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USING SHOCK EXCITATION IN CONDITION MONITORING OF PRESTRESSED STRUCTURES

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Abstract

Relying on the assumption that occurrence of damage in prestressed elements can result in change of stress distribution across the entire cross-section and appearance of tensile instead of compressive stresses, and the related emergence of a neutral axis, we proposed a method of evaluating early stages of defect formation that rely on the analysis of the process of vibroacoustic signal generation process. Assuming that changes of stress will lead to disturbance in the propagation of the stress wave across the pre-stressed structure that is incited by a pulse, the proposed diagnosis algorithm refers to the analysis of frequency structure, including the analysis of the envelope and frequency modulation in defined frequency bands that are characteristic for the examined object.

In paper are presented results of experiments elaborate on real structures with simulated faults of different types.

INTRODUCTION

Assuming that early stages of formation of macro-defects in a pre-stressed structure will be accompanied by the change of distribution of stress in the cross-section, the purpose of the study is to develop a non-invasive method of detecting changes of distribution while relying on the information contained in a vibroacoustic signal generated during tests.

While referring to the current state of knowledge it is worth noting that in the process of examining of pre-stressed structures the focus has been on detection of existence of faults and defects of materials. Similarly attempts have been made to exploit the dynamic response of structures, where the main problem is defect detection and location as well as determination of the degree of defect development. While defining the structural defects as a kind of deviation of geometrical and material-related properties, one can expect changes in the dynamic response of a system to defined loads.

Recently a lot of research has been directly or indirectly associated with detection of defects while relying on the analysis of a structure's dynamic response. One can among others point to use of identification techniques [1], system transmittance analysis methods, FRF (frequency response function) [2], intensively developed random decrement damping estimation technique [3] and diagnostic techniques using the information on changes of modal parameters. The essence of all these methods is the use of the relative change of a structure's proper vibration frequency and of the damping value in connection with the emergence of cracks, notches or other defects that have influence on the dynamic properties of a structure [4,5].

In spite of extensive research, including the analysis of the values that characterize the changes of the mode shape of a structure [6] and in spite of obtaining numerous interesting results (vibration-based damage detection), so far we have not been able to obtain fully satisfactory results, especially in a situation when we have had no model vibroacoustic signal generated by an undamaged system. Difficulties increase along with the uncertainty related to modeling, measurement and analysis of the obtained signal and also as attempts are made to identify early stages of defect development.

In contrast with the driven-date approach, the method of diagnosis proposed in this project provides for analysis of relations between the distribution of stress in the cross-section and the changes of vibroacoustic signal parameters. This method of diagnosis exploits the phenomenon of relationship between the parameters of sound wave propagation and the stress occurring in the examined object. The phenomenon is manifested by modulation of vibroacoustic signal's parameters as a result of changes of velocity of sound wave propagation in the material, which is in turn is the function of distribution of stress in the cross-section of a pre-stressed structure. Assuming that the occurring defects may bring about decrease of stress compression can expect the relevantly measurable distribution of stress in the cross-section and the occurrence of changes of modulations of relevant parameters of vibroacoustic signal, which will consequently enable the development of a relevant diagnostic procedure referring to the phenomenon of dispersion caused by changes of distribution of stress in a beam, which will have influence on the dynamic properties and thus on the frequency structure of the generated vibroacoustic signal.

MODELLING AND STUDYING DISPERSION EFFECTS

Using a model of the Bernoulli-Euler beam

The problem of influence of stress on frequency structure of vibration signal of elastic structures has been constantly analysed in the literature on dynamics of continuous systems, with application of different models. Graff [7], for example, while analysing vibrations of a beam submitted additionally to stretching takes the Bernoulli-Euler model, adding the tension forces to it (Fig.1).

