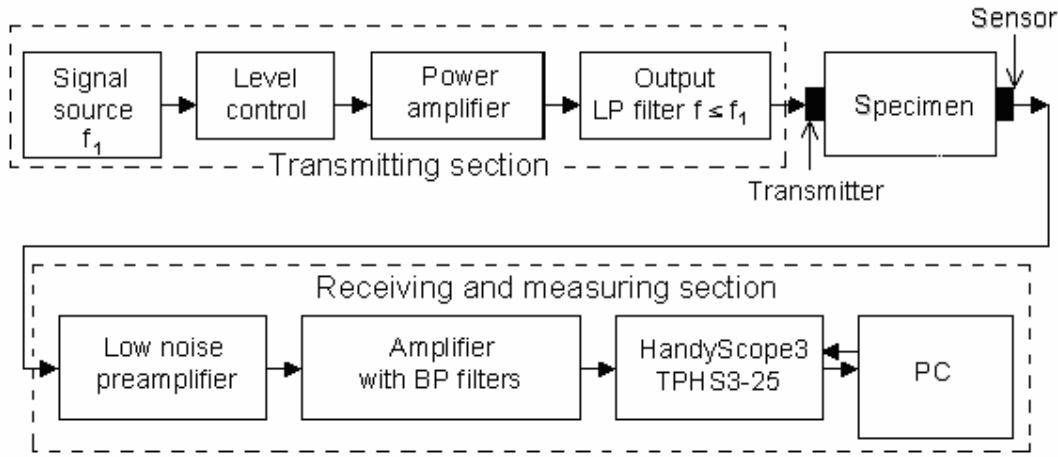


Fig. 4. Block diagram of the measuring apparatus

The measuring apparatus consists of two principal parts, namely, a transmitting section and a receiving and measuring section. The transmitting section consists of four functional blocks: a controlled-output-level harmonic signal generator, a low-distortion 100 W power amplifier, an output low-pass filter to suppress higher harmonic components and ensure high purity of the exciting harmonic signal and transmitter. The main chain of the receiving section includes an input amplifier with filters designed to minimize the receiving chain distortion and a band-pass filter amplifier. Having been amplified, the sensor output signal was fed into a THPS3-25 HandyScope3 measuring instrument to be sampled and analyzed. For the purpose of improving the reliability and accuracy of the nonlinear experiments and minimizing the error effects the attention was focused to transmission between transmitter and sensor. Elements meeting the given requirements were chosen (Korenska et. al., 2006). A program package to control the measuring process, the data processing and evaluation makes an indispensable tool. The measurement results were represented in the form of frequency spectra.

In the second experiment stage, a double-signal non-linear ultrasonic spectroscopy was applied, see Fig. 2. Usage of this method requires completing the measuring apparatus (Fig. 4) with another transmitting section. In the case of our experiment, the frequency difference fell into a frequency range below 5 kHz. From the relatively high difference between the exciting signal frequencies and the difference component frequency there results a distinctive advantage of directly detecting this difference component, provided that an analog high-dynamic-range (up to over 120 dB) pre-filtering network is used.

3.3. Experiment Results

Generation of higher harmonic frequencies for an exciting frequency of $f = 29$ kHz was studied in the first stage of experiment. The measurement results can be expressed in the form of frequency spectra, as is shown in following Figures. The spectrum of Fig. 5a) shows the measurement results obtained from a reference (intact) specimen measured under the conditions of transversal orientation. Higher harmonic amplitudes are decreasing with their increasing serial number. The surface area available for fitting the transmitter onto the specimen was restricted by the steel reinforcement in the case of longitudinal excitation. Therefore, a smaller-sized high frequency

exciter was used. The longitudinal orientation results are shown in Fig. 5b). This frequency spectrum shows again a drop of higher-frequency amplitudes with increasing serial number. Lower amplitudes, which were measured in the longitudinal orientation conditions, are due to the lower output of the HF exciter at the exciting frequency 29 kHz.

