INFLUENCE OF NON-LINEAR ELEMENTS AS A SYMPTOM OF CHANGES IN TECHNICAL OBJECTS CONDITIONS[1]

Grzegorz KLEKOT

Warsaw University of Technology, Institute of Machinery Design Fundamentals
02-524 Warszawa, Narbutta 84, fax 022 234 86 22, email gkl@simr.pw.edu.pl

Summary

The processes of propagation of vibroacoustic energy can be modeled for use in technical condition assessment focusing only on their linear part; however, the model description will get closer to the real state if the non-linear elements are taken into account. Change of vibroacoustic signal, resulting from the ways of propagation of vibroacoustic energy having been modified as a direct result of a damage or wearing processes in technical object can be visible first of all in the amplitude spectrum.

It is confirmed by the results of model analysis compared to the results of studies of actual objects with modified parameters that non-linearity of a system is very important while considering and evaluating the technical state. It seems that the influence of non-linear elements reflected by spectral differences of vibroacoustic signal can be taken as a symptom of changes in the object's condition.

Key words: vibroacoustic signal; identification; vehicle.

EFEKTY ODDZIAŁYWANIA ELEMENTÓW NIELINIOWYCH JAKO SYMPTOM ZMIANY STANU

Streszczenie

Modelowanie procesów rozprzestrzeniania energii wibroakustycznej na potrzeby oceny stanu technicznego może ograniczać się do rozważenia części liniowej, niemniej lepsze przybliżenie opisu modelowego do rzeczywistości osiągnąć można z uwzględnieniem elementów nieliniowych. Zmiana sygnału wibroakustycznego będąca rezultatem modyfikacji dróg propagacji energii wibroakustycznej bezpośrednio spowodowanej uszkodzeniem bądź zużyciem eksploatacyjnym obiektu technicznego jest w szczególności dostrzegalna na widmie amplitudowym.

Rezultaty analiz modelowych zestawione z wynikami badań obiektów rzeczywistych o modyfikowanych parametrach potwierdzają znaczenie nieliniowości układu w rozważaniach dotyczących oceny stanu technicznego. Zasadna wydaje się teza, że odzwierciedlenie oddziaływania elementów nieliniowych różnicami widm sygnału wibroakustycznego może być traktowane jako symptom zmiany stanu.

Słowa kluczowe: sygnał wibroakustyczny, identyfikacja, pojazd.

1. INTRODUCTION

Considering real properties of technical objects, many simplifying assumptions have to be made. Modeling systems consisting of many interconnected continuous structures influencing each other seems unrealistic, same as obtaining accurate analytical solutions for such complex tasks. What can be done therefore is to apply simplified models, directed to the analysed phenomena and supported by empirical studies of real technical objects [1].

Studying real objects is extremely important for verifying intended properties of prototypical constructions. It is also impossible to optimize exploitation processes only on the ground of numerical simulations, passing over painstaking and expensive experimental studies. One of the main reasons is the non-linear phenomena present at almost every stage and usually impossible to be described in a very accurate way, nor to be accurately solved.

The classic approach to the problems of non-linear phenomena analysis consists in solving systems of one (maximum a few) degree of freedom, as well as in qualitative research. Developments in numeric technology have also allowed more extended application of approximate methods. However, it seems that the results useful in practice can be mainly obtained by compromise matching complexity of the model and the costs of empirical studies. The identification has proved to be

[1] Financed as a research grant within the national scheme for science 2006-2009.

a particularly useful tool, allowing for non-linear effects to be taken into account in considering a linear model.

2. BASES FOR IDENTIFICATION

The algorithms elaborated for evaluation of objects condition often use description based on the dynamic model. In general case it is the matrix equation of form:

$$\mathbf{M}\ddot{x} + \mathbf{C}\dot{x} + \mathbf{K}x = \mathbf{P}(t) \quad (1)$$

where x symbolizes the generalized co-ordinate; **M** is the matrix of generalized masses; **C** – damping matrix; **K** – rigidity matrix; **P(*t*)** is the extortion vector. In practice, the matrix equation quoted above can be replaced with a system of differential equations solved in form of the function:

$$X_i = f(t, m_1 \ldots m_n, k_1 \ldots k_n, c_1 \ldots c_n) \quad (2)$$

If in the time moment t the measured value of the co-ordinate is $X_{mi}(t)$, while the equation (2) result is $X_i(t)$, then the error of model can be defined by the following relationship:

$$X_{mi}(t) - X_i(t) = \Delta X(t) \quad (3)$$

Parametrical identification consists in choosing the correction coefficients in all the equations of form (2) resulting in the minimum possible error of model description:

$$\left(\bigwedge_{t \in T} X_{mi}(t) - X_i(t, m_i, k_i, c_i) \rightarrow \min. \right) \Rightarrow m_i, k_i, c_i \quad (4)$$

Obviously, one equation of form (2) and one point in the observation space allow for definition of only one parameter in identification process.

