STRUCTURAL CONDITION EVALUATION OF PRESTRESSED CONCRETE STRUCTURES BASED ON VIBROACOUSTIC MONITORING

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Summary

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 was the main research task during COST Action 534 project duration. 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.

Keywords: technical diagnostcs, presstresed structures, amplitude modulation.

OCENA STANU TECHNICZNEGO BETONOWYCH KONSTRUKCJI SPRĘŻONYCH NA PODSTAWIE MONITORINGU WIBROAKUSTYCZNEGO

Streszczenie

Analiza zjawiska modulacji wibroakustycznych parametrów sygnału, a w szczególności amplitudy i struktury częstościowej obwiedni, która jest bezpośrednio związana ze zjawiskiem prędkości grupowej, może być efektywnym narzędziem w diagnozowaniu stanu technicznego struktur sprężonych. Ten zakres pracy, jak również badanie wpływu występowania miejscowych wad było głównym zadaniem kończącej się Akcji COST 534. Zadaniem, szczególnie interesującym i wymagającym dalszych analiz i eksperymentów, jest rozwój i adaptacja użytecznych algorytmów demodulacji.

Słowa kluczowe: diagnostyka techniczna, struktury wstępnie sprężone, modulacja amplitudowa.

1. INTRODUCTION, PROJECT AIM AND DESCRIPTION OF PROBLEM

COST Action 534 is UE research project in subject: "New Materials and Systems for Prestressed Concrete Structures". Project started in 2003 and ended in December 2007.

In project were involved 35 participants. Project was divided to 5 Work Groups and each WG had several Group Projects. Author's research project was realized in framework of Work Group 3 – "New assessment methods". WG3 project aimed to evaluate the structural condition of reinforced and prestressed concrete infrastructure facilities by means of acoustic monitoring and by improving the applicability of the dynamic evaluation techniques. Group Project 4 – "Structural condition evaluation of prestressed concrete structures based on acoustic monitoring", whose coordinator was Stanisław Radkowski, was aimed to develop vibroacoustic methods allowing for evaluation of condition of structure. In this Group Project participated researches from: Warsaw University of Technology, KWH Bautechnologen AG, AGH University of Science and Technology, Poznań University of Technology, Bouwdienst Rijkswaterstaat and Advitam, Budapest University of Technology and Economics, National Technical University of Athens.

In this paper authors would like to present results of their research in framework of COST Action 534 and conclusions related with this subject.

It was intended to achieve the structural evaluation by analysis of the relationships between the distribution of stress in the cross-section and changes of vibroacoustic signal's parameters.

It is generally known that infrastructure facilities (viaducts, bridges, etc.) age over time with an increasing rate due to intensified loads by traffic and aggressive exposure conditions. For concrete structures this process results in cracking in many cases. Consequently, the problem of structural performance regarding to load capacity and user safety becomes of increasing importance. From an owner's perspective condition evaluation by non-destructive techniques could therefore be very helpful in supporting management and maintenance decision's making process.

Basic assumption is that increase and decrease of prestressing forces are accompanied by a change of stress distribution in the cross-section of concrete structure. The parameters of propagation path will change due to this phenomenon.

Using monitoring technique based on the change of their dynamic characteristics to classify structures, it is necessary to determine a numerical relationship between the measurable dynamic characteristics and the degree of deterioration. The availability of several physical models regarding deterioration of prestressing structure makes it possible to establish relationships between defects resulting from degradation of prestressed steel and the stress distribution in the cross section of structure. As the stress level affects the velocity of wave propagation, vibroacoustic is used to provide quantitative information on the general stress. This information is used to evaluate the overall condition with respect to the load-bearing capacity of structures using appropriate numerical modeling tools. It is therefore important to note that the project was aimed at overall condition evaluation of structures rather than provide information on the level of single defects. Based on the development of stress distribution over time predictive evaluation of structure condition to establish the residual service life is performed.

The to-date research, concerning components of machines and especially the shafts, that is the beam-type structures, shows that changes of stress in the outer layer of concrete can be detected by methods of vibroacoustic signal demodulation. Accordingly, the occurrence at the quantitative change of stress distribution leads to the change of distribution of amplitudes around the relevant carrier frequency, usually the natural frequency of structure vibration. Thus, apart from the selection of the relevant model of the modulation phenomenon, the essential task in the proposed project was to define the method and the criteria of selection of modulated bands of diagnostically essential carrier frequencies.

