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Assessment of the Correlation Between the Numerical and Experimental Dynamic Characteristics of the Bucket Wheel Excavator in Terms of the Operational Conditions

In the paper authors present their attempt in the validation process of the numerical model on the basis of experimental results. The Modal Assurance Criterion between the numerical and experimental model was selected as the indicating factor. Moreover, changes in frequencies and the degrees of freedom influencing the most the correlation level were reconsidered.

The numerical and experimental models, in most cases, did not cover the influence of the operational load on the dynamic characteristic of the construction. In the new, operational approach, the change in the numerical model composition must be reconsidered, while the old one is no longer valid. Modal analysis performed out of the operational load, give good results but does not represent actual state of the construction in operation. In that case, we have two separate systems with different dynamic characteristics. Identification of the modal model with use of the Operational Modal Analysis gives the information about the object in operation which is a real point of the interest.

Keywords: *Modal Analysis, Bucket Wheel Excavator.*

1. INTRODUCTION

At present, most of the surface mining machines working in the lignite mines in Poland are even twenty or thirty years old. In the case of such complicated structures, proper and sufficient identification of dynamic characteristics was not fully achievable till now. Recent development of mathematical, numerical methods and the power of computers allowed to face with that problem in full scale [1]. Up to now the only reliable method for determination of dynamic characteristics was an experiment. Obtained results gave full information but about the already built object. What is more, proper implementation of the experimental procedure on such objects is not a simple task [2-4].

Dynamic characteristic of the object is a useful needle for the operation of the machine [5], especially in the case of the big size surface mining machines which are highly exposed to the dynamic load. This type of machines are spreaders (Figure 1) and bucket wheel excavators (Figure 2) [6].

In the case of excavators, the high variability of the excavation force is a common phenomenon [7]. Additionally, vibrations are generated in drives [8], conveyors [9] and by the transported material (hitting the pulleys and discharge points). Technological movements like travel, rotation or derricking are also a source of vibrations. Spreaders are not so exposed to the dynamical loads as bucket wheel excavators, but due to their slenderness it is also easier to excite vibrations.

In reduction of negative results of the vibrations, knowledge about dynamical characteristics is one of the key factors. An indirect result of the amplitude decrease is the significant positive influence on durability of the structure, mainly due to the fatigue phenomenon reduction [10]. There are known cases where dynamical displacements lead to the collision of the machine elements [11]. Proper identification of the modal model allowed to implement changes in construction that will prevent this negative phenomenon. Nowadays, even more sophisticated methods [12-14] can be applied to reduce the vibration but still good identification of a modal model is needed. In many other cases, operation in resonant areas makes the operation difficult.

What is worth noting, the vibrations generated by the machines can also excite human organs vibrations. Permissible acceleration levels are defined in the standards [15-16]. In ultimate cases, human body organs can vibrate in resonance. Following the general trends of human protection [17-19], vibrations must also be taken into consideration.

2. OBJECT OF INVESTIGATIONS

Preliminary investigations performed on the bucket wheel excavator SchRs 4600.50 [20] revealed that the correlation level of numerical and experimental results differ in particular operational conditions. This lead to the conclusion that an attempt to update numerical models should be done to obtain better correlation.

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Figure 1. Spreader A2RSB12500

Also, the source of differences between experimental models should be investigated. Both of the problems are discussed in the present paper.

The investigated object was the bucket wheel excavator SchRs 4600.50 (Figure 1). This is one of the biggest surface mining machines operating in Poland. The height exceeds 64 me-ters, length 120 meters and the mass (without discharge bridge) is around 5000 tonns.

Figure 2. Bucket wheel excavator SchRs 4600.50

The necessity for investigations of the dynamic behavior was caused by the need of modernization of the excavating unit [21]. Excitation generated during machine operation is the key factor influencing the vibrations of the machine. Detailed information about the dynamic characteristics of the object allowed to design a new bucket wheel with properly selected number of buckets (direct influence on the excitation frequency).

