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Indicator of Vibroacoustic Energy Propagation as a Selection Criterion of Design Solution

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Contemporary tools which help to design technical objects refer to the conclusions drawn from studying the changes of physical processes accompanying the exploitation, especially to vibroacoustic processes. The main problem is to define such vibroacoustic measures, where their changes would model the analyzed physical phenomena in the best way. Basing on simple indicators which refer to occurring phenomena, it is possible to obtain accurate solutions with a satisfactory reliance level without using complex computing techniques needing detailed descriptors. According to the author, the indicators which are based on the analysis of vibroacoustic energy propagation are very useful in solving engineering problems. These indicators are useful while diagnosing the condition of technical systems, identifying and minimizing the vibroacoustic risks. The possibilities of using such indicators in order to find design solution are illustrated by sample results of the research of the structures with vibroacoustic elements which reduce the noise of rail vehicles by the rail vibration damping.

Keywords: vibration damping, vibroacoustic energy propagation.

1. Introduction

One of the conditions of comfortable, safe, and fail-safe exploitation of technical objects is an appropriate choice of conceptions of constructional solutions which are directed to specific needs and applications. Engineering works which aim to obtain established utility values are determined by assumptions from the concept stage. They are used to specify these assumptions, develop the number of possible options and the choice of the best one in specific conditions.

Today, two extreme approaches to solving engineering problems are worth paying attention. The first direction which results from the dynamic development and almost infinite possibilities of modern computing tools is connected with modeling which is based on very detailed descriptions of phenomena and processes which can be observed in technical objects. Numerical methods allowing to obtain the solutions of systems with several unknowns make it possible to do complex simulation analyses. The multitude of performed operations is no longer the barrier for modeling with a vast number of parameters. In some scientific communities there is an opinion that it is possible to solve any complicated problem through numerical simulations, and the conclusions from calculations are reflected in technical realities. As a rule, results of the most precise simulation calculations cannot be transferred directly to practical applications: they usually need empirical verification. The reliability of obtained solutions increases after identification of correct parameters of the adopted computing model – if such identification is based on the results of the research of real objects (Dąbrowski, 1992).

The second approach stresses the need of theoretical analyses of phenomena taking place during the exploitation processes referring mainly to algorithms including outlines present in the norms, directives, and other acts. Such outlines are often based on empirical indicators supported by the experiment in developing and exploiting the technical objects. Algorithms of progress have the form of procedural records and use simple qualifying criteria (often considered by the protagonists of simulations to be unreliable and leading to serious errors). They allow different people to accomplish repetitive activities and obtain comparable and satisfactory results – making themselves the part of philosophy of management systems which are gaining a greater recognition in various fields of human activity. Improving the effectiveness of such procedures is possible through applying indicators sensitive to changes of specific features of considered objects, these indicators relate to fundamental physics laws and a sense of analyzed phenomena.

According to the author, there are a lot of situations when, while solving specific engineering problems, there is no need to use sophisticated and complex computing techniques which are based on particular descriptors, and the use of uncomplicated indicators which refer to occurring phenomena allows to make precise conclusions (Klekot, 2012). Particularly, the problem of recognizing and minimalizing vibroacoustic threats or evaluation of objects' technical state (Klekot, 1992) can be analyzed on the basis of the value of defined indicators taking into account the phenomena accompanying vibroacoustic energy propagation.

2. Comments on the use of vibroacoustic signal

It is generally known that the vibroacoustic signal carries a series of information potentially useful in making conclusions about the state of a technical object and recognizing and minimalizing the threats of vibration and noise. The analysis of changes of vibroacoustic energy propagation, in particular, the analysis of the signal features reflecting these changes (Randall, 2009; Maruyama *et al.*, 2011) has an important role in the process of a proper exploitation and for improvement of devices' ergonomics (in the range of low noise and vibration level). Because of the dynamic character and complexity of vibroacoustic processes, such problems should be solved in a complex, with taking into account the series of factors which shape the signal form. The tool will be effective under the condition of defining features in the form of measurable parameters whose weight will depend on the solved problem.

