Analysis of vibrodiagnostics methods in the technical state study of designed multimedia mobile scenes

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Abstract. The paper presents the possibilities of using vibroacoustic methods in the study of the technical condition of designed multimedia mobile scenes. In particular, the possibility of implementing modal analysis methods in modelling and diagnostic research process has been presented. The use of virtual methods enables diagnostic tests both at the design stage and at the stage of normal operation, whereas modal methods help to explain the nature of the work of the element under investigation.

1 Introduction

The process of designing new technical objects always poses a great challenge and adventure for the constructor. Through the implementation of a new design, the constructor can imprint their mark on the new technical object, showcasing their knowledge and skills. Newly created objects often change the future of humanity. A well-designed machine often sets new trends and introduces changes in everyday human life, often a few decades after its creation - examples include airplanes, ships etc. These and other complex technical objects often improve from year to year becoming more reliable and useful [1].

The multimedia mobile scenes can be classified into technical and constructional complex technical objects. These are modern mobile constructions enabling the realization of concerts or other artistic events in the open air. Mobile scenes are complicated constructions mounted on a car chassis, equipped with electrical and hydraulic systems. Event organisers of music concerts or other autistics events often allow mobile scenes to be installed in a designated place. The construction of mobile scenes requires the designer to carry out the appropriate design process including already at the design stage of diagnostic systems and procedures that ensure proper security of service and use of this facilities.

Modern machines are characterised by such features as: functionality, safety, reliability, mobility and exploitational susceptibility. The purpose of machine diagnostics is therefore to determine the technical condition of the object based on the generated diagnostic signals (symptoms) and compare them with the nominal values. An example of a mobile scene is shown in Figure 1.

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Fig. 1. Multimedia mobile scene.

One of the most frequently used diagnostic methods encompass vibroacoustic methods, and among them, often used in the study of complex technical constructions, modal analysis methods. Due to the complexity of the modal analysis methods, dedicated IT systems have been created enabling engineers to create a virtual model of any object. Then, if necessary, the engineering team can carry out research on both a virtual and real object. It creates the possibility of introducing diagnostic elements to the object at the stage of its construction, modifying it and making changes to the object without incurring financial expenses for creating costly prototypes.

2 Basis of vibrodiagnostics

The increasing complexity of modern technical facilities and the growing safety requirements force constructors and users of these facilities to supervise their current technical condition. Technical condition of designed object should be verified by diagnostics means and procedures. The basic problems of machine diagnostics include the following:

- acquisition and processing of diagnostic information,
- building models and diagnostic relations,
- diagnostic inference and limit values,
- classification of machine states,
- predicting time of the next diagnosis,
- imaging decision-making information [2,3,4,5,6].

The vibrodiagnostics is one of the machine technical condition description methods - organised set of methods and means to the technical state estimation of technical systems, with utilization of vibration processes or the noise signal [7].

Vibroacoustics is a discipline of knowledge focussing on all vibration processes, acoustic and pulsating processes setting in technique and machines. The vibroacoustics processes are not only harmful but they are also positive phenomenon. If applied suitably, they can be a good carrier of the energy which can be used for the realization of various technological processes [7].

The vibroacoustics processes are dynamic phenomena set in a technical device with frequency range from zero to tens thousands of hertz. Vibrations are a rich source of information about the threats of the machine's condition, which are comparatively easy to record, processing and identification. We can introduce vibration processes in the following aspects [7]:

- the generation of strengths variables in time, acting on the structure and surrounding environment,
- propagation and transformation of energy in structures,
- the sound radiation through the elements of environment and mechanical structures.

The investigations of vibroacoustics processes in many cases are very complicated, in particular when vibration processes step out in real physical arrangements. During analysis of vibroacoustics process we focus on the following aspects:

- the temporary and spatial schedule of energy coming from the source,
- the arrangement response and transfer by the propagating media,
- the correlation between sources [7].

Obtaining the right technical construction response during vibroacoustic tests is possible with the use of appropriate measuring equipment, specialised software and appropriate conditions during research. The individual stages of the processes involved during investigations are shown in Figure 2.

After selection of the appropriate measurement method is completed, the scientist conducting experimental research often faces a dilemma. Specifically, he or she needs to determine - in which place of the technical object there should be points of signal reception carrying information about the object's condition. Engineers know that each object, depending on the structure, has certain places considered appropriate for signal reception. However, there is always a high probability of an erroneous decision.

Geometric modelling, implemented in modern engineering software, may be very helpful. After entering the parameters of the technical object, the modelling process generate a grid of potential points where measurements of the examined physical quantity should have been made. Consideration should be given to significant technical relationship during tests. Specifically, the higher the degree of tested object complexity, the greater density of the network's measurement points should be installed in the object. Even computer programs are utilised, the number of points generated is usually too high, which entails a longer global measurement process. In each experiment, we strive to obtain an optimal geometric model which is usually based on the subjective feelings of the experimenter and his or her professional experience.