An important information carrier in the process of evaluation of condition of a technical object is vibroacoustic signal produced as a result of the processes carried out by its particular elements and units. Damages and wearing effects modify propagation paths of vibroacoustic energy and the process should be translated into changes in the signal registered by a receiver. If we assume that the receiver is registering the signal y*(t)* resulting from the system's response to the input x*(t)*, then in the frequency domain the Fourier transform of received output signal Y(*f*) will have the following form [2]:

$$Y(f) = X(f) \cdot H(f) \cdot \Phi^*(f) \cdot \Psi^*(f) \quad (5)$$

X(f) is the Fourier transform of input; ***H(f)*** is the transmittance of propagation path; **Ψ*(*f*)** – exterior disturbances (noise). This description allows for identification of the element **Φ*(*f*)** representing non-linear influences in order to estimate its value. Considering the linear phenomena its value equals one.

Taking into account characteristics of the processes under scrutiny, as well as substantial absolute differences in analysed numeric values, the relationship (5) can be submitted to double-sided operator transformation and take the logarithmic form, being used all the time for analyzing decreases of levels [3]:

$$L(f) = L_s(f) + \Delta L_h(f) + \Delta\Phi^*(f) + \Delta\Psi^*(f) \quad (6)$$

In this relationship **L(*f*)** means the level of output signal; $\mathbf{L_s}(f)$ – the level of input signal; $\Delta\mathbf{L_h}(f)$ reflects the decreasing/increasing level as a consequence of system transmittance; **ΔΨ*(*f*)** represents the description error, or the change resulting from random disturbances. The change of level at the output, provoked by the non-linear disturbances has been denoted as **ΔΦ*(*f*)**. The influence of these effects in dynamic system on the form of output signal, analysed as summing up of the levels has been shown in diagram in the Figure 1.

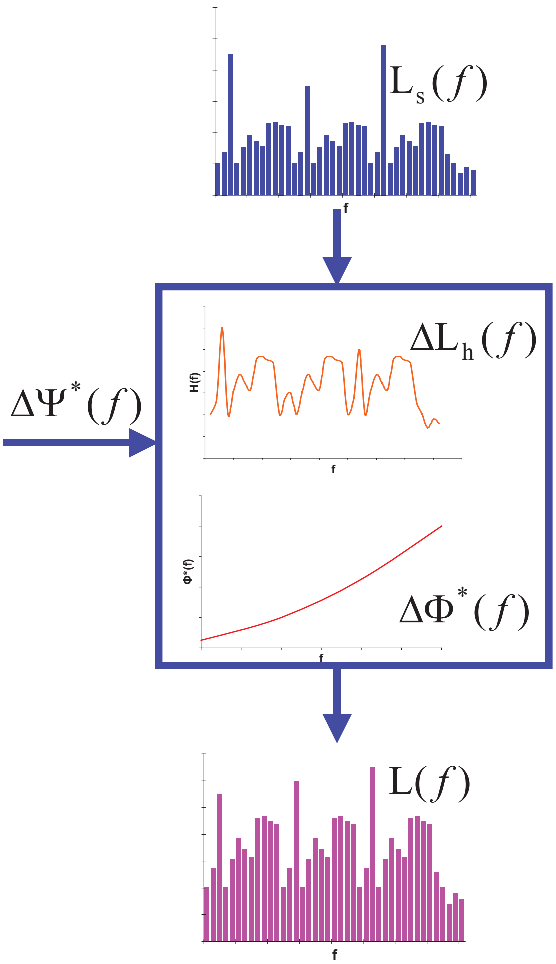

Fig. 1. Influence of the effects in dynamic system on the form of output signal

Identification in the frequency domain can be brought to definition of the correction vector **Δ(*f*)** and the operator **Φ** the product of which expresses the error of model for specific frequencies:

$$\Phi \cdot \Delta(f) = Y_{i_m}(f) - Y_i(f) \quad (7)$$

The correction coefficient **Φ** and the correction vector are selected in such a way as to minimize the errors of model in the given frequency range:

$$\left(\bigwedge_{f \in F} \mathrm{Y}_{mi}(f) - \mathrm{Y}_i(f) \to \min . \right) \Rightarrow \Phi, \Delta(f) \qquad (8)$$

