Assessment of Damage in Reinforced Concrete Girder by Using Nonlinear Ultrasonic Spectroscopy

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Abstract
Concrete and reinforced concrete are classical examples of materials to which the application of conventional ultrasonic methods is very complicated. This is why they make an ideal medium for the application of nonlinear ultrasonic methods. The object of this experimental study consists in the application of nonlinear ultrasonic testing to assess the structure integrity of a reinforced concrete girder, which was extracted from a bridge structure during the reconstruction of the bridge. The girder was tested in two stages: prior to loading and when loading was completed with the aim of identifying the parameters correlating with the girder structure integrity damage. The nonlinear ultrasonic spectroscopy was used, namely, method with one exciting harmonic signal was applied. Frequency spectra of the transmission responses were analyzed. Defects occurring in the structure under investigation give rise to heavy nonlinear effects accompanying the propagation of elastic waves, which took effect in emphasizing the odd-numbered harmonic components among the newly generated frequencies. Therefore, the amplitudes of the latter were evaluated. Structure integrity damage was identified in the girder by means of the frequency spectrum analysis.

Keywords: Nonlinear ultrasonic spectroscopy, wave propagation, nonlinear effects, frequency analysis, structure integrity, reinforced concrete testing

1. Introduction
Nonlinear ultrasonic testing methods started to develop in the last two decades, spreading into the areas which are inaccessible for classical methods [1], [2]. The principle of these methods consists in anharmonic oscillations of atoms at the defect or crack faces. The point is that the oscillating atom energy versus displacement plot does not follow exactly the quadratic law [3]. Consequently, odd-numbered harmonics of the fundamental frequency are generated prevailinglly. This phenomenon provides us with an efficient tool to discriminate between damaged and undamaged specimens [4]. The ultrasonic defectoscopy is therefore a powerful tool to study defects and cracks in solids. In some cases, provided the method has been calibrated, the extent and type of the damage can be determined. As most of the nonlinear effects are amplitude-dependent, taking effect only after sufficiently high-amplitude exciting signals are applied, it is evident that the exciting signal amplitude plays a crucial role in the nonlinear ultrasonic testing methods. The threshold exciting amplitude, which is capable of bringing about a recordable nonlinear response, depends, above all, on the type of the material under test, the damage nature and the excitation type.

Thanks to its composition, concrete is a heavily hysteretic material, which shows a certain degree of nonlinearity even under no-load conditions [5], [6]. If there are defect regions in the concrete specimen under test, these regions will make additional sources of nonlinearity which exceeds by several orders of magnitude the specimen's own nonlinearity. Under ultrasonic tests, the nonlinear behaviour of the material takes effect in a deformation of the ultrasonic waves propagating through the specimen, thus resulting in nonlinear effects in frequency spectra of the specimen under investigation. The nonlinear effects consist in amplitude-dependent occurrence of higher harmonic components \(f_2, f_3,\ldots\) when a single-frequency excitation with a frequency \(f_1\) is used, and a marked growth of odd-numbered harmonics and formation of side bands \((f_1 \pm f_2, f_1 \pm 2f_2,\ldots)\) when simultaneous excitation by two frequencies \(f_1\) and \(f_2\) is used. Another option of time-dependent excitation is the application of
an impulse signal. In this case, the application of a mechanical impulse signal may result in a substantially higher output response. Beside the generation of new harmonic components, the defect induced nonlinearity also results in a change of the specimen transfer characteristics and both of these phenomena can be analysed at a time.

Thanks to its robustness and relative simplicity, the nonlinear ultrasonic spectroscopy, NEWS, as a method based on evaluating the higher harmonic component amplitude ratios, has proved to be suitable for concrete and reinforced concrete testing. As all of the phenomena employed in the NEWS methods are amplitude dependent, we focused our attention on amplitude characteristics of higher harmonics \(f_2, f_3\) and their ratio, \(f_n / f_1\). When applying the impulse excitation, we focused on the frequency analysis of the response versus the exciting impulse intensity function.

2. Tested object and experimental arrangement

The object of our experiment was a reinforced concrete girder of KA type, its dimensions being 0.5 m x 0.6 m x 11.5 m. It was placed on an elastic cushion, which in turn was seated on two concrete guard rails. A special frame had been assembled for the purpose of its loading. For safety reasons, it was designed so as to allow the loading process to take place beneath the girder itself, see Fig. 1. The girder was measured at 4 points symmetrically determined in the right and the left part. The measurements were realized successively in two stages: prior to loading and when the loading was completed. The measured points, henceforth denoted as measurement positions. The objective of these measurements consisted in monitoring the structure integrity damaging.