The starting point for further considerations will be a signal which is recorded at least by two measurement converters. We should notice that two synchronously recorded signals make it possible to examine the vibroacoustic energy flow between the points (Adamczyk *et al.*, 1999). A greater number of places where the signal is recorded, results in wider possibilities to make conclusions in relation to the whole object (Dąbrowski *et al.*, 2007a). However, not always the increase in number of measuring points is purposeful, since it inevitably leads to an uncontrolled increase in the number of obtained information, whose multidimensionality will result in small usefulness in implementation of established goals (Natke, Cempel, 1997). During the analysis of mutual relations, each subsequent recorded signal increases dimensionality of observation space, which consequently leads to information chaos (Bolc *et al.*, 1991). Thus, in order to formulate a proper problem, it is important to adjust the number and kind of recorded signals to an engineering problem which is being solved.

On the basis of executed analyses it is possible to try to make preliminary proposition of vibroacoustic characteristics of the object (considered in time and frequency domains). Such characteristics will be improved with the use of modeling and with special stress on main excitations. Modeling supported by an experiment allows i.a. to optimize the location of measuring converters in terms of realization of particular problems (Dąbrowski *et al.*, 2007b; Deuszkiewicz *et al.*, 2009; Klekot, 2011).

The next step which simplifies the solution of the problem is decomposition. On the one hand, this concept is about division of the object into assemblies and components generating vibroacoustic processes and responsible for their propagation; on the other hand, the concept of decomposition covers decomposition of a signal into harmonics (i.a. with the spectrum analysis use) which enables one to assign particular features to specified exploiting parameters. Numerical values of particular harmonics will make a space which characterizes vibroacoustic process, and consequently – characterizing the considered technical object.

At this stage we have a big number of partially grouped data ready for further processing or direct use. It is experimentally proved that the process of making effective conclusions can be occasionally carried out without additional classification tools. The choice of classifiers is the absolute minimum, this choice is usually preceded by the design of descriptors which are based on the parts of the space which characterizes the vibroacoustic process.

Verification of usefulness of the indicators and proposed classifiers is possible under the condition of carrying out experiments on real objects, which on the one hand will allow to execute the identification of the parameters of model, on the other hand they will narrow the area of the value of the object parameters represented by particular descriptors.

The final result of all described stages is the presentation of the state of the considered object in the form (from the viewpoint of a task) of complete information about its exploitation properties.

The scheme (Fig. 1) depicts a generalized procedure with pointing at mutual relations between particular stages. Precise description of a particular stage is possible after taking into account the nature of concrete technical objects and problems being solved. The ele-