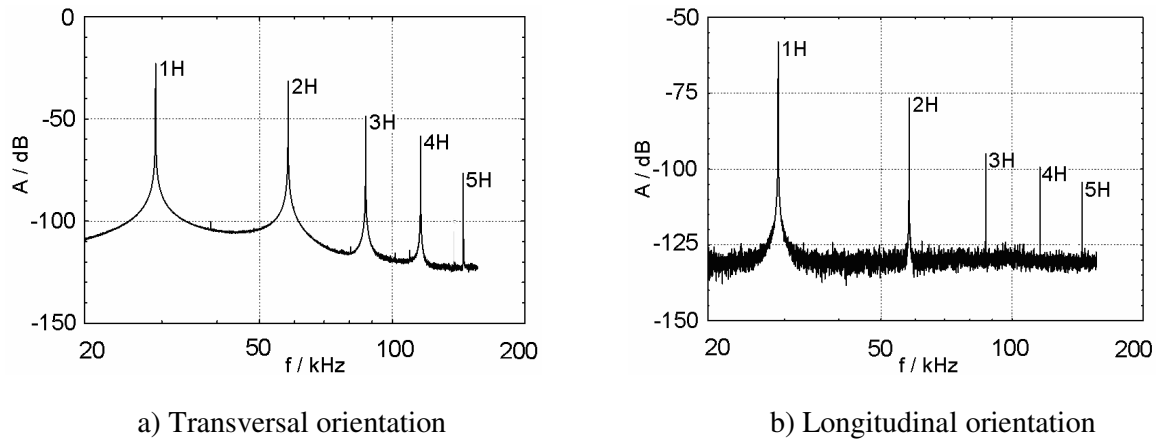


Fig. 5. 05TP8C0 reference specimen - transversal orientation

Measurement results obtained after 82 corrosion cycles had been applied are shown in Fig. 6. The chart of Fig. 6a) corresponding to the transversal orientation contains not only the harmonic frequencies but also some other frequency components, whose amplitudes are comparable with those of the fourth (4H) and fifth (5H) harmonic frequency. The same effect was observed in light-concrete joists after they had been stressed in a pressing machine until a visible crack appeared (Matysik et. al., 2007, Korenska et. al. 2008). The longitudinal-orientation transfer function curve differs from that of the intact specimen, see Fig. 6b). In the frequency spectrum the amplitudes of the odd-numbered harmonic frequency components 3H/5H exceed those of the even-numbered ones 2H/4H.

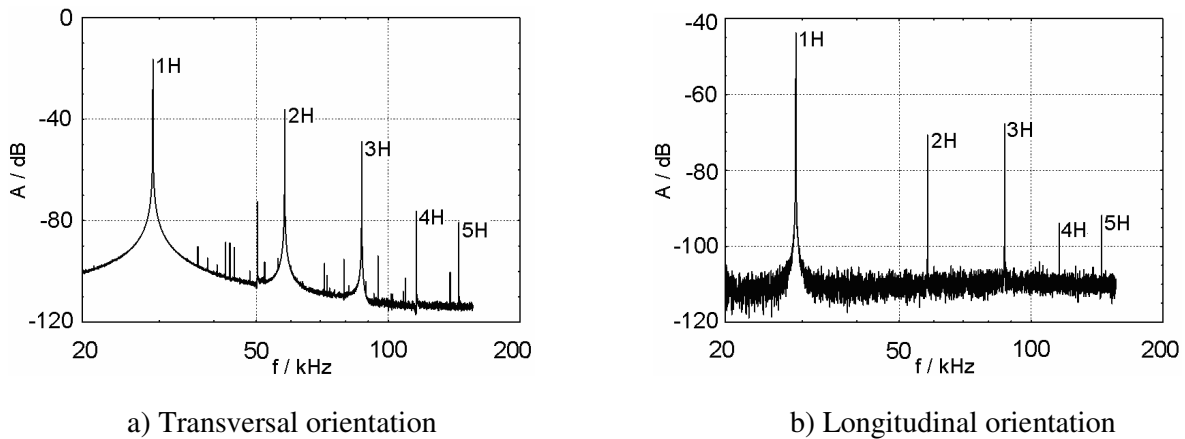


Fig. 6. 10TP8C82 specimen after 82 corrosion cycles

The next Fig. 7 and 8 represented the results of our measurement when two ultrasonic signals $f_1 = 32$ kHz, $f_2 = 29$ kHz have been applied on specimens. A difference component of a frequency $f_v = 3$ kHz was looked for. The chart of Fig. 7 corresponding to reference specimens.

