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MAIN ELEMENTS OF INVESTIGATION OF MEASURES OF VIBRATION ENERGY PROPAGATION IN STRUCTURES

Katarzyna Jeleniewicz[1], Mariusz Żółtowski[2]✉

[1] Institute of Civil Engineering, Warsaw University of Life Sciences – SGGW, Warsaw, Poland
[2] Water Centre, Warsaw University of Life Sciences – SGGW, Warsaw, Poland

ABSTRACT

The paper indicates the possible range of applications of investigation of measures of vibration energy propagation, used in modeling of vibration processes and methods of modal analysis in the area of research methodology and detailed methodologies of technical sciences. Theoretical analyzes and practical verification of results of testing of many different materials and structures indicate a wide range of applications of the described achievements. Recognizing the need to improve methods of testing of building structures in order to assess their degradation state, this work presents generalized, significant results of a research procedure within the scope of verification of the effectiveness of the developed methodologies for detailed application of vibration measures in simulation, bench and operation tests.

Key words: modal analysis, natural vibrations, modeling of vibration processes

INTRODUCTION

Classically, one can distinguish the methodologies of exact, natural (here: technical) and social sciences. In the technical sciences, in order to prove a thesis or verify hypotheses with use of appropriate measures, various measurements are made in experiments, and the obtained results are compared with the results obtained by other researchers. To work out the cause and effect of the obtained results, a mathematical description are applied, mainly statistical methods. Many sciences have their own methodologies or use achievements of others, borrowing their methods in a modified form and adopting them to the needs of the problems being solved (Allemang & Phillips, 2004).

This paper presents generalized procedures for investigations of dynamic properties of various elements of machines and building structures, taking into account simulation tests and their verification in stand and operational tests (Żółtowski & Cempel, 2004; Żółtowski, Żółtowski & Liss, 2016).

The issues of description and examination of changes in the state of destruction of elements, materials, structures and machines are mainly carried out with the use of vibration diagnostics measures and vibration-based modal analysis methods. An important issue here is the description and study of vibration energy flow, useful in the already widely used vibration diagnostics and in some less frequently used methods of modal analysis (Żółtowski & Cempel, 2004; Avitabile, 2015).

Assessment of the dynamic state of building structures by means of vibration energy propagation measures requires the association of the structure features of the object under assessment with a set of measures and assessments of output processes. This is the area of identification where the vibrations introduced into the object are evolving and maintain the equilibrium

Katarzyna Jeleniewicz https://orcid.org/0000-0002-7109-2737; Mariusz Żółtowski https://orcid.org/0000-0003-0305-2378
✉mariusz_zoltowski@sggw.edu.pl

conditions between the state of inertia, elasticity, damping and excitation. Disturbances propagate from wave sources in a manner dependent on the physical properties and boundaries of the configuration, dimensions and shape of the structure. Consequently, wave energy dissipation, deflection, reflection and mutual overlap occur. As a result of the existence of the input and the implementation of the transformation of states representing the features and properties of the structure, a series of measurable characteristic symptoms, contained in the output processes, arises. Vibrations may affect the state of use of a building by reducing the comfort of people working there and may also reach a level threatening the safety of the structure. The influence of vibrations on the structure manifests itself mainly as additional stresses in a section under consideration, which are added to the stresses from static loads, and may lead to the destruction of a given technical system (Cempel, 2003).

Modal analysis, based on the use of vibration energy propagation measures, is used in the assessment of the state of structure degradation at the stage of testing and improving the prototype, during operation as well as in the modification of existing structures. The described research presents the procedures of the methodology of vibration testing of various objects and analyzes the usefulness and effectiveness of modal methods (experimental and operational) as well as selected measures of the vibration process for the assessment of the state of destruction of selected elements and building structures during operation (Żółtowski & Cempel, 2004; Uhl, Sękiewicz, Hanc & Berczyński, 2005; Stepinski, Uhl & Staszewski, 2013; Liss, Żółtowski, Żółtowski, Sadowski & Kuliś, 2016).

The purpose of the research described in this work is to develop a methodology for testing and assessing the state of degradation (damage) in materials and structural elements with use of estimators in vibration diagnostics and methods of modal analysis.