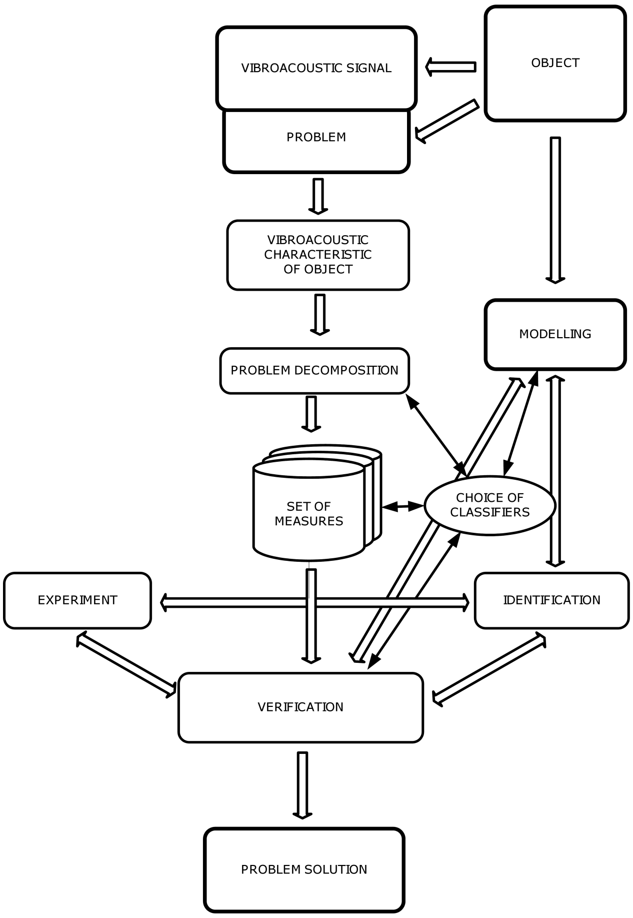

Fig. 1. Scheme of using features of the vibroacoustic signal as tools in the design process and exploitation of technical objects.

ments of the block scheme map the actions adequate to a detailed engineering issue.

3. Indicators of vibroacoustic energy propagation

In order to compare dynamic signals, root mean square value is commonly used as an uncomplicated parameter directly proportional to the energy signal which is variable in time (Crocker, 1998; Klekot, 2003), thus, directly connected with examined processes. Linking root mean square values of signal amplitudes which are recorded at the input and output of the system enables the proposition of indicator H which is directly connected with energy propagation in the form of:

$$H = \frac{\int_0^T (x(t))^2 \, \mathrm{d}t}{\int_0^T (P(t))^2 \, \mathrm{d}t}, \tag{1}$$

where $x(t)$ is the initial signal, and $P(t)$ – extortion.

In order to compare numerical values in view of a large range of amplitudes of vibroacoustic signals the logarithmic scale is useful:

$$H_{[\log]} = \log(H). \tag{2}$$

Such recording is one of the ways of data compression into values in a form of one number. It does not exclude analysis of the results written in a matrix form with the use of many indicators calculated e.g. by integration in different intervals or after the transformation of signals – which creates further big potential research opportunities.

The conception of indicator of vibroacoustic energy propagation naturally refers to Parseval's theorem (Bendat, Piersol, 2010) from which the sameness of the signal energy presented in time and frequency domain results:

$$\int_{-\infty}^{\infty} x^2(t) \, \mathrm{d}t = \int_{-\infty}^{\infty} |X(f)|^2 \, \mathrm{d}f. \tag{3}$$

It is possible, thus, to formulate an analogical indicator of vibroacoustic energy propagation also in the frequency domain. Equation (1) will replace relation (4):

$$H_f = \frac{\int_{-\infty}^{\infty} |X(f)|^2 \, \mathrm{d}f}{\int_{-\infty}^{\infty} |P(f)|^2 \, \mathrm{d}f}. \tag{4}$$

In relation (4) $X(f)$ stands for the spectral density of the signal power, $P(f)$ stand for the spectral density of the forcing signal power, and f is the frequency (expressed in hertz).

The measure defined in such a way truly corresponds in the frequency domain to the squared gain (square transmittance module) of a linear system with constant parameters. A subtle difference can be noticed that the gain coefficient refers to the spectral density, and the measures of vibroacoustic energy propagation depend on the energy of the process reflected by the spectrum or time course, treating equivalently calculations in time and frequency domain.

Proposed energy indexes, which use rms amplitudes in both domains, are calculated with the use of multiplication operation. The undeniable value is the possibility of their selective use: by the choice of integration interval the measure can be sensitized for low-energy changes which are unnoticeable while observing complete process accomplishment.

4. The choice of constructional solution

The implementation of indicator of vibroacoustic energy propagation in order to choose a constructional solution is illustrated by the example of noise minimization of the tramway. The properties of a structure with four variants of damping elements are compared on the basis of the results of experimental studies of vibration accelerations of impulsively forced steel profile and changes of vibroacoustic pressure in a direct neighbourhood of the structure. The values of indicators linking the RMS amplitude values of vibration acceleration and vibroacoustic pressure with the driving force were calculated. Four constructional solutions are illustrated by Fig. 2.

