Article citation info:
RADKOWSKI S, SZCZUROWSKI K. Use of vibroacoustic signals for diagnosis of prestressed structures. Eksploatacja i Niezawodnosc. Maintenance and Reliability 2012; 14 (1): 84–91.

Stanisław RADKOWSKI
Krzysztof SZCZUROWSKI

USE OF VIBROACOUSTIC SIGNALS FOR DIAGNOSIS OF PRESTRESSED STRUCTURES

WYKORZYSTANIE SYGNAŁU WIBROAKUSTYCZNEGO W DIAGNOSTYCE STRUKTUR SPRĘŻONYCH*

The paper presents the issue of assessment of the technical condition of a prestressed structure while particularly underscoring the possibilities offered by amplitude modulation effects which are found in the observed vibroacoustic signal. The basis for such an approach is the thesis that change of distribution of stress in the cross-section of a prestressed structure is accompanied by a measurable change of the parameters of a vibroacoustic signal.The thesis stems from the assumption that the condition of prestressing of a structure, as it is being bent, is accompanied by the phenomenon of dispersion and hence of the change of wave propagation parameters, especially the occurrence of a measurable difference between the values of phase and group velocities.Analysis of the relations between the state of stress and the values of phase and group velocities creates the possibilities of developing the reverse diagnostic models and determining the quantitative changes of such parameters of technical condition as compressive forces, Young's modul or the stress in the structure. The paper has been developed on the basis of the author's Ph.D. thesis.

Keywords: *technical diagnosis, amplitude modulation, group velocity, phase velocity, prestressed structures.*

W pracy przedstawiono zagadnienie oceny stanu technicznego struktury sprężonej ze szczególnym uwypukleniem możliwości wykorzystania efektów modulacji amplitudowej występujących w obserwowanym sygnale wibroakustycznym. Podstawą takiego podejścia jest teza że zmianie rozkładu naprężeń w przekroju poprzecznym struktury sprężonej towarzyszy mierzalna zmiana parametrów sygnału wibroakustycznego.Wynika ona z założenia, że wraz z wywołaniem stanu sprężenia wstępnego w zginanej konstrukcji zachodzi zjawisko dyspersji, a tym samym zmiana parametrów propagacji fali, w szczególności występowanie mierzalnej różnicy wartości prędkości fazowej i grupowej.Analiza relacji między stanem naprężeń a wartościami prędkości fazowej i grupowej stwarza możliwość budowania diagnostycznych modeli odwrotnych i wyznaczania ilościowych zmian takich parametrów stanu technicznego, jak siły sprężające, moduł Younga czy naprężenia panujące w konstrukcji.Praca powstała na podstawie rozprawy doktorskiej autora.

Słowa kluczowe: *diagnostyka techniczna, modulacja amplitudowa, prędkość grupowa, prędkość fazowa, konstrukcje sprężone.*

1. Introduction

At the turn of 20th century the communities associated with use of prestressed concrete structures started extensive work related to gaining in-depth knowledge on the conditions which would assure durability of existing structures and extend their useful life to as long as 80 years (the structures were designed for 50 years), minimize the cost of repairs and monitoring as well as improve safety in the long run [8]. Unfortunately in many cases tens of years have passed since construction of such structures and even the originally planned operating life of the structures has ended. Thus a problem has emerged of how to evaluate the condition of the structures from the point of view of safety requirements. Consequently attention started to be paid to the methods of detecting the degree of such structures' degradation, their faults, cracks and other types of defects, of which some could prove critical and cause catastrophic defects of the entire structure.

One of the major directions of work was to find the new methods of evaluating the condition of prestressed structures. The paper provides information on the work related to application of vibration and acoustic methods while making the assumption that the early phases of development of micro-defects in a prestressed structure will be accompanied by change of distribution of stress in the cross-section. Thus an attempt was made to develop a non-invasive method of detection of changes in distribution of stress while relying on the information contained in the vibroacoustic signal generated by a dynamically excited prestressed structure.

Ultrasonic methods can be divided into two groups. The first one involves measurement of the velocity of ultrasonic

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** wave propagation across a reinforced concrete structure while the other one involves analysis of changes of the parameters of a wave propagating in the material.

Measurement of propagation velocity takes place while using two surfaces of the examined element and it is intended to measure the distance travelled by a propagating wave. Examination of the velocity of an ultrasonic pulse in a material involves introduction of an ultrasonic wave to the material and measurement of the time it takes for the head of this wave to travel from the transmitting processor to the receiving processor. Knowing the time it takes the pulse to travel and the length of the path one can determine the velocity at which the wave passes [11].