MODAL ANALYSIS IN CONDITION IDENTIFICATION

Modal analysis is widely used in the study of damage, structure modification, update of the analytical model or condition control, and it is also used to monitor the permissible vibration level of many different structures in civil engineering (Żółtowski, 2012; Żółtowski & Martinod, 2015; 2016).

Often used in various applications, modal analysis is a technique for examining the dynamic properties of structural fragments, using modal model parameters, consisting of modal frequencies, damping and vibration modes (Wiliams, Crowley & Vold, 1985; Cempel, 1991; Liss et al., 2016).

For complex, often non-linear systems, modal analysis is used to identify structure degradation. As a result of its implementation, on the basis of stabilization diagrams, a modal model is obtained allowing to predict the reactions of an object to any disturbance, both in the time and frequency domains (Uhl et al., 2005; Żółtowski, 2012; 2014).

The parameters of the modal model enable decoupling of the equations describing the vibrations of the system, and their values are determined from the relationship (Uhl, 1997; Żółtowski et al., 2016):

$$m_r = \frac{1}{2 j \varpi_r R_{ir}}$$

$$k_r = \varpi_{nr}^2 m_r$$

$$c_r = 2 m_r \varpi_{rn} \delta_m$$

These quantities describe the properties of the system related to r – the eigenfrequency, and the changes of the eigenfrequency depend on the magnitude of the changes in stiffness or mass as well as the location of the damage development in the structure. The modal model can be further identified on a real object on the basis of the results of an identification experiment (Żółtowski & Żółtowski, 2014; 2015a).

In practical application in the research signaled in this paper, in most applications it is assumed that as a result of damage, the stiffness of the structure changes locally, what causes changes in the modal model parameters. By tracking changes in the mode of free vibrations, it is possible to determine the area in which significant destruction occurs (Żółtowski et al., 2016).

EXAMPLES OF APPLICATION MEASURES OF VIBRATION ENERGY PROPAGATION

Indications for the use of vibration energy flow measures in the quality assessment and degradation of technical systems are presented on selected fragments of various studies. Various configurations of the available equipment and software are used in the vibration energy propagation studies, for example shown in Figure 1.

Vibration measures in the degradation elements and entire building structures. Simple and complex measures used in vibration diagnostics of machines and building structures are defined in terms of amplitude, time and frequency (A, t, f) on the basic signal from vibration measurement $A(t)$ (Fig. 2).