For real-life structures continuous acoustic monitoring using surface applied sensors are a practical way of condition evaluation. The results thus obtained indicate the occurrence and the location of tendon failure. By appropriate filtering techniques the method is capable of providing useful information even in a noisy traffic environment. The data can be used to support decisions regarding management and maintenance of structures.

2. LABORATORY EXPERYMENTS - RESULTS

Examined method of diagnosis relies on the relationship between the parameters of the wave propagation as a function of stress occurring in a given object. This is manifested by changes to the modulation of the vibroacoustic signal's parameters, which is caused by the disturbance of propagation of the sound wave in the material as a result of changes to the distribution of stress in the cross-section of the pre-stressed structure. Defects appearing in structure leads to the decrease of compressing stress what result in a change in the distribution of stress in the cross-section that is measurable in a degree allowing one to detect the qualitative change of the effect of modulation of the vibroacoustic signal's parameters.

Paper presents method of evaluating the technical condition of a prestressed structure while underscoring the possibilities offered by use of amplitude modulation effects which occur in the observed vibroacoustic signal.

2.1.Description of laboratory tests

In frame work of research project many tests in laboratory conditions were performed. Examined samples were made for purposes of tests. As a result of analysis of signals obtain from measurements, it was possible to define algorithm of failure detection and identification.

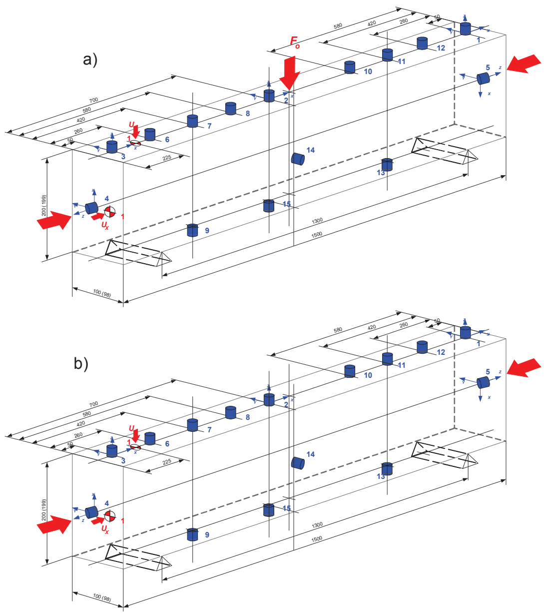

Fig. 1. Location of vibration sensors and directions of vibration-causing forces in the prestressed concrete beam: a) - scheme of measurement made in Kielce and Warsaw (with perpendicular force), b) - scheme of measurement made in Poznań (without perpendicular force)

Tests were aimed for investigation of dynamic response of prestress structure behavior under changeable loading conditions: what is frequency structure of a response pulse and how it depends on technical state and failure evolution.

Preliminary set of tests were carry out in beginning of project and made in Kielce University of Technology. Measurements were carry out on a prestressed concrete beams made of B20 class concrete with dimensions 1500x100x200mm. The specimen was placed in the strength testing device bed, supported by two symmetrically placed supports and during measurements it was loaded by machine's bending punch with a pre-defined force. Exact description of tests can be found in [5, 6]. The tests were carried out with load changing from 0.5 kN to 70 kN, because loading with force 75 kN resulted in breaking of the beam. The first small cracks usually emerged when the load of 45kN was exerted.