The assessment of the technical object condition is estimated on the basis of diagnostic tests, consisting of measurements and analyses of the results obtained during tests. In order to carry out diagnostic tests, models of diagnostic objects are adopted, based on which diagnostic algorithms are generated.

Fig. 2. Stages of proceeding in the research process.

3 Basis of modal analysis

Application of the modal analysis as one of the vibroacoustics tools constitutes a new approach to the technical analysis of the complex technical object such as multimedia mobile scenes. Modal analysis is the process of determining modal parameters of a structure for all modes in the frequency range of interest. Modal parameters are: modal frequency, modal damping and mode shapes. The modal analysis methods are divided into [10,11,12]:

- theoretical modal analysis - which requires its own solution to the problem for the adopted structural model of the object. Determined sets of own frequencies, damping coefficients for own frequencies and forms of natural vibrations allow simulations of the behavior of the structure at any extortion, selection of controls, modification of structures and others. It is used in the design process when it is not possible to conduct research on a similar real object,
- experimental modal analysis- controlled experiment requiring identification, during which forces the movement of an object (e.g. vibration) and measures the force and response in many measurement points distributed on the test object.

Conducting experimental modal analysis requires measuring the vibrations of a structure excluded from motion at many of its points - at the same time, the force of vibration must be measured. Estimation of the parameters of the modal model consists

in approximation of the measured characteristics of the structure by means of a function for which the variables are parameters of the modal model,

- operational modal analysis - based on operational experiment in which measurements are made only in response to the number of measurement points, while the movement of the subject is caused by the actual operating motion. Operational modal is the name for the technique of modal analysis performed on operational data - cases where we do not stimulate the structure artificially but just allow the natural operating loads to excite the structure.

Modal analysis of mechanical systems is therefore a method of testing dynamic properties of structures based on vibroacoustic signals. The idea behind this method is observation of the changes in parameters of the modal model that arise as a result of deregulation, normal usage, damage or failure, during current monitoring of the object. In this method, a modal model is created in the form of a set of own vibrations, mode shapes and damping coefficients, for the object without damage, as a pattern. Then, during operation, the modal model is identified and its correlation with the model for the undamaged object is examined. In the case where such a correlation occurs, it can be concluded that the object is in the good technical state. In the absence of correlation, the object is not working properly – for example due to damage [12,13,14].

Owing to the complexity of the structure characterised by the multimedia mobile scene, the theoretical modal analysis should be applied at the design stage. In case of building the prototype estimated modal models should be verified in real conditions with operational modal analysis tests carried out on the real object, during its normal operation. These tests will allow to verify the correctness of the adopted design assumptions and to make possible constructional changes for the designed mobile scene.

3.1 Operational modal analysis – method theory

In order to verify the real behavior of the multimedia mobile scene in the conditions of real operation, it is necessary to conduct modal tests of the operational modal analysis. There are a number of methods used. However, the theoretical basis of operational modal analysis in this work is based on the Least Squares Complex Exponential (LSCE) method.

In LSCE method determination of the modal model parameters is followed by correlation function which is approximated by the sum of exponentially decaying harmonic functions. This method, applied to impulse response of system is a well known method in modal analysis yielding global estimators of system poles – the root of the transfer function denominator. It can be proved that the cross correlation function can be used to identify modal system parameters in identical way as does the impulse response of the system. The dynamic equation of the system motion can be expressed by formula [8,9]:

$$M\ddot{x} + C\dot{x} + Kx = F(t) \quad (1)$$

where: M,C,K – mass, damping and stiffness matrices, $\ddot{x}, \dot{x}, x$ – acceleration, velocity and displacement vectors, F(t) – vector of exciting forces.

The next step is transformation of formula (1) to principal coordinates applying the transformation expressed by the formula [8,9]:

$$x(t) = \Psi q(t) = \sum_{r=1}^n \Psi_r q_r(t) \quad (2)$$

where: Ψ – matrix of modal vectors, the columns of which are eigenvectors corresponding to the given free vibration frequency, q_r – principal (modal) coordinate, n – number of vibration forms included in the model of vibration forms.

Assuming that damping is small and proportional, on substituting relation (2) into formula (1) and multiplying by Ψ^T , de-coupled equation set is obtained in the form [8,9]:

$$\ddot{q}_r(t) + 2\xi_r \omega_{nr} \dot{q}_r(t) + \omega_{nr}^2 q_r(t) = \frac{1}{m_r} \Psi_r^T f(t) \quad (3)$$

where: ω_{nr} – is the r-th free vibration frequency, ξ_r – is the modal damping coefficient for the r-th vibration form, m_r – is the modal mass.

Cross correlation function for two response signals at point i and j, resulting from an excitation applied at point k in the form of white noise has the following form [8,9]:

$$R_{ijk}(T) = E_o[x_{ik}(t + T)x_{ik}(t)] \tag{4}$$

where: E_o – denotes the expected value operator.