The second group of ultrasonic methods includes Impact-echo [12], Pulse-echo [7] and surface method [11].

These methods exploit the effect related to the disturbance which affects ultrasonic waves as they pass through a material and bounce of the boundary of an element or another discontinuity of a material. After relevant analyses of a signal (e.g. FFT) it is possible to infer about the path that a wave traveled.

These methods enable quick determination of the thickness of elements to which access is possible only from one side, such as platform slabs, road surfaces, and they enable location of all types of internal defects of reinforced concrete structures, such as inclusions of other materials (e.g. wood), deficiencies (e.g. void pockets of air), cracks or corrosion.

The Pulsed Eddy Current (PEC) method is a relatively new non-destructive method. It is used for inspecting and identifying hidden corrosion in the layer of structures containing ferromagnetic elements [9]. Its main advantage is the possibility of covering a wide range of frequencies excited by a strong pulsation of the electromagnetic field. The method is also quite simple while the equipment required to use it is relatively cheap.

The Acoustic Emission method is a passive monitoring method which involves detection of disturbance caused by the stressing wave emitted as a crack develops or when a fiber breaks. In contrast with this, the classic ultrasonic methods of defect detection are of active type, which means that they involve sending a stressing wave into the examined object in order to identify the existing defect.

Effectiveness of the Acoustic Emission method was verified in several studies. It turned out that a stressing wave was generated as a result of existence of corrosion and micro-cracks and that this wave could be detected with the use of acoustic emission sensors [4].

The method can be used for constant monitoring without any limitations. Unfortunately it is a passive method and it can be only used for registration of signals generated as a result of cracks or other changes inside the material, however it does not offer the possibility of direct assessment of severity of defects as they emerge.

Magnetic methods were often used in examination of concrete structures to locate the elements of reinforcement. They were also used for routine inspections of fibers and overhead lines. Burdekin et al. [1] presented a project realized in the 1970's and 1980's at Southwest Research Institute. The project was devoted to detection of corrosion and fractures of steel stressing elements in pre-tensioned prestressed concrete and post-tensioned prestressed concrete beams.

Nonlinear Vibroacoustic Methods were developed in the 1980's at the Institute of Applied Physics of the Russian Academy of Sciences for the purpose of controlling the quality of thermoinsulating screens used in Russian space shuttles. Dimitri M. Donskoy and Alexander Sutin [13], who were developing these methods, presented a method based on the analysis of a non-linear vibroacoustic signal The traditional linear acoustic methods use the effects of reflection, dispersion and absorption of acoustic energy. These methods enable detection of defects on the basis of momentary changes of a signal's phase and/or amplitude. Thanks to the non-linear relations it is possible to detect these changes in other frequency bands than the emitted signal's bands. It all depends on the type of non-linear transformation of acoustic energy by a defect. The method mentioned here assumes that the materials with cracks cause change of the signal and generate its much bigger non-linearity.

The advantage of non-linear methods is the possibility of their application in highly non-homogenous structures such as composites and concrete. When a sinusoid acoustic wave encounters a defect, it changes at the contact surface (growth of compression, reduction of stress). It is a phenomenon which to some degree is analogous to closing of a crack during compression and its opening during stressing. It leads to generation of further harmonic frequencies of the generated signal.

While referring to the current state of knowledge, it is worth noting that the research of prestressed structures mainly focuses on detection of faults and defects of materials. It is also from this point of view that the dynamic responses of structures are analyzed.

2. Assessment of existing methods

All the methods mentioned here have the purpose of detecting cracks, inclusions, corrosion or other defects in prestressed concrete structures and they are directed at finding the places of their occurrence, that is places affected by corrosion in reinforcing strings or bars, corrosion of concrete, cracks in tendons or concrete, inclusions or other defects of the material. It is only on the basis of the obtained information that it becomes possible to determine whether a given defect is critical for a whole structure. Acoustic emission could be an example as it enables detection of emerging cracks without determining their influence on the entire structure or the magnetic methods which are used for observing changes of the magnetic field around the damaged stressing strings. In addition, determination of the state of the entire structure with the use of the above mentioned methods requires substantial time since each test can only cover part of a structure.

3. A proposal of a new approach

The proposed new approach of assessing the condition of prestressed elements, such as prestressed concrete elements, involves observation of dynamic changes of the characteristics of entire elements as they take place under the influence of changes in the structure of stress [2].

In the existing practice, the dynamic response of a structure is used for detecting, locating and defining the degree of defect development in non-destructive research. By defining a structural defect as a kind of a deviation of the geometric and material-related properties from the norm, we can expect changes to occur in the dynamic response of a system to a defined load.