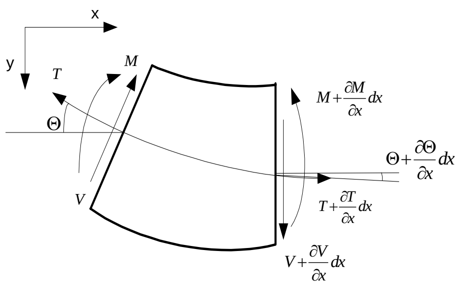

Figure 1. The element of the Bernoulli-Euler beam.

Consequently, the equation of motion takes the following form:

$$-V+\left(V+\frac{\partial V}{\partial x}dx\right)-T\Theta+\left(T+\frac{\partial T}{\partial x}dx\right)\left(\Theta+\frac{\partial \Theta}{\partial x}dx\right)=\rho A dx\frac{\partial^2 y}{\partial t^2} \tag{1}$$

Omitting higher order of increment *dx* and assuming that:

$$V=\frac{\partial M}{\partial x};\qquad \Theta=\frac{\partial y}{\partial x};\qquad EI\frac{\partial^2 y}{\partial x^2}=-M;$$

and additionally that the tension force is constant:

$$\frac{\partial T}{\partial x}=0;\qquad and\qquad a^2=\frac{EI}{\rho A}$$

the equation of motion (17) takes the following form:

$$\frac{\partial^4 y}{\partial x^4}-\frac{T}{EI}\frac{\partial^2 y}{\partial x^2}+\frac{1}{a^2}\frac{\partial^2 y}{\partial t_2}=0 \tag{2}$$

There is an element in the equations that depend on the tension force, which points at the fact that the dispersion phenomena occur and it is necessary to define the relationship between the phase velocity and the tension and shear forces. Consequently, the equation defining the wave number has the following form:

$$k^4+\frac{T}{EI}k^2-\frac{\omega^2}{a^2}=0 \tag{3}$$

$$k=\pm\left\{-\zeta\pm\left(\zeta^2+\frac{\omega^2}{a^2}\right)^{\frac{1}{2}}\right\}^{\frac{1}{2}} \tag{4}$$

so the relationship defining the phase velocity will take the following form:

$$c_f = \frac{1}{k}\sqrt{a^2\left(k^2 + \frac{T}{EI}\right)^2 - \left(\frac{T}{EI}\right)^2} \tag{5}$$

Since the tested material has got the characteristics of dispersion centre, defined by shift of envelope, the group velocity will change according to the formula (6), while the absolute value and the frequency characteristic will differ.

$$c_g = c_f + k\frac{\partial c_f}{\partial k} \tag{6}$$

$$c_g = c_f - \frac{1}{2}k\frac{2a^2k - 2\frac{b^2(a^2-1)}{k^3}}{\left(a^2k^2 + 2a^2b + \frac{b^2(a^2-1)}{k^2}\right)^{\frac{1}{2}}} \tag{7}$$

were: $a^2 = \frac{EI}{A\rho}$, $b = \frac{T}{EI}$.

As an example of possible use of information about the phase velocity variation in changing stress distribution of beam cross-section we can take the results of laboratory experiment on a prestressed beam.

The basis for the research is the observation that occurrence of differences between wave and group velocity will lead to the occurrence of amplitude modulation in the vibroacoustic signal generated by the test pulse.

Laboratory test of prestressed beam.

The object of our research was a presstresed concrete beam made of B20 class concrete with dimensions 1510x102x200mm. The beam was prestresed with four steel rods with diameter Ø10 installed along the axis of the beam at the distance of 25 mm from its edges. The prestrssing of the beam was supplemented with supporting cross-bars keeping the main bars in the desired location. The cross-bars were rods with diameter of Ø6 installed at ca. 100 mm spacing.

The beam was placed in the strength testing device bed, supported by two symmetrically placed supports. The distance between the supports places was 1300mm. In the centre of the beam the load was exerted on the object by the machine’s punch (stamp) with a pre-defined force. The material which vibroisolated the vibration coming from the load exerting system was placed between the supports and the beam as well as between the punch and the beam.

