

SIMULATION OF THE VIBRATIONS PRODUCED TO THE HUMAN BODY DURING OPERATION OF THE BUCKET WHEEL EXCAVATORS. A CASE STUDY OF ERc 1400-30/7 TYPE EXCAVATOR

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Abstract: The paper deals with the analysis of the dynamic response over time of the excavator boom during operation. For a start, we determined the variation in time of the forces acting on the rotor shaft, due to the excavation. These forces have high values and a slow variation over time, which depends on the rotation speed of the bucket wheel and the number of buckets installed on it. A virtual model of the BWE boom was proposed, for which the dynamic response in time due to the excavation forces was determined, for a point in the main cabin of the BWE. A virtual sensor has been attached to this point corresponding to seat of the operator. The simulation of the dynamic response over time was performed taking into account a global damping of 2% of the critical damping. The simulation was performed both for the excavation of a homogeneous material and for the case of a shock (a sudden appearance of an inclusion of hard material during the cutting of the homogeneous material).

1. Introduction

The bucket wheel excavator (BWE) is part of the technological system used in open-pit lignite exploitation, used at the beginning of the technological process, where it excavates large quantities of material. The BWE model ERc 1400-30/7 is the most widespread in the mines situated in the Oltenia Basin, and it is used to perform all simulations within the paper (Figure 1).



Figure 1. ERc 1400-30/7 model bucket wheel excavator

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The operating tool is the bucket wheel. It performs a rotation in vertical plane and a horizontal slewing as well as a vertical rising-lowering together with the boom [1], [2].

The present paper proposes a new approach to the analysis of the response in time to the loads generated during the excavation process, based on a virtual model of the excavator boom. An analysis of the vibrations at the boom of a BWE was performed in [3] by measuring the accelerations resulting from the sequence: starting the bucket wheel followed by starting the conveyor belt and subsequently stopping both subassemblies. The measurement of vibrations and modal frequencies was performed in [4] following the generation of a mechanical impulse obtained by shooting the cables used to suspend a weight to the bucket wheel in two scenarios, with the bucket wheel suspended and touching the coal-face.

The boom of the ERc 1400-30/7 excavator is a spatial structure (Figure 2) subjected to loads, and it can be divided into 3 sections:

1. A joint section between the boom and the BWE structure, which allows for both vertical and horizontal plane movements;
2. The middle section on which the conveyor belt is mounted for the discharge of the excavated material; and
3. The bucket wheel support section on which the drive mechanisms, as well as the boom hoist cable attachment device, are mounted [5].

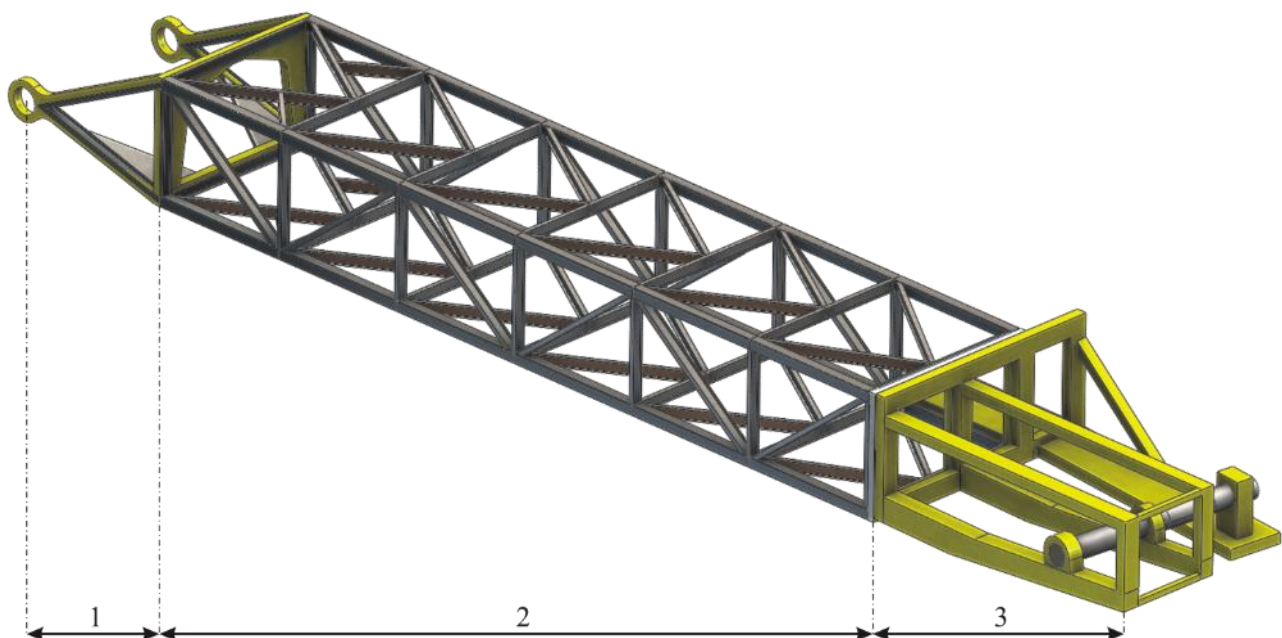


Figure 2. Sections of the BWE boom

During the excavation process, the energy consumption at the bucket wheel level has two major components [5]: the energy needed for cutting the material from the face and the energy needed for lifting the loose material that results from excavation. Between these, the energy necessary for cutting the material is predominant, between 60 to 90% of the energy necessary for operating the bucket wheel.

2. Simulation and modeling of the resultant force acting on the bucket wheel during excavation

In order to determine the resultant force acting on the bucket wheel shaft, SOLIDWORKS was used to build a model of the ERc 1400-30/7 bucket wheel in its updated version [6], equipped with nine cutting-loading buckets and nine cutting buckets. Figure 3 also shows the forces acting on each bucket during excavation: The resultant cutting forces, the forces corresponding to the weight of the lifted material and the inertia forces caused by unloading the buckets. The cutting forces are tangential to the circle described by the cutting edges. The forces corresponding to the weight of the material are parallel and with the same directional as gravitational acceleration [6].

