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On the dynamic modelling of bucket wheel excavators

This paper deals with procedures for dynamic modeling of structure and mechanisms for bucket wheel excavators (BWE). Identification of external load caused by resistance to excavation presented in the paper enables including of all relevant structural parameters, as well as parameters of duty cycle and soil characteristics. By applying before mentioned procedures corresponding dynamic models are set up for BWE TAKRAF SRs 1200 and KRUPP SchRS 1760. Based on dynamic models we have solved some specific problems for BWE: defining loads in stays of bucket wheel boom, response of mechanism for bucket wheel boom lifting, estimation of rheolinearity level, analysis of impact of counterbalance weight on the dynamic parameters and system response.

Keywords: *bucket wheel excavator, structure, dynamics, resistance to excavation, mechanisms.*

1. INTRODUCTION

The operation of the bucket wheel excavators (BWE) is characterized by the phenomenon of an expressively dynamic character. The basic causes of this phenomenon mentioned above are the following facts:

- Bucket repetitively gets into contact with the soil;
- Unbalance in the elements of driving mechanism, as well as in the bucket wheel and rotational components of belt conveyors;
- Strokes of the fragments of soil in consequence of emptying the buckets.

The analysis of the dynamic behavior of BWE is of an extreme importance, above all, in order to prevent the possible occurrence of the resonance in the system and to create a basis for the analysis of the stress conditions in structural elements of the system, as well as for calculation of lifetime.

Dynamic behavior of BWE under the forced action of resistance to excavation depends on relatively numerous factors that can be classified in two groups. The first group comprises dynamic features of supporting structure and mechanisms, while the second one involves soil characteristics. Analysis of dynamic behavior demands to solve previously, in a suitable manner, the following two problems:

- How to create dynamic model of the machinery;
- How to create model of the external load caused by resistance to excavation.

2. DYNAMIC MODELS OF STRUCTURE

There is deficiency in references dealing with specific problems of modeling structure and mechanisms of BWE. Fundamental reference concerning BWE is certainly monograph [13]. Irrespective of some annotations to this book is important due to following facts:

- Fundaments of modeling supporting structure, mechanisms, and resistance to excavation are expressed;
- Dynamic models for real constructions of BWE are settled;
- Comparative analysis of theoretical and experimental researches is done;
- Several problems related to dynamic behavior of BWE in operating conditions are recognized, including some still non-solved problems.

Monograph [9] is characterized by subtle mathematical approach. However, its principal drawback in comparison with [13] can be found in the fact that problems of modeling subsystems of BWE and their behavior in real operating conditions are treated marginally.

The basic elements of upper structure of BWE (pillar, counterbalance arm, bucket wheel and stacking boom) are mostly space trusses.

During digging process the elements of upper structure are exposed to loads that cause transverse - flexural, longitudinal - axial and torsional vibrations. According to [13] longitudinal vibrations of truss structures can be considered independently from flexural and torsional vibrations due to the large value of axial stiffness. Therefore, for modeling BWE structure by corresponding selection of reference nodes and their degrees-of-freedom (DOF) it is necessary to include flexural and torsional vibrations of substructures.

In general references concerning structural dynamics, problems of modeling spatial truss girders are not discussed. For modeling planar truss the following assumptions are adopted:

- Nodes of truss are ideal;
- Vibrations of whole truss are dominant;
- Masses of rods are lumped in nodes.

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The consequence of first assumption is diminution of nodes stiffness; thereby decrease of whole structure stiffness implies in lower natural frequencies for model comparing with real structure. The second assumption is based on the fact that transverse and longitudinal vibrations of singular rods are not affecting vibrations of the whole truss. Influence of the third assumption on the accuracy of defining natural frequencies and eigenvectors depends on geometry of truss girder and relationship between masses of singular rods. However, for small vibrations of truss and if the truss rotates as a rigid body around an axis, as is the case for subsystems of truss upper structure, the impact of mass reduction on the inertia moment for truss with respect to the rotation axis must be considered [2]. In [1] is given an original approach of mass reduction that enables simultaneously obtaining of fine approximations for natural frequency, amplitude of free-end displacement and fixed-end bending moment.