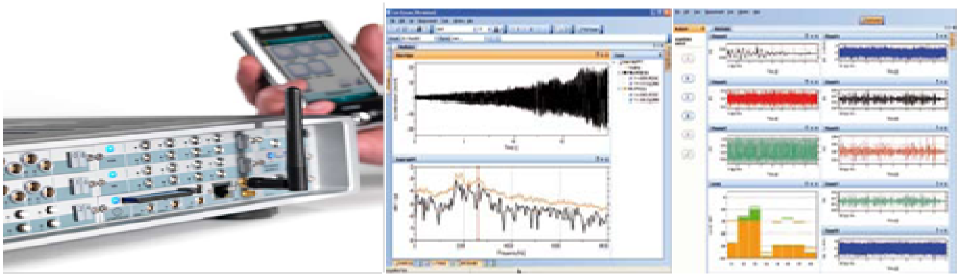

Fig. 1. Measurement system with preliminary data processing

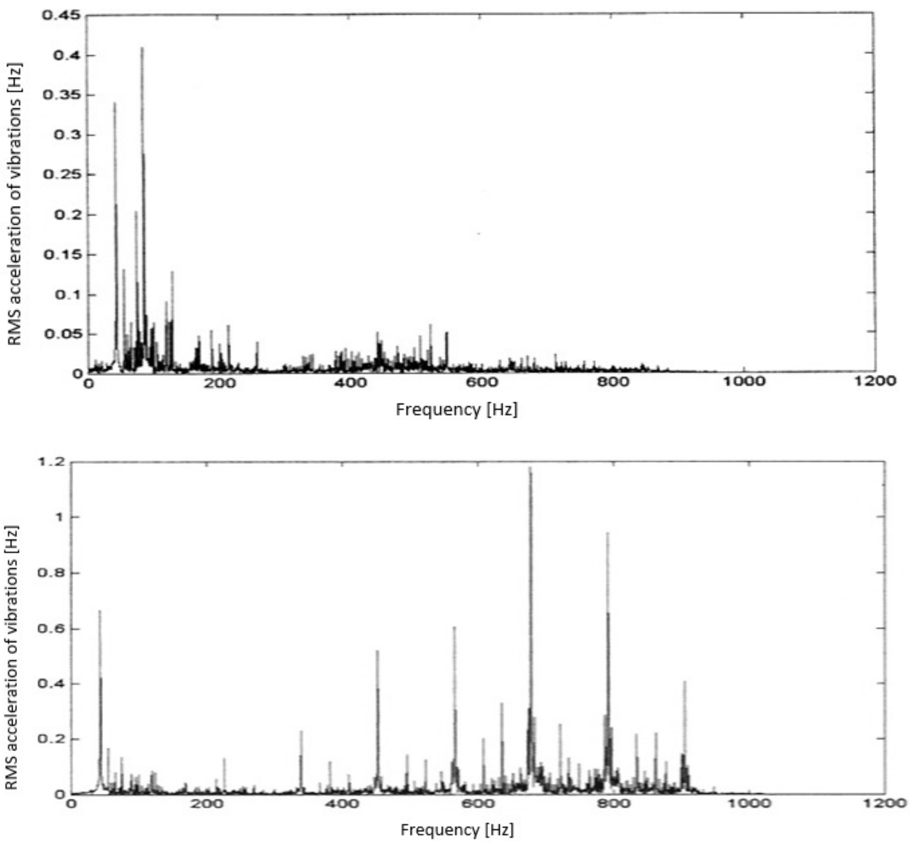

Fig. 2. Spectrum of vibrations of a fit bearing (left side) and a damaged bearing (Żółtowski & Martinod, 2015)

Selection of information. The presented exemplary measures of the state of degradation better or worse reflect the studied changes in the state, what forces the need to select the acquired information.

OPTIMUM is a proposed initial methodology of selection of information, organizing the measured symptoms in a ranking order depending on the distance from the ideal point (Allemang & Phillips, 2004). Statistical measures are used here (e.g. symptom variability, coefficient of variation, correlation) describing the sensitivity and usefulness of the measured symptoms, and for further inference, the best ones (Fig. 3), located closest to the ideal point, are arbitrarily selected (Żółtowski & Cempel, 2004; Żółtowski, Łukasiewicz & Kałaczyński, 2012; Żółtowski & Żółtowski, 2015b).

Singular value decomposition (SVD) is a numerical methodology of information processing during multidimensional observation of the destructive processes in construction. It recommends the use of all measurable measures of vibration processes in making conclusions (Cempel, 1994), obtaining information about the number of developing failures after normalizing the measures, assessing the usefulness of the measures in making conclusions and predicting sensitive symptoms (Fig. 4). Both methods of obtaining qualitative information on destruction can be used independently on each other.

Bonding models describing the cause-effect relationships (what and how depends) use the measures proposed for inference in the OPTIMUM and SVD procedures. The goodness of the model in relation to