$\mathbf{Y}_{mi}(f)$ is the solution for a model of actual frequency f, while $\mathbf{Y}_i(f)$ means the value of this particular component of real signal.

3. THE RESULTS OF EXPERIMENT

It is generally known that the acoustic signal of a vehicle carries a lot of information concerning its technical condition. Isolating in the spectrum of noise in the cabin the effects triggered by the elements of non-linear characteristics, modifying the propagation of vibroacoustic energy, does not seem a very difficult task either.

A diagnostic experiment with an electricity powered vehicle consisted of recording vibrations of the power unit and noise in the cabin of the vehicle in motion. The object was tested in two different states: with the power unit fixed directly to the supporting structure, and fixed with the elements of non-linear flexibility characteristics.

The analysis was based on the relationship (6), stressing the basic inputs generated by the most important units: the electric engine, the toothed gear and the chain transmission. The approach is justified by the form of amplitude spectrum of level of acoustic pressure in the cabin: what is dominating there it is the stripes (in the Figure 2 marked with circles) of components of frequencies resulting from work of the units.

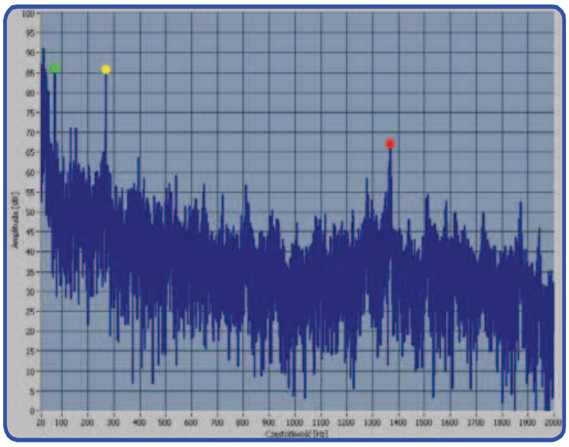

Fig. 2. Spectrum of noise in the cabin

Level of acoustic pressure in the vehicle cabin taken as the response of system to the vibrations of power unit (the amplitude spectrum of level of accelerations has been shown in the Figure 3) can be used in determining transmittance (understood as level increase/ decrease) for particular components.

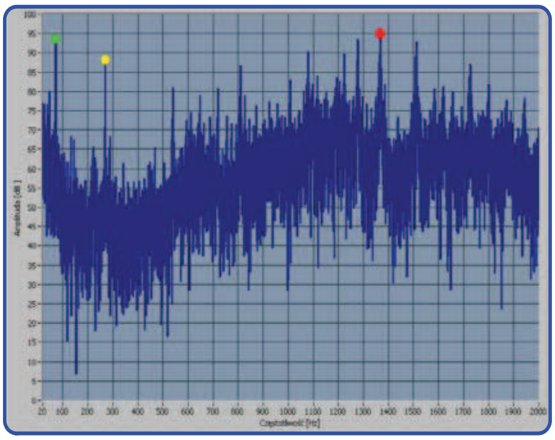

Fig. 3. Spectrum of acceleration of vibrations in the power unit

However, it seems that the procedure just described does not fully do for forecasting the form of outcome signal after the object's condition has changed, if the change is related to elements of non-linear characteristics. Smaller non-linearity can be decomposed into components of linear characteristics, and as a result particular input components can be replaced with vectors of co-ordinates p_i submitted to transmittances of linear character $\mathbf{H}_{i_{lin}}$ [3]. The resultant is therefore the result of summing the linear components up:

$$\mathrm{Y}(f) = \sum p_i \, \mathrm{H}_{i_{lin}} \qquad (7)$$

Because of technical realities approximate description of systems with non-linear effects consisting in summing the linear components up results in many cases in solutions differing from reality, while the identification of model gives plausible results only within the area directly adjacent to the real object used in the identification process. Then, the components resulting from non-linear transmittance of the system can be easily shown in the spectrum [4].