How to make the reduction of model as an elastic body on the model with finite DOF is analyzed in details in references [9,10,13]. Basic features of the considered problem in these references are:

- A priory resolution of oscillatory motion of bucket wheel boom on bending vibrations along two orthogonal planes (horizontal and vertical), and on torsional vibrations;
- The boom in vertical plane is modeled as a beam with continually distributed mass and with one or two degrees-of-freedom. The axial inertia moment of equivalent beam is obtained based on the equality between deflections of characteristic sections, while the shape of dynamic deflection is assumed independently from the real construction and real boundary conditions;
- In horizontal plane the boom is modeled as a girder whose lumped mass is reduced on its tip [10,13], i.e. as a girder with continually distributed mass and in advance assigned shape of dynamic deflection [9];
- Vibrations of bucket wheel boom are considered independently from vibrations of other structural components of upper structure, i.e. coupling of vibrations for subsystems of upper structure has been neglected.

In references [2,4] the procedure for setting up dynamic model of subsystems for BWE KRUPP SchRs 1760 upper structure is presented, where we would like to remark the following features:

- Possibility of modeling asymmetrical spatial trusses;
- Possibility of modeling systems whose reference planes are not coinciding;
- Sustentation of coupling of subsystems vibrations alongside displacements;
- Structural elements of trusses are considered as girders in order to avoid truss idealization;
- Shape functions are defined by using FEM for the model corresponding to the real construction and real support conditions.

Dynamic models of column with counterbalance arm are presented in figures 1 and 2.

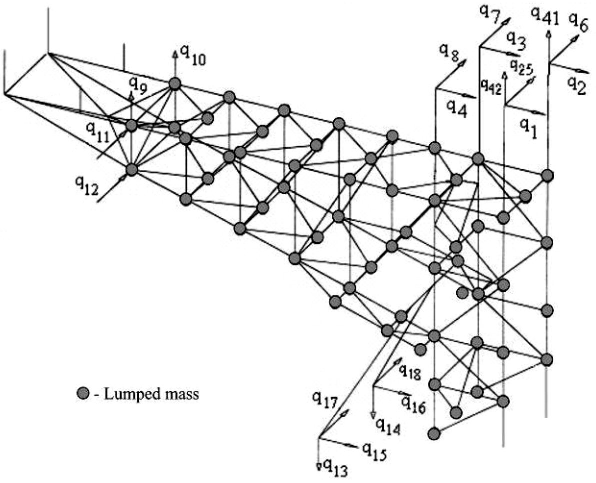

Figure 1. Reduced dynamic model of pillar and counterbalance arm for BWE KRUPP SchRs 1760 [4]

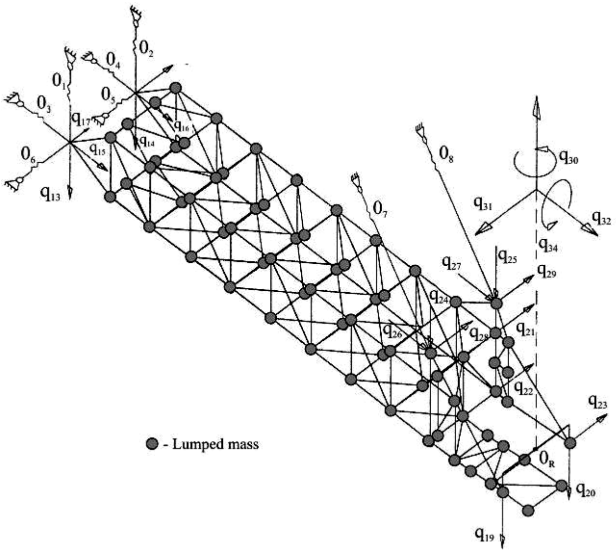

Figure 2. Reduced dynamic model of bucket wheel boom (BWE KRUPP SchRS 1760) [4]

By synthesis of discrete dynamic models for basic substructures, spatial dynamic model of superstructure of BWE KRUPP SchRS 1760 is created. It enables consideration of various problems in dynamics of BWE with satisfying accuracy for engineering calculus.

