Nonlinear Ultrasonic Spectroscopy of Structural Components

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Abstract. Current methods of material non-destructive ultrasonic testing are based on the analysis of elastic wave reflection, absorption and interference. Their application is advantageous, above all, to the defectoscopy of homogeneous materials and bodies of elementary shapes. However these methods are difficult to apply to inhomogeneous building materials showing tiny cracks and defects distributed throughout the specimen bulk, or in the cases where the defect size is comparable with the wavelength. Analysis of these phenomena occurring in intricate shapes is difficult, too. To cope with such problems, application of wave propagation related non-linear effects and higher harmonic signal generation in the defect vicinity is advisable. Due to the presence of defects, the atom potential energy ceases to be exactly harmonic. Second and third harmonic frequencies arise. In this domain, methods employing the non-linear acoustic spectroscopy.
These novel defectoscopic methods are based on the non-linear behaviour of current defects and inhomogeneities regarding the elastic wave propagation processes. Unlike the electromagnetic and acoustic emission methods, allowing to localize currently emerging cracks and defects only, the non-linear ultrasonic defectoscopy is all-defect-sensitive, thus constituting a method applicable to characterizing the quality and reliability of materials.

Introduction

Regarding their assumedly higher sensitivity and more accurate quality and reliability characterization capacity, the non-linear ultrasonic spectroscopy methods are ranking among the most promising material quality and reliability characterization tools. 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.). Non-linear parameters have proved to be very sensitive to the presence of any inhomogeneities and progressing degradation of the material structure. Non-linear wave methods thus open new horizons to the acoustic non-destructive testing: they provide higher sensitivities, application speed and easy interpretation. Non-linear ultrasonic spectroscopy, combined with acoustic and electromagnetic emission methods, should allow a deeper insight into the material characteristics and structure.

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. Some of the 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 improving the defectoscopy and material testing methods in civil engineering.

1. Experiment setup

Based on the results of our studies of building material non-linear behaviour, a measuring apparatus for diagnosing the structure of ceramic tiles of two groups has been assembled. The first group comprised intact tiles and the second, tiles having been subject to thermal stress in two different modes. A single harmonic ultrasonic signal method was applied. The measuring apparatus consisted of two principal parts, namely, a transmitting unit and a receiving unit.

The transmitting units consists of threefunctional blocks: a controlled-output-level harmonic signal generator, a low-distortion 100 W power amplifier and a low-pass output filter designed to suppress higher harmonic components and ensure high purity of the exciting harmonic signal.

The main chain of the receiving unit 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 is sampled in a DL920 transient recorder, to be subsequently saved in a computer memory for evaluation, see Fig. 1. As measurement results, we obtained frequency spectra to be subsequently analyzed by means of FFT.