3. NUMERICAL MODAL ANALYSIS

A Discrete model of the complete superstructure of the machine consists of the slewing platform, counterweight boom, central part, bucket wheel boom and front and rear tower. In the numerical model, undercarriage elements like platform or driving elements assemblies and the discharge bridge were not included. Those elements were taken under consideration, while the most important, concerning vibrations problem is the superstructure. However, stiffness of the undercarriage elements must be substituted in the model in other way, while it influences the global modes of the machine. In the described discrete model the bucket wheel excavator SchRs 4600.50 superstructure was supported in the area where railway of the main bearing is assembled. The stiffness of the reduction elements was adjusted to the stiffness of all the undercarriage parts. This approach gives only approximated representation of the real conditions. But, even if the whole undercarriage were included to the simulations there is still big unknown of the ground stiffness and even perfectly built model of the whole machine does not give the exact stiffness value. Eventually, results point out that the simplified approach allows to obtain results on the satisfied level.

Results of the performed numerical simulations are presented in the Table 1. Eight main modes were selected and most of them are the global one.

4. ON SITE MEASUREMENTS AND RELATION WITH NUMERICAL RESULTS

Numerical measurements gave the basis for the preparation of proper modal experiment in real conditions. At first, the measurement points were selected (Figure 3).

Measurements were taken in several operational conditions, which can be observed during lifetime of the excavator. From all the data sets, the three of them (most reliable) were selected for the analysis: upward excavation, downward excavation and machine travel. Comparison of MAC [22] factor for each load case is presented in Figure 3.

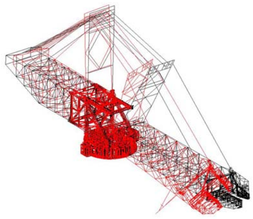
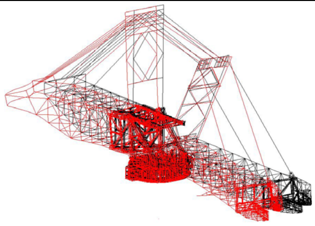
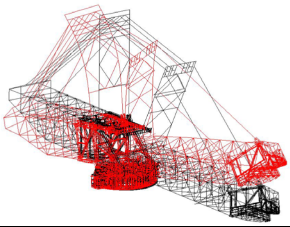
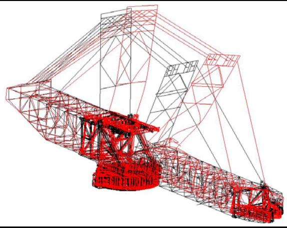
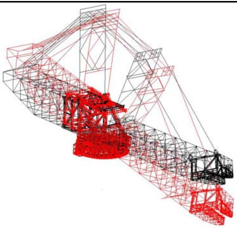
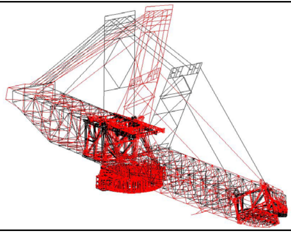
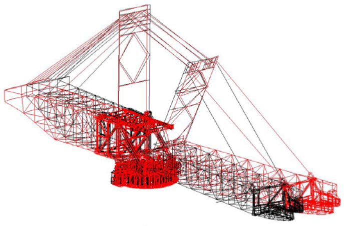
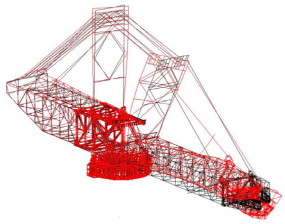
Mode	Description	Mode	Description
	Mode 1–0.28Hz bucket wheel boom torsion		Mode 5-0.53Hz bucket wheel and counterweight boom bending in horizontal plane
	Mode 2-0.32Hz superstructure vibrations in vertical plane		Mode 6-0.82Hz side vibrations of front and rear mast
	Mode 3-0.37Hz superstructure vibrations in vertical plane		Mode 7-0.96 rear mast bending
	Mode 4-0.38Hz superstructure vibrations in horizontal plane		Mode 8-1.68Hz front mast torsion

Table 1. Heading (Helvetica 8 bold) – Align left

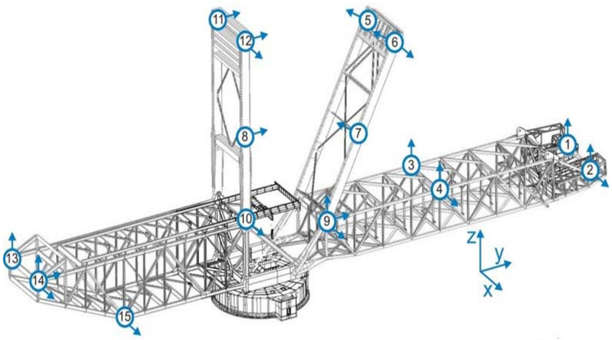


Figure 3. Measurement points [18]

While independently of the load case the correlation with numerical model did not change significantly [1], the attempt for increasing the correlation of the numerical and experimental modal model were performed.