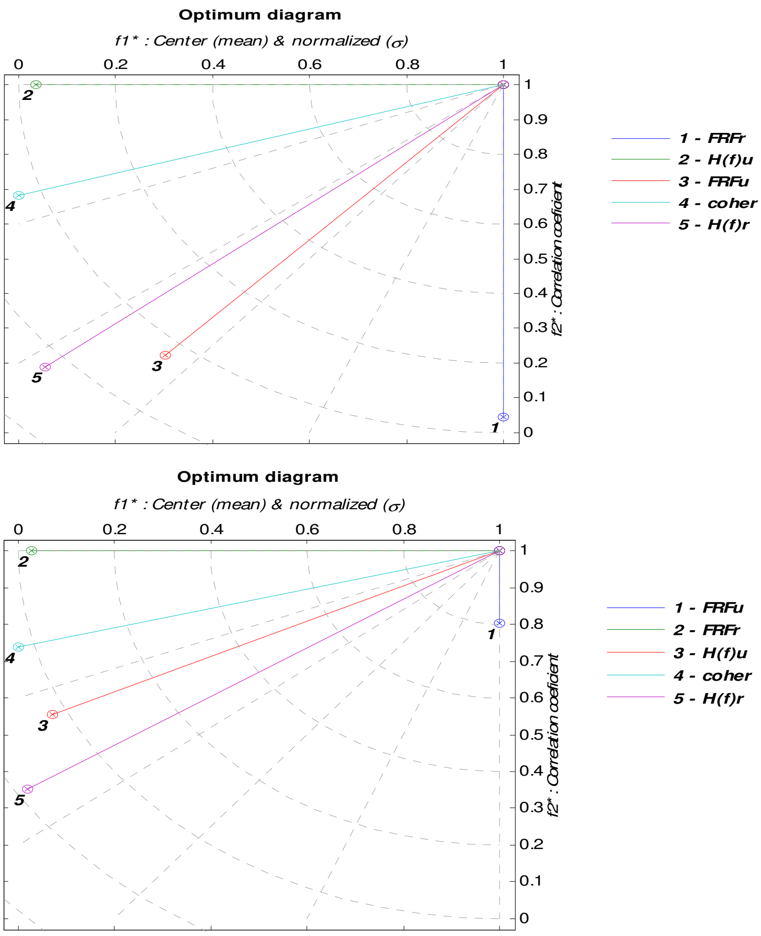

Fig. 3. Ranking of the sensitivity of vibration measures of ceramic segments

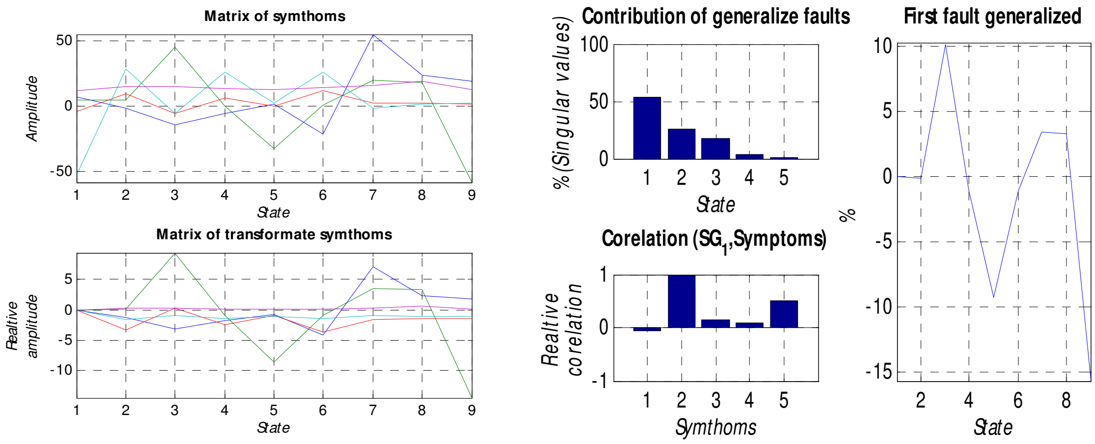

Fig. 4. Results with SVD for tested steel elements along the X axis

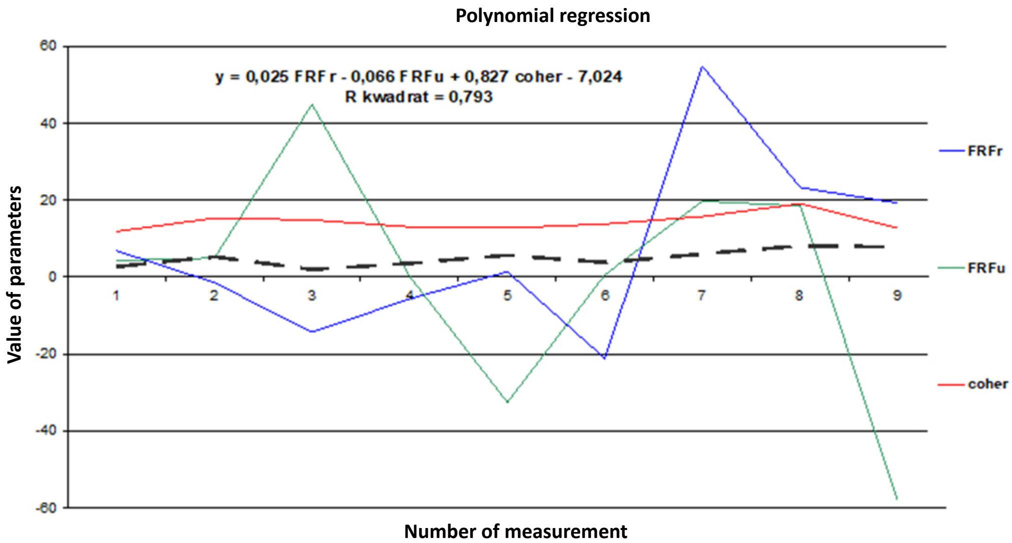

Fig. 5. Mathematical model of steel structure destruction

the measurement results is assessed with the coefficient of determination (R^2). The available Microsoft Excel and MATLAB® software is very useful at the stage of creating inference models and they present the results in a friendly way (Fig. 5).

Modal analysis in the description of state degradation. The dynamic properties of linear systems with constant parameters can be characterized by a pulse transition function $h(t)$ defined in the time domain or by a transfer function $H(f)$ defined in the frequency domain. The research procedure to determine the transmittance in the experimental modal analysis (EAM) of any structure is shown in Figure 6.