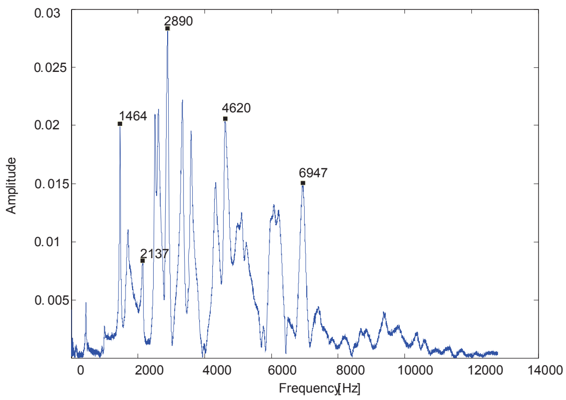

Fig. 2a. Signal spectrum obtained from one of measurements

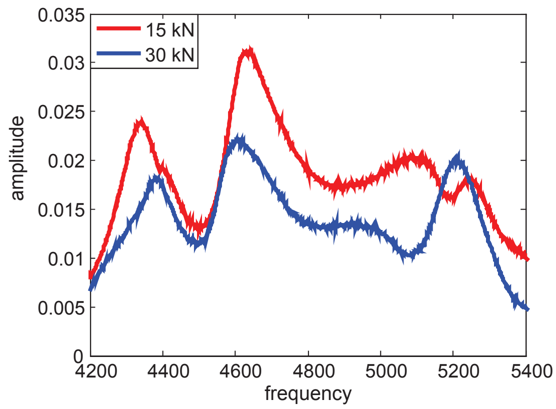

Fig. 2b. Selected frequency band - changes in amplitude modulation resulting from change of load

In order to observe the changes in terms of propagation of the wave through the examined beam vibration sensors were placed on the beam. Their exact locations, locations of impulse excitation force and point of loading are presented in Fig. 1a.

Recorded 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 5).

Figure 2a presents example of signal spectrum obtained from one of measurements. Figure 2b presents sideband of previous spectrum concentrated around 4800 Hz.

First observation was change of natural frequency as a function of crack expansion figure 3). Changing of loading caused a bending of a specimen. Bending lead to change of stress distribution in beam and change from compressive to tensile. This lead to arise and further expansion of crack under increasing loading. It can be seen that before arise of crack there is no change in natural frequencies and after arise of crack change is significant. Basing on change of natural frequency it is possible to infer about crack appearance and its evolution. This is related with change of mechanical properties of specimen and stress distribution in structure with cracks. However this method gives no information about stress distribution in stage before failure formation so it is impossible to predict how close to failure structure is.

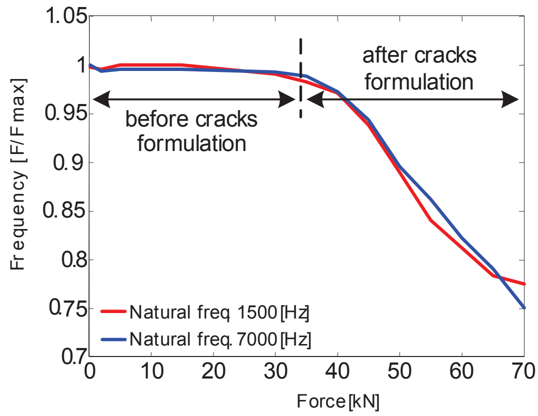

Fig. 3. Change of natural frequency as a function of crack propagation

It was also observed that due to dispersion phenomena in concrete, it is possible to observe not only phase velocity but also the group velocity.

As it was also observed, that around natural frequencies modulation bands are present. These bands are not equivalently distend from carrier frequency, and they are shifting due to change of load.

Next measurements were made in Poznań University of Technology. Set of 11 prestressed concrete beams was tested. Each specimen differs with degree of prestress. Beams had prestressing from 0 kN to 100 kN, with step of 10 kN. Beams dimensions were: 1300x140x110 mm. Specimens were produced in factory with maintaining of production and standard procedures.