When comparing both modes, not only information about the mode shape similarity, but also information how it is related the frequency of compared mode is important.

For that reason, to make it quick and easy, the author's generalized correlation factor (k_u) was used in the following form (1):

$$k_u\left(f_b\right) = MAC_{ab}\left(1 - \left|\frac{f_a - f_b}{f_b}\right|\right) \tag{1}$$

where f_a is the frequency of the mode from the numerical model, f_b is the frequency of the mode form the experimental model MAC_{ab} is the correlation of numerical (a) and experimental (b) mode.

The modifications of the numerical model covered boundary conditions related to the changes in operational conditions. As main factors influencing dynamics of the machine, circumferential force and damping were assumed (Figure 5). This assumption was made on the basis of the analysis of the experimental results (Figure 4). It is visible that the operational conditions influence most the global modes in the vertical plane along the axis of the machine.

The damping coefficient value (c_{kr}) was selected according to the Eq. (2) [23]:

$$k_u\left(f_b\right) = MAC_{ab}\left(1 - \left|\frac{f_a - f_b}{f_b}\right|\right) \tag{2}$$

which describes the critical damping for the single degree of freedom system. In the case of the global vibration modes along the main axis of the machine in the vertical plane, this assumption represents the vibrations motion in a proper way.

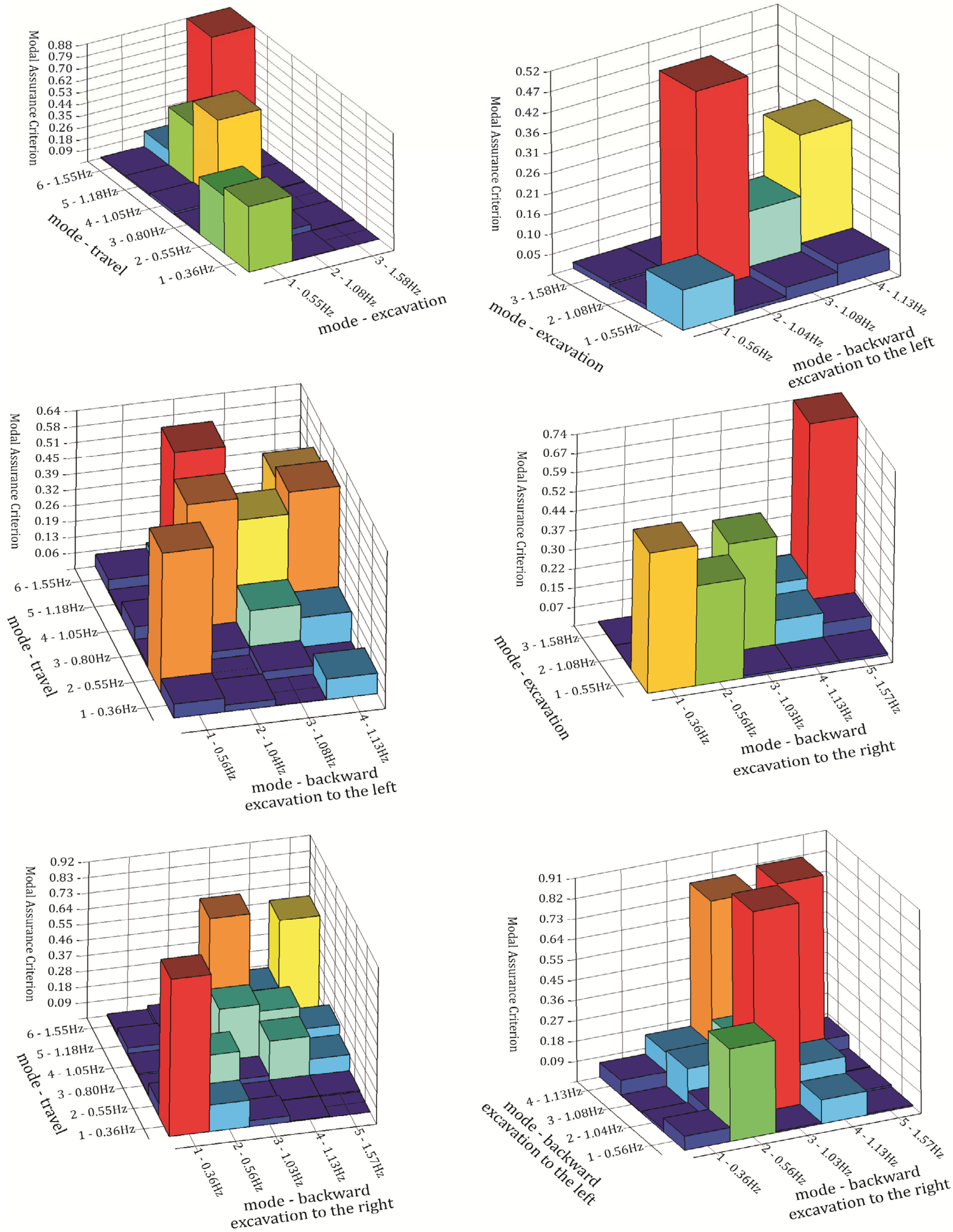