A phenomenon which is important in prestressed structures is the qualitative change in the structure of stress in the cross-section. Compressive stress is applied across the whole cross-section during the construction stage. During operation the degradation processes lead to changes in the designed distribution of stresses in the cross-section. The possibility of detecting the changes in the distribution of stresses creates an opportunity for determining the condition of the prestressed structures and for forecasting the residual time of their use.

The phenomenon of modulation of a vibroacoustic signal's parameters, trigerred by changes in the conditions of wave propagation across material as a result of changes in distribution of stress in the cross-section of a prestressed structure, is used overcome the aforementioned difficulties in the proposed method of diagnosis.

3.1. Examination of frequency changes in a prestressed structure

Impact of pre-stressing on the frequency structure of vibration signal in prestressed structures is analyzed in the literature devoted to the dynamics of continuous systems while using various models. For example Graff [5], while analyzing vibration in a beam subjected to stretching, adopted the starting Bernoullie-Euler model to which he additionally applied stretching forces (Fig. 1).

The vibration equation takes the following form:

$$EI\frac{\partial^4 y}{\partial x^4} - T\frac{\partial^2 y}{\partial x^2} + \rho A\frac{\partial^2 y}{\partial t^2} = 0 \qquad (1)$$

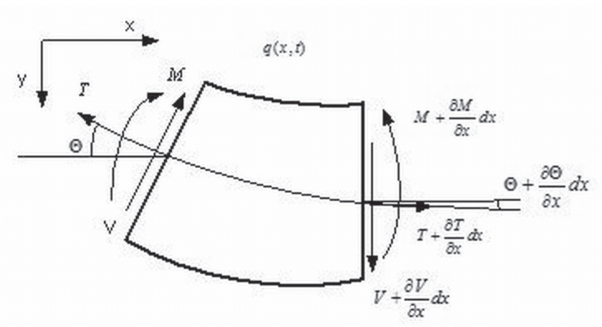

Fig. 1. Element of a model of a Bernoullie-Euler beam [5]

In the case of occurrence of compressive forces, the orientation of force T has to be changed to the opposite one in equation (1). By solving equation (1) we will obtain an expression defining the value of the frequency of n-th form of vibration depending on the value of the compressive force:

$$f_n = \frac{n^2\pi^2}{l^2}\left(\frac{EI}{\rho A}\right)^{\frac{1}{2}}\left(1 - \frac{Tl^2}{n^2\pi^2 EI}\right)^{\frac{1}{2}} \qquad (2)$$

Equation (2) demonstrates that application of tensile forces leads to growth of frequency of a beam's natural vibration, while application of compressive forces leads to the reduction of frequency. When the distribution of stress in the beam's cross-section changes, the effect of wave propagation at various speeds will occur, which could become an additional important factor having influence on the process of generation of a wave's group velocity and the associated phenomena of modulation of a vibroacoustic signal's parameters.

Based on the model of a Bernoullie-Euler's beam, as presented in Fig. 1 and described by the following relation (1)

$$\frac{\partial^4 y}{\partial x^4} - \frac{T}{EI}\frac{\partial^2 y}{\partial x^2} + \frac{1}{c^2}\frac{\partial^2 y}{\partial t^2} = 0 \qquad (3)$$

where, $c^2 = \frac{EI}{\rho A}$ we can determine the wave number.

Occurrence in the equations of a factor which depends on the tensioning force points to the phenomenon of dispersion and the necessity of determining the dependence of phase velocity on the value or ratio of the forces. Hence the relationship which defines the phase velocity can be presented in the following form:

$$c_f = k \cdot c = c\sqrt{\frac{T}{2EI} + \left(\frac{T^2}{4E^2I^2} + k^4\right)^{\frac{1}{2}}} \qquad (4)$$

while the relation between the group velocity and phase velocity can be presented as:

$$c_g = c_f - ck^4\left(\frac{T}{2EI} + \left(\frac{T^2}{4E^2I^2} + k^4\right)^{\frac{1}{2}}\right)^{-\frac{1}{2}} \cdot \left(\frac{T^2}{4E^2I^2} + k^4\right)^{-\frac{1}{2}} \qquad (5)$$

Relationship (5) points to dependence of the group velocity on the value of compresive forces and the wave number k.

While using the relationship between the speed of wave propagation and length of a wave:

$$f = \frac{k \cdot c_f}{2\pi} \qquad (6)$$

where $k = \left(\frac{\omega}{c}\right)^{\frac{1}{2}}$, it becomes possible to determine the dispersion curve, presented in Fig. 2, which describes the frequency of proper vibration of the examined beam in the function of wave velocity.

