Monitoring of Concrete Components Structure Condition Using a Nonlinear Ultrasonic Spectroscopy

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Abstract

Nonlinear ultrasonic spectroscopy methods appear to rank among highly promising methods to identify the structure defects in a wide range of materials. These methods are employing the fact that a crack-induced nonlinearity makes an extremely sensitive material impairment indicator.

The paper deals with nonlinear interaction between elastic wave and structural defects in concrete materials. First, the short summary and comparison of various methods of nonlinear ultrasound spectroscopy is shown. Method with one pure harmonic exciting signal which uses the analysis of response frequency spectrum generated from a continuous wave transmission through the sample structure was chosen. In the first stage of the experiment, we have examined whether or not the inhomogeneous concrete material gives rise to parasitic components being able to generate non-linear phenomena in the signal transmission. In the second stage were measured the specimens with structure damaged by the pressing machine and a correlation between the response frequency spectrum and the specimen structure deterioration was looked for.

The results showed that the effect of a concrete material inhomogeneity was very low in the case of nonlinear ultrasonic spectroscopy, its nonlinear effect being substantially lower than in cases of common defects. In the second stage was also verified that the transfer functions of degraded specimen correlated fairly with the material structure defects.

Keywords: Nonlinear spectroscopy, elastic wave, concrete, structure integrity, frequency spectrum.

1. Introduction

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 past, however, concrete structures often experienced degradation after years of service. Rehabilitation techniques have been developed for several decades showing a rapid development in general. However, the absence of an acceptable, relatively fast and cheap monitoring method, which would be capable of detecting structure faults at an early stage, thus making a simple and cost-effective maintenance possible, is still persisting [5].

Filling this gap, acoustic testing methods, rank among the most promising methods of building element and structure diagnostics. Non-linear ultrasonic spectroscopy methods are opening new horizons in the non-destructive acoustic testing of material degradation.

2. Non-linear Ultrasonic Spectroscopy

On the basis of non-linear effect studies, new diagnostic and defectoscopic methods have been designed, which are based on the elastic wave non-linear spectroscopy. Existing linear acoustic methods focus on the energy of waves reflected at structural defects, analyzing the reflected wave energy, wave velocity or amplitude variations. It is to be emphasized, however, that none of these linear wave characteristics is as sensitive to the structural defect occurrence as the non-linear response of the material.

One of the fields in which a wide application range of non-linear acoustic spectroscopy methods may be expected to take place is civil engineering. Poor homogeneity of materials and in some cases also intricate shape of the specimens, restrict heavily the applicability of the classical ultrasonic methods. Precisely these non-linear acoustic spectroscopy methods are less susceptible to the mentioned restrictions and one may expect them to contribute a great deal to further improvement of the defectoscopy and material testing in civil engineering.

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 [1, 2]:

- measurements using a single harmonic ultrasonic signal (a single frequency f_1)
- measurements using multiple harmonic ultrasonic signals (usually, two frequencies f_1, f_2).

We pay attention to single harmonic ultrasonic signal measurement method which was used in experimental part. In this case, where a single exciting frequency f_1 is used (Fig. 1), the non-linearity gives rise to other harmonic signals, whose frequencies f_v obey the Fourier series formulas:

$$f_v = n f_1 \qquad \Big| \, n = 0, 1, 2, \ldots \infty$$

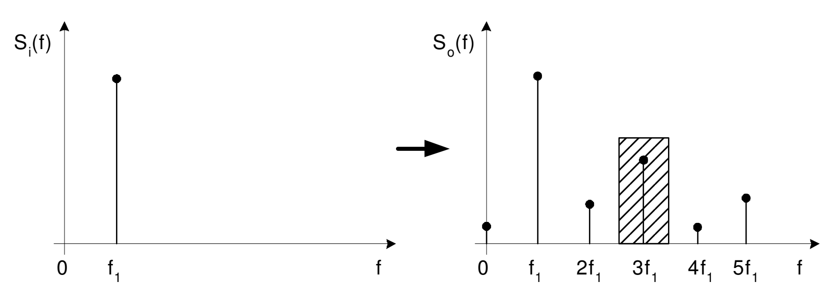


Fig. 1: Frequency spectrum of a non-linear medium response

In general, these frequency component amplitudes are falling when the harmonic order natural number, n, is increasing. If the non-linearity effect is not entirely symmetrical, there can arise low-amplitude second and higher even-numbered harmonic components, whose amplitudes may be much lower than those of the odd-numbered ones. Among these emerging components, the third harmonic is the most distinctive one [3]. Therefore, its amplitude is being evaluated most frequently.

3. Experiment

3.1 Experiment Set-up

Concrete joists of dimensions of 10cm×10cm×40cm, whose average flexural bending strength amounted to, by definition, f_{cf} = 3,4 MPa, have been measured in our experiments. The joists were divided into two groups consisting of four joists each. The first group joists were left intact. The second group joists were loaded in a pressing machine.

The loading force increased until a visually observable crack was observed or, until the deformation started growing abruptly although the load did not increase. The cracks arose in the tension stressed zone between the loading rollers (concrete tensile strength is substantially lower than the compressive strength). After the crack had been identified, the specimen load was released so as to prevent total destruction of the specimen. After the specimen had been stress-relieved, the crack closed and was no more naked-eye-observable.

The maximum strength values σ_{max} achieved at the end of the loading process of the different specimens were as follows:

T01 specimen - σ_{max} = 3,0 MPa, T02 specimen - σ_{max} = 3,1 MPa,

T03 specimen - σ_{max} = 3,1 MPa, T04 specimen - σ_{max} = 2,7 MPa.

The structure of crack containing specimens (T01 through T04) as well as that of intact joists (T05 through T08) was tested. The effect of the structure integrity deterioration on the elastic wave propagation in the specimen was evaluated.

A measuring apparatus featuring a single exciting harmonic ultrasonic signal has been applied to this purpose, Fig. 2 [4].

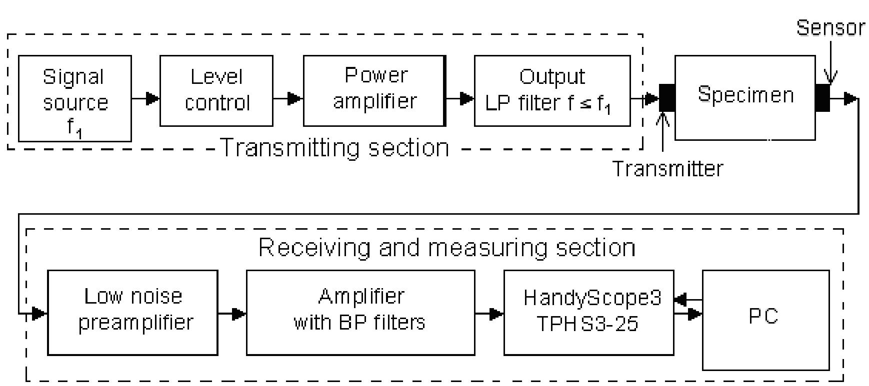


Fig. 2: Block diagram of the measuring apparatus

During the measurements, an exciting ultrasonic signal of a frequency 29 kHz was applied. The positions of the transmitter and the sensor are shown in Fig. 3.