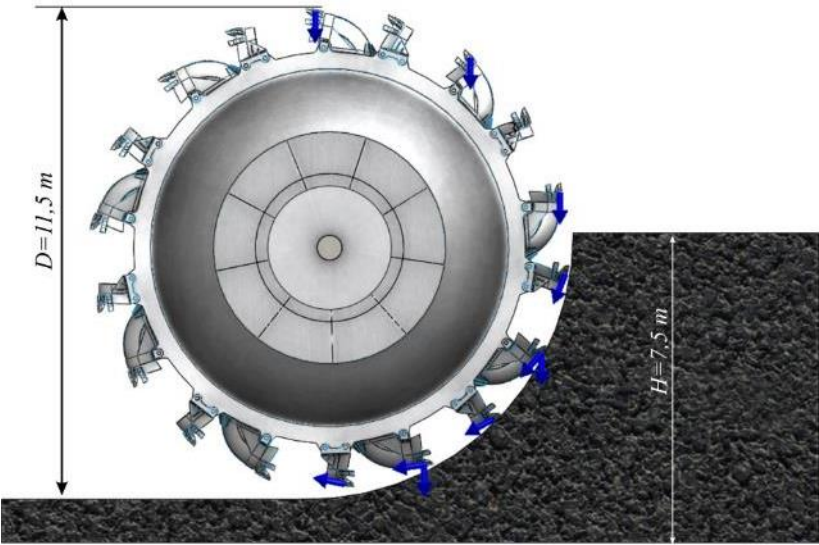


Figure 3. The bucket wheel model and forces acting on the buckets

Figure 4 shows the variation diagram of the force corresponding to the weight of the material, for one cutting-loading bucket. The first part of the chart (ascending line) corresponds to loading of the cut material, the horizontal part corresponds to the lifting of the loaded bucket up to the discharge level, and the descending part corresponds to the discharge of material on the conveyor.

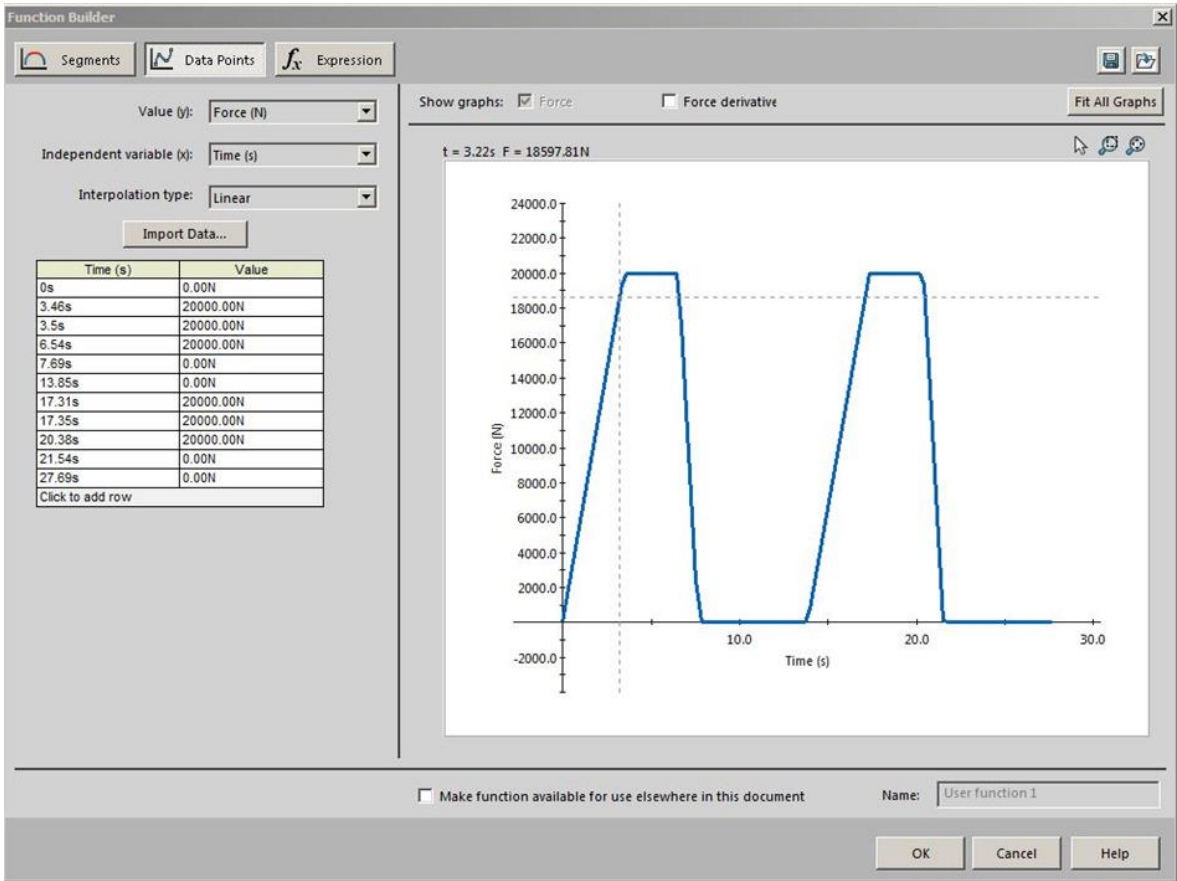


Figure 4. Diagram of the forces corresponding to the weight of the material over time

Figure 5 presents the variation diagram of the cutting forces. These act both on the cutter-loader and the cutter type buckets.