The tests were carried out for the following cycle of loads: 0.5 kN, 2 kN, 5 kN, 15 kN, 30 kN, 35 kN, 40 kN, 45 kN, 50 kN, 55 kN, 60 kN, 65 kN, 70 kN. The first small cracks emerged when the load of 45kN was exerted. These cracks increased substantially at 70 kN. Only the further increase of the load up to 75 kN resulted in breaking of the beam.

In order to observe the changes in terms of propagation of the wave across the examined beam we placed six vibration sensors on the beam. Their exact locations are presented in Fig. 2.

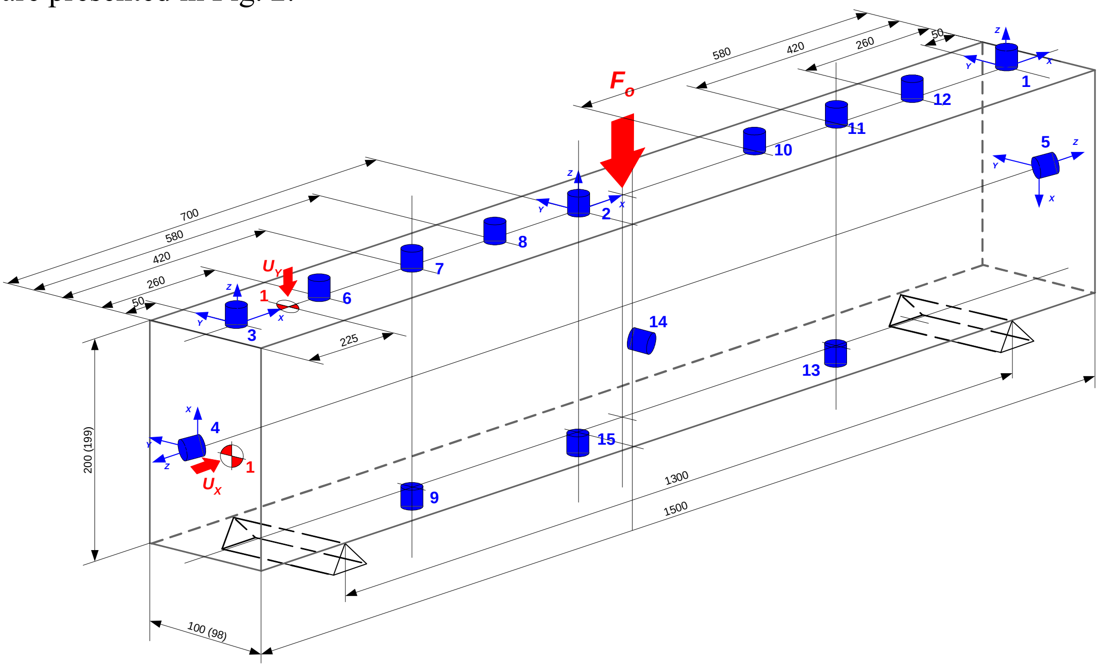

Fig. 2. Location of vibration sensors and directions of vibration-causing forces in the reinforced concrete beam.

The registered results of measurements were subjected to analysis in order to define the conditions of propagation of the waves caused by a pulse input. Distinct differences were observed in the values of response delay for the detector located at the opposite side of the beam (see detector no 2).