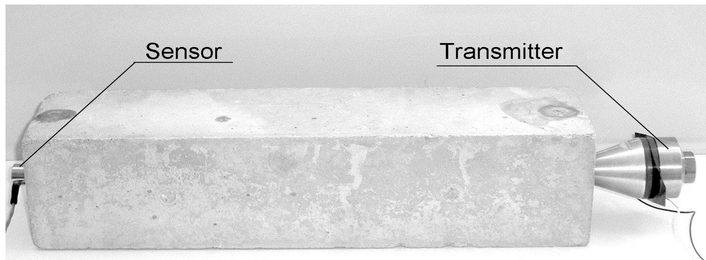
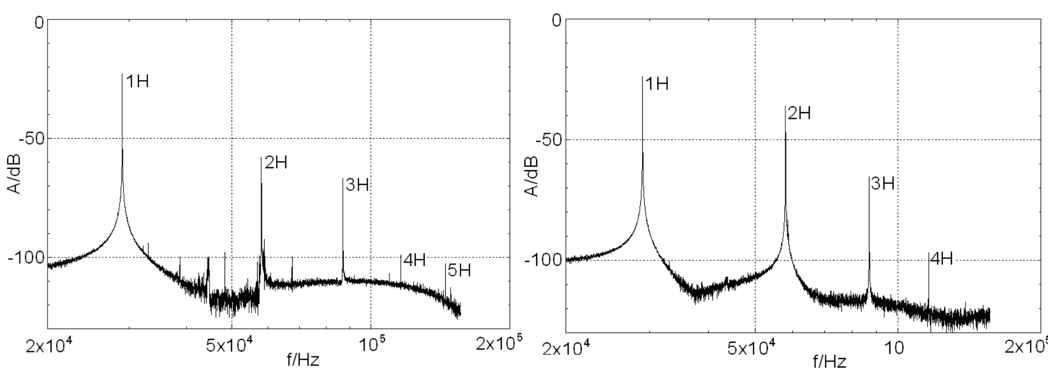


Fig. 3: Location of the transmitter and the sensor on the specimen under test

3.2 Experiment Results

The measurement results are represented by frequency spectra. Fig. 4 corresponds to a mechanically-loaded specimen / unloaded joist. The Table 1 summarizes the measurement results obtained on all joists. The high harmonics' amplitudes relative to the first harmonic's amplitude and the correlation coefficient squared r^2 were evaluated. If the amplitude decreases with no non-linearity symptoms being observable (which is the case of intact specimens), the correlation coefficient is drawing near unity. When the linearity deteriorates, the correlation coefficient is decreasing as well. Graphical comparison of the parameters which have been included into the Table is shown in Figures 5 through 8.

Fig. 4a) shows the typical frequency spectrum of concrete joists specimens after their being loaded in a pressing machine, specimen T04. The transfer function features the occurrence of several non-harmonic frequencies whose amplitudes are comparable to those of the fourth (4H) and fifth (5H) harmonics. No non-linear effects of this kind occur in the frequency spectra of intact joists, see Fig. 4b).



a) loaded specimen T04 b) intact specimen T05

Fig. 4: Frequency spectra of concrete joists

The measurement results are characterized by parameters listed in Table 1.Figure 5 shows the values of the parameters from Table No 1 for the group of loaded joists. The diagram shows clearly a high attenuation accompanying the propagation of the fourth harmonic frequency signal, which is apparently due to the generation of non-harmonic components, as was seen in the diagram of Fig. 4a). The most pronounced demonstration of non-linearity effects, according to this diagram, takes place in T02 and T03 specimens. For both of these specimens, the loading process was terminated when the maximum tension σ_{max} = 3,1 MPa was reached, in consequence of which the structure degradation was higher. Figure 6) shows the measurement results obtained from intact joists. In this case, T06 through T08 joists give almost identical results, only T05 joist exhibits a more abrupt fall of the fourth harmonic 4H.

Joists	specimen	f2/f1	f3/f1	f4/f1	r^2
loaded	T01	54,2%	43,1%	6,9%	0,890
	T02	50,0%	41,4%	1,4%	0,857
	T03	54,5%	48,1%	0,0%	0,842
	T04	51,3%	44,9%	2,6%	0,836
intact	T05	83,1%	44,2%	6,5%	0,950
	T06	84,1%	43,9%	13,4%	0,941
	T07	79,3%	39,0%	12,2%	0,948
	T08	74,4%	36,6%	11,0%	0,972

