Validation of the number of buckets on the working device of a bucket wheel excavator from the aspect of dynamic behavior of the system

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The method for validation of the number of buckets on the working device of a bucket wheel excavator from the aspect of dynamic behaviour of the system, partially presented in this paper, was developed on the basis of the original spatial reduced dynamic model of the bucket wheel excavator with two masts, which enables modal analysis and analysis of the dynamic response of the system for continuous variation of constructional parameters and parameters of excitation. The set of 16 seemingly-acceptable solutions, all of which satisfied the rigid design restrictions which were: (a) use of the same bucket wheel drivetrain, (b) preservation of the theoretical capacity, (c) possibility of the excavation of soil of the fourth category and (d) preservation of the superstructure centre of gravity position, was analyzed. On the basis of limiting vertical and lateral accelerations, derived from dynamic coefficients prescribed by the code DIN 22261-2, of the bucket wheel centre, which for a proper geometrically-designed bucket wheel excavator structure represents a well grounded indicator of its dynamic behaviour, 14 out of 16 analyzed solutions were discarded, yielding the set of possible solutions to only 2, the originally designed one (with 17 buckets) and the solution with 20 buckets installed on the bucket wheel.

Keywords: *bucket wheel excavator, dynamic behaviour analysis, limiting accelerations, number of installed buckets*

1. INTRODUCTION

Due to the perennial exploitation in extremely harsh working conditions (for example, more than half of the BWEs operating in open-cast mines in Serbia are in exploitation for more than 30 years [1]), failures and breakdowns of the bearing structures and mechanical subsystems [2-7] occur relatively frequently. The most important consequence of the aforementioned failures, apart from the risk for safety and life of workers, is the downtime of the machine, which accumulates extremely high financial losses. Modernization of the BWE fleet is conducted in two equally represented directions. Apart from the acquisition of new units, redesign of the dated and obsolete machines and their subsystems is also executed in order to reduce the power consumption, reduce the maintenance costs by decreasing the number of scheduled repairs and, most importantly, to increase the productivity by reducing the number of accidental stops. Apart from the age of excavating units, relatively frequent failures and accidental stops are also the consequence of the everlasting tendency towards improving the performances of BWEs, which has not been adequately supported by the calculation methods and technical regulations, drawing a conclusion that it was practically impossible to carry out a detailed stress-strain analysis and the dynamic behaviour analysis during the stage of their design, as stated in [8]. Redesign, conducted in order to achieve modernization of the machine, is a procedure inevitably followed by the alternation of operating (constructional) parameters which strongly influence the structural behaviour of the BWEs.

The excavating subsystem, consisting of a bucket wheel (BW) with its belonging drivetrain, is the most important part of a BWE, since its construction determines the output and total behaviour of the machine. Although it is clearly stated, by the literature relevant to the field of BWEs, that the redesign of an excavating system, in order to correct the design errors, would be difficult and expensive, if at all possible after the machine has been constructed [9], in the modern engineering practice there is a rising number of scientific institutions and research and development centres dealing with this extremely complex engineering challenge. As a part of the overall modernization of the excavating units operating on the open-cast mines in the Oltenia coal basin, which represents the backbone of the lignite production in Romania, which started as early as 1995, 17 out of 33 BWEs of the same design (SchRs 1400), responsible for the 80% of total lignite and overburden exploitation on the said surface mine, have been subjected to the process of reconstruction [10], whose key aspect was based on the replacement of the existing BW drivetrain (essentially replacing the

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gearbox of the classical design with a planetary one) and the change in the number of buckets on the BW (9 filling + 9 cutting with 20 filling-cutting buckets) [11]. Aside from the analysis of the influence of change in the number of buckets on the BW on the modal characteristics of the bucket wheel steel structure [12], additional information on the consequences of said changes on the dynamic behaviour of the BWE were not available to the authors of this paper. Similar project, on a smaller scale, was conducted in the Kolubara open-pit mine in Serbia, when the 55-year old BWE SchRs 350 has been subjected to the process of redesign of the excavating subsystem [13], which included substituting the planetary gearbox for the existing spur-geared one, as well as the installation of two additional buckets on the BW (increasing the total number of 8 to 10). In paper [14], the analysis of excitation due to the resistance to excavation and conclusions on the potential of a more favourable influence of the said excitation on the dynamic behaviour of the system, have been presented. Negative dynamic effects, which have been diagnosed experimentally, gave rise to the need to replace the existing bucket wheels on the two conceptually-different BWEs (SchRs 4600.50 and SchRs 4600.30), operating in the Belchatow surface mine in Poland [15]. On the basis of the experimental and numerical modal analyses of the entire structures, conclusions have been drawn on the design of a unique BW steel structure and the corresponding number of buckets which would satisfy the requirements for the safe operation of both BWEs without changes to the existing drivetrains.