For solving some problems in structural dynamics of BWE exposed in this paper we have used dynamic model of superstructure presented in figure 3.

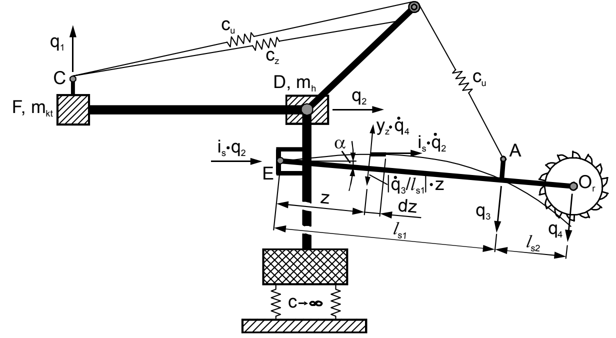

Figure 3. Discrete dynamic model of upper structure for BWE KRUPP SchRS 1760 [11]

3. DYNAMIC MODELS OF MECHANISMS

One of the expected questions following this chapter can be: Is it necessary to include mechanisms of bucket wheel drive, revolving platforms, and mechanisms for boom lifting whence their frequencies are significantly higher than natural frequencies of structure. If we consider dynamic model of BWE merely for defining spectra of natural frequencies of system, it will be certainly possible to model independently structure and mechanisms with accuracy quite acceptable from engineering point of view. However, if we need to analyze dynamic loads, it is necessary to include mentioned mechanisms in model.

Specific problems of modeling mechanisms of bucket wheel drive and revolving platform are discussed in details in [10,13].

Model of reducer for bucket wheel lifting (BWE TAKRAF 1200, Fig. 4) is used for analysis of impact of coupling stiffness on the system response.

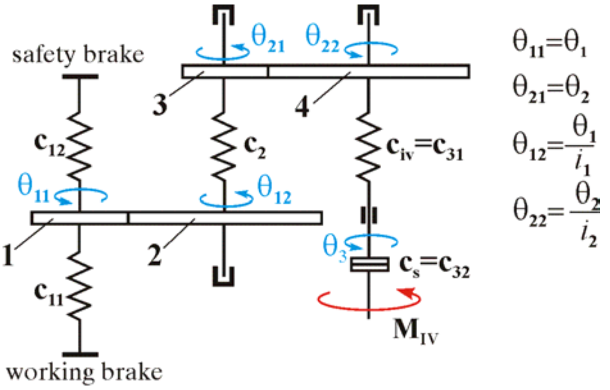

Figure 4. Dynamic model of gear reducer for BW boom lifting [4,5]

In order to analyze behaving of constructed flexible coupling, it is necessary to determine its working characteristics. Sensitiveness of rubber gaskets to circumferential force transmitted by coupling is determined by finite element method.

4. MODELLING OF EXCITATION

Identification of external load distribution, caused by resistance to excavation, requires defining the following characteristic values:

- Chip cross section dimensions;
- Specific resistance to excavation;
- Disposition of resistance to excavation components.

When speaking about problem for defining chip dimensions, available references can be divided in two groups. The first one given in [6,8,10,12] is characterized by defining chip geometry on absolutely rigid model of system. In reference [2] is shown critical retrospective view regarding results obtained by diverse authors, and it is exposed the procedure of the chip's geometry identification developed based on the model comprising all relevant structural parameters and parameters of BWE duty cycles. Model presented in [2] is suitable for broadening and consideration of different structural bucket shapes.

Influence of superstructure vibrations on the chip dimensions is discussed in references [2,11,13].