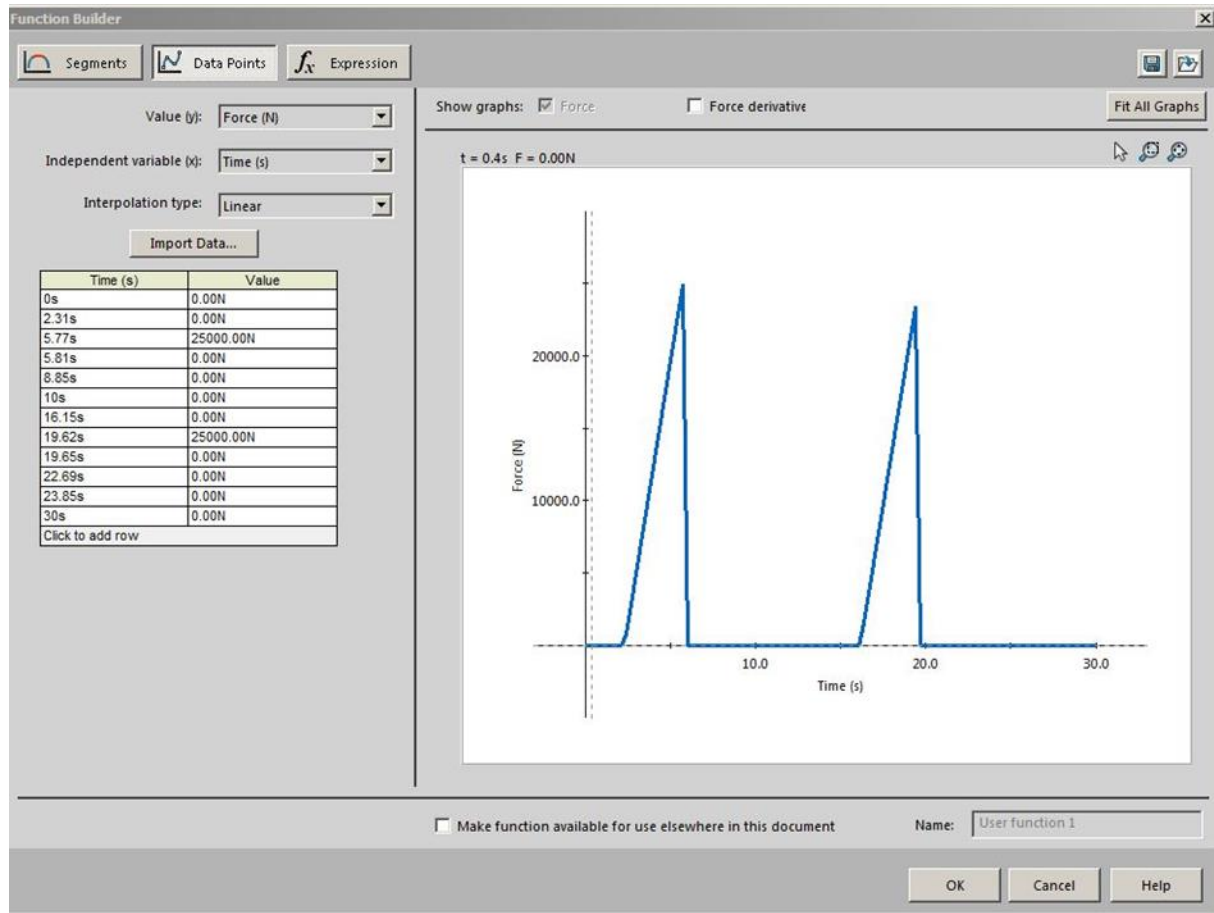


Figure 5. The diagram of the cutting forces acting on both the cutter-loader and cutter buckets.

The time of the simulation corresponds to two complete rotations of the bucket wheel. The offset time between two successive curves seen in figures 4 and 5 is depending on the rotation speed of the bucket wheel. For this BWE model the nominal speed is 4.33 rpm which is equivalent to a discharge rate of 39 buckets/min. The excavation time is influenced by the maximum excavation height, which is $H=7.5$ m in this case.

After running the simulation in SOLIDWORKS Motion Analysis, the variation of the resultant force at the bucket wheel shaft is determined for homogenous material excavation, as shown in figure 6. Based on the plot it can be seen the values of this force are between 77kN and 102kN, with an average value of 89.5kN.

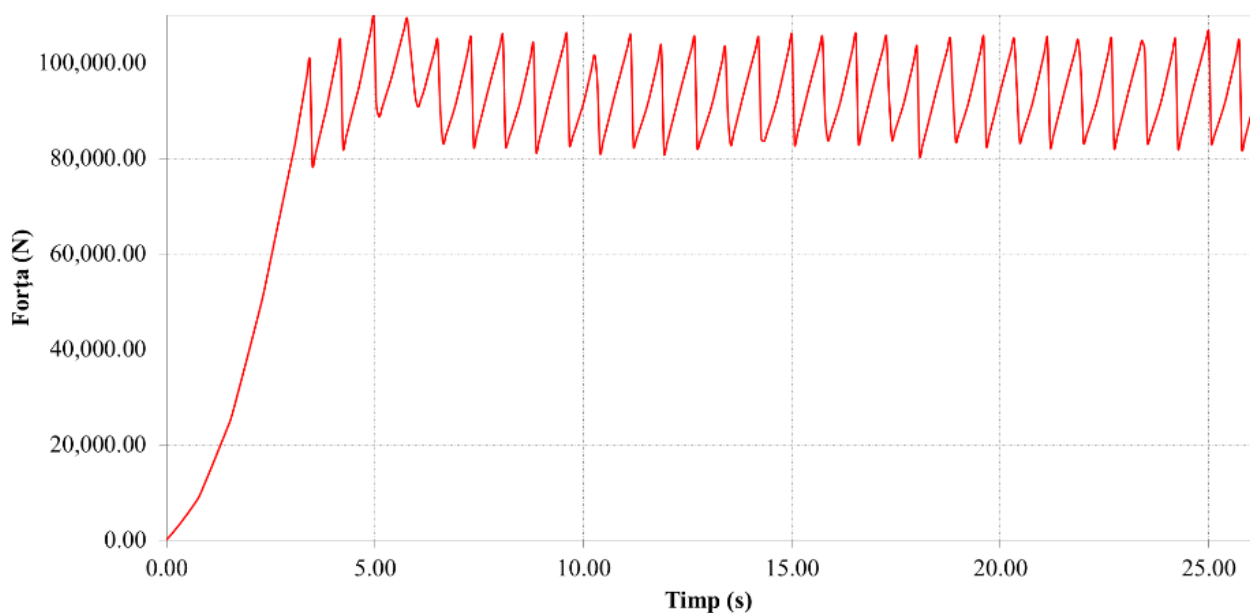


Figure 6. The variation of the resultant force at the bucket wheel shaft during homogenous material excavation

The appearance of an inclusion of hard material during the excavation of homogeneous material is a probable event that causes vibrations with higher amplitudes, causing an increase in the cutting forces exerted on the buckets.

In order to simulate the phenomenon, we considered this hard formation appears during the first rotation at the 4th bucket, with a diagram of the cutting force as shown in figure 7.