To the authors' knowledge, none of the aforementioned cases provide any information regarding the influence of variation of the number of buckets on the BW on the dynamic response of the system. As it will be shown in the remainder of this paper, said variation is a key parameter because of its influence on the overall dynamic behaviour of the machine and, as such, is vital in the process of selection and validation of the appropriate design solutions. The method for validation of the number of buckets on the working device of a BWE from the aspect of dynamic behaviour, will be presented using the technical characteristics of the BWE SchRs 1600, Fig 1, as the base model.

Figure 1. BWE SchRs 1600 in operating conditions: mass (with mobile conveyor) 3345t, theoretical capacity 6600m^3/h

2. REDUCED SPATIAL DYNAMIC MODEL

The analysis of the dynamic responses of large scale machines such as bucket wheel excavators can often prove difficult to perform due to several obstacles such as the extreme complexity of the corresponding dynamic system, small number of modifiable parameters after the mounting of the structure and the limitation of the finite element analysis (FEA), which is reflected on the discrete nature of the method.

The analysis of the dynamic behaviour of the BWE SchRs 1600 superstructure was performed on the basis of a reduced spatial dynamic (RD) model with 64 DOF. The model was developed and validated according to the procedures presented in [16-18]. Validation of the said procedure, which supplements the finite element method in its application in the dynamic behaviour analysis of the BWE spatial truss structures, has been performed on the basis of relevant measurements and used to develop models and conduct dynamic response analysis of excavators with different design conceptions [19,20]. The model, presented in Fig. 2, for which the development procedure is enclosed in detail in [21], enables modal analysis as well as analysis of the dynamic response in a continuous domain of both constructional and parameters of excitation variation.

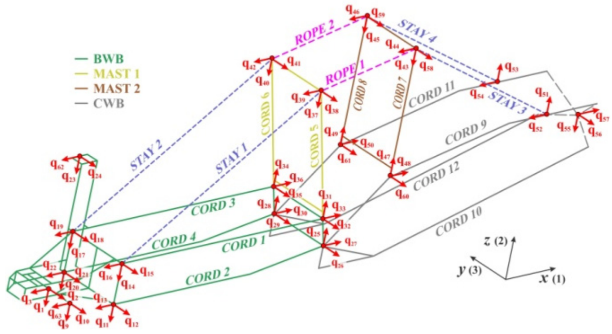


Figure 2. A reduced spatial dynamic model of the BWE SchRs 1600 [21]

Although BWEs are constructions with changeable configuration, which makes the analysis of their dynamic behaviour extremely complex [17,22,23], according to the findings presented in [18], the influence of the BW boom inclination angle on modal characteristics of the analyzed excavator is not significant. Thus, the horizontal position of the BW boom has been adopted as referent for further analysis.

3. SELECTING THE APPROPRIATE DESIGN SOLUTIONS

The choice of number of buckets, from the aspect of the dynamic behaviour of the machine, was conducted in three stages, with respect to the extremely rigid design restrictions which are, as already stated:

- use of the same drivetrain,
- preservation of the theoretical capacity,
- possibility of the excavation of soil (overburden) of the fourth category, dominantly present on the "Kolubara" open pit mine and
- preservation of the superstructure centre of gravity position.

In the first stage, the analysis was conducted for continuous variation of the number of buckets in the range from 9 to 24 buckets on the BW. Although the aforementioned parameter is of discrete nature, the analysis was conducted in a continuous domain in order to perceive the influence of the proximity of certain resonant states on the dynamic response of the construction. After defining the set of possible solutions using the limiting accelerations, derived from dynamic coefficients prescribed by the code [24] as a cut-off criterion, the influence of the adhered material (incrustation on the bucket wheel and bucket wheel chute blockage) on the modal characteristics and dynamic response of the system was analyzed. In the final stage, the mass of the bucket wheel steel structure was varied in the range of ±20% of the original solution, while preserving the centre of gravity position by modifying the mass of the counter-weight.

Some results of the first stage of the research will be presented in the paper. Namely, for a proper geometrically-designed BWE structure the BW centre (point of penetration of the BW shaft axis through the vertical symmetry plane of the buckets) presents a referent point whose dynamic response is a well grounded indicator of the dynamic behaviour of the superstructure. In the RD model of the BWE, motion of the BW centre (BWC) is defined with three generalized coordinates (q_1, q_2, q_3) [21]. Maximum vertical ($a_{1,max}$) and lateral ($a_{2,max}$) accelerations of the said referent point will be used for determining the appropriate design solution in terms of the dynamic behaviour.

3.1 Excitation loads assumptions

Identification of the external loads caused by the resistance to excavation was performed according to the procedures presented in [25,26]. The obtained external loads were approximated with trigonometric polynomials with five harmonics, using the Fourier coefficients, with respect to the results and conclusions made in [20].

The dependence of the moment of excavation (M_T) on the number of buckets (n_k) on the bucket wheel is shown in Fig 3.