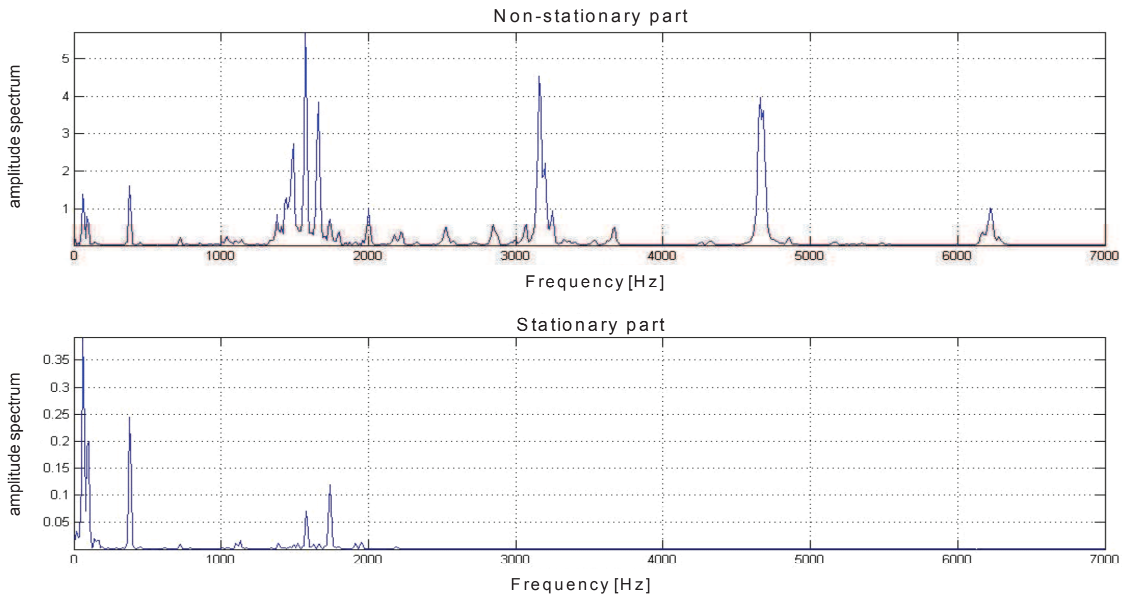

Fig. 4. Spectrum of non-stationary and stationary part of vibroacoustic signal

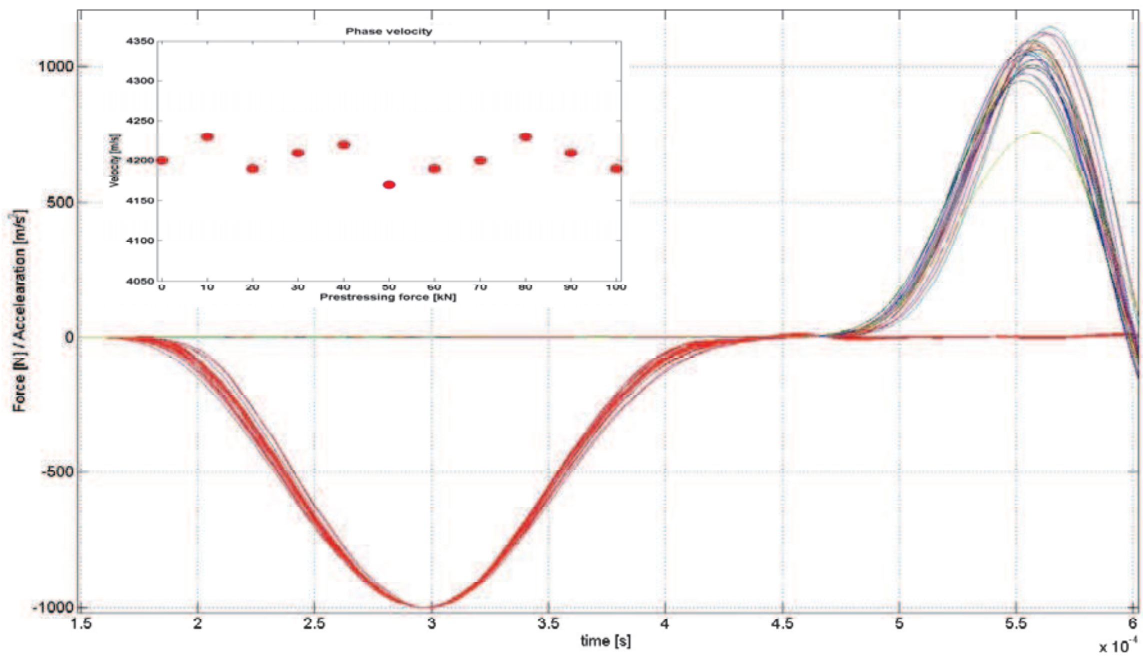

Fig. 5. Changes of phase velocity as a function of prestressing force and waveform of excitation and structure response on opposite end of beam