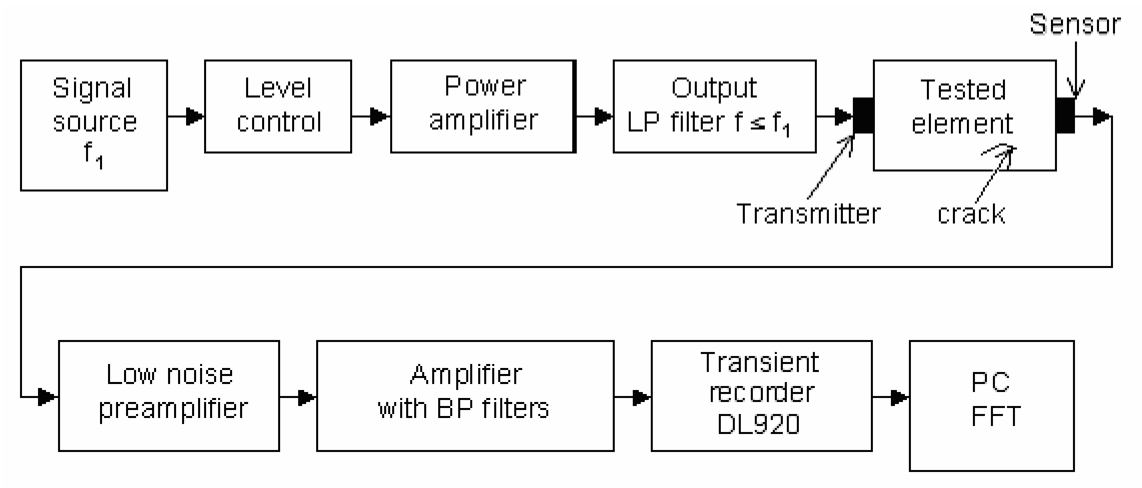


Fig. 1 Block scheme of the measure equipment

2. Specimen description

The specimens under test were cold-pressed glazed ceramic tiles, of dimensions 330 mm × 330 mm × 9 mm, surface density 23 kg•m^{-2}, abrasion resistance: class IV, manufacturer: RAKO. Manufacturer recommended application: facilities having direct access from the street, heavily loaded hall floors, supermarket and restaurant floors.

Ceramic tiles supplied directly by the production plant, certified as conforming with the quality standard [76], were tested. They were subdivided into three groups:

- the first group included the tiles which were preserved intact in the delivery condition – group A

- the second group tiles were subject to thermal stress consisting of three hundred freeze-thaw cycles – group B
- the third group of specimens was subject to four degradation cycles in liquid nitrogen vapours – group C.

During the first measurement phase, the positions of the exciting element and of the sensors were optimized. The selected locations of the exciter (at the specimen centre) and the sensors are shown in Fig. 2.

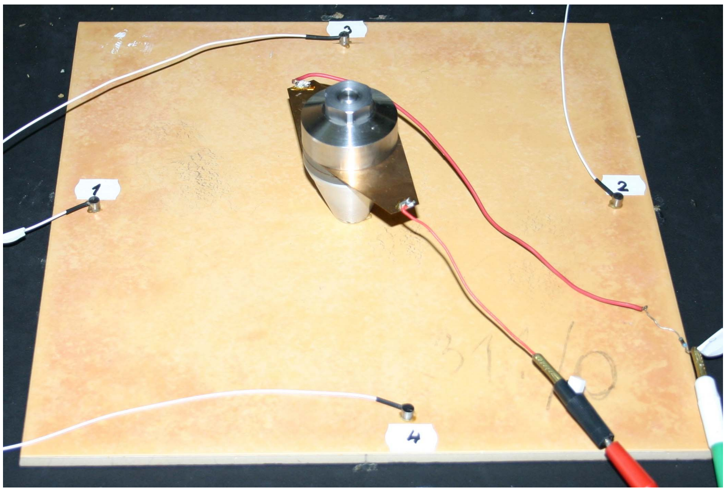


Fig. 2 Test specimen with transmitter and sensors

3. Measurement results

In order to check the measuring setup applicability, an intact duralumin sheet of dimensions 400 mm x 80 mm x 2 mm was tested first. An ultrasonic harmonic signal of a frequency of 24.7 kHz was used to excite the specimen. The resulting response spectrum is shown in Fig. 3. A continuous magnitude downturn is seen in the diagram for ascending harmonic component order (from 1H to 7H). The spectrum shape makes it clear that no non-linearities are manifested in the material structure, i.e., the structure being apparently internal-defect-free.