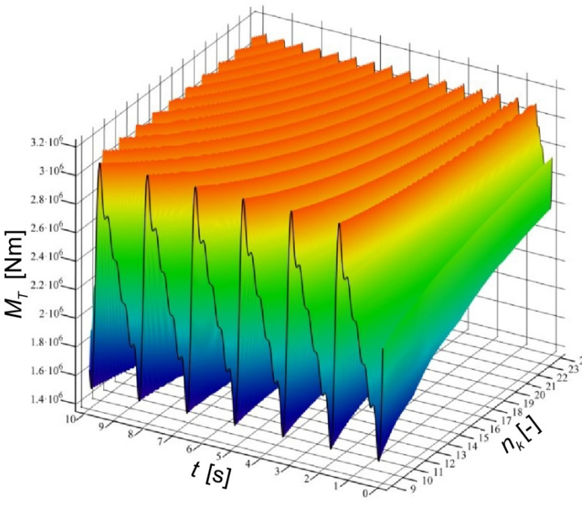


Figure 3. Moment of excavation

From the presented diagram, it is evident that the maximum values of loads caused by the resistance to excavation remain constant, which is a consequence of the adopted parameters of the BW drive, which are unchangeable. Mean values of the loads ($M_{T,m}$) rise, while the amplitude values ($M_{T,a}$) decline with the increase of the number of buckets that are in interaction with the soil, Table 1. It can also be observed that the value of the first (and therefore higher excitation frequencies) rises as the number of buckets on the BW is increased.

If the designed state of the excavator (17 buckets on the wheel) is taken as the basis for the analysis of the results presented in Table 1, it can be concluded that, for the case of 9 buckets on the BW, the mean values of loads caused by the resistance to excavation are 12.5% lower, while the load amplitudes are 65.5% higher. For the case of the bucket wheel with 24 buckets, mean values of loads are 4.7% higher, and load amplitudes are 25.5% lower than those of the designed state, Table 2. Values of excitation frequencies are in the range between -47.1% and +41.2%.

Table 1. Dependence of the moment of excavation and the first frequency of excitation on the number of buckets on the bucket wheel

n_k(-)	9	10	11	12	13	14	15	16
$M_{T,m}$(kNm)	2296.1	2363.2	2408.1	2439.8	2492.6	2530.4	2558.6	2580.3
$M_{T,a}$(kNm)	797.4	730.3	685.4	653.7	600.9	563.1	534.9	513.2
f_{E1}(Hz)	0.612	0.680	0.748	0.816	0.885	0.953	1.021	1.089
n_k(-)	17	18	19	20	21	22	23	24
$M_{T,m}$(kNm)	2611.6	2635.8	2655	2670.5	2691.3	2708.1	2722	2733.6
$M_{T,a}$(kNm)	481.9	457.7	438.5	423	402.2	385.4	371.5	359.9
f_{E1}(Hz)	1.157	1.225	1.293	1.361	1.429	1.497	1.565	1.633

Table 2. Percent deviation of the moment of excavation and the frequencies of excitation

n_k(-)	9	10	11	12	13	14	15	16
$\left[\left(M_{T,m,n_k}-M_{T,m,DES*}\right)/M_{T,m,DES}\right]100$ (%)	-12,1	-9,5	-7,8	-6,6	-4,6	-3,1	-2,0	-1,2
$\left[\left(M_{T,a,n_k}-M_{T,a,DES}\right)/M_{T,a,DES}\right]100$ (%)	65,5	51,5	42,2	35,6	24,7	16,8	11,0	6,5
$\left[\left(f_{E,j**,n_k}-f_{E,j,DES}\right)/f_{E,j,DES}\right]100$ (%)	-47,1	-41,2	-35,3	-29,4	-23,5	-17,6	-11,8	-5,9
n_k(-)	17	18	19	20	21	22	23	24
$\left[\left(M_{T,m,n_k}-M_{T,m,DES}\right)/M_{T,m,DES}\right]100$ (%)	0,0	0,9	1,7	2,3	3,1	3,7	4,2	4,7
$\left[\left(M_{T,a,n_k}-M_{T,a,DES}\right)/M_{T,a,DES}\right]100$ (%)	0,0	-5,0	-9,0	-12,2	-16,5	-20,0	-22,9	-25,3
$\left[\left(f_{E,j,n_k}-f_{E,j,DES}\right)/f_{E,j,DES}\right]100$ (%)	0,0	5,9	11,8	17,6	23,5	29,4	35,3	41,2

*designed state of the construction, n_k = 17
**j = 1,2...5 – frequency of excitation

The non-uniformity of loads caused by the resistance to excavation is expressed with the non-uniformity coefficient (κ_n), which represents the ratio between the maximum and minimum load values, Fig 4, as well as with the coefficient of dynamism (κ_d), which is the ratio of maximum and mean load values, Fig 5.