LMS™ Test.Xpress measuring equipment was used to measure the time courses of the excitation and response of the tested system as well as to determine the $H(f)$ function. This software allows to easily perform a modal analysis of structural elements as well as any other building structures. The program has an easy and pleasant user-friendly interface.

Basic data for the modal model (vibration frequencies, damping) are determined from the stabilization diagrams obtained in the research. For characteristic and important vibration frequencies, vibration modes can be generated which are very useful for inference (Cempel, 1991; Uhl et al., 2005). The stabilization

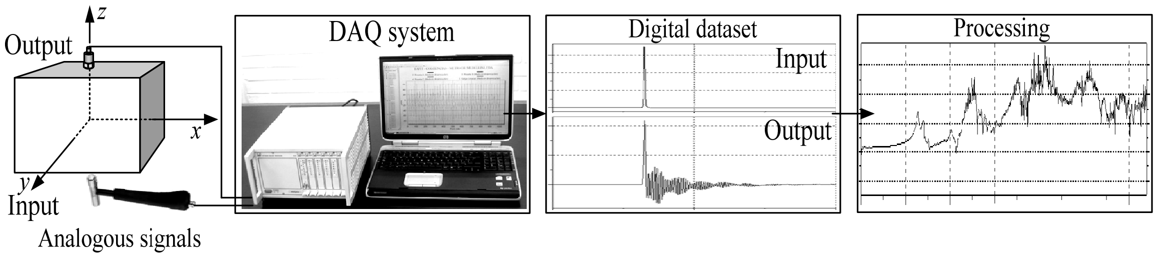

Fig. 6. The idea of determining *H*(*f*) of any structures in EAM

diagrams presented in Figure 7 (with an additionally determined spectrum of vibrations of the dominant frequencies) determine the natural frequencies for various states of brick wall degradation.

Table 1 presents a table of natural frequencies generated for measurements of various degradation states of the tested brick structure with the use of experimental model analysis.