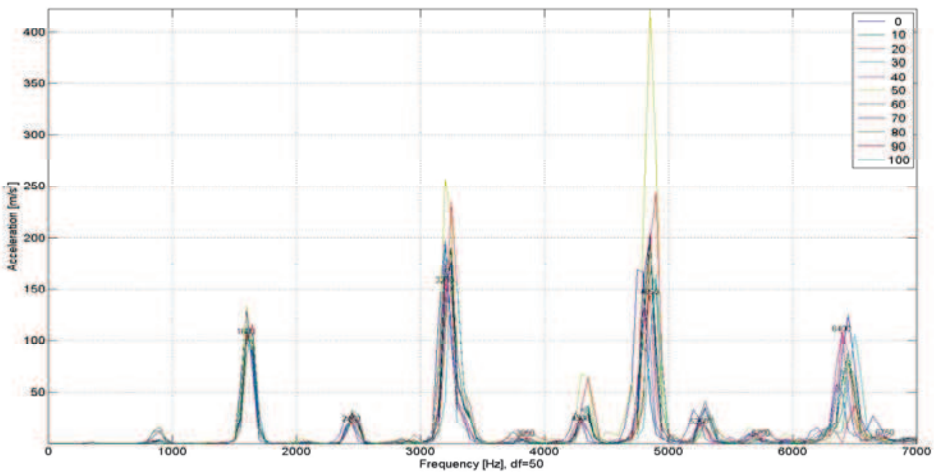

Fig. 6. Spectrum of response signals for different prestressing

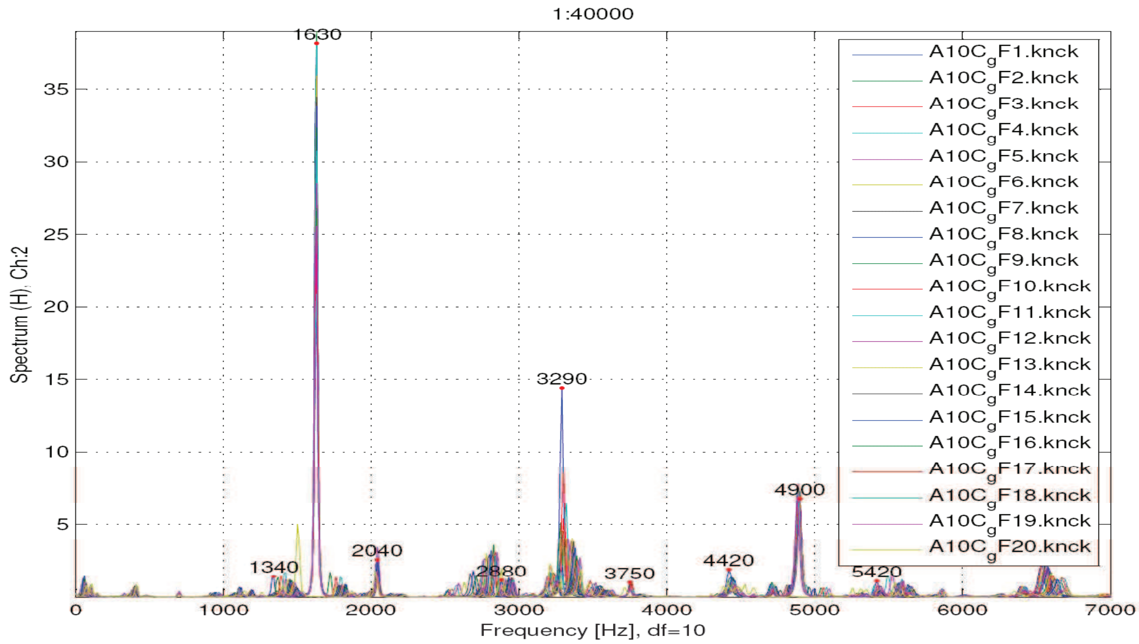

Fig. 7. Signals spectrums for beam with prestressing force 100 kN and different loading

Tested beam was supported on steel prisms and expanders allowing for free vibrations of beam. This was made to verify which support gives more informative results and bring in less disturbances. No additional, external forces were applied to specimen during measurement. Measurements aimed to investigate influence of prestressing force on distribution in spectrum of natural vibrations.