As can be easily noted, typical harmonics cannot be expected in materials having dispersion properties since the frequencies of subsequent forms of vibration are a multiple of the fundamental frequency [3].

Changes which phase velocity undergoes also affect group velocity. In accordance with the adopted assumption, changes of group velocity, accompanying growth of transverse force, should be visible in the form of changes of modulating frequency around the carrier frequency which changes along with the changes of phase velocity.

The above mentioned effect could have been observed in the spectra of the dynamic response of prestressed beams examined at the test-bed in Kielce University of Technology. Fig. 3 presents an example of this phenomenon.

In addition occurrence, in the equations, of an element which is dependent on the tensile force, points to the existence

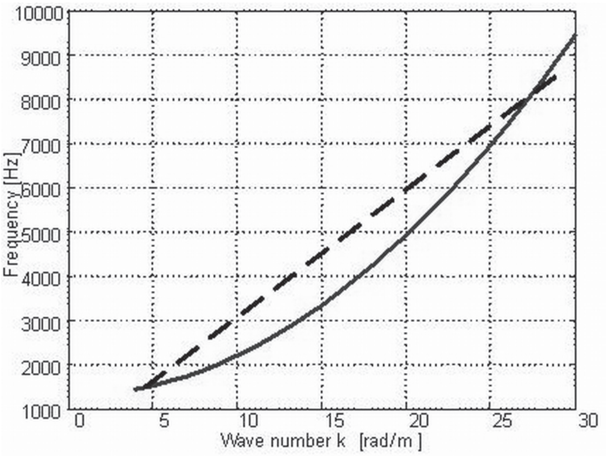

Fig. 2. Change of frequency based on relation (5) [3]

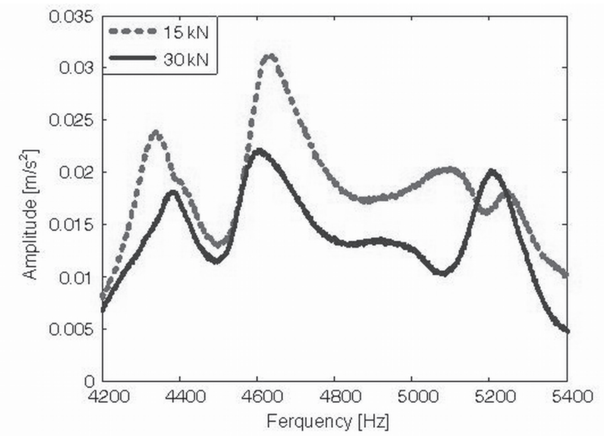

Fig. 3. Changes of amplitude modulation accompanying changes of the load in a selected band [3]

of dispersion and the necessity of determining the dependence of phase velocity on the value of the forces [3; 10].

While using the aforementioned model, vibration frequency is obtained as a function of tensile forces and the wave number:

$$\omega = kc\left(k^2 + \frac{T}{EI}\right)^{\frac{1}{2}} \tag{7}$$

By presenting the compressive force equal to zero (T = 0), we obtain the generally known relation between the frequencies, wave number and wave propagation velocity. It is worth noting that under such an assumption it is still possible to adopt the same wave number as in the case of lack of dispersion since the boundary conditions do not change. Finally, while accounting for the relations $c_f = k\,c$ and $\omega = k\,cf$, we can obtain:

$$c_f^2 = \omega \cdot c = kc^2\left(k^2 + \frac{T}{EI}\right)^{\frac{1}{2}} \tag{8}$$

where the dependence of wave propagation on both, the wave number and the stressing force is visible. As the tensile force increases, so will the wave propagation velocity, while in the case of growth of compressive force – wave propagation velocity will decrease.

The relation obtained on the basis of equation (1), which defines the group velocity in a prestressed structure, has been confirmed in terms of quality during an experiment while quantitative estimates would be burdened with too big an error.

The next item which was analyzed was the model of longitudinal vibration of a beam.

3.2. Equation of longitudinal vibration of a beam

Let us consider free longitudinal vibration of a beam so as to then take into account the effect of compression under a transverse load. In accordance with the model presented in Fig. 4, the relevant equation will take the following form:

$$c_0^2\frac{\partial^2 y}{\partial x^2} = \frac{\partial^2 y}{\partial t^2} \tag{9}$$

where $c_0 = \sqrt{\frac{E}{\rho}}$ is the velocity of propagation of displacement or stress in a beam.