These remarks let us to the conclusion that the influence of non-linear elements resulting in changes of spectrum of vibroacoustic signal can be taken as symptoms of changes in conditions of a technical object. It has been confirmed by the experimental studies of an electricity powered vehicle when condition of the object was changed by replacing the metal mounting sleeve of power unit with metal-rubber elements of non-linear flexibility characteristics.

The result of modification is illustrated by the spectrum of level of acoustic pressure in the cabin represented in the Figure 4. Decreasing level of amplitudes of the main input components can be forecasted by applying the relationship (6), taking damping properties of rubber-metal elements expressed by the decreasing level $\mathbf{\Delta L_h}(f)$ resulting from the system transmittance.

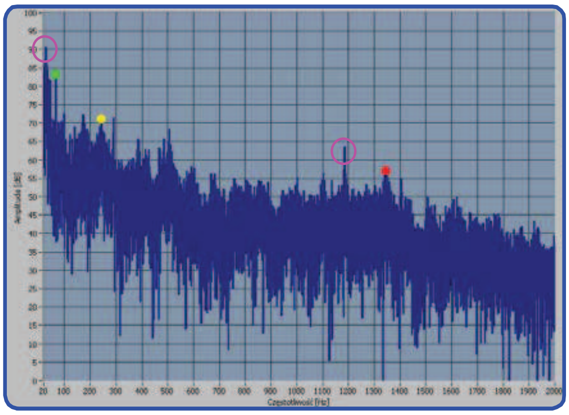

Fig. 4. Spectrum of noise in the cabin: state with elements of non-linear characteristics

Interpretation of relatively high level of components of the spectrum marked with circles results the most difficult task. The fact that the low frequency sounds are not being damped can be an indication that this particular area cannot be considered as a systemic response to the input by working power mechanisms but rather to some exterior disturbances $\Delta\Phi^*(f)$. High level of amplitude of components exceeding 1200 Hz is resulting from non-linear flexibility characteristics of rubber-metal sleeves used for alternating the object's condition. These spectrum characteristics result from influence of non-linear elements and can be taken as a symptom suggesting changes in condition of technical object.

4. CONCLUSION

The above remarks are part of broader study on methodology of using the information contained in vibroacoustic signal for monitoring vehicles condition, as well as in environmental noise management. The analysed object – prototype electricity powered vehicle – was chosen because of its ecological qualities that make us strongly consider future development of this group of individual transport means.

Due to the fact that non-linearity affects the majority of real processes we cannot omit it while considering evaluation of objects condition. Vibroacoustic signal treated as information carrier reaches the receiver in form of a resultant shaped also by non-linear elements. However, if a deep, detailed analysis of their role is usually not possible, the way they affect the system can be quite easily determined. The effects of non-linear elements visible in the spectrum of vibroacoustic signal reflect changes in condition of a technical object.

REFERENCES

[1] Dąbrowski Z.: *Modeling and identification of nonlinear system for technical diagnostics*. The 8th International Congress on Sound and Vibration, Hong Kong, China, 2001, pp. 1083÷1090.
[2] Dąbrowski Z., Radkowski S., Dziurdź J., Dybała J., Mączak J., Tomaszek S.: *Kształtowanie właściwości wibroakustycznych elementów i zespołów maszyn (uwagi metodyczne)*. Warszawa 2000 (ISBN 83-912190-4-6).
[3] Klekot G.: *Ocena wpływu elementów nieliniowych na propagację energii wibroakustycznej*. Przegląd Mechaniczny, nr 11/07 Warszawa 2007, 30÷32.
[4] Dąbrowski Z., Dziurdź J., Klekot G.: *Studies On Propagation Of Vibroacoustic Energy And Its Influence On Structure Vibration In A Large-Size Object*. Archives Of Acoustics 32, 2, 203 – 212 (2007).
[5] Klekot G.: *Selected Diagnostic Aspects Of Propagation Of Vibroacoustic Energy*. Diagnostyka, Vol. 4(44)/2007, str. 53-56.

Dr eng. **Grzegorz KLEKOT**, assistant professor at the Institute of Machine Design Fundamentals, Faculty of Automobiles and Heavy Machinery Engineering, Warsaw University of Technology, member of the Polish Society of Technical Diagnostics.