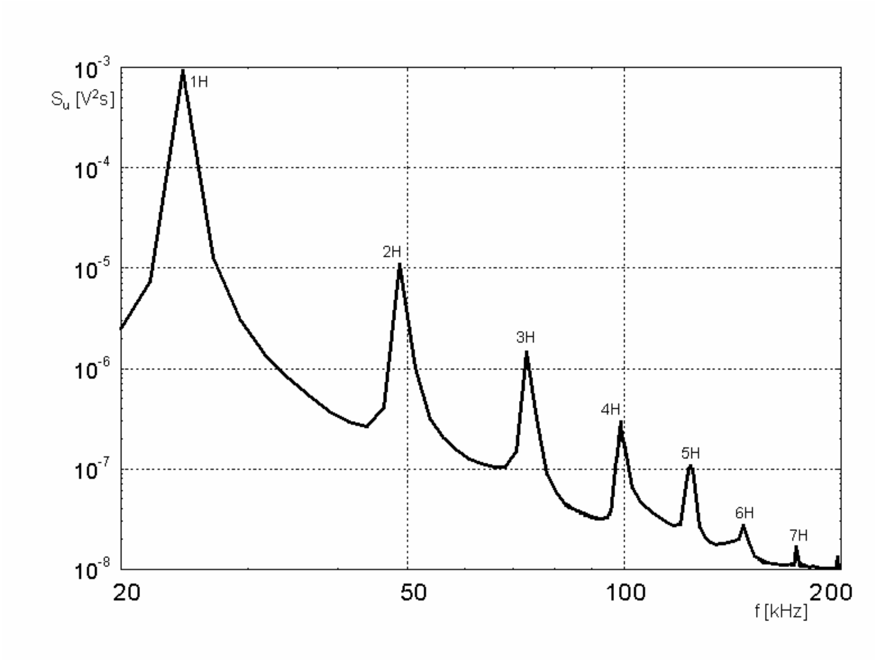


Fig. 3 Response frequency spectrum of duralumin sheet

Three sample spectra are shown in each of the following Figures, corresponding to: A – a defect free specimen, B – a specimen having been impaired by thermal stressing (three hundred freeze-thaw cycles), C – specimen having been exposed to liquid nitrogen vapours in the course of four degradation cycles. The measurements ware carried out both on the upper-side glazed surface and the bottom-side non-glazed surface. The exciting signal response was picked up from the specimen faces as well as edges. The curves shown in Fig 4 correspond to the glazed surface measurements, the response being picked up from the surface (position 1) and the exciting frequency being 24 kHz.

The A-curve corresponds to a defect free tile, which was not subject to any thermal load. Four harmonic components are apparent in the spectrum, their amplitudes decreasing with the harmonic component order. The frequency spectrum shows no non-linearity-induced distortion.

The B-curve shows the response frequency spectrum for a specimen having been subject to three hundred freeze-thaw cycles, which apparently resulted in the specimen structure impairment. Two frequency components appear to be predominant: the first harmonic (1H) and the third harmonic (3H), whose amplitudes are magnitude-comparable. The second (2H) and the seventh (7H) harmonic components are only slightly pronounced. The shape of this spectrum reflects a certain non-linearity effect.

The last curve, C, represents a tile specimen, which was exposed to liquid nitrogen vapours in four degradation cycles. Two frequency components are predominating in this spectrum, too, their amplitudes comparing to each other: the first (1H) and the third (3H) harmonic frequency component. Even-numbered harmonics are suppressed, only the fourth harmonic (4H) shows a slightly noticeable peak. Non-linearity-induced distortion is apparent again.