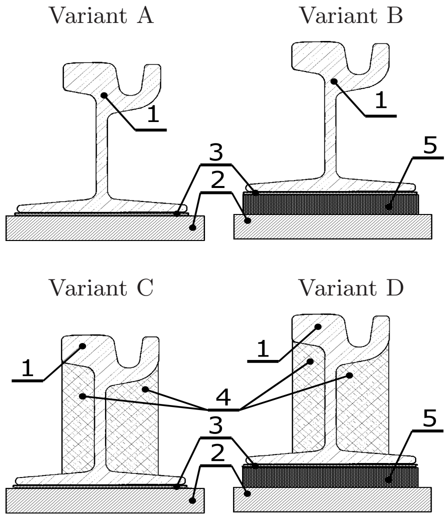

Fig. 2. Constructional solutions of the damping elements: 1 – rail profile, 2 – fundamental, 3 – rubber liner, 4 – damping inserts, 5 – vibroinsulating mat.

Each time the forcing pulse and accelerations of the profile vibration and changes of vibroacoustic pressure over the station were recorded. Vibrations were forced with an impact hammer equipped with a force transducer, the impulses of driving force were reaching 3–5 kN. The indicator values of vibrations' propagation efficiency H_a were calculated according to the dependency (5) as the average for series of 10 of subsequent impulses; analogically, according to dependency (6) the indicator values of sound propagation efficiency H_p:

$$H_a = \frac{\int_0^T (a(t))^2 \, \mathrm{d}t}{\int_0^T (P(t))^2 \, \mathrm{d}t}, \tag{5}$$

$$H_p = \frac{\int_0^T (p(t))^2 \, \mathrm{d}t}{\int_0^T (P(t))^2 \, \mathrm{d}t}. \tag{6}$$

In dependencies (5) and (6) $a(t)$ is the signal of vibration accelerations, $p(t)$ is the signal of the vibroacoustic pressure, and $P(t)$ is the driving force.

The results obtained after the transformation of the recorded time signal for four sets of damping elements is illustrated in the charts. Low values of indicators represent small vibroacoustic energy propagation, which corresponds to a better effectiveness of particular solutions.

The comparison of values presented in Fig. 3 allows to note an important role of rail rubber inserts and vibroinsulating mat for limitation of the energy flow of mechanical vibrations to the environment. The use of rubber damping elements directly glued to the profile is justified because it substantially changes dynamic properties of the steel elastic element.

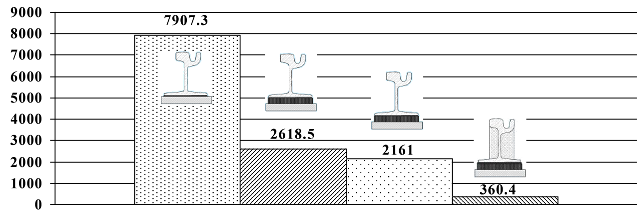

Fig. 3. Values of the efficiency indicator of sound propagation to the environment.

While computing (according to dependency (5)) the indicator which illustrates the effectiveness of vibration propagation by the examined steel profile, the signal of vibration accelerations recorded by the accelerometer fixed to the rail and extortion made with an impact hammer were used. The value analysis from the chart in Fig. 4 confirms an important limitation of vibration transformation owing to the inserts.

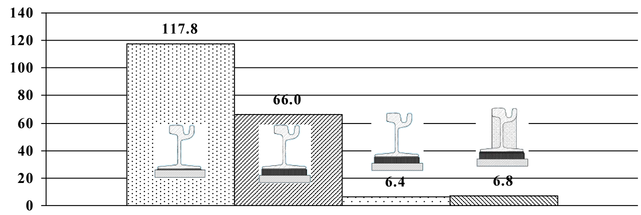

Fig. 4. Values of the efficiency indicator of vibration propagation by the rail.

The inserts are less important for the reduction of transmitting the vibration from the profile into the fundamental: in this case, the vibroinsulating mat which is fixed between the steel profile and the fundamental acts as the vibration isolator. In order to evaluate the effectiveness of transmitting the vibrations into the fundamental in accordance with (5), the recorded accelerations of fundamental vibrations were used. The chart from Fig. 5 allows for the comparison.