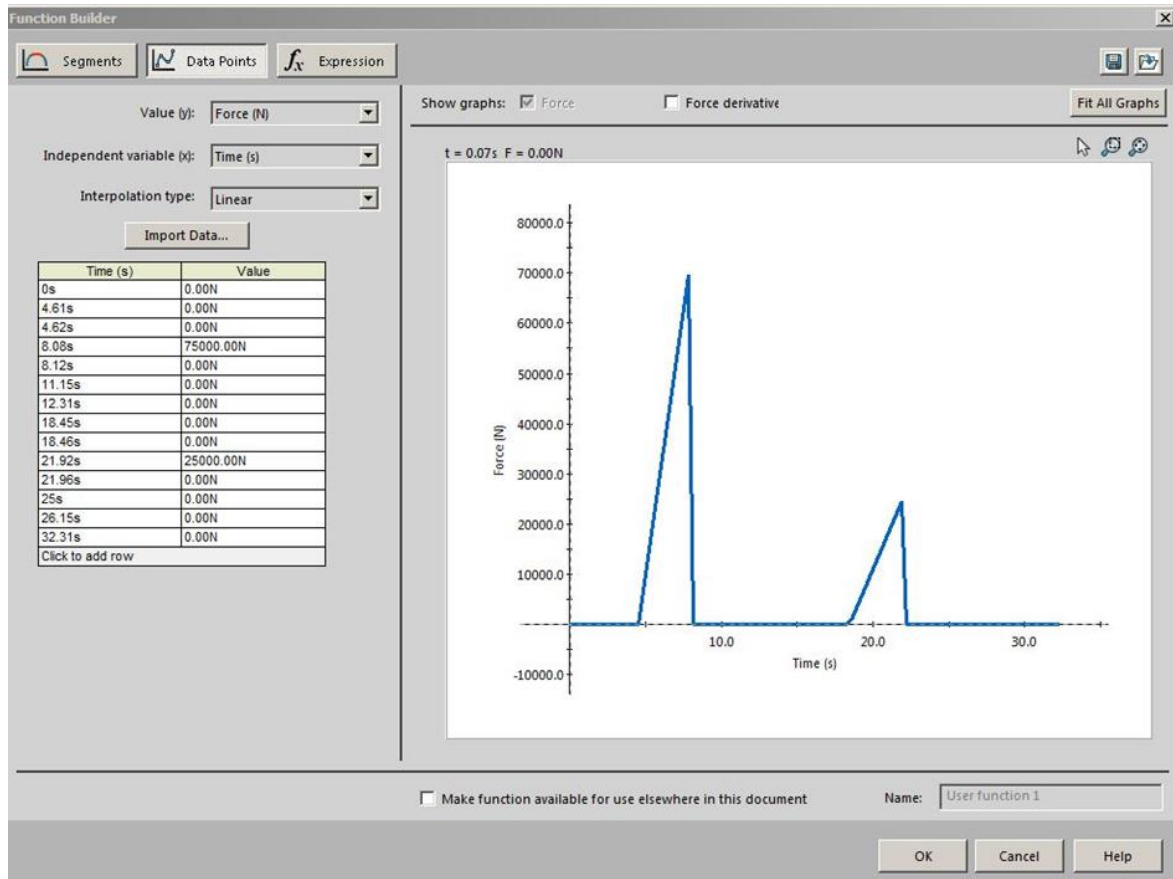


Figure 7. The diagram of the cutting forces acting on buckets in the case of a hard inclusion of material

The simulation was run similarly in SOLIDWORKS Motion Analysis for this scenario, and the variation of the resultant force at the bucket wheel shaft is determined as shown in figure 8.

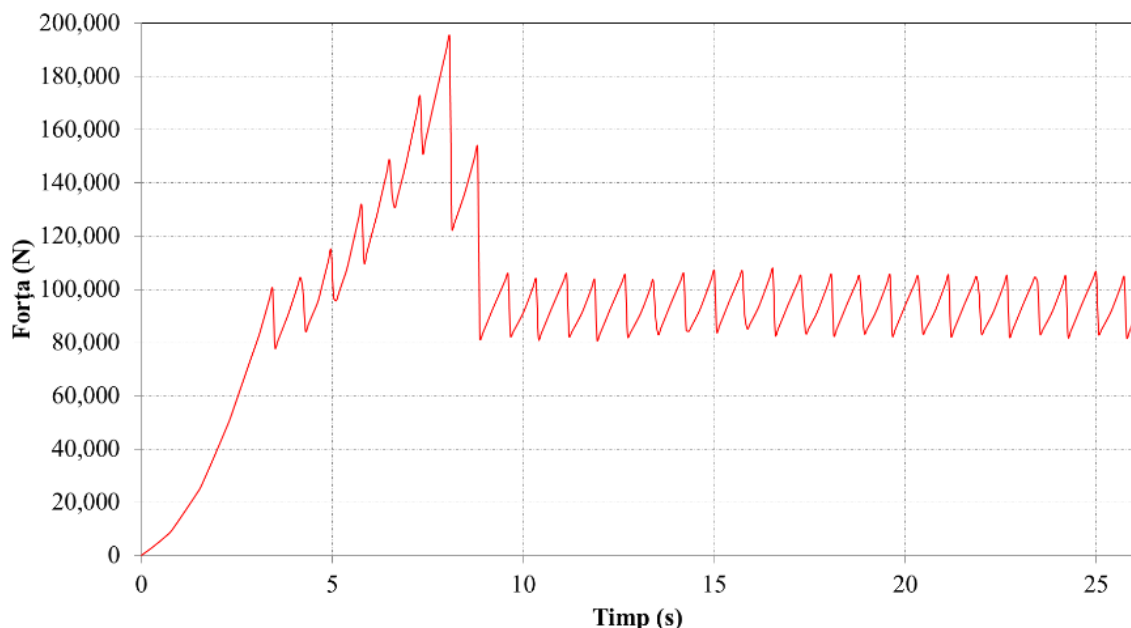


Figure 8. The variation of the resultant force at the bucket wheel shaft in the case of a hard material inclusion

3. Modeling of the ERc 1400-30/7 BWE boom

Based on the manufacturer specifications for this type of BWE, SOLIDWORKS software was used to develop a model of its boom. This will be used to analyze the time response to the loads generated by the excavation process [2].

3.1. Modeling of the bucket wheel

A simplified model of the bucket wheel was developed at real scale, with its dimensions as noted in figure 9. In order to have the same static load acting on the boom as in the case of the real part, the material on the model was defined to have a $\delta=373 \text{ kg/m}^3$ density. The placement of the bucket wheel model is shown in figure 10, where the coordinate system (X, Y and Z directions) that will be referred to during the research is also highlighted.