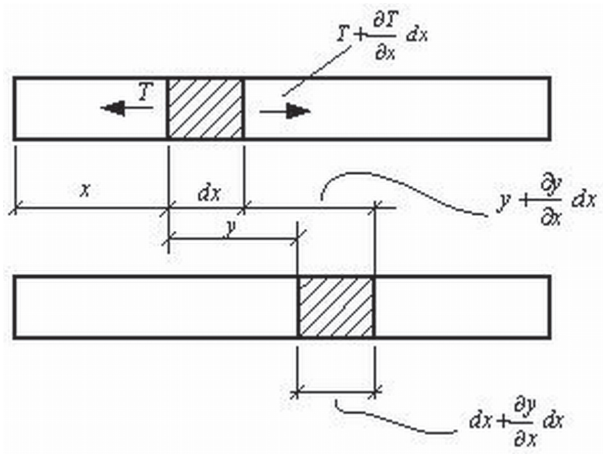

Fig. 4. Model of propagation of longitudinal vibration

Once the stressing forces are taken into account, equation (9) can be expressed in the following form:

$$\frac{\partial^2 y}{\partial x^2} - \frac{p}{T}y = \frac{1}{c_0^2}\frac{\partial^2 y}{\partial t^2} \tag{10}$$

As a result we will obtain relationships defining the phase velocity

$$c_f = c_0\left(1 + \frac{p}{Tk^2}\right)^{\frac{1}{2}} \tag{11}$$

and the group velocity

$$c_g = c_f - c_0\frac{\frac{p}{T}}{k^2\left(1 + \frac{p}{Tk^2}\right)^{\frac{1}{2}}} \tag{12}$$

This way we have demonstrated that two velocities of wave propagation can occur in this case: the phase velocity and the group velocity, which is the requirement for occurrence of amplitude modulation. Fig. 5 illustrates the obtained relation .

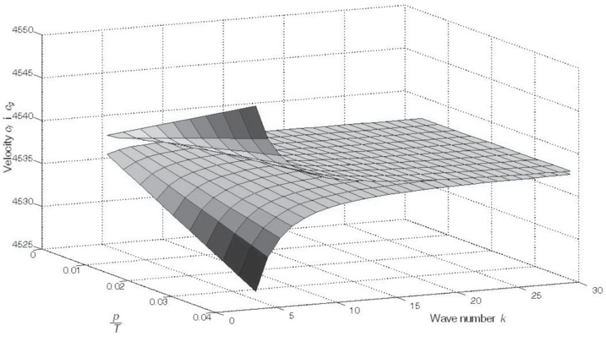

Fig. 5. Changes of group velocity depending on the relation between longitudinal and transverse forces (p/T) in a situation of change of k wave number and change of the direction of stress

To explain the issue of occurrence of amplitude modulation even further, let us quote, after Ignacy Malecki, the model of propagation of two harmonic waves whose ω_1 and ω_2, differ slightly:

$$c_g = c_f - c_0 \frac{\frac{p}{T}}{k^2\left(1+\frac{p}{Tk^2}\right)^{\frac{1}{2}}} \qquad (13)$$

While continuing the analysis of the terms of occurrence of amplitude modulation, relation (13) can be presented in the form of a product:

$$y = 2A\cos\left(\frac{1}{2}(k_2-k_1)x - \frac{1}{2}(\omega_2-\omega_1)t\right)\times$$
$$\times\cos\left(\frac{1}{2}(k_2+k_1)x - \frac{1}{2}(\omega_2+\omega_1)t\right)$$

While accounting for further transformation:

$$y = A\cos(k_1x-\omega_1t) + A\cos(k_2x-\omega_2t) \qquad (15)$$

where $\frac{d\omega}{dk} = c_g$, $\frac{\omega}{k} = c_f$

The obtained relation demonstrates connection between amplitude modulation and the necessity of existence of (14) two different wave velocities: phase velocity (c_f) and group velocity (c_g).

4. Description of the object of research

As part of the research several types of prestressed beams were prepared out of which the first type was selected for preliminary research, namely the beams made of B20 class concrete with the dimensions of 1510×102×200mm, reinforced by four bars with diameter of Ø10 made of reinforcing steel which have been installed along the centerline of the beam. The bars have been run at the distance of ca. 25 mm from the sides, with prestressing between 17 and 20 MPa which has been realized by two tendons strings with seven wires. The second set of bars included prestressed concrete beams with dimensions of 110×140×1300 mm which were made of C 40/50 concrete. Prestressing was achieved under the influence of 4 prestressing bars (with ø 6.8 mm), spaced symmetrically. The prestressing force in the beams changes from 0 kN to 100 kN. The beams did not have any additional reinforcement.