Conclusions concerning the effectiveness of particular damping elements are similar if we use a different parameter of a global nature: expressed in seconds by

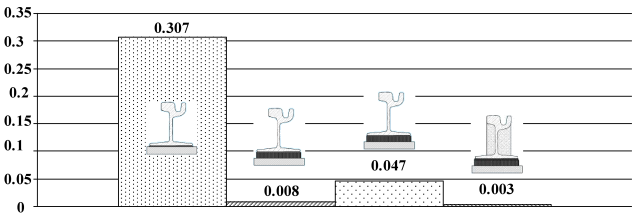

Fig. 5. Values of the efficiency indicator of vibration propagation between the rail and fundamental.

the time after which a decaying amplitude decreases thousand times (known as reverberation time). A little longer time of the sound decay in the neighbourhood of the profile placed on the vibroinsulating mat than without the mat (Fig. 6) can be justified by little stiffness of the elements separating the rail from the fundamental. The nature of the graphs in Fig. 7 and Fig. 8 reflect the damping properties of the various constructional solutions in analogy to the diagrams in Fig. 4 and Fig. 5.

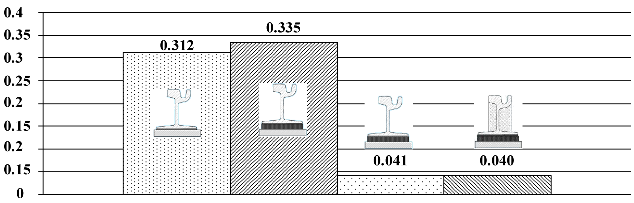

Fig. 6. Time of the sound decay (in seconds) in the neighbourhood of the examined objects.

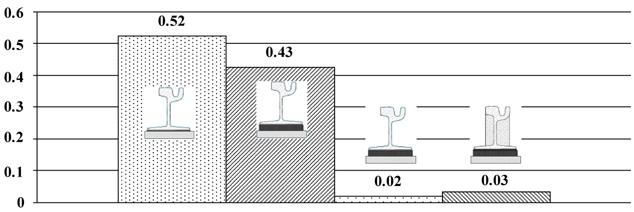

Fig. 7. Time of the rail vibration decay (in seconds).

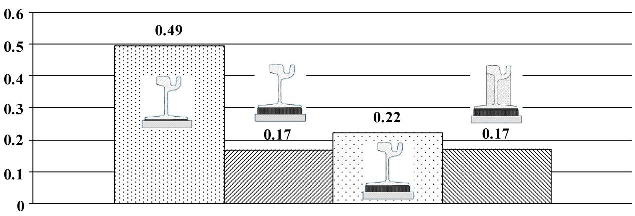

Fig. 8. Time of the fundamental vibration decay (in seconds).

To conclude, vibroinsulation of the designed tramway was made in accordance with variant D presented in Fig. 1.

5. Conclusion

The research technique used during the recognition and minimization of vibroacoustic risks and during the evaluation of the state of objects allows to use identically defined indicators in design problems and for exploitation diagnostics needs. The indicators referring to the physical basis of the described phenomena are characterized by a large versatility of applications. The computing algorithm from the point of view of usefulness for engineering applications should satisfy two basic conditions: have the features of an object or phenomena and guarantee that the space of founded descriptors is metric; the fulfillment of these two conditions allows to execute some calculations on the indicators.

Energy indicators work well in various domains, even for low-energy processes with an average energy process established in sufficiently long time it is possible (basing on the noticed changing shape of instantaneous spectrums) to take into account appropriately chosen frequency bands and examine the energy changes in these bands. Since in many cases the vibroacoustic energy propagation determines the functional values of an object, and the part of this energy always scatters, it is reasonable to use the descriptors which take into account the role of structural and internal damping and individual properties of considered objects. The example of a choice of a constructional solution of tramway vibroinsulation on the basis of the evaluated effectiveness of damping structures illustrates one of the possibilities of specific engineering applications of this kind of indicators.

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