Problem of selection of identifiers of resistance to excavation (specific resistance to excavation reduced on unit chip section area and unit length of cutting edge) is analyzed in [2]. In [2,4] stochastic character of specific resistance to excavation is simulated by random number generator (Fig. 5).

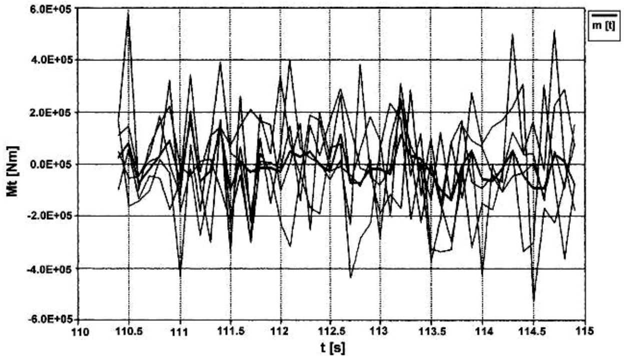

Figure 5. Some realization of torque as stochastic process [2,4]

In references [6,8,10,12,13] for analysis of loads is adopted assumption that tangent and normal component of resistance to excavation are in the plane of bucket wheel rotation. The error obtained in such modeling depends on the configuration and kinematics of reclaiming device. Procedures for identification of loads caused by resistance to excavation given in [2,4] are not based on mentioned assumption and enable to take into consideration all relevant structural parameters and duty cycle parameters for defining coordinates of principal vector and principal moment for gravity center of bucket wheel masses.

5. PRACTICE AND DYNAMICS OF BWE

By applying models shown in chapters 2 and 3 we have solved several practical problems in BWE dynamics that occurred in Serbian open pits. We will present subsequently a short survey of researches dealing with mentioned problems.

5.1 BWE TAKRAF 1200 [3, 4, 5]

During exploitation of BWE TAKRAF SRs 1200 there were several failures of reducer output shaft in the system for changing inclination angle of bucket wheel boom. The observed system, figure 6, consists of: bucket wheel boom (1), bucket wheel (2), stays (3), moving crab with reeving system and sheaves (K), reeving system with stationary sheaves and tightening pulley (N) attached with counterweight (T), and drum (D) with drive unit.

Load identification in rope arms encountering drum, and consequently, reducer output shaft during excavation process, requires, primarily defining forces in stays. Based on the model of reclaiming device of BWE developed in [2], and using original software, in the first instance components of external loading are defined, due to resistance to excavation, reduced on coordinate system $O_Rx_3y_3$, figure 7.

Afterwards, based on the model shown in figure 8, forces in bucket wheel boom stays (Fz) are defined, figure 9.