All the beams were subjected to three-point bending, from zero until full fracture of a beam. The diagram is presented in Fig. 6. With a defined load, the structure was forced with a modal hammer which enables force measurement. The dynamic response was registered with the use of accelerometers in the preselected points.

5. Experiments and experimental verification of models

In the case of the first type of beams, while analyzing the dynamic responses it could be noted that a distinct qualitative change of the observed diagnostic parameters occurred when the load of ca. 35 kN was applied. One should note that the analytical calculations, which include the assumed values of initial stress, point to the possibility of occurrence of tensile stress for the preset value of the shearing force. Analyses of dynamic phenomena, especially the frequency-related analysis of the registered signals, were conducted to confirm the occurrence of the observed boundary between the occurring phenomena.

5.1. Examination of the frequency of the beam's natural vibration

Beams of the first type (B20) concrete were used in the research, however the beams marked as 118 and 125 were the good beams while defects, having the form of local moisture development (119) and damage to the part of the cross-section of the string (122) were simulated in the remaining ones.

Figures 7 and 8 present the changes that the selected frequencies undergo as the load on the beams increases. Particular attention should be paid to two characteristic frequencies, 1500 Hz and 7000 Hz. These are the frequencies which are distinctive among the vibration frequencies for all the beams, even in spite of the fact that in the case of the beam affected by moisture, the first of the two frequencies has much more bigger value.

To enable easier comparison of the changes, the scale has been changed in two ways. The first one involved dividing all the frequencies by the maximum frequency (Fig. 7), the other involved deduction of the maximum frequency from all the frequencies (Fig. 8).

In addition the approximated waveforms of the changes was presented with the use of the curves of the second order. In the case of non-defective beams the description relying on a curve of the second order seems to be sufficient. In the case of the beams to which defects were introduced, the description seems not to be very precise and thus higher order curves are necessary to use. Unfortunately examination of the changes of vibration frequency calls for applying substantial loads to the beams, which could lead to their destruction, thus rendering

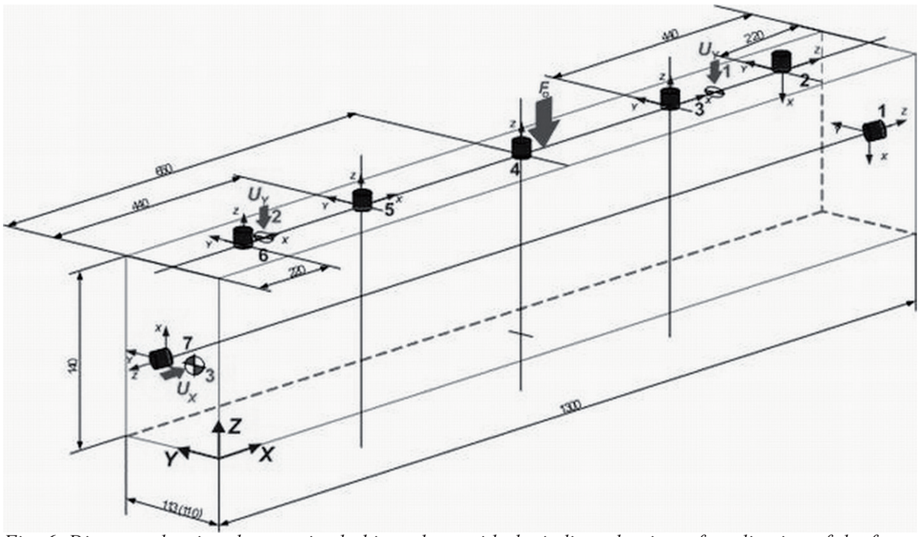

Fig. 6. Diagram showing the examined object along with the indicated points of application of the force, measurement points and places of excitation

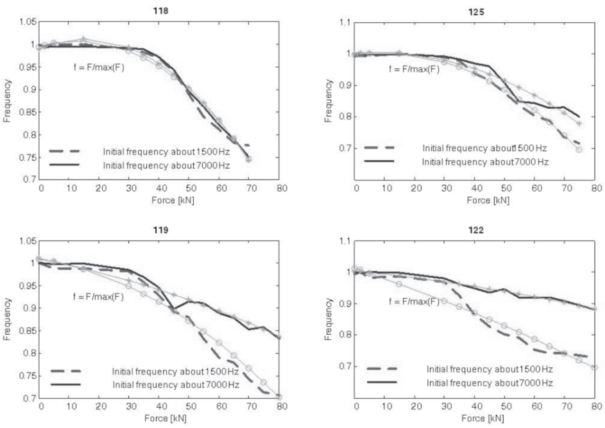

Fig. 7. Changes of selected frequencies depending on the load, with the scale changed in the following form f = fi/fmax