Excitation of vibrations was made by modal hammer and measured by set of vibration sensors attached to surface of specimen. Data acquisition was made using NI equipment with high sampling frequency.

Support on steel prisms introduce less disturbances by damping free low frequency vibrations. For further analysis signals from prisms were examined. An interesting observation is related with frequency structure of response for excitation. From informative point of view, response signal can be divided in to two parts – stationary and non-stationary.

Non-stationary part approximately ends around 0,05 second, from beginning of signal, and its spectrum contains many informative frequencies - higher natural frequencies, modulations around them additional peaks. Problem is duration of this signal, what influence spectrum frequency resolution. Spectrum of stationary part (from 0,05 till ~0,25 sec.) contain peaks of lower frequencies related with free vibrations (fig. 4). Analysis of signal combined from non-stationary and stationary part, in spite of increasing frequency resolution, is not giving improvement in information contained in signal due to decreasing of amplitude of peaks.

A surprising result achieved from analysis of signal was that change of degree of prestess has no influence on phase velocity of wave. Figure 5 presents changes of phase velocity in a function of prestressing force and waveform of excitation and structure response on opposite end of beam. It can be seen that for unify waveforms of excitation (below 0 line), there is no trend in changes of response waveforms (over 0 line). Such changes were detected in signals coming from measurements made in Kielce.

Also it was discovered that there is no unique and significant changes in signal spectrum for differed prestressings (Fig. 6).

Taking in to consideration that the diagnostic experiment was performed without perpendicular force, it is obvies, that no dispersion phenomenon in prestressed structure was indicated on this way.

It must be remembered that each specimen, having own presterssing, was a different object. This leads that despite of maintaining production procedures difference from assumption can be present. Following conclusions came out after measurements: dynamical behavior of tested structure was very similar, changes of degree of prestress do not influence phase velocity. Phase velocity can not be used as a tool for inferring on stress exiting in structure. Also the measurable change of group velocity was not observed.

Basing on those results additional tests were made in laboratory of Research Institute of Roads and Bridges in Warsaw. Tests were made on selected beams (prestressing force 0 kN, 3 kN, 5kN, 10 kN) from set of specimens tested earlier in Poznań. Thanks to this errors due to different specimen were avoided and could be compared with results from earlier measurements.

During this measurement session, vibration response, to impulse excitation, of each beam, was registered. Specimens were placed in durability machine which implement force on prestressed concrete beams using bending punch. Specimen dimensions: 1300x100x140 mm, distance between supports in durability machine was 1060 mm. Examined structure was banded until arise of crack. Bending force was changing from 0 kN to 19 kN, with step 1kN.

Analysis of signals gives very interesting results. Similarly to results of measurements made in Poznań, no change in phase velocity has been observed – in both cases - as a function of prestressing and as a function of bending force. Spectrums of signals from beam with prestressing force 10 kN and different loads are presented on figure 7. It can be seen that natural frequencies are not shifting, what is related with stability of phase velocity, in contrast to sidebands around them, what is related with group velocity. This phenomenon is caused by dispersion. It is well visible on side bands around carrier frequency 1630 Hz. (natural frequency).

3. ALGORITHM OF DIAGNOSING

As it was presented in [1-4, 7] dispersion phenomena cause change of group velocity of wave traveling through beam. This change cause as an effect amplitude modulation of carrier frequency. It can be also seen that shift of sidebands has tendency – with increase of stress in cross-section sidebands are shifting in direction of higher frequencies. Main conclusion based on results is that changes of phase velocity carry information about failure development and group velocity may be a very useful tool for estimation of stress distribution in structure.

The analysis of the phenomenon of modulation of a vibroacoustic signal, especially the amplitude and the frequency structure of the envelope which is directly associated with the effect of existence of group and phase velocity, may prove to be an effective tool in the process of diagnosing the technical condition of prestressed structures.