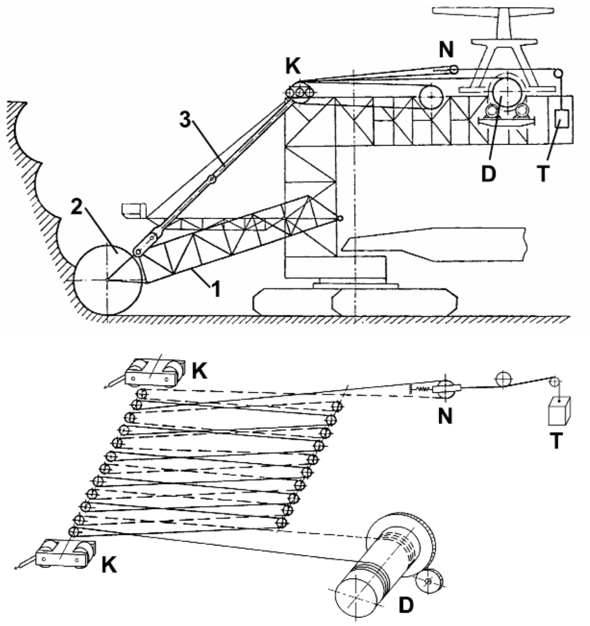

Figure 6. System for changing inclination angle of BW boom

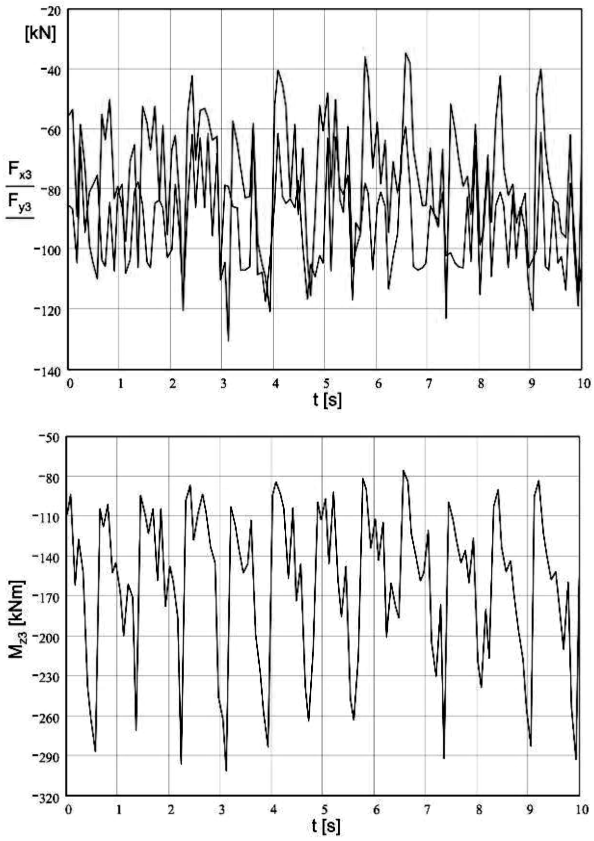

Figure 7. Resistance to excavtion obtained by simulation, top – forces, bottom - moment

Measurements in the real operating conditions (done in open pit "Tamnava – Zapadno Polje") for BWE have been done in order to establish the credibility of simulation model [7]. The goal was to make the external validation of obtained force in left stay in time domain by direct comparison of characteristic values from the model (deterministic and stochastic) and from the real system. Comparison of force diagram in left stay is presented in figure 9.