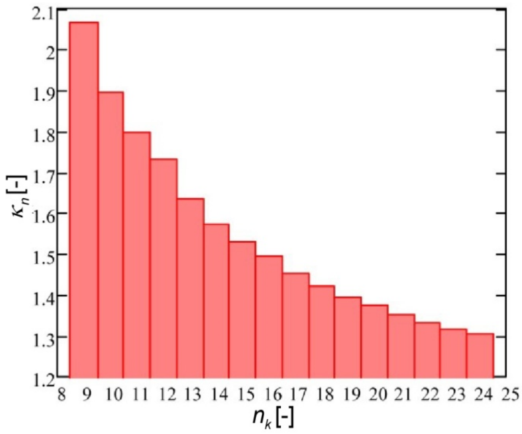


Figure 4. Coefficient of non-uniformity

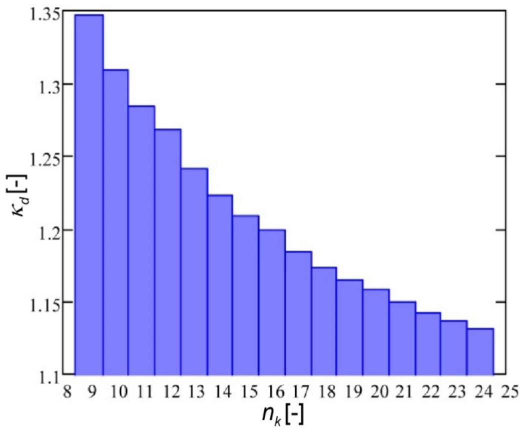


Figure 5. Coefficient of dynamism

Based on the experimental-analytical research, conducted by the Mining institute of Zemun [27], the characteristics of soil found in the open pit mines of Serbia mostly befall under the IV category. According to [27], the specific resistance to excavation reduced to the cutting surface (k_F) befalls in the range between 3.1 and 6.4 daN/cm^2. Papers [28,29], which simulate the loads on the bucket wheel excavators of three different designs, each operating in the open pit mine "Kolubara", adopt the average specific resistance to excavation of $k_{F,u}$ = 5.0 daN/cm^2. Based on the presented data, it can be concluded that each of the analysed cases of the number of buckets on the BW could perform the excavation of the soil of the IV category, Fig 6.

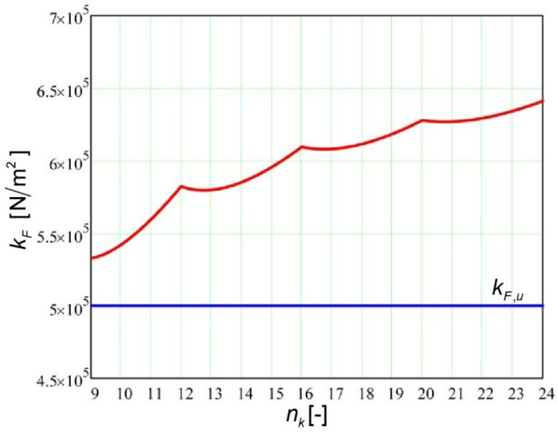


Figure 6. Specific resistance to excavation

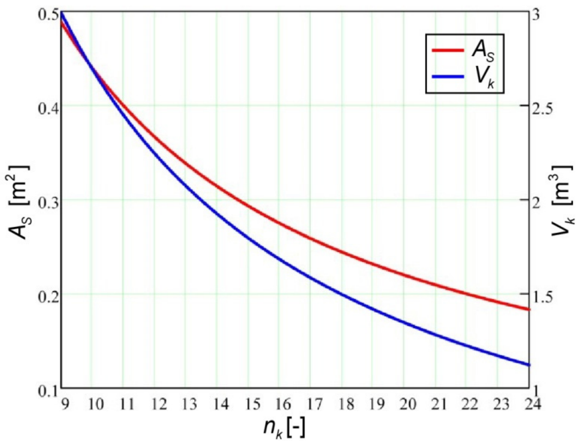


Figure 7. Dependence of the chip cross section area and the capacity of the bucket of the number of buckets installed on the BW

Chip cross section area, and therefore nominal bucket capacity, decreases with the increase of the number of buckets on the bucket wheel, Fig 7. In order to achieve the designed theoretical capacity, which is the basic condition of the analysis, the capacity of a bucket, for cases of 9 and 24 buckets on the BW, has to be ~89% higher and ~24% lower than that of the designed state, respectively.

Reduction of the chip cross section area results in the increase of the specific resistance to excavation. Specific resistance to excavation which the system for the excavation of material with 9 buckets on the BW is able to overcome is 12.4% lower, while in the case of 24 buckets this resistance is 5.4% higher than that of the designed state.

3.2 Determining the set of possible solutions

Comparative display of the first fourteen natural frequencies and five frequencies of excitation on the range from 9 to 24 buckets is presented in Fig 8. In the analysed interval of the number of buckets, for frequency ranging up to 8 Hz, 31 resonant states are observed. The values of analyzed parameter which lead the system into resonant states are presented in Table 3.