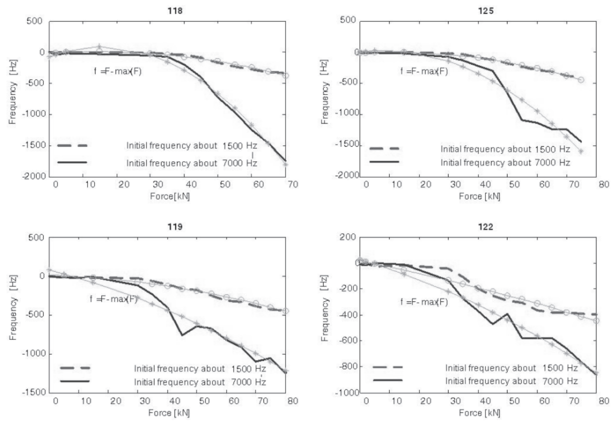

Fig. 8. Changes of selected frequencies depending on the load in a situation of change of scale. f = Fi - Fmax

the procedure useless from the point of view of non-destructive techniques.

5.2. Examination of the phenomenon of dispersion

Relevant combination of loads (ratio of transverse forces to longitudinal forces) contributes to the occurrence of the effect of dispersion, differentiation of group velocity and causing the accompanying effect of amplitude modulation, as presented in Fig. 9. Change of the modulating frequencies, as presented in Fig. 10, was caused by the changes of distribution of stess in the cross-section of the beams and could be used for evaluating the ratio of transverse to longitudinal forces (Fig. 11).

The phenomenon of dispersion was observed this way and in addition the changes of the impact of the load on a structure's dynamic response were analyzed.

6. Conclusions

Relevant combination of loads (applying a transverse load) has contributed to the occurrence of the dispersion effect, diversification of the group velocity and generation fo the accompanying effect of amplitude modulation. At the same time, change of modulating frequencies has been caused by changes of the distribution of stress in the cross-section of the beams and it could used for evaluating the ratio of transverse forces to longitudinal forces, as presented in Fig. 10. This observation enables construction of models on the basis of which one can determine the compressive forces in structures which can be then used to determine whether the assumption regarding non-occurrence of tensile stress is still valid. Thus obtained information will enable determination whether the examined structure could continue to be operated and in what conditions (e.g.reduction of the permitted load for a bridge). The propsed method could be also used for new structures in which it is necessary to determine whether stressing was done correctly, as discussed more extensively by the authors in [6].

The article has been written on the basis of a successful Ph.D. dissertation which was realized as part of COST Action 534 EU Program which was carried in the Technical Diagnosis and Risk Analysis Team.

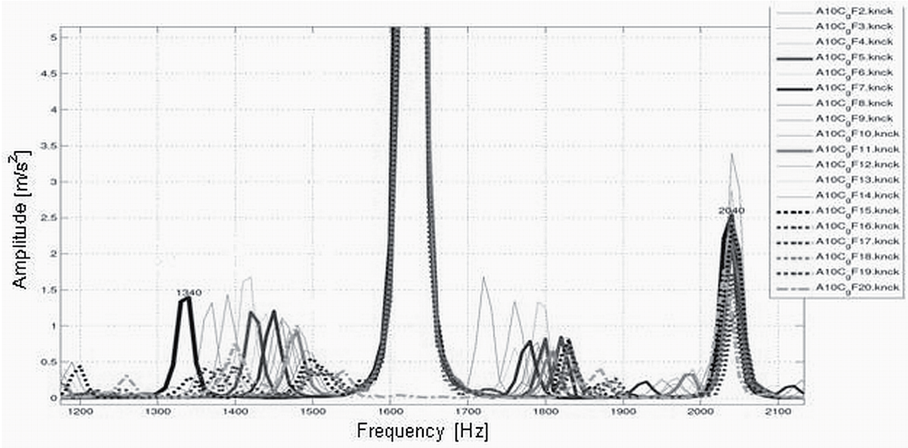

Fig. 9. Fragment of the signal's spectrum for a sample to which load was applied in the form of a transverse force with a frequency of around 1630 Hz, with the effect of dispersion