Tab. 1: Relative amplitudes (in per cent) of the different frequencies with respect to that of the first harmonic and the correlation coefficient squared values

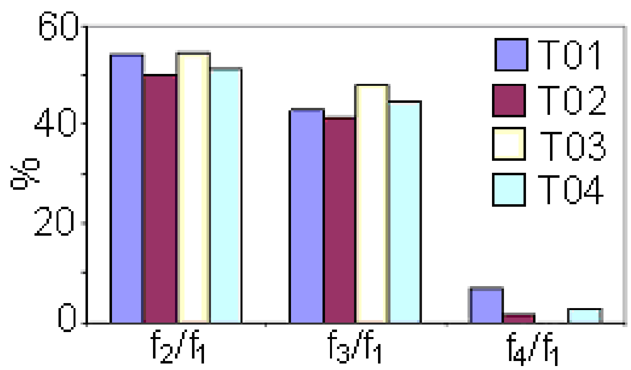


Fig. 5: Relative amplitude values - loaded joists

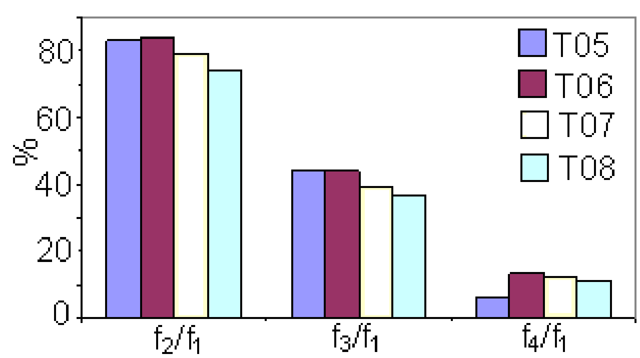


Fig. 6: Relative amplitude values - intact joists

Graphical comparison of the mean values of these parameters for the different groups, see Fig. 7, shows that the specimens which were subject to loading cause a noticeable attenuation of harmonic frequencies, except the third one, 3H, whose relative value appears to be emphasized. Comparison of correlation coefficient squares r^2 confirms again the drop of values for mechanically loaded specimens, see Fig. 8

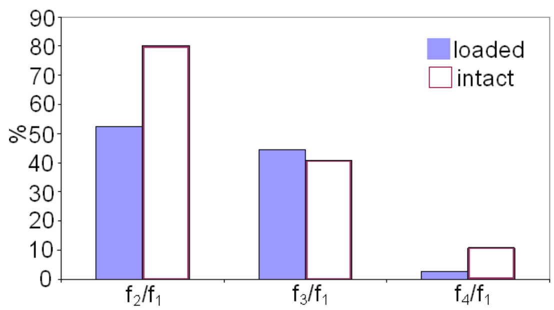


Fig. 7: Relative amplitude - mean values

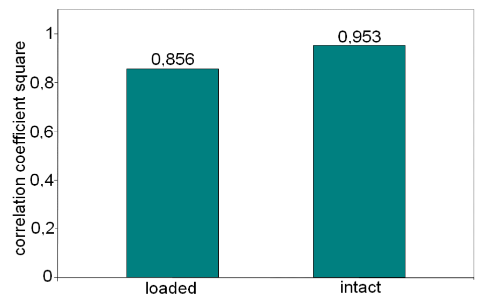


Fig. 8: The correlation coefficient

4 Conclusion

Based on the analysis of the results obtained by the non-linear ultrasonic spectroscopy we may state:

Intact specimens measurements show that the effect of a material inhomogeneity is very low in the case of non-linear ultrasonic spectroscopy, its non-linear effect being substantially lower than in the case of common defects.

Mechanical-loading-induced specimen structure integrity deterioration has caused changes in the signal propagation frequency dependence function. Structural integrity deterioration has given rise to non-linear effects in the transfer functions, which correlated with the deterioration degree.

Verification measurements of fundamental physical quantities have proved the structural degradation to be caused by specimen mechanical loading, too.

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