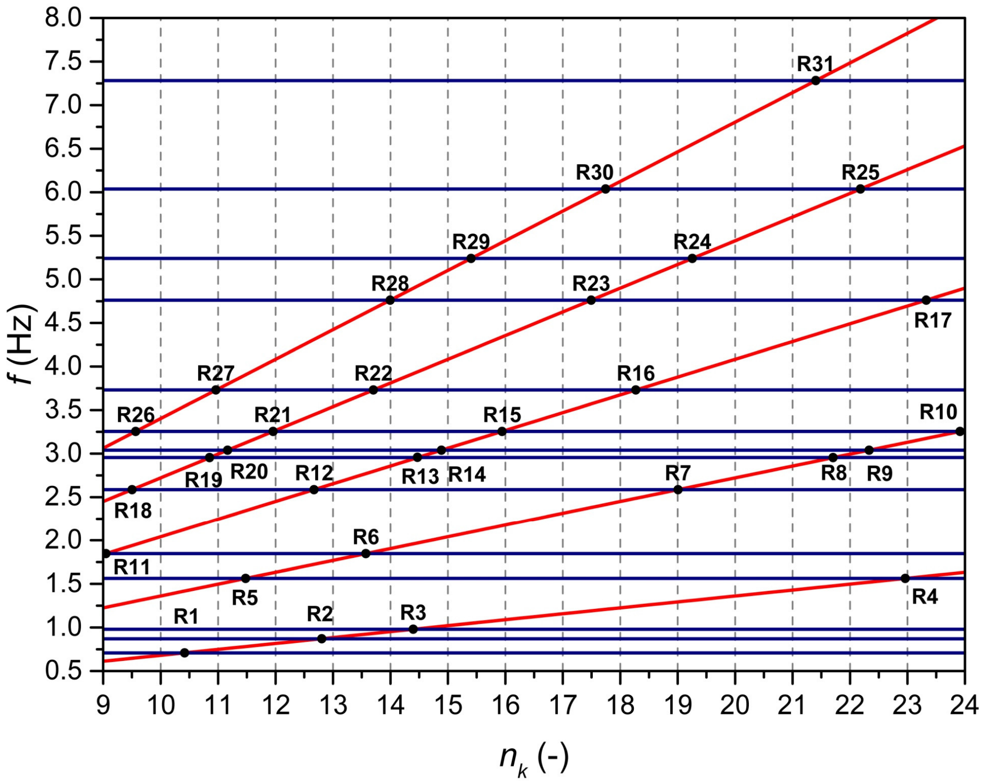


Figure 8. Comparative display of natural frequencies (blue coloured lines) and frequencies of excitation (red coloured lines) dependant on the number of buckets (resonances are marked with black dots and label R_i, i=1,2,...,31)

Table 3. The order of resonance and values of the analysed parameter

Order*	I				II			
Label	R1	R2	R3	R4	R5	R6	R7	R8
n_k(-)	10.42	12.8	14.4	22.96	11.48	13.57	19.01	21.71
Order	II		III					
Label	R9	R10	R11	R12	R13	R14	R15	R16
n_k(-)	22.33	23.92	9.05	12.67	14.47	14.89	15.94	18.27
Order	III	IV						
Label	R17	R18	R19	R20	R21	R22	R23	R24
n_k(-)	23.33	9.50	10.85	11.17	11.96	13.70	17.50	19.26
Order	IV	V						
Label	R25	R26	R27	R28	R29	R30	R31	
n_k(-)	22.18	9.57	10.96	14.00	15.40	17.75	21.40	

* the order of resonance is determined in regard to frequencies of excitation

Based on the results presented in Table 3, it can be concluded that, for the analyzed number of buckets on the BW (n_k=9, 10, ..., 24), only one case leads to the appearance of a resonant state. Said resonant state occurs for the design solution which includes 14 buckets on the BW, which can be discarded based on the results of a modal analysis alone.

However, based on the presented data, comments on the effects of the proximity to certain resonant states on the response of the system cannot be made, nor can any conclusion on the quality of the adopted design be derived. This is because modal analysis, as it is well known, cannot provide any insight on the ranges of resonant areas, thus, in combination with the lack of proper recommendations by the known literature, it is necessary to perform the analysis of the dynamic system response.

German standard [24] prescribes the limiting accelerations of the referent points, which are used as a cut-off criterion for the diagnosis of negative dynamic effects during the experimental and analytical analysis of the dynamic response of BWEs [4,19,30-32].

Maximum values of the vertical and lateral accelerations of the BWC of $a_{V,zul}$ = 1 m/s^2 and $a_{Q,zul}$ = 0,167 m/s^2, respectively, are prescribed by the said standard, but it does not prescribe its maximum allowed axial acceleration. In the preliminary stage of the process of selection of the number of buckets on the BW, the maximum values of vertical and lateral accelerations of this referent point, Figs 9 and 10, have been used to determine the number of buckets which would satisfy the criteria prescribed by the standard.