a

b

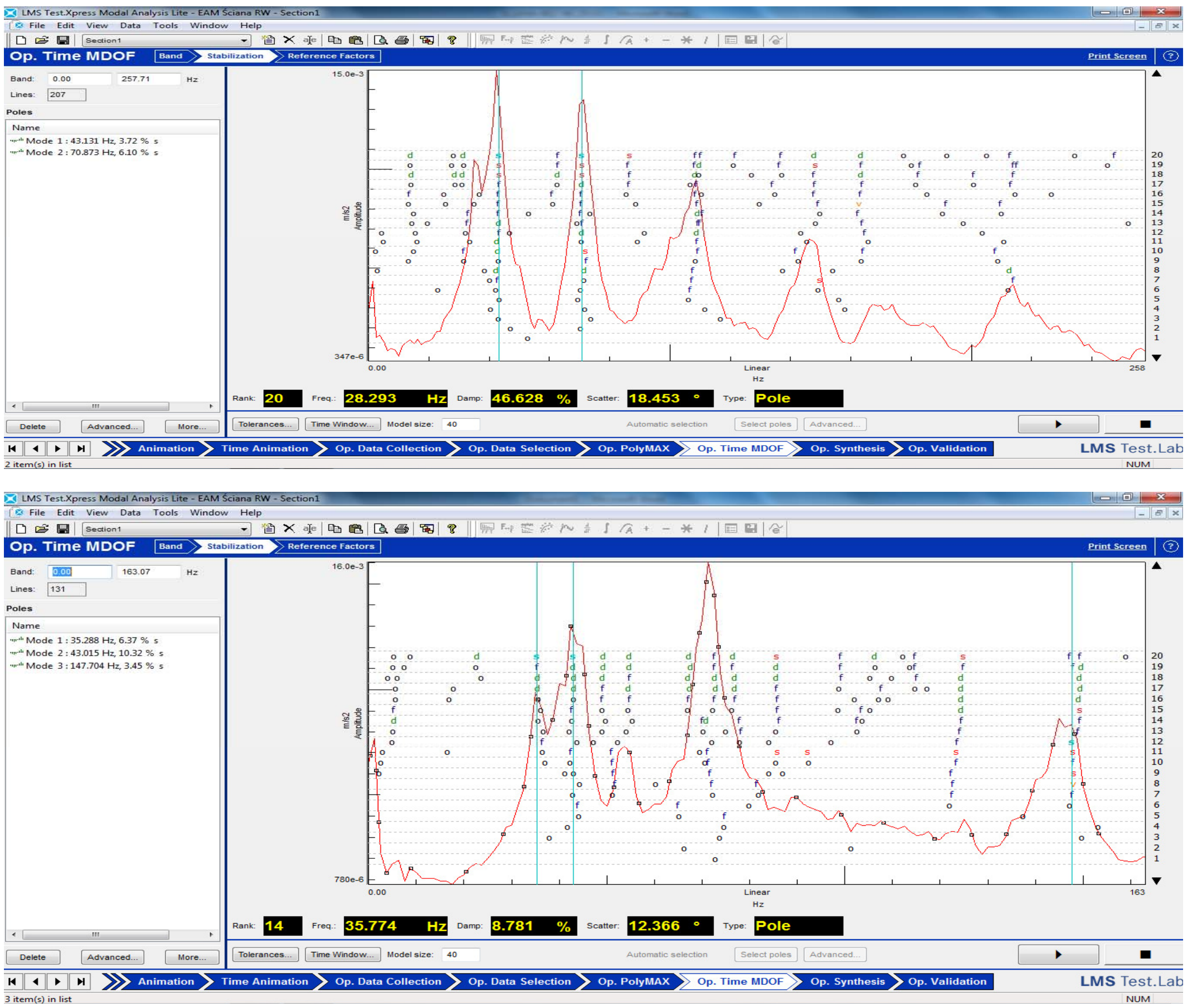

Fig. 7. Diagrams of stabilization of a brick wall with one crack (a) and with two cracks (b) with forcing

From the above-mentioned test results, it can be initially concluded that for suitable brick masonry structures the natural frequency of 70–80 Hz was generated, and for damaged structures, natural frequencies were generated at a much lower level – 30–40 Hz (Żółtowski & Żółtowski, 2015b).

Improving FEM with methods of modal analysis. Methods of modal analysis are used to improve the practical verification of the quality of destruction models in the finite element method (FEM). A selected fragment of the truss structure was modeled in the Inventor® software. Individual elements of the structure were linked by means of geometric relations, in accordance with the nature of cooperation of these elements. Figure 8 shows the physical model and the model created in the software of a structure fragment tested using theoretical modal analysis (Liss et al., 2016).

Structural models built in accordance with the principles of the finite element method (FEM) were used to describe the dynamics of the structure. As part of the theoretical calculations using the modal analysis method, characteristic frequencies of free vibrations were generated for the tested fragment of the crane structure. These frequencies are listed in Table 2. During the simulation, the number of determined natural frequencies was limited to 20.