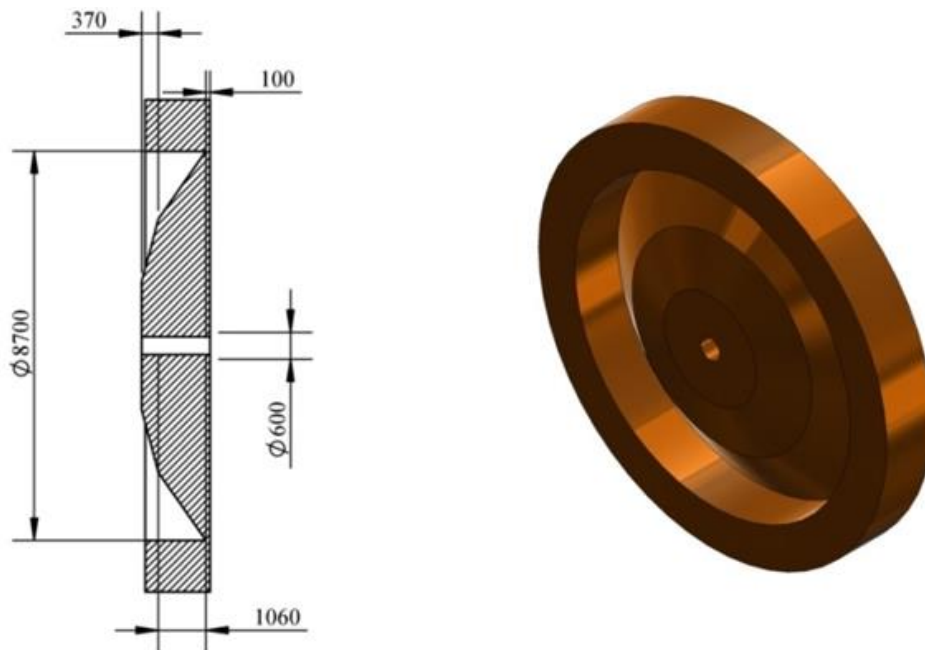


Figure 9. The bucket wheel model and its dimensions

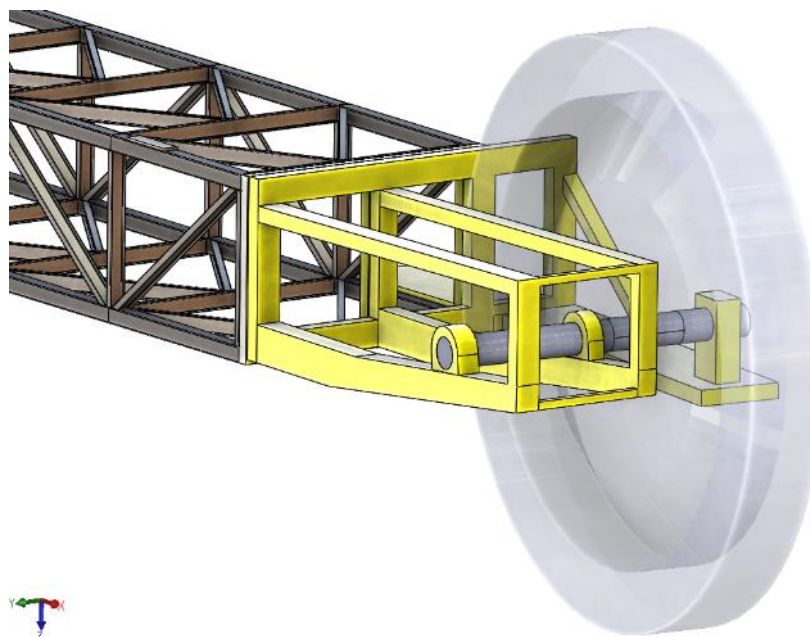


Figure 10. Placement of the bucket wheel model on the boom

3.2. Modeling of the drive chain of the bucket wheel

The elements that make up the kinematic chain of the excavator bucket wheel drive system are simulated using a uniformly distributed mass as shown in Figure 11.

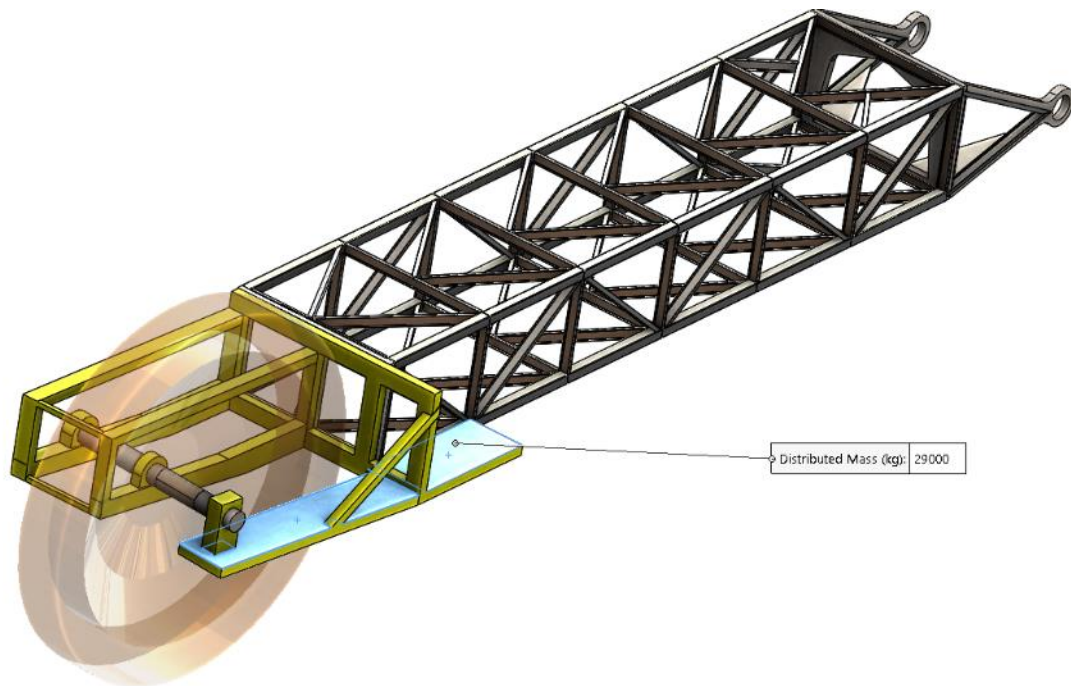


Figure 11. Modeling of the drive chain of the bucket wheel

3.3. Modeling of the conveyor belt inside the boom

The conveyor belt mounted inside the structure of the excavator boom was modeled by a remote type mass whose value according to the documentation is 25,000 kg (Figure 12).

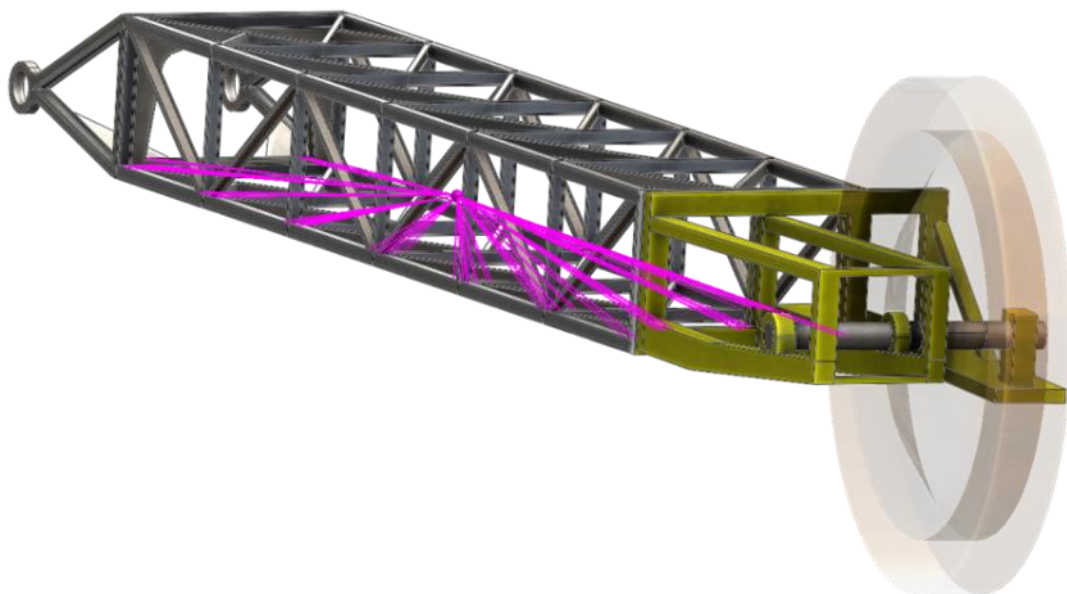


Figure 12. Modeling of the conveyor belt

3.4. Modeling of the boom hoisting cables

The 10 cables used to raise and support the boom of type WSΦ40-6 x36 galvanized steel zinc alloy are modeled by two springs (Figure 13) subjected to elongation, which have the constant of elasticity equal to 35,000,000 N / m for one cable.