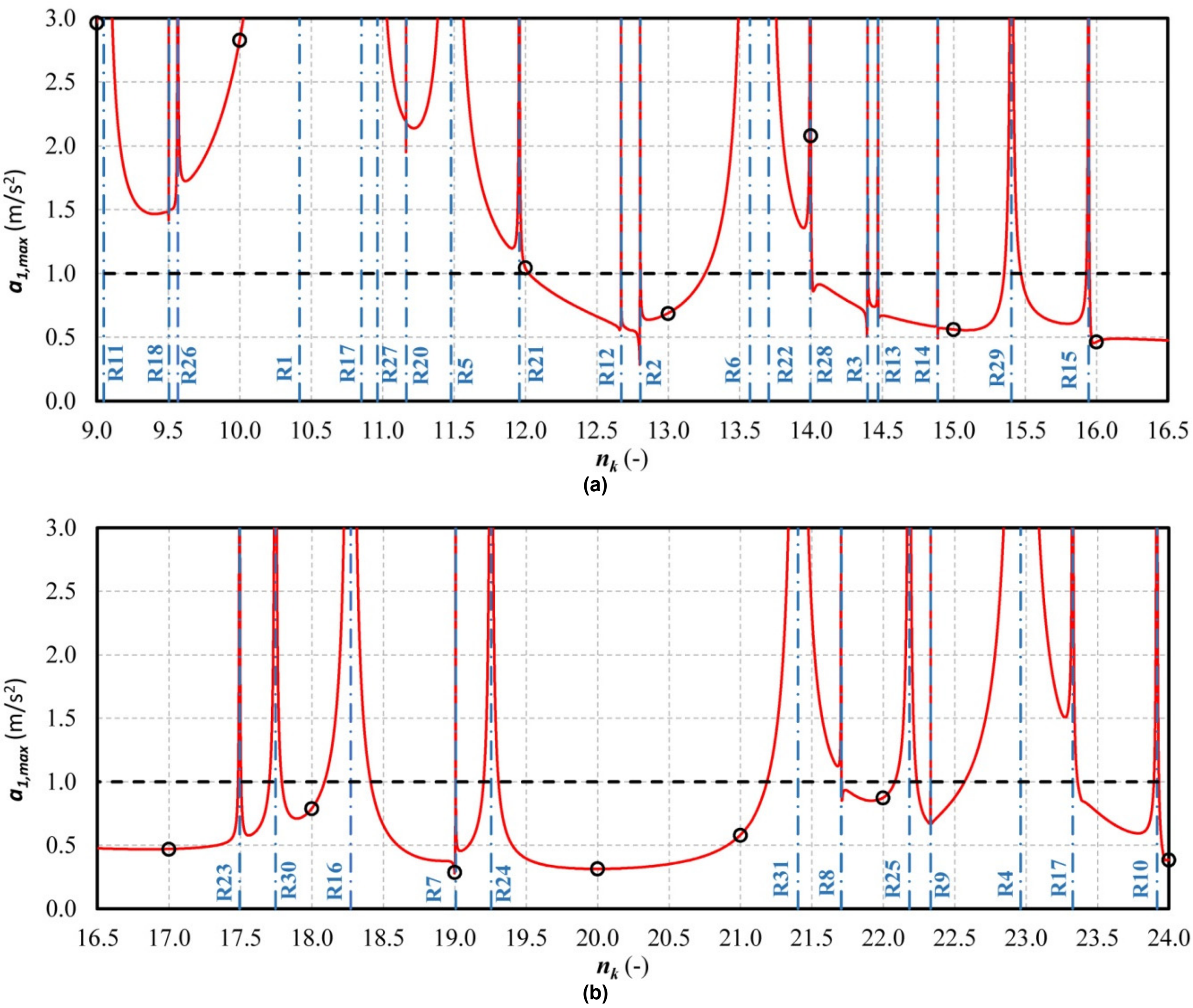
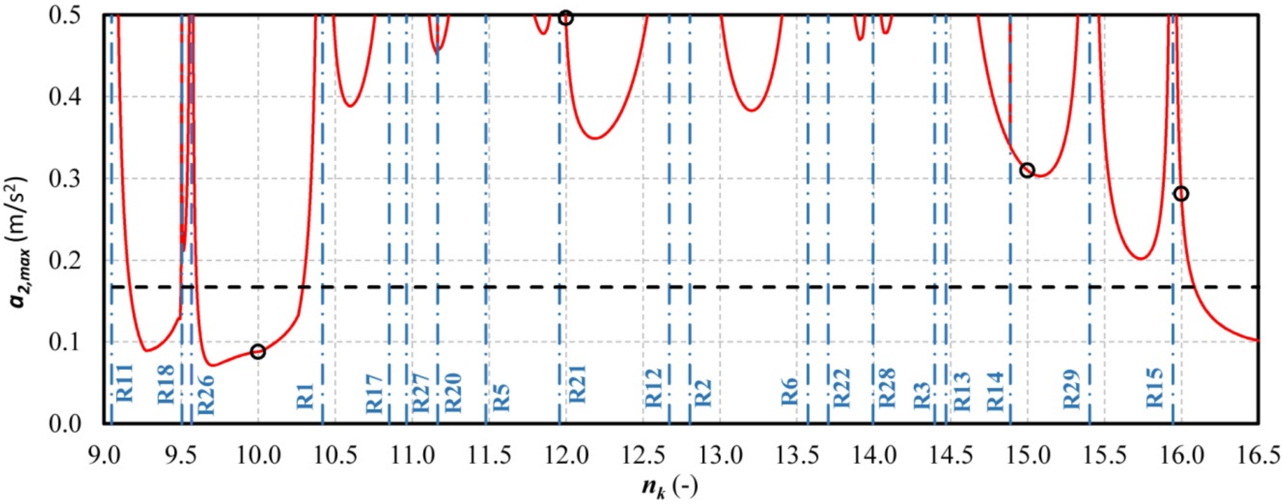