If we know relation between cross correlation function, having the form of a sum of exponentially decaying harmonic functions and impulse transition function for direct application to do modal analysis tests, correlation function can be transformed to the form [8,9]:

$$R_{ij}(T) = \sum_{r=1}^n \frac{\psi_{ir}g_{jr}}{m_r\omega_{rd}} \exp(-\xi_r\omega_{nr}T) \sin(\omega_{rd}T + \vartheta_r) \tag{5}$$

where: ϑ_r – the New phase angle, G_{jr} – constant.

3.2 Operational modal analysis – sample test results

Initial research was carried out at the University of Science and Technology in Bydgoszcz. The LMS Scadas Recorder with the attached LMS Test.Xpress software was used for the tests. The identification of modal parameters in the operational modal analysis is based only on the measurement of the system response. Identification methods are divided into those implemented in the time domain and those implemented in the frequency domain [10,11,12]. The apparatus used in the research makes it possible to use the following methods to identify modal parameters:

- 1) implemented in the field of time domain (module Op. Time MDOF):
- BR (Balanced Realisation), parameter estimation using the autoregression function of response signals in a stochastic subspace,
 - LSFD (Least Squares Frequency Domain) – mode shapes estimation - parameter estimation using the non-linear least-squares method in the frequency domain,
- 2) implemented in the field of frequency domain (module Op. PolyMAX):
- pLSCFD (Polyreference Least Squares Complex Frequency Domain) – method implemented on the basis of operational transmittance,
 - LSFD (Least Squares Frequency Domain) - mode shapes estimation - parameter estimation using the non-linear least-squares method in the frequency domain.

Estimation of modal parameters is one of the most important stages of operational modal analysis. The number of available methods for estimating modal parameters is enormous, but this does not mean that all of them will be perfectly suited to the research being carried out. Each of the applied methods has its own advantages and disadvantages, which in the case of the above mentioned are presented in Table 1.

Table 1. Advantages and disadvantages of estimating modal parameters[10,11].

Estimation in time domain	
Advantages	more effective for noisy data
	additional errors resulting from spectrum leakages are avoided, etc.
	more effective in wide frequency ranges
Disadvantages	difficult analysis of systems with high damping
Estimation in frequency domain	
Advantages	a simpler way of data averaging
	more effective in the case of a large effect of the vibration form outside the frequency range
	much easier to determine the poles of the system in systems with high damping
Disadvantages	not very effective for wide frequency ranges

The basis for modal analysis is the proper creation of a modal model of the real mechanical construction. Such a model is created during the course of modal analysis and is understood as a ranked set of natural frequencies, values of damping coefficients and the order of the modal model. In order to have any grounds for the assessment of the technical condition, the obtained modal model should be compared with the model created in the case of a machine in good working condition. Modal model during test is obtained on the basis of stabilisation diagram. Examples of stabilisation diagrams obtained for the same object using time and frequency estimation methods are shown in Figures 3 and 4. In the following stabilization diagrams, individual symbols are visible, which means: s - stable pole, o - unstable pole, f - constant frequency pole, v - constant frequency pole and modal vector, d - constant damping pole [8,9,13-15].

The modal parameters determined from the stabilisation diagram constitute a description of the modal model and are basic comparative parameters of a given technical object in the state of proper working condition. In the case of damage to a technical object, completely or slightly different modal parameters describing the modal model are obtained.

Fig. 3. Stabilisation diagram determined by the PolyMAX method.

Fig. 4. Stabilisation diagram determined by the Time MDOF method.

An additional benefit to this process is the visualisation of individual forms of vibrations on the geometrical model of the diagnosed mechanical structure. The basis for identification issues is the appropriate verification of built models based on the collected experimental data. The verification process of the modal model consists of:

- visual checking of the model quality,
- study of the properties of coefficients describing the relationship between the object of study and the model,

- analysis of the suitability of the modal model, in the application for which the model was identified.

Based on the obtained modal parameters data from two different states of the technical object, a diagnostic inference process can be carried out regarding the change in the condition of the machine's fitness.

4 Conclusions

At the moment of creating and designing new objects, diagnostic problems must have their application already at the construction stage and the knowledge of the constructor should be supported by the experiments of the diagnostic teams. The issue of diagnosing the condition of technical objects necessitates the diagnosticians possess an in-depth diagnostics knowledge and to be up-to-date with a number of methods and diagnostic measures.

The diagnostic methods presented in this paper, based on the methods of vibrodiagnostics, appear to be viable and justified for the implementation of newly designed mobile scenes. Particularly noteworthy are the methods of modal analysis, which are discussed in the paper as an example of these modern tools supporting the work of the constructor. Identification of potential technical problems, improvement of the quality of designed mobile scene construction based on modern software tools will eliminate a number of problems at the design stage. This will shorten the time to complete the scene and to ensure a high level of safety of the mobile scene.

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