The frequencies and modes of free vibrations obtained as a result of the simulation allow to indicate the most dynamically susceptible areas of the examined structure fragment (Fig. 9).

Table 1. Summary of free vibration frequencies [Hz] for various states of structure degradation

Variant	Wall with no crack	Wall with 1 crack	Wall with 2 cracks
Without extortion	71.388	39.999	29.831
Without extortion	81.699	40.806	39.207
With extortion	43.526	41.271	70.844
With extortion	81.699	147.588	110.296

a b

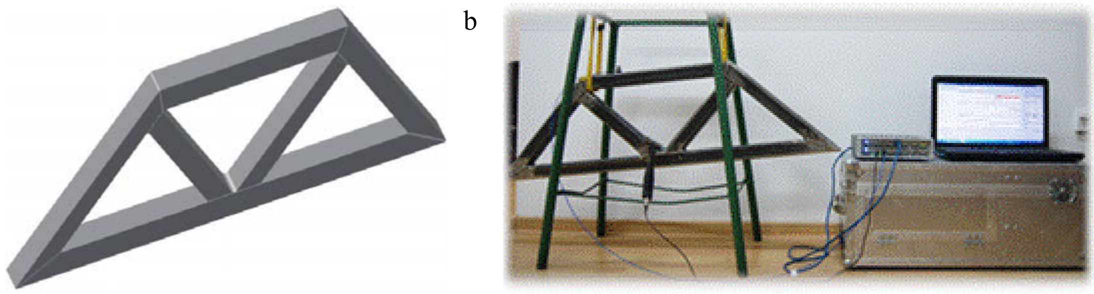

Fig. 8. Theoretical model (a) and real model with research stand of truss element (b)

Table 2. Free vibration frequencies [Hz] generated by theoretical modal analysis

F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
71.29	289.40	345.10	350.83	792.55	904.46	995.99	1 063.37	1 063.84	1 168.01
F11	F12	F13	F14	F15	F16	F17	F18	F19	F20
1 273.96	1 373.37	1 577.62	1 702.82	1 814.78	1 847.73	1 930.23	2 076.51	2 290.80	2 357.98