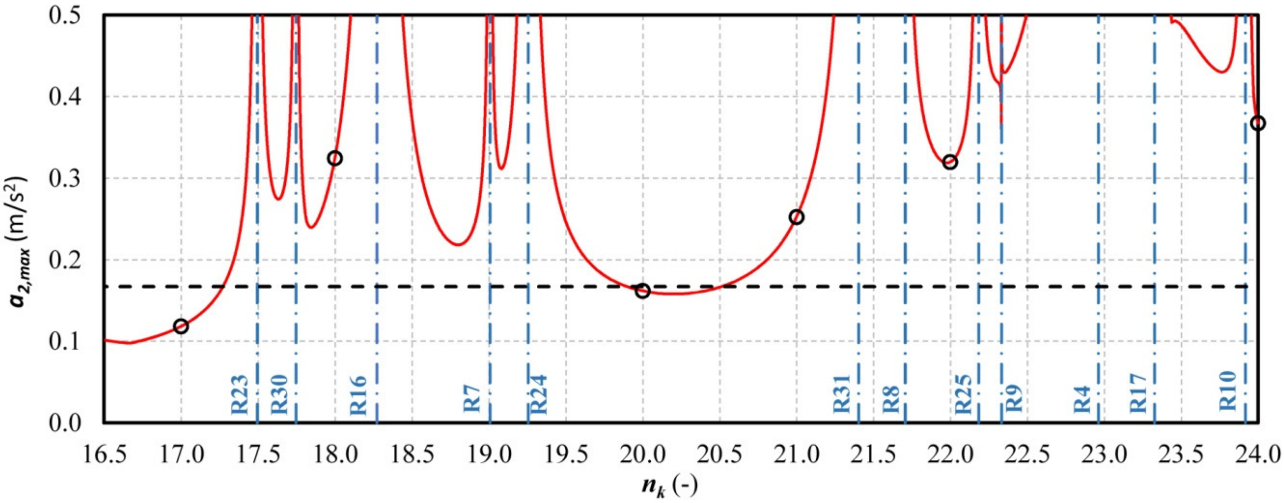
Figure 9. Maximum vertical accelerations of the BW centre: (a) n_k = 9÷16.5; (b) n_k = 16.5÷24 (red coloured line presents maximum vertical accelerations for continuous variation of n_k, blue dash-dot lines are resonances, black circles are values of maximum vertical accelerations for n_k=9, 10, ..., 24, while the limiting vertical acceleration of the BWC, $a_{V,zul}$ = 1m/s^2, is presented with black dash-dash line)

Table 4. Maximum vertical accelerations of the BWC for n_k=9, 10, ..., 24

n_k(-)	9	10	11	12	**13**	14	**15**	**16**
$a_{1,max}$ (m/s^2)	2.964	2.826	3.979	1.045	**0.687**	2.078	**0.560**	**0.462**
n_k(-)	**17**	**18**	**19**	**20**	**21**	**22**	23	**24**
$a_{1,max}$ (m/s^2)	**0.469**	**0.787**	**0.287**	**0.313**	**0.579**	**0.874**	9.487	**0.383**



(a)



(b)

Figure 10. Maximum lateral accelerations of the BW centre: (a) n_k = 9÷16.5; (b) n_k = 16.5÷24 (red coloured line presents maximum lateral accelerations for continuous variation of n_k, blue dash-dot lines are resonances, black circles are values of maximum lateral accelerations for n_k=9, 10, ..., 24, while the limiting lateral acceleration of the BWC, $a_{Q,zul}$ = 0,167m/s^2, is presented with black dash-dash line)

Table 5. Maximum lateral accelerations of the BWC for n_k=9, 10, ..., 24

n_k(-)	9	**10**	11	12	13	14	15	16
$a_{2,max}$ (m/s^2)	0.617	**0.088**	1.461	0.496	0.516	2.652	0.310	0.281
n_k(-)	**17**	18	19	**20**	21	22	23	24
$a_{2,max}$ (m/s^2)	**0.118**	0.324	1.098	**0.162**	0.252	0.32	5.972	0.367

Based on the data presented in Fig 9 and Table 4, it can be concluded that 6 out of 16 possible design variants do not satisfy the criterion of limiting vertical acceleration of the BWC. That includes the variant with 14 buckets on the BW, which has already been discarded after the modal analysis.