Figure 4. crossMAC factor for particular operational case

As a result, diagrams (Figure 6 to Figure 8) of the generalized correlation factor between numerical model (covering all the eleven load cases) and the particular experimental case were prepared. It is visible that none of the changes did influence significantly on the correlation level, no matter what is the experimental case. However, those simulations revealed that the simplest model, based on the Stability Proof, is actually the most proper.This indicates additionally that for the proper simulation of the changing operational condition, more complex approach is required. With high probability, the phenomenon of the interaction of the buckets and excavated soil must be included. Realization of that task required complicated experimental studies that will give the basis for further analysis.

Table 2. Numerical model boundary conditions.

	Numerical model boundary conditions			
Lp.	superstructure according to the Stability Proof	Overburden and pollution of the superstructure	circumferential force	frequency value [Hz]
1	X	---	---	---
2	X	x	---	---
3	X	x	x	---
4	X	x	---	0,40
5	X	x	x	0,40
6	X	x	---	0,57
7	X	x	x	0,57
8	x	x	---	0,78
9	x	x	x	0,78
10	x	x	---	0,97
11	x	x	x	0,97

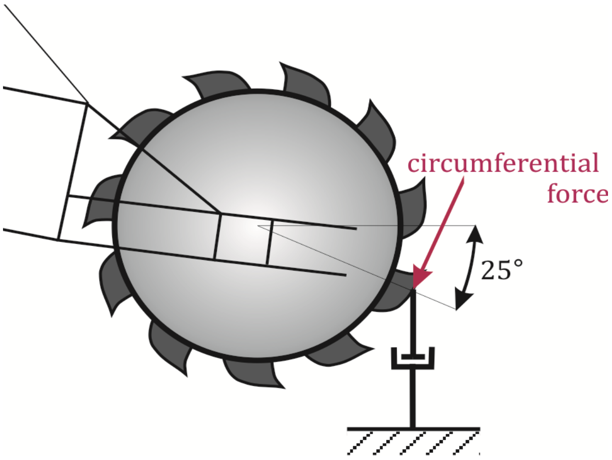


Figure 5. Numerical model boundary conditions scheme

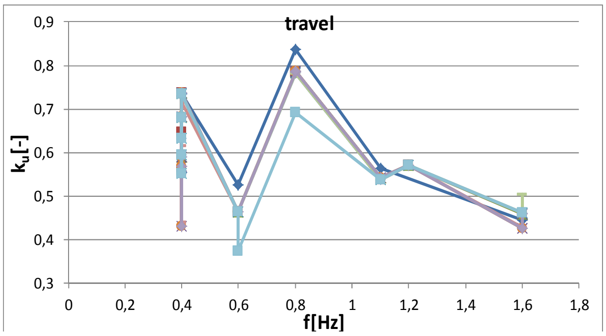


Figure 6. Generalized correlation factor level for travel and numerical model (for every set from table 2)