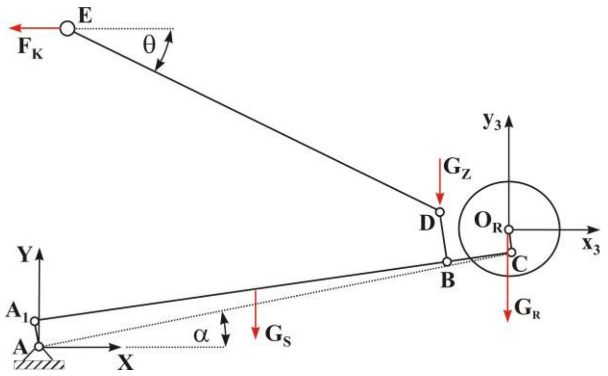

Figure 8. Calculation model for defining load in bucket wheel stays

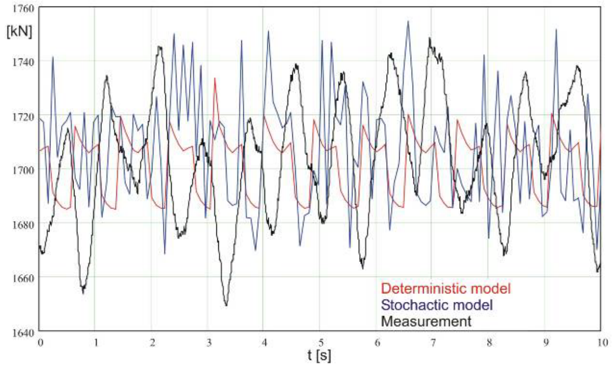

Figure 9. Comparison of force diagram in left stay

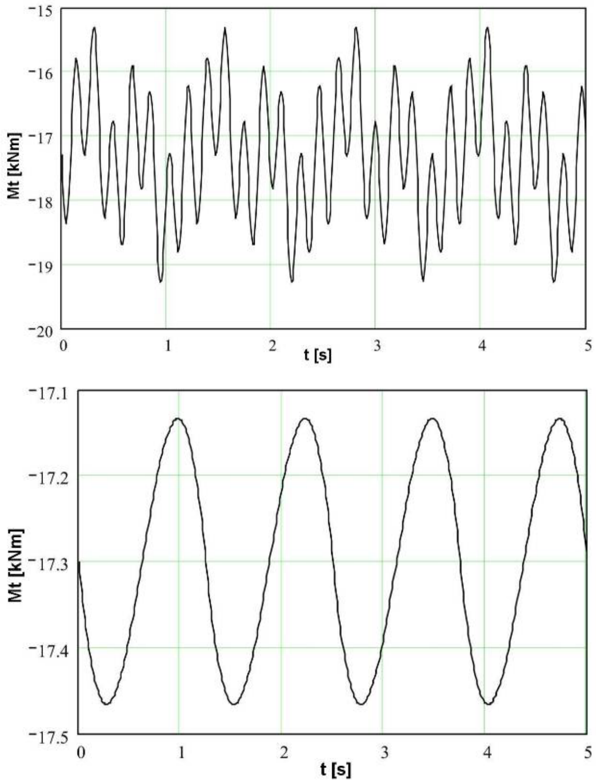

Figure 10. Diagram of torque change for output reducer shaft

It is observed that non–synchronized operation of driving motors as well as operation of braking system can cause malfunction of the flexible coupling in input reducer shaft. In order to correct these effects reducer output shaft and connecting shaft are connected with rubber elastic coupling.

Based on the response of dynamic model of reducer for changing inclination angle of bucket wheel boom, figure 4, it is concluded that the amplitude of changing torque for output shaft is smaller for mechanism with built in rubber flexible coupling, which is consequence of amortization of higher vibrations modes of excitation force, figure 10.

5.2 BWE KRUPP SchRS 1760 [2, 4, 10]

Mathematical model of system is set up by applying Lagrange's equations. If the supporting structure of BWE is considered as system of elastic bodies, then by initiation of corresponding generalized coordinates of model in expressions defining chip geometry parameters, coupling between response and excitation is fulfilled. That leads to dependence between generalized non–conservative forces and generalized coordinates, i.e. time–variability of some elements of stiffness matrix. Namely, numerical value of observed stiffness coefficient, in any moment, can be expressed as the sum of constant term and time depending term.

Diagrams for change of time–depending partial stiffness coefficients are presented in figure 11.

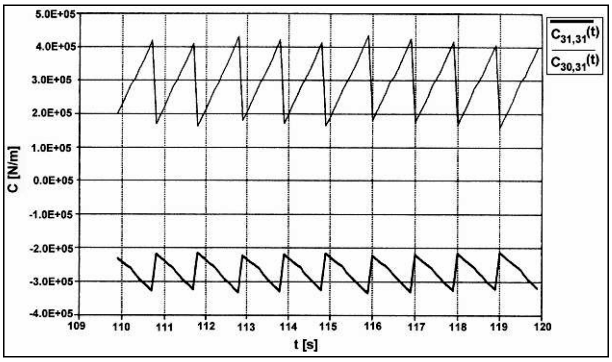

Figure 11. Diagram for change of time–depending partial stiffness coefficients

By comparing values of constant and time–depending term in sum, the estimate of rheolinear level for the system is achieved. Maximum absolute values of variable terms, in this case, are:

$$C_{r,s}(t) = C'_{r,s} + C''_{r,s}(t)\,,\quad C'_{r,s} = \text{const}\,.$$

Numerical values of constant terms for considered stiffness coefficients are:

$$\left|C''_{30,31}\right| = 4{,}34\cdot 10^{5}\ \left[\frac{\mathrm{N}}{\mathrm{m}}\right] \text{ and } \left|C''_{31,31}\right| = 3{,}33\cdot 10^{5}\left[\frac{\mathrm{N}}{\mathrm{m}}\right].$$

Based on that it is concluded that time–depending terms are small values of higher order, i.e. that the rheolinear level of the system is very low.