The lateral acceleration of the BWC has a significantly higher sensitivity to the proximity to the resonant states, thus resulting in only 3 out of 16 considered variants being adequate when this cut-off criterion is considered, Fig 10 and Table 5.

It is interesting to note that the design variant with 10 buckets on the BW satisfies the lateral acceleration criterion but, at the same time, this cut-off parameter has insufficient sensitivity to the appearance of the first order resonance (R1) whose modal deflection shape (see Figs 7(a) and 7(b) in [21]), singles out the vibrations of the system in the vertical plane as the dominant form of the system oscillations. With that in mind, said variant has been discarded, reducing the set of possible solutions to only 2 – the originally designed one and the variant with 20 buckets on the BW.

4. DISCUSSION AND CONCLUSION

Out of the 16 seemingly-acceptable solutions, all of which satisfied the rigid design restrictions (defined in the 3rd chapter of this paper), one was discarded based on the results of the modal analysis alone. By introducing the criterion of limiting accelerations of the bucket wheel centre, prescribed by the code DIN 22261-2, 13 more solutions were found to be unsatisfactory, thus reducing the set of possible solutions to just 2, confirming the fact that, as is also stated in the relevant literature, simultaneously reconstructing the bucket wheel and ensuring there are no changes to the safe operation of the machine is an extremely difficult task. This implies that any attempts at drawing conclusions without prior analyses of the dynamic response of the system may lead to fallacies.

Namely, the results of the modal analysis, on their own, without any additional insight such as knowing the energetic potential of the 31 resonances of the first and higher order, all of which appear in the low-frequency range (below 8 Hz), do not provide enough information for determining the appropriate variant solution. This fact is further supported by the lack of any relevant guidelines for assessing the width of the resonant areas in literature dealing with this class of machines.

The results obtained from the analysis of the dynamic response of the bucket wheel centre, lead to the following conclusions:

- Limiting vertical acceleration of the BWC cannot be the sole criterion for validation since it eliminates only 6 out of 16 possible design variants;
- When the limiting lateral acceleration of the BWC is used as the cut-off parameter, 13 out of 16 solutions are discarded, leading to a conclusion that the lateral acceleration of the BWC has a significantly higher sensitivity to the proximity to the resonant states;
- None of the analysed cut-off criteria are sufficiently sensitive to be applied on their own, and therefore have to be used in conjunction as presented in the example of 10 buckets installed on the bucket wheel.

Conclusions on the validity of the remaining two design solutions (the originally designed one and the variant with 20 buckets on the bucket wheel) can be derived only after the following additional investigations are conducted:

- the analysis of response of the remaining referent points of the dynamic system. This is required because in some modes the majority of the potential energy is generated by the substructures other than the bucket wheel boom [21];
- the analysis of the influence of the additional mass on the bucket wheel body which is the consequence of inevitable soiling. This is supported by the fact that, for the design solution with 20 buckets on the bucket wheel, the maximum lateral acceleration of the bucket wheel centre is only 3% lower than the limiting acceleration;
- the impact of differences between the masses of the reconstructed bucket wheel and the original design solution on the dynamic behaviour of the entire system, while accounting for the preservation of the position of the superstructure centre of gravity.

Just from the results presented in this paper, multiple observations have been made, all of which attest to the superiority of the 20-bucket redesign variant over the original design with 17 buckets on the bucket wheel, including:

- the first and therefore the remainder of the excitation frequencies of the 20-bucket variant are 17.6% higher than those of the original solution;
- the coefficients of dynamism and non-uniformity are 2.2% and 5.2% lower for the 20-bucket variant, respectively;
- the 20-bucket redesign variant is able to overcome 3.3% higher resistance to excavation.

Using the reduced spatial dynamic model of a bucket wheel excavator with two masts superstructure, with the introduction of the limiting accelerations of the referent system points, it is possible to avoid the appearance of negative dynamic effects as early as during the machine's design stage. This way, the risk of failures and breakdowns of substructures of the considered class of bucket wheel excavators is significantly reduced.

The results presented in this paper represent a contribution to the field of dynamic behaviour of the bucket wheel excavators, even more so having in mind the fact that, in engineering practice and the effective technical regulations, insufficient familiarity with the dynamic processes is compensated with use of the quasi-static approach.

The development of the procedure for validating the number of buckets on the bucket wheel from the aspect of the dynamic behaviour of the system, whose fundamental steps are presented in this paper, represents an important step forward in defining the constructional parameters of this class of machines for continuous excavation.

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