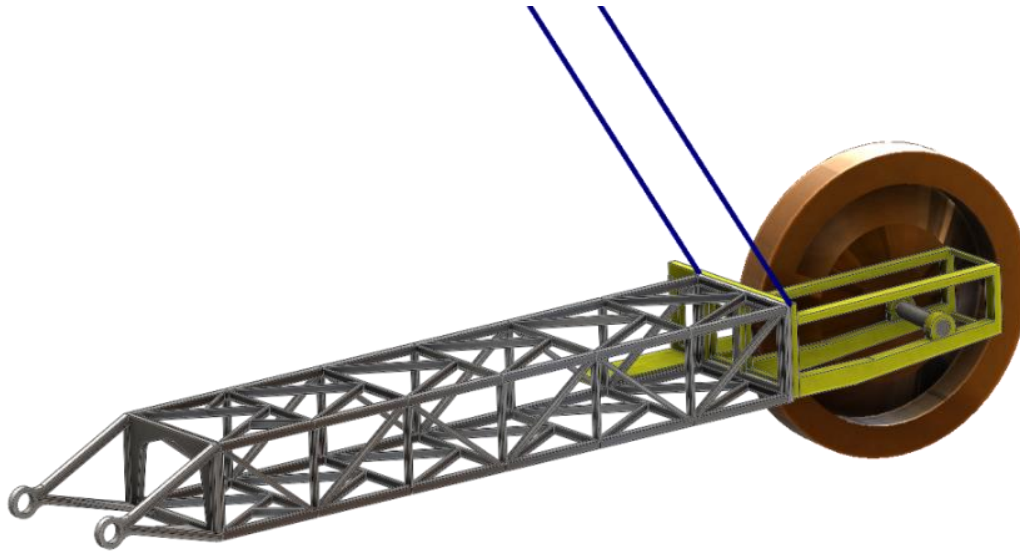


Figure 13. Modeling of the boom hoisting cables

The main static loads to which the BWE boom is subjected and the elements that generate these loads are shown in Table 1, and also the SOLIDWORKS® Simulation type of load used is also specified. Both the conveyor belt mounted on the rotor arm and its kinematic drive chain are vibration generators. In the adopted model we considered only the static effect of their presence, thus being able to highlight the dynamic response of the boom structure under the action of excavation forces.

Table 1. Static loads acting on the BWE boom

No	External load	Unit	Value	Solidworks type of load
1	Conveyor belt inside the boom	Kg	25.000	Remote Loads/Mass
2	Drive chain of the bucket wheel	Kg	29.500	Distributed Mass
3	Bucket wheel model	Kg	39.600	Part
4	Boom hoisting cables	N/m	2x35.000.000	Spring

3.5. Modeling the operator cabin and its supporting structure

The real operator cabin, its placement on the boom and the support structure are shown in Figure 14 a and b. This was modeled in SOLIDWORKS® using the structure developed shown in figure 15.



a



b

Figure 14. The main BWE operator cabin

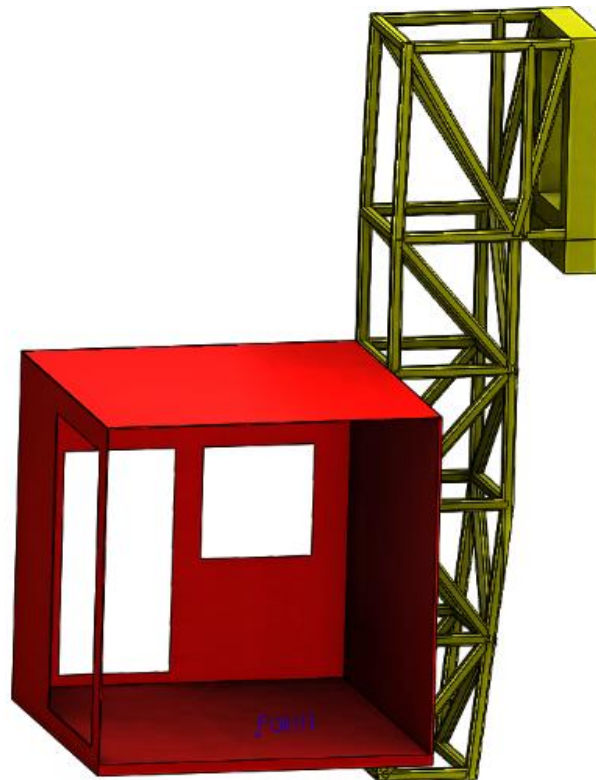


Figure 15. The model of the BWE operator cabin

All the components developed in the previous paragraphs are assembled to obtain the complete model of the BWE boom as seen in figure 16.