Taking in mind that in expressions defining variable stiffness coefficients there is a specific resistance to excavation force whose character is stochastic, it is conclusive that deterministic character of some stiffness coefficients is lost, figure 12.

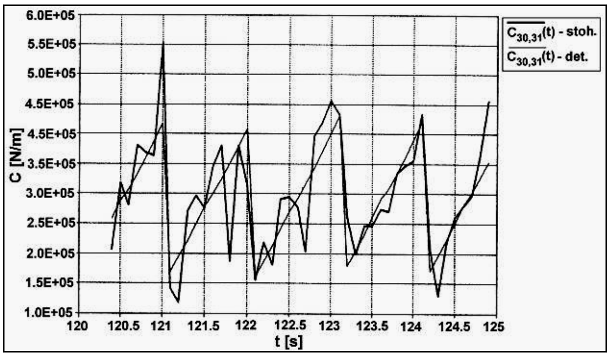

Figure 12. Stochasticity of time depending partial stiffness coefficient

Based on analysis shown in this chapter it is concluded that rheolinear level of mathematical model of BWE KRUPP SchRS 1760 is low, i.e. there is no risk of appearance of parametric resonance.

Dynamic model of superstructure in vertical plane shown in figure 3 was used for analyzing influence of counterbalance weight on dynamic features and response of the system excited by resistance to excavation. Based on the fulfilled analysis we have concluded that:

- The third eigenfrequency of the system is most sensitive on the change of counterbalance mass that was expected, because at that the influence of pillar and counterbalance arm is dominant.
- Even relatively small change of counterbalance mass (3%) can be detrimental from the aspect of dynamic behavior of upper structure, because of significant increase of maximum values and amplitudes of generalized displacements (Figs. 13 and 14) and can menace the supporting structure of machine.

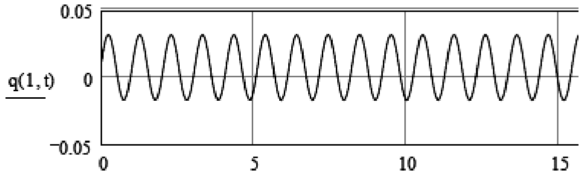

Figure 13. Diagrams for change of q_1 for designed counterbalance mass (500,5 t)

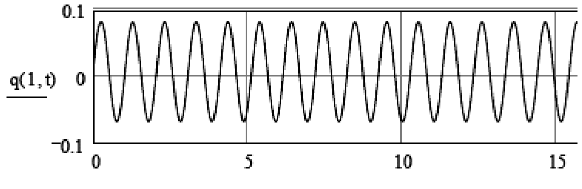

Figure 14. Diagrams for change of q_1 for designed counterbalance mass (520,5 t)

6. CONCLUSION

Over the last decades earthmovers, specially BWE as continuous excavation machines, being first and main component in BWE-conveyors-stacker system influencing other components, and the largest structures in earth based technology, have become progressively larger and their mechanisms more efficient. Natural tendency of permanently improving performances of BWE, especially their capacities, has not been adequately followed by calculation methods. A good proof of this is relatively frequent damaging of BWE in open pits in Serbia. Non–allowed deformations and fractures of BWE subassemblies are primarily caused by lack of compliance while analyzing real dynamic loads. Finally, the analysis of the dynamic behavior of BWE carried out, and presented in this paper through various dynamic models quite accurate from the engineering point of view, ensures a more complete definition of the performance of the machine.

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