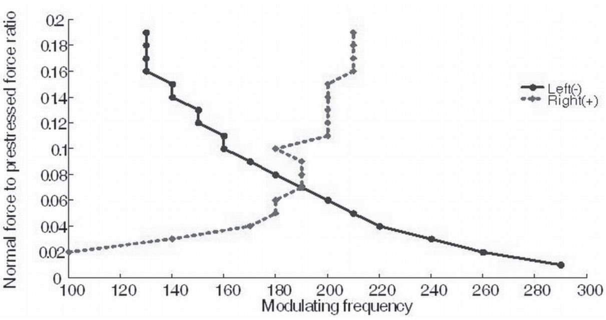

Fig. 10. Changes of modulating frequencies depending on the change of the ratio of transverse forces to longitudinal forces

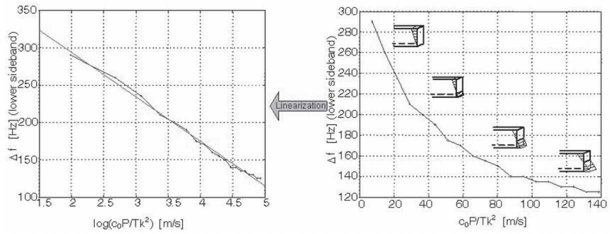

Fig. 11. Linearization of the frequencies of modulating functions depending o the change of the ratio of transverse and longitudinal forces

7. References

1. Burdekin F M, John D G, Payne P A , Locke C, Smith T A, Simm K and Dawson J L. Non-destructive methods for field inspection of embedded or encased high strength steel rods and cables - Phase I NCHRP Project 10 - 30(1), University of Manchester. 1986.
2. Gałęzia A, Mączak J, Radkowski S, Szczurowski K. A method of stress distribution assessment in prestressed structures, 7th International Seminar on Technical System Degradation Problems, Liptovský Mikuláš 200; 39-40
3. Gałęzia A, Mączak J, Radkowski S, Szczurowski K. – co-authors of Chapter 3.5.5: Amplitude modulation for diagnosis of the stste of prestressed structures w Rob POLDER et al.: COST ACTION 534. New materials, Systems, Methods and Concepts for Prestressed Conrete Structures. Final report COST Office, Brussels, 2009; 194÷202,
4. Gołaski L, Świt G. Acoustic non-destructive techniques as a new method for evaluation of damages in prestressed concrete structures: failure of concrete structures. Second Workshop of COST on NTD assessment and new systems in prestressed concrete structures, COST Action 534 New materials and systems for prestressed concrete structures. Kielce, 2005; 151 - 159.
5. Graff K F Wave motion in elastic solids. New York: Dover Publications. Inc. 1991.
6. Jurkiewicz A, Micek P, Apostoł M, Grzybek D. O potrzebie monitorowania procesu sprężenia konstrukcji mostowych (Of the need of monitoring the process of prestressing of bridge structures). Eksploatacja i Niezawodnosc – Maintenance and Reliability 2008;1: 17-22.
7. Krause M, Wiggenhauser H. Ultrasonic pulse echo technique for concrete elements using synthetic aperture. UTonline Application Workshop, NDTnet - May 1997, Vol.2 No.05.
8. Memorandum of understanding for the implementation of a European Concerted Research Action designated as COST Action 534: „New materials and systems for prestressed concrete structures" COST Office, Brussels, 2002.
9. Moulder J C, Kubovich M W, Uzal E, and James H R. Pulsed Eddy-Current Measurements of Corrosion-Induced Metal Loss: Theory and Experiment. Review of Progress in Quantitative Nondestructive Evaluation. 1995; 14: 2065 - 2072.
10. Radkowski S., Szczurowski K. Hilbert transform of vibroacoustic signal of prestressed structure as the basis of damage detection technique Dubrovnik: Proceedings of the Conference on Bridges. 2006; 1075 - 1082.

11. Runkiewicz L. Badania Konstrukcji Żelbetowych (Research of Reinforced Concrete Structures). Warszawa, Biuro Gamma. 2002.
12. Sansalone M.J., Streett W.B. The Impact-Echo Method. The Online Journal of Nondestructive Testing & Ultrasonics, NDTnet 1998 February, Vol.3 No.2.
13. Suzin, A.M., and Donskoy, D.M. Nonlinear Vibro-Acoustic Nondestructive Testing Technique. NDT & E International Volume 34, Issue 4, 1 June 2001, 231-238.

Prof. dr hab. inż. Stanisław Radkowski
Dr inż. Krzysztof Szczurowski
Institute of Vehicles
Warsaw University of Technology
Ul. Narbutta nr 84, 02-524 Warszawa, Polska
E-mail: kszczur@simr.pw.edu.pl