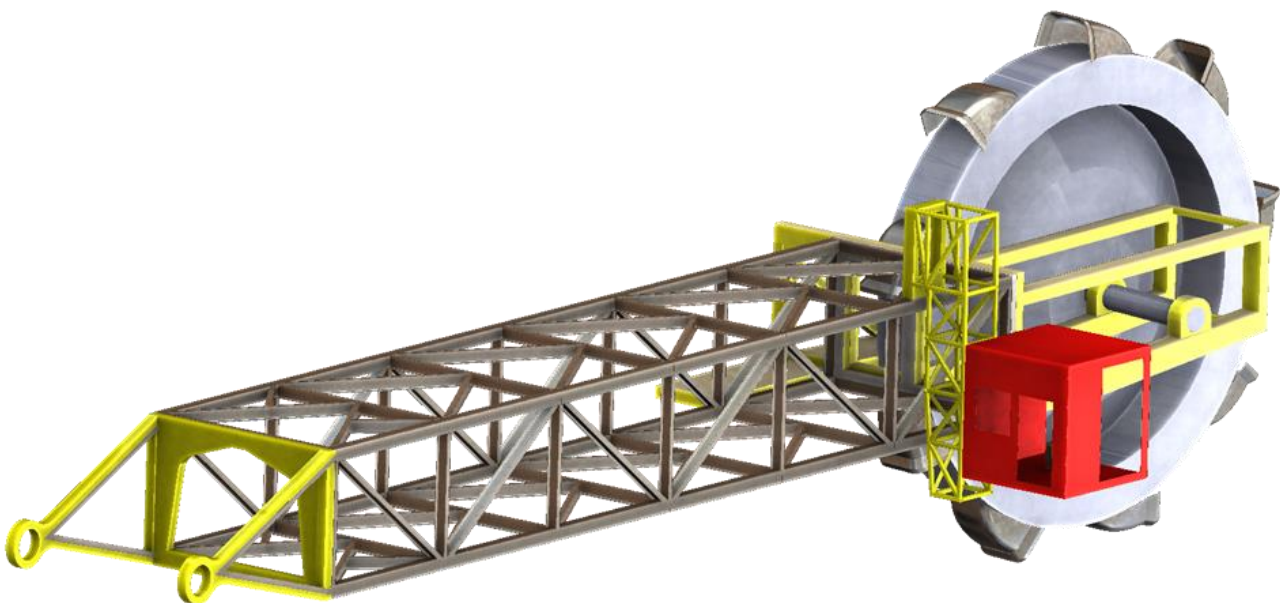


Figure 16. Complete model of the BWE boom assembly

3.6. Objectives of the simulation of the excavator boom

The simulation of the excavation process and the analysis of its effects on the excavator boom was performed using SOLIDWORKS® Simulation application. Figure 17 shows the nodal network of the boom structure of beams. Also in this figure, the position of a virtual sensor that is placed on the floor of cabin the main operator cabin is highlighted. This sensor will be used to record the response of the structure during the dynamic analysis.

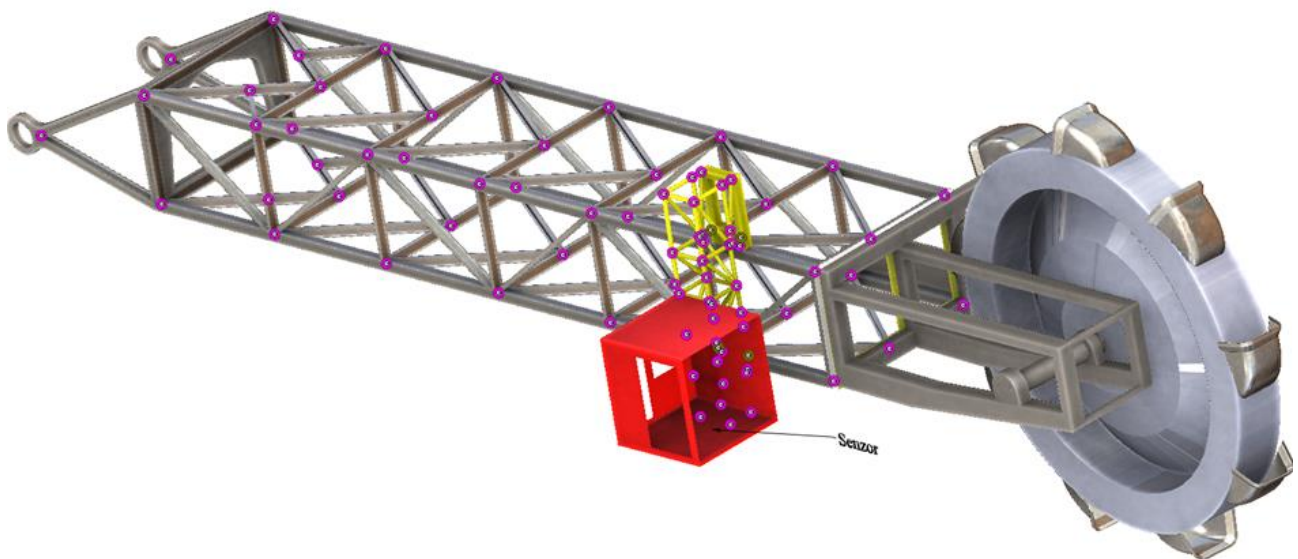


Figure 17. The nodal network of boom structure and the virtual sensor placement

4. Dynamic analysis of the time response of the ERc 1400-30/7 excavator boom model

4.1. Theoretical aspects of the time response analysis

The dynamic time response analysis implies that the load applied to the structure is an explicit function of time, mass, and damping properties with the characteristic equation expressed as [7, 8]:

$$[M]\ddot{d} + [C]\dot{d} + [K]d = F(t) \quad (1)$$

where $[M]$ is the mass matrix; $[C]$ is the damping matrix; $[K]$ is the elasticity matrix; $F(t)$ is the vector of nodal loads, expressed as a function of time; and d is the unknown vector of nodal displacements.

The results of the dynamic time response analysis for both permanent and transient regime, were obtained by interrogating the virtual sensor previously presented. Graphs of the variation of accelerations and deformations due to the excavation force for the X, Y and Z directions were drawn. The force that will produce the vibration in the boom structure is variable over time, being generated by the whole excavation process (cutting, lifting and unloading the material). Figure 18 shows how the resultant excavation force is applied to the bucket wheel shaft.

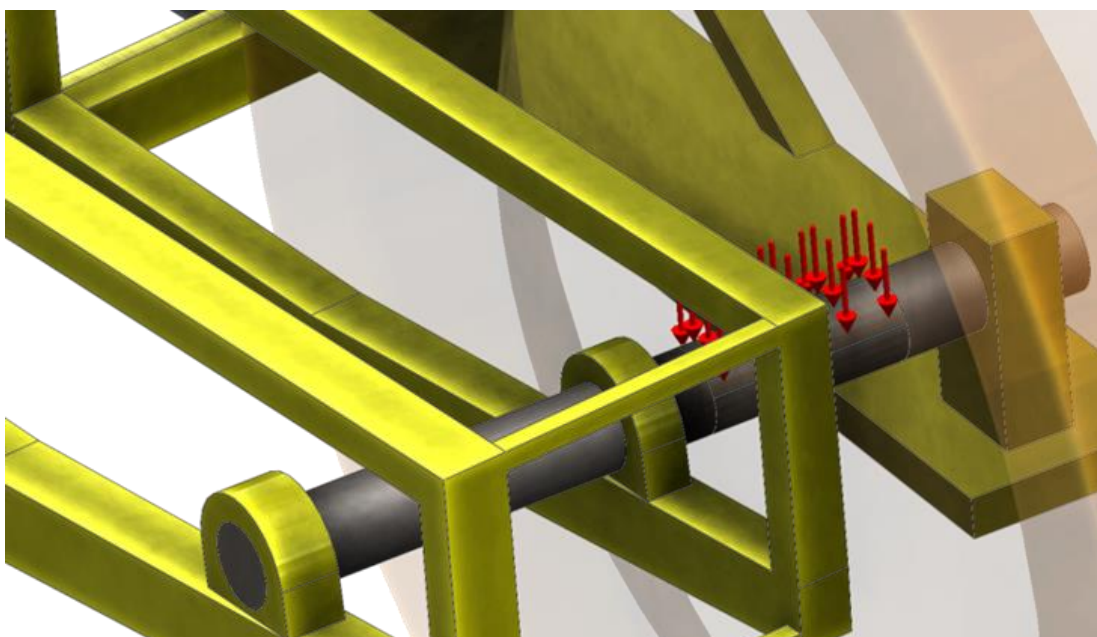


Figure 18. The excavation force applied to the bucket wheel shaft

The properties of the dynamic time response analysis of the BWE boom structure are presented in figure 19, where the number of modal frequencies taken into consideration, the type of solving algorithm, the time range and its increment step were defined [9].