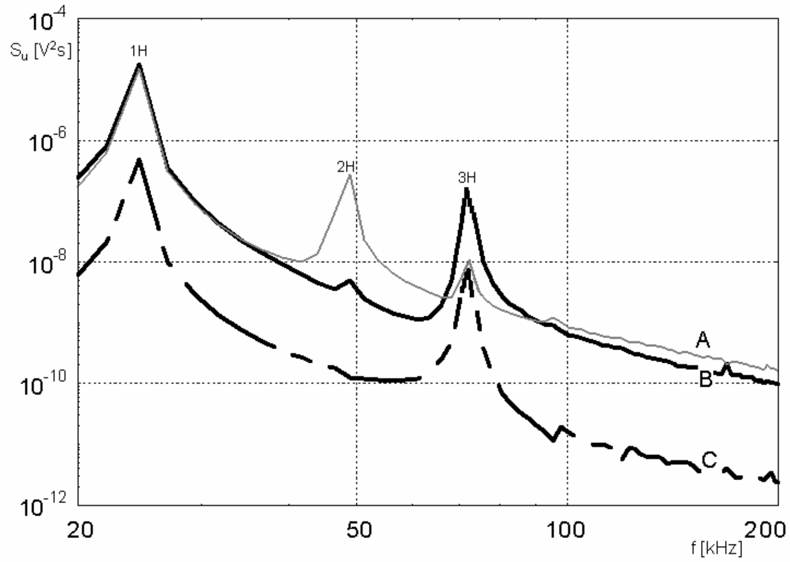


Fig. 4 Response frequency spectrum of ceramic tiles, glazed surface

Non-glazed surfaces of the specimens were measured, too. The resulting spectra are shown in Fig. 5. The curve designation is analogous to that of Fig. 4. Like in the glazed-surface specimen case, the peak amplitudes decrease with the harmonic component ascending order in the intact-tile spectrum (A). The B-curve (the specimen having undergone three hundred freeze-thaw cycles) shows four odd-numbered harmonic frequency peaks: the first - 1H, third - 3H, fifth - 5H and seventh - 7H, of comparable amplitudes. Even-numbered harmonics are suppressed entirely. The C-curve frequency spectrum (the specimen having been exposed to liquid-nitrogen-vapours in three degradation cycles) features five harmonic components. Higher amplitudes are apparent in odd-numbered frequency components. It holds for the respective spectral density magnitudes: Su(2H) < Su(3H), Su(4H) < Su(5H). Both frequency spectra, B and C, give evidence of non-linearity effects.

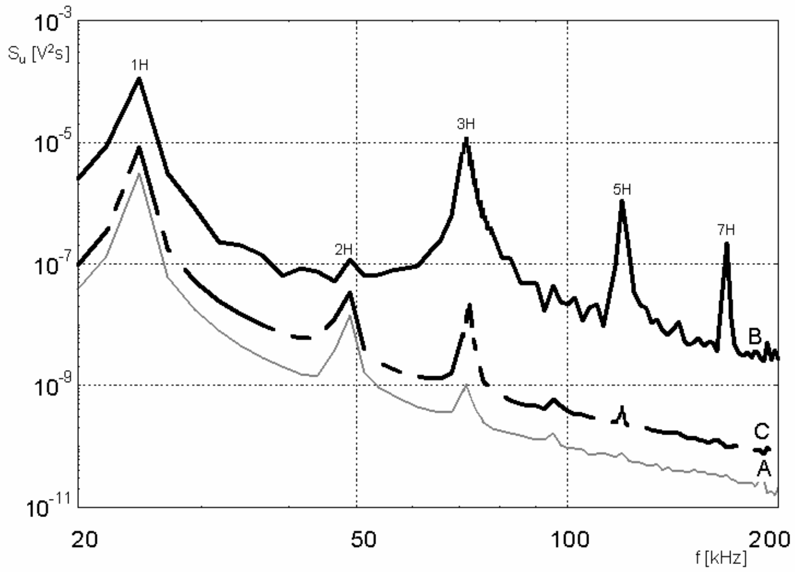
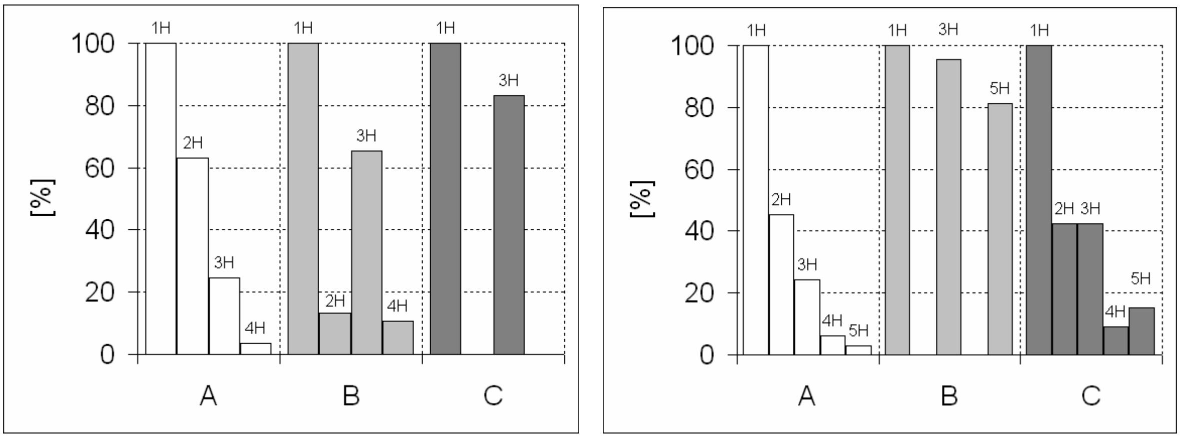