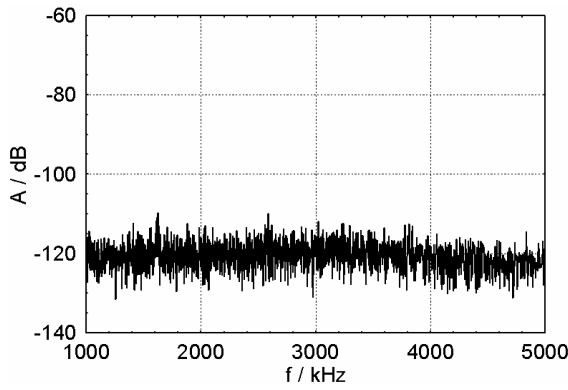


Fig. 7. Reference specimen 05TP8C0

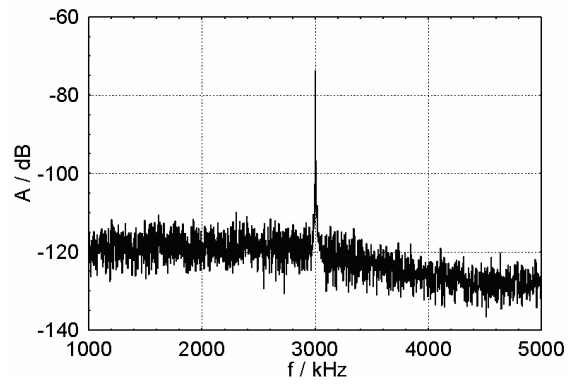


Fig. 8. Specimen after 82 cycles 10TP8C82

It is clear from the diagram that no inter-modulation of the two ultrasonic signals takes place, which gives evidence of the structure integrity of the specimen under test being intact. Measurement results of a specimen after 82 degradation cycles are represented in Fig. 8. The predominating magnitude of the amplitude occurring at this difference component is due to the presence of a defect in consequence of reinforcement corrosion.

4. Conclusions

In the first stage of the experiment, with a single-frequency harmonic exciting signal, it has been proved that the frequency spectra of reference (non-corroded) specimens do not exhibit non-linearities in the signal transmission. On the other hand, transfer characteristics of the specimens measured after the application of 82 corrosion cycles do show non-linear effects, which correlate with the steel armature corrosion consequences.

These non-linear effects are apparent for both transversal and longitudinal excitation arrangements from the relative high harmonic amplitude behaviour. The respective amplitudes do not show the gradual decrease with the increasing harmonic order number, as is the case of the reference specimens. Moreover, the distorted structure showed to generate non-harmonic frequency components in the case of transversal excitation.

When a double-frequency exciting signal method was applied, the consequences of the corrosion gave rise to a large-amplitude component whose frequency equalled to the exciting frequency difference.

Following conclusions have been drawn from the application of the above mentioned methods: The single harmonic signal exciting method provides a very sensitive detection and accurate defect localization. However, it requires – particularly in the case of bulky specimens – a high exciting power, which is rather difficult to generate with the required spectrum purity.

The double harmonic signal modulation method, using exciting signal whose frequencies near each other, does not require a pure signal spectrum, however, requires a certain degree of the source linearity – to minimize mutual non-linear interaction. A certain drawback of this method consists in a rather low frequency of the exciting signal, which in its turn lowers the localisation potential of this method.

In conclusion, it is to be noted that a mechanical impulse exciting signal carries much higher power than any pure harmonic signal electric excitation. The measurement sensitivity of such a measuring method is much higher. These methods are especially suitable for pronounced resonance response exhibiting specimens, where the broad-band impulse excitation results virtually in a narrow-band or even harmonic response. A typical example of pulse excitation used in everyday practice is a spectral analysis carried out by a human ear during a hammer-tap test of a railway wagon wheel, or the change in the sound spectrum of a broken bell. Beside the generation of new

harmonic components, the defect induced non-linearity also results in a change of the specimen transfer characteristics and both phenomena can be analysed at a time.

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