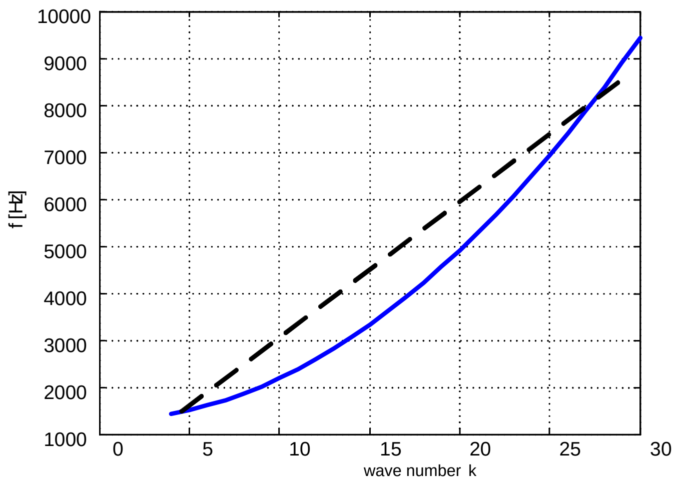

Figure 3. Changes of frequency of free vibration resulting from dispersion.

The results are discussed in full in [8].
Let us realize here that the relationship between the Young module and the structure of tensions in the beam, as well as the relationship between the module's value and the actual phase velocity (Fig.3) and the group velocity will influence the process of generating a vibraocoustic signal. The changes of phase velocity influencing the spectrum of acceleration of vibrations of the beam is shown in the Figure 4, where the frequency bands corresponding with subsequent wave numbers are marked.

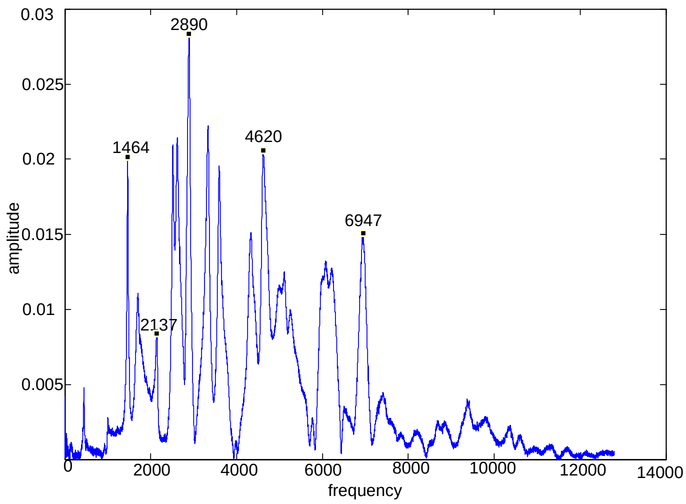

Fig.4. Spectrum of dynamic response to impulse input for the beam, frequency bands corresponding with subsequent wave numbers marked

While exploiting the results of the research presented in [9].
In accordance with the presented relationships, while increasing the load in the subsequent steps we change the distribution of stress, which results in change of Young's module, thus the subsequent dispersion curves will have a different run depending on the stress. The nature of these changes is presented in Fig. 5.

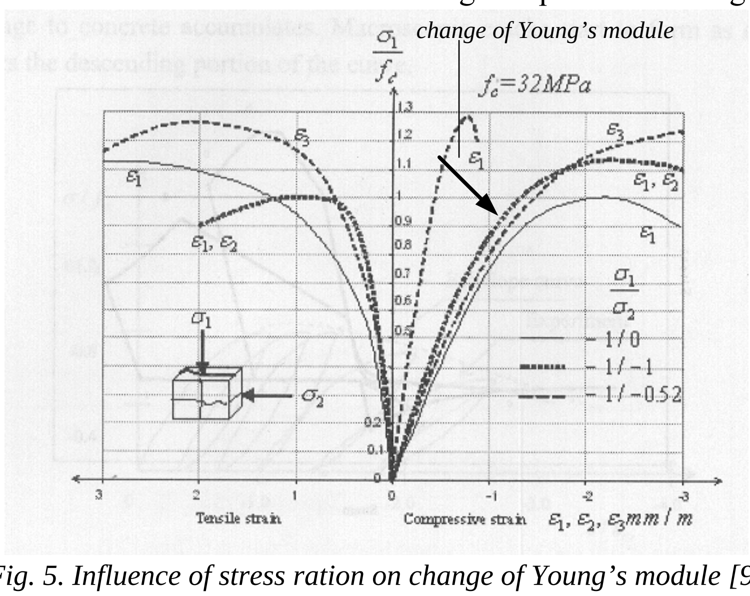

Fig. 5. Influence of stress ration on change of Young's module [9]

The changes affecting wave velocity also apply to group velocity, described by (7), which is presented in Fig. 6. Changes of group velocity, occurring along with the growth of the transverse force, will be visible as the change of modulating frequency around the carrier frequency which changes along with the changes of group velocity.