2.1 Measurements with a single harmonic ultrasonic signal

Two measurement positions differing from each other in the steel armature pattern were tested; see the photo of the right part in Fig. 2. The location of exciter E and sensor S is diagrammatically shown in this figure for measurements on position No. 2. During the measurement on position No.1 the exciter E and sensor S were placed above and under the measurement position, similarly to situation with measurement on position No.2.
The single exciting signal method is described in detail, together with the measuring apparatus, in [7], [8], [9]. A harmonic exciting signal of a frequency \( f = 29 \) kHz was applied, transmission responses of the girder, as picked up by the sensor, were analyzed [10]. The measurements results are presented in the form of frequency spectra signal detected on the signal output. By way of illustration, Fig. 3 shows this frequency spectrum for No. 1 measurement position after girder loading. The diagram shows an abrupt fall of the second harmonic amplitude however the third harmonic amplitude slightly exceeds the second harmonic amplitude. Next the abrupt fall is visible at the forth harmonic amplitude and the slightly fall follows at the fifth harmonic amplitude. The third harmonic 3H reaches the maximum value among higher harmonic components and it gives us information on the occurrence of structure-defect-induced nonlinear effects. It is in accordance with cited foreign sources and our knowledge from results of extensive laboratory measurements.

The measuring results in Fig. 4 are represented by the values of higher harmonic frequencies amplitudes expressed as a percentage of the 1st harmonic (exciting frequency \( f_1 \)) amplitude. This Figure corresponds to girder before 4(a) and after 4(b) loading. From their comparison we may infer that better structure quality corresponds to measuring before loading. In the
case of the measurement before loading (Fig. 4a), the relative amplitudes are decreasing uniformly with the harmonic frequency order number. Structural defects of the girder took effect on the transfer function for measurement after loading (Fig. 4b). The third harmonic 3H reaches the maximum value among higher harmonic components.

![Figure 4](image)

**Figure 4.** Higher harmonic frequency amplitudes expressed as a percentage of the first harmonic amplitude, No. 1 position: (a) Before loading, (b) After loading

Furthermore, the correlation coefficient square, $r^2$, was evaluated. This quantity serves to evaluate the linearity of the harmonic frequency amplitude decrease curve. The correlation coefficient square nears unity if the amplitude vs. frequency plot decrease shows no nonlinear effects, which is the case of intact structure. The more the amplitude decrease plot shape differs from the straight line, the more $r^2$ tends to zero. The correlation coefficient squared shows a decrease in value ($r^2 = 0.9216$) for the after loading measurement compared to the before loading measurement ($r^2 = 0.9728$).

![Figure 5](image)

**Figure 5.** Variation of the correlation coefficient square for the first three harmonic frequency amplitudes

### 2.2 Measurements with two harmonic ultrasonic signals

Secondly, two harmonic ultrasonic signals whose frequencies neared each other ($f_1 = 29$ kHz and $f_2 = 25$ kHz), were applied. Schematic illustration of the exciters E1, E2 and the sensor S locating for measurement on position No. 1 is shown in Fig. 6. During the measurement on position No. 2 the exciters E1, E2 and sensor S were placed similarly to situation with measurement on position No. 1.
In the frequency spectrum, which corresponds to No. 1 position after loading measurement, Fig. 7, there occurs, beside some parasitic components, the excitation frequency difference component, $\Delta f = 4$ kHz. This difference component did not exceed background in the case of the pre-loading measurement.

3. Conclusions

The objective of these experiments was to verify the applicability of the nonlinear ultrasonic spectroscopy to monitoring the damage development in bulkier building elements in situ. The reinforced concrete KA girder, which had been extracted from the bridge structure in the course of the bridge reconstruction, was tested. Two nonlinear ultrasonic spectroscopy methods were applied to test the structure quality, namely, the single and the double harmonic ultrasonic signal methods. The measurement was carried out prior to the girder loading, the response was picked up during the girder dynamic loading and finally, the measurement was carried out after the girder loading was completed. When analyzing the measurement results obtained from the single exciting harmonic ultrasonic signal method, we found out that the damaged structure caused a marked growth of
the third harmonic amplitude and the values of the square of the correlation coefficient to decrease. Occurrence of a new component whose frequency equalled the difference of the exciting frequencies in the frequency spectra obtained when using two exciting signals served as nonlinearity and structure damage indicator.

The experiments were a continuation of the large laboratory measurements. The existing measuring set-up, which was assembled for laboratory testing, was supplemented and optimized, a high-frequency power amplifier was added for more extensive usage. The novelty of the experiments is the use of nonlinear ultrasonic spectroscopy methods to monitoring structure integrity damage in bulkier structural elements in situ measurements. Based on our analyses, we may state that the application of the nonlinear ultrasonic spectroscopy methods appears to be a promising approach to assessing the reinforced concrete structure integrity. Continual or repeated monitoring in specified time intervals and subsequent analysis of selected parameter variations will provide information on structure changes taking place in the building object under investigation.

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References