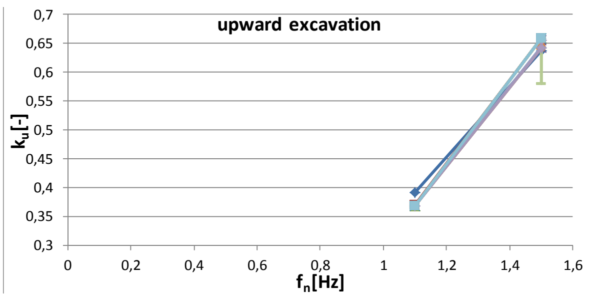


Figure 7. Generalized correlation factor level for upward excavation and numerical model (for every set from table 2)

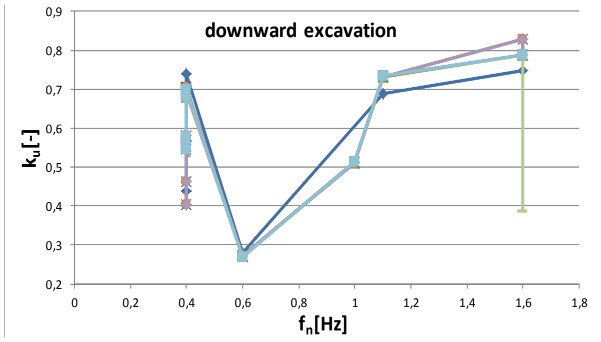


Figure 8. Generalized correlation factor level for upward excavation and numerical model (for every set from table 2)

Additionally, if we analyze the response of the machine in case of the operational condition, it is possible to see that there is a difference in the band of the excitation. This proves the relation between the operational condition and the presence of the modal modes. If take a look at the Figure 9 it is visible that the excitation during excavation does not supply enough energy in the lowest range of frequencies. On the other hand, the travel is the case that can excite the modes even in the lowest band. Even if there are no the characteristics of excitation it is possible to describe it in general.

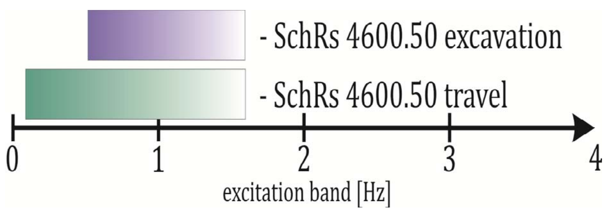


Figure 9. Excitation band for the excavation and travel case

5. CONCLUSIONS

In presented paper differences between particular experimental modal models were presented. The level of the correlation (crossMAC matrices) indicates the presence of every particular mode in terms of operational conditions.

Moreover, the application of the generalized correlation factor shows a simple and very useful method for the comparison of correlation level, both modal deflection shape and frequency. It was applied for the comparison of the modified numerical model and particular experimental modal model which correspond to the particular operational case. No significant changes in the correlation level were observable. This leads to the conclusion that the simplest model, without additional boundary conditions, gives the same results like the modified one. However, this reveals lack of knowledge in the field of exact influence of the boundary conditions, during excavation process, to the dynamic behavior of the machine.

The excitation band for the bucket wheel excavator SchRs 4600.50 was established. Having no information about the characteristics of the excitation signal it was possible to estimate its general character on the basis of the response of the structure.

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ПРОЦЕНА КОРЕЛАЦИЈЕ ИЗМЕЂУ НУМЕРИЧКИХ И ЕКСПЕРИМЕНТАЛНИХ ДИНАМИЧКИХ КАРАКТЕРИСТИКА РОТОРНОГ БАГЕРА СА АСПЕКТА РАДНИХ УСЛОВА

Eugeniusz Rusiński, Jerzy Czmochowski, Przemysław Moczko, Damian Pietrusiak

Рад представља покушај аутора да изврше валидацију нумеричког модела на основу резултата експеримената. Модални критеријум квалитета између нумеричког и експерименталног модела је изабран као меродавни фактор. Осим тога, поново су размотрене промене фреквенција и степена слободе који највише утичу на ниво корелације.

У већини случајева, нумерички и експериментални модели не укључују утицај радног оптерећења на динамичко понашање конструкције. Код новог приступа који обухвата радне услове мора се поново размотрити структура нумеричког модела, јер стари приступ више није валидан. Модална анализа извршена на основу радног оптерећења даје добре резултате, али не приказује стварно стање конструкције у радним условима. У том случају, имамо два посебна система са различитим динамичким карактеристикама. Одређивање модалног модела коришћењем радне модалне анализе пружа информације о објекту који ради а који је и предмет нашег интересовања. .