Fig. 5 Response frequency spectrum of ceramic tiles, non–glazed surface

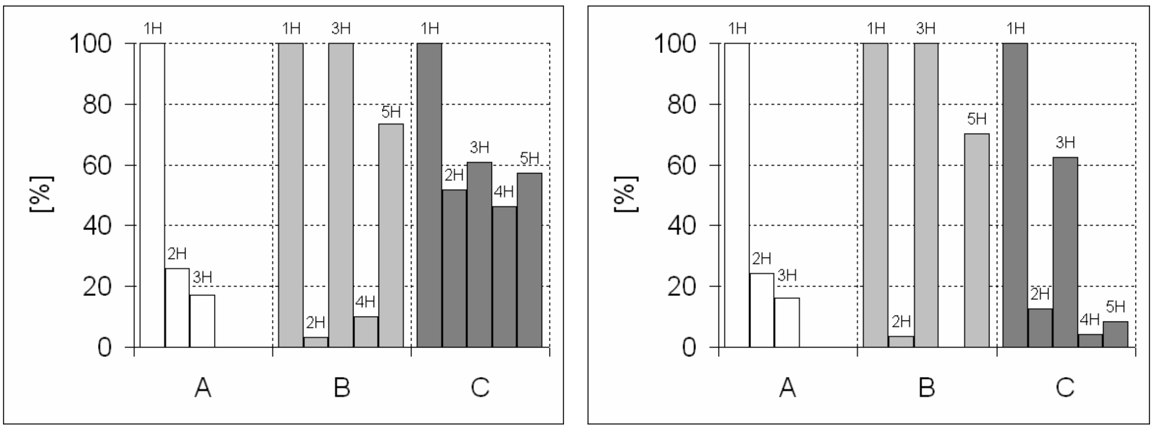
Figure 6 compares the higher harmonic component amplitudes in relative units, the first harmonic amplitude being taken as unity, corresponding to the defect free specimen group A and the thermal-load groups B, C.



a) b)

Fig. 6. Frequency spectra of specimen response - normalized amplitude magnitudes,
a) measuring and exciting on the glazed surface,
b) measuring and exciting on the non-glazed surface

Similar results were obtained with the sensors being placed on the tile edges, as is seen in Fig. 7, comparing the harmonic frequency components analogously



a) b)

Fig. 7 Frequency spectra of specimen response - normalized amplitude magnitudes,
a) exciting on the glazed surface, b) exciting on the non-glazed surface

4. Conclusions

The results of our measurements give evidence that the non-linear techniques are extremely sensitive methods to detect early stages of the defect development. In our experiments, the non-linearity which was due to the generation of defects caused by the specimen thermal load, was reflected in frequency spectrum changes. The material structure defects caused the even-numbered harmonics to be either suppressed or entirely eliminated and, on the other hand, a marked growth of the third and fifth harmonic amplitudes.

The non-linear ultrasonic spectroscopy methods make currently the subject of intensive research. They have already been successfully used in a number of industrial applications.

Thanks to the relatively straightforward application and result interpretation as well as high reliability, this method appears to make a suitable tool for continuous monitoring of the building structure and structural element condition, from the moment of their shipment from the production plant up to their long-time utilization.

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