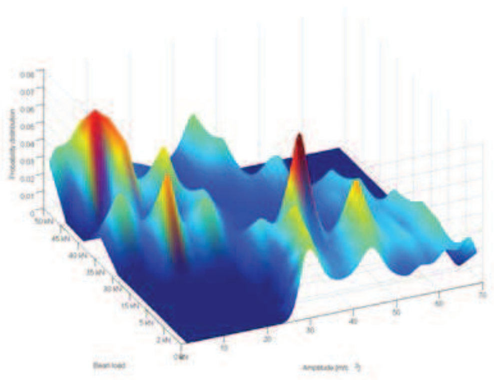

Fig. 8. Probability distribution of acceleration envelope

As an example of usage of probability distribution of acceleration envelope as a diagnostic parameter of technical state of prestressed construction, the quantity change in amplitude due to formation of structure cracks could be considered (figure 8).

On the one hand there occurs the relationship between phase velocity and frequency while on the other the group velocity changes leads to the phenomenon of amplitude modulation. The existence of direct relation between the stress in the concrete and in the pre-stressing bars on the one hand, and the values of phase and group velocities, on the other, create the possibility of building inverse diagnostic models and thus determining the quantitative changes of such parameters of technical condition as Young's modulus or stress in the concrete and in prestressed steel bars.

The descriptions of the phenomena listed here, the relevant mathematical and diagnostic relations, are presented in [1-6]. They enabled addressing in the present document, the task of developing the algorithm for measuring, analysis, diagnostic inference and estimation of technical condition of a prestressed structure.

Basing on this following algorithm was proposed [7].

In the first step the signal registration and the preliminary analysis of correctness of registered signals are performed. With the use of a signal coming from a force sensor, placed in a modal hammer used for excitation, all the signals are rescaled and averaged (assuming linear relationship with the excitation force). At the stage of research related to prestressed concrete structures we examined the relation between the excitation force and the amplitude of response. Since the amplitude depends on the force in a linear manner, thus its scale can be changed in any way.

In the next step the averaged signals are subjected to a Fourier Transform. At this stage we can observe the changes of own vibration frequency which, as paper [3] demonstrates, are subject to substantial changes along with the emergence of cracks. Defining the values of frequencies of subsequent forms of own vibration enables determination of phase velocity, while its relation to frequency enables initial estimation of stressing forces occurring in the examined structure.

In the further part of the task we determine the bands surrounding own vibration frequency where we can expect the emergence of modulated bandwidths containing relevantly-oriented diagnostic information. After filtering in the bandwidths and demodulating the results, we obtain the information on instantaneous values of the envelope.

At this point attention should be drawn to the need for selecting relevant frequency bands due to the possibility of omitting the information in a situation of its improper selection. Attention should be drawn to the phenomenon of asymmetrical modulation, which was discussed in earlier papers and reports [2, 4].