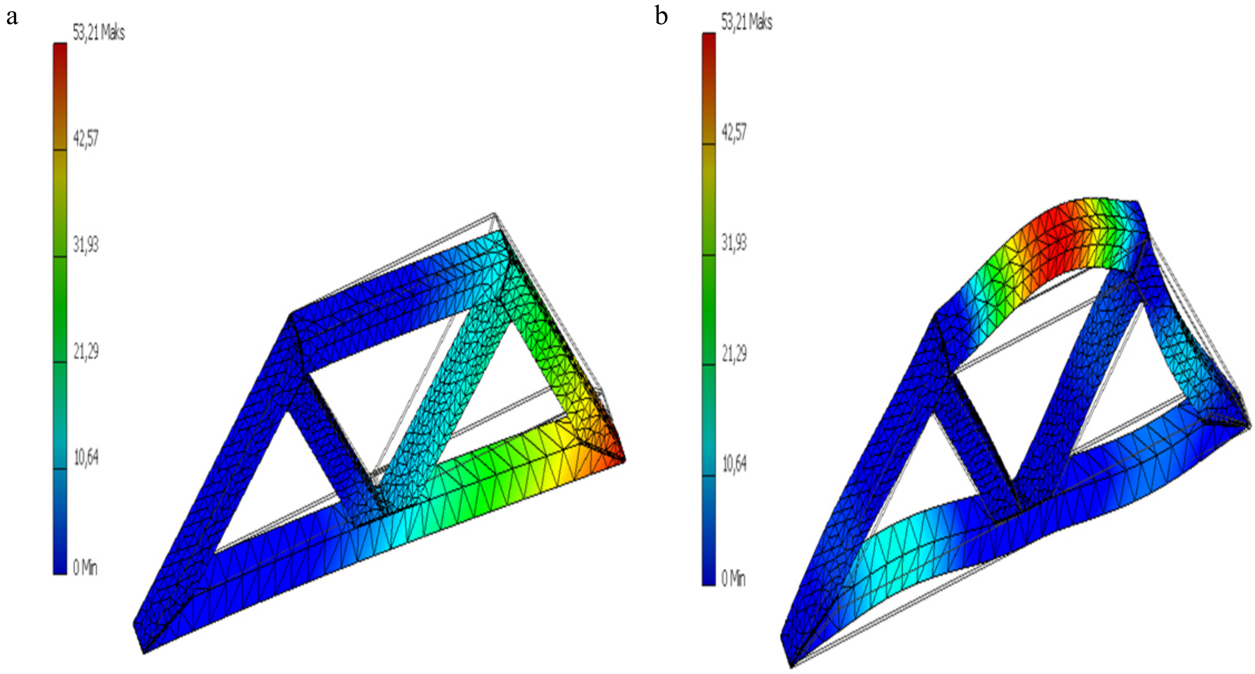

Fig. 9. Flexural vibrations of a welded truss at frequency 71.29 Hz (a) and first form of flexural-torsional vibrations at frequency 995.99 Hz (b)

A detailed analysis of the mode of free vibrations obtained from the study of stabilization diagrams enables comparison with the results of FEM and a very thorough understanding of the structure and state of degradation, but it requires combining knowledge from several other fields of technical sciences (Żółtowski et al., 2016).

The results of theoretical considerations in simulation modeling and their bench verification on the physical truss fragment model provide grounds for the methodology of exploratory vibration tests of fragments of complex objects using modal analysis methods and constitute the beginning and preparation for a wider study of real objects.

CONCLUSIONS

The presented issues of many years of theoretical and experimental research are included in the area of research and assessment of the state of destruction of structures in terms of optimization of their dynamic state, reflecting the energy flow in modern structures, with various inputs. In practical applications, this subject allows for a better understanding of the behavior of complex structures, their optimization in the design process and assessment of hazardous conditions in operation.

The content of this study is part of the development of new technologies for diagnostics and identification of damage to structures and machines in construction, with the use of vibration energy flow testing methods, and in this case mainly vibration diagnostics and modal analysis.

The presented research results indicate that it is possible to distinguish the material properties of structures, what has an impact on the possibility of distinguishing the state of degradation and strength properties.

The research showed unequivocal changes in the values of the measured symptoms of vibration energy flow in various applications and in a specific range of variability described in detail as research results in many publications. The results of simulation tests verified by the results of modal tests confirm the possibility of improving FEM with modal methods.

The practically verified assessment of the sensitivity of the vibration estimators and modal model components to the degree of degradation of building structures shows, to a degree that is satisfactory for practice, the differences between a fit and a damaged structure. Therefore, it becomes possible to determine non-invasive construction hazards on the basis of testing selected measures of vibration energy propagation.

Authors' contributions

Concept of work: M.Ż. and K.J.; methodology: M.Ż.; software: M.Ż.; data validation: M.Ż. and K.J.; formal analysis: K.J.; research: M.Ż.; resources: M.Ż.; compilation and processing of data: M.Ż.; preparation of the draft version of the article: M.Ż.; editing and proofreading of the article: M.Ż.; visualization and graphic design: M.Ż.; supervision: K.J.

All authors are familiar with the version of the manuscript intended for publication.

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ELEMENTY GŁÓWNE BADANIA MIAR ROZPŁYWU ENERGII DRGAŃ W KONSTRUKCJACH

STRESZCZENIE

W pracy wskazano zakres możliwych zastosowań badania miar rozpływu energii drganiowej wykorzystywanych w modelowaniu procesów drganiowych i analizie modalnej w obszarze metodologii badań i metodyk szczegółowych nauk technicznych. Analizy teoretyczne i weryfikacja praktyczna badania wielu różnych materiałów i budowli wskazują na szerokie możliwości zastosowań opisanych dokonań. Uznając potrzebę doskonalenia metod oceny stanu degradacji konstrukcji budowlanych, w pracy przedstawiono uogólnione, istotne wyniki postępowania badawczego w zakresie weryfikacji skuteczności opracowanych metodyk szczegółowych zastosowania miar drganiowych w badaniach symulacyjnych, stanowiskowych i eksploatacyjnych.

Słowa kluczowe: analiza modalna, drgania własne, modelowanie procesów drganiowych