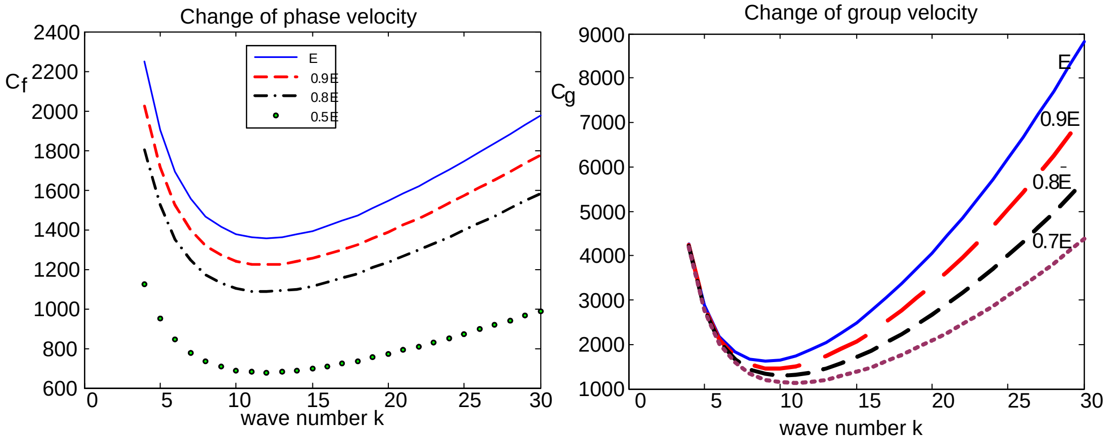

Fig. 6. Influence of change of Young's module on group velocity.

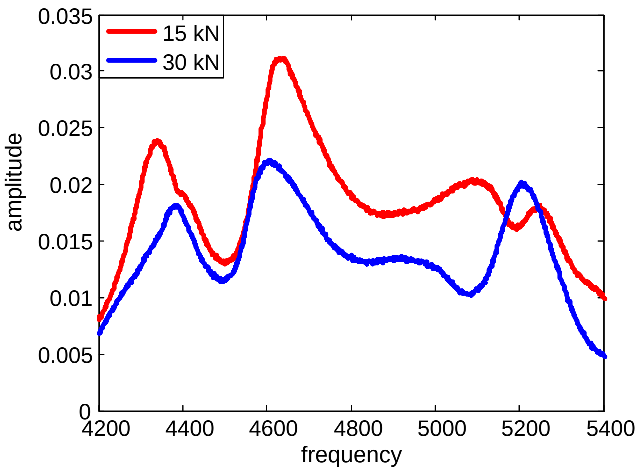

Fig.7. Changes in amplitude modulation resulting from change of load in a selected band.

The above mentioned phenomena can be observed in the spectra of dynamic response of examined beams (the example is presented in Fig. 7).

CONCLUSION

Analysis of the phenomenon of modulation of vibroacoustic signal's parameters, especially the amplitude and the frequency structure of the envelope which is directly associated with the occurrence of group velocity, may prove to be an effective tool for diagnosing the technical condition of pre-stressed structures. This scope of work and the examination of the influence of local defects and of the environmental impact will be the main research task during the next stage of our work. An issue that is particularly interesting and that calls for additional analyses and experiments will be the development and adaptation of effective de-modulation algorithms.

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