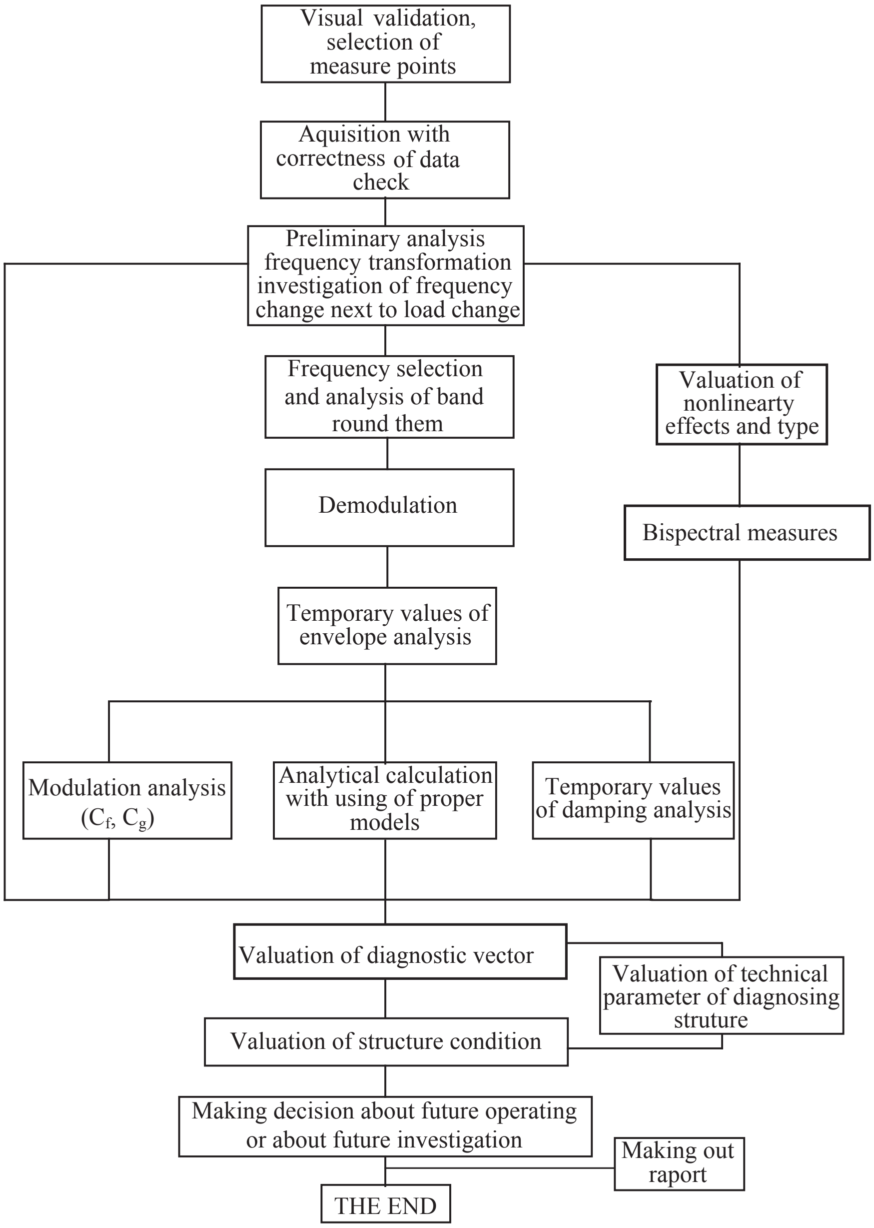

Fig. 9. Algorithm of diagnosing

While observing the changes taking place in the signal's envelope, one can initially define the state of stress: is it in the area of load where stressing or stretching loads occur? It is also possible to initially determine the occurrence of defects in the examined object.

When using demodulation it is possible to examine the phenomena associated with group velocity, which along with phase velocity enables us to define the stress in the cross-section of the examined structure. While relying on the same signal, it becomes possible to define the damping of the examined signal by the structure. In accordance with the examples presented here, while relying on the changes in the damping phenomenon, one can determine the occurrence of unfavorable events, e.g. defects of the prestressing string or significant, local moisture having influence on the strength of a structure.

The algorithm analyzes the tasks resulting from the description in a relevant sequence. What is worth noting is the necessity of maintaining constant control of correctness of measurement results' registration. It is the outcome of extensive requirements related to measurements, in particular the registration at the sampling frequency, which enables determination of instantaneous phase velocity of wave propagation. Respectively, in the next step one should select the parameters of transformation to the frequency domain. The selection of frequency bandwidths should be supported by the analysis of the dynamic model of a structure – in this case a beam, and by the analysis of sensitivity of relevant bandwidths to changes of group velocity as a function of its dependence on the properties of materials and the state of stress or magnitude of prestressing forces.

Signal demodulation, performed as the next step in earlier selected bandwidths, enables estimation of the signal's frequency structure, the frequency structure of the envelope in this case. The demodulation can be performed while using various methods – Hilbert transform was used in this case, which in the task of determining the envelope enables us to obtain results which are satisfactory, correct and precise-enough.

The results obtained this way allow us to define the parameters of the envelope, which are required for further analysis, especially their instantaneous values. Then, based on the relationships developed earlier, the parameters of the envelope obtained this way are in the next algorithm step used for determining the value of phase velocity and group velocity. Similarly, while using a dynamic model which describes transient motion, it becomes possible to determine the damping value. It is worth noting that for the purpose of defining the degree of the influence and type of non-linearity occurring or dominating in a structure, the algorithm provides for the possibility of conducting the relevant bi-spectral analysis.

After conducting the presented activities we have a multi-dimensional vector of diagnostic parameters, which in the next step of the algorithm can be used for calculating the technical parameters of the diagnosed technical structure. As an option the proposed procedure offers the possibility of drafting of reports in a selected format.

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