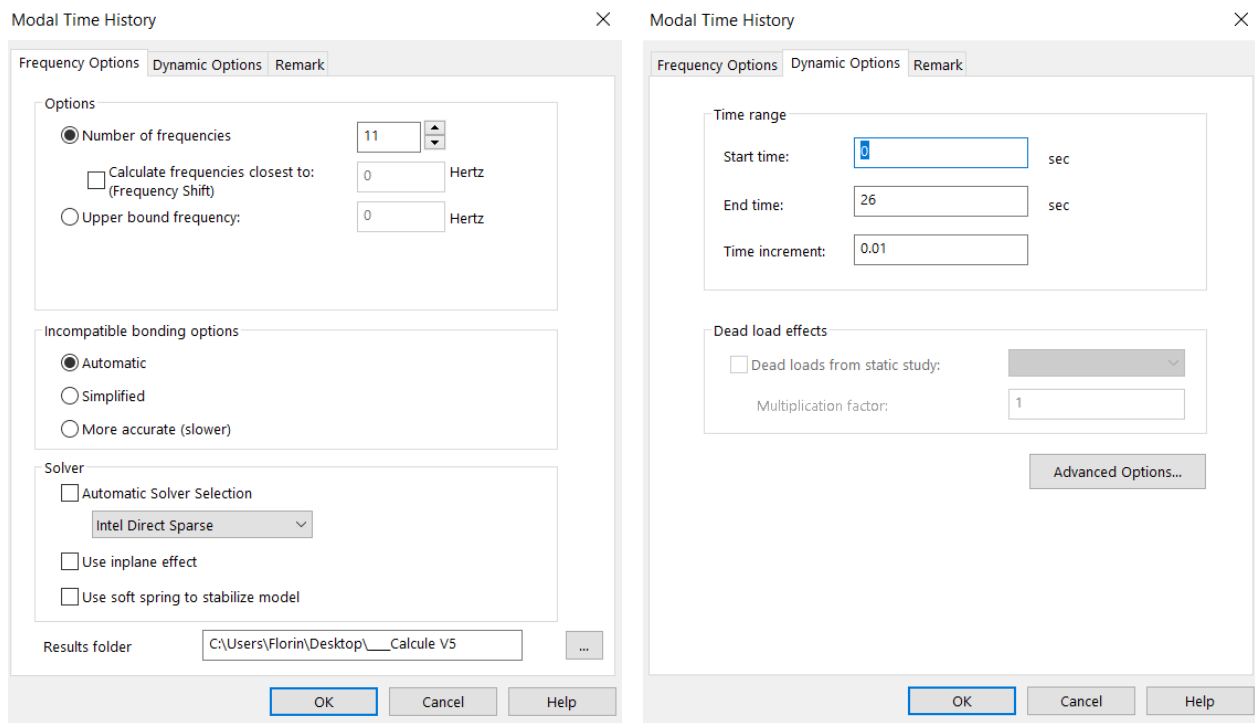


Figure 19. Defining the properties of the dynamic time response analysis

Figure 20 shows the finite element meshing process for the structure of the BWE boom. It can be seen that it has an inhomogeneous structure, depending on the type of the components forming the boom (Solid or Beam).

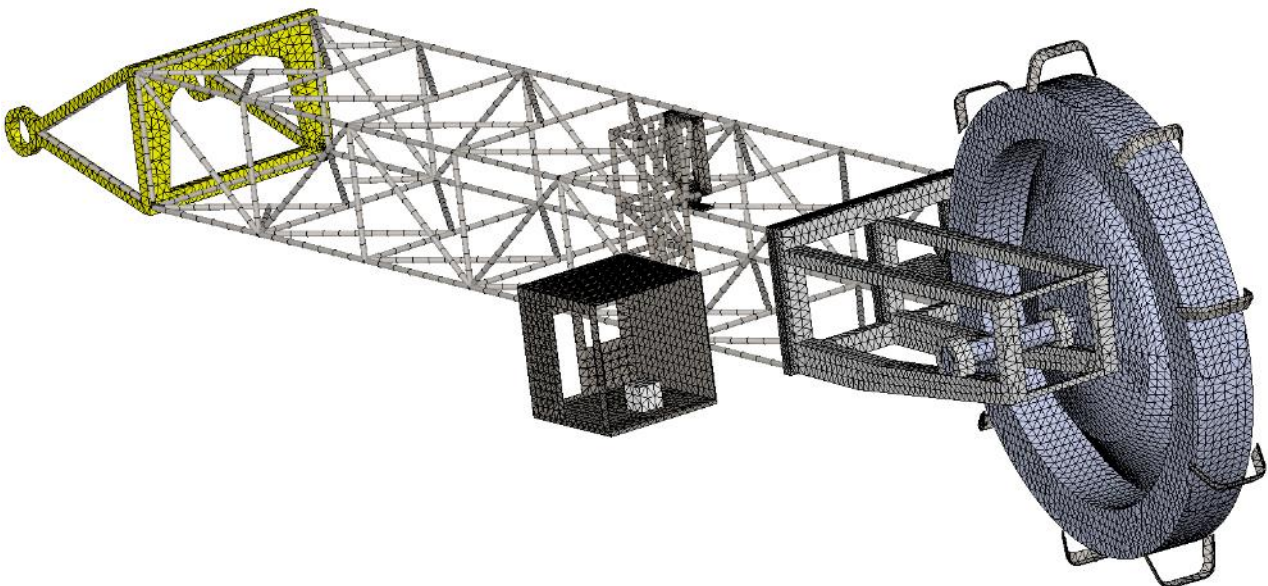


Figure 20. Meshing of the BWE structure into finite elements

4.2. Dynamic time response analysis during permanent regime

We presented in figures 21, 22 and 23 the graphs of the accelerations resulted on the X, Y and Z directions, resulted from the dynamic time response analysis of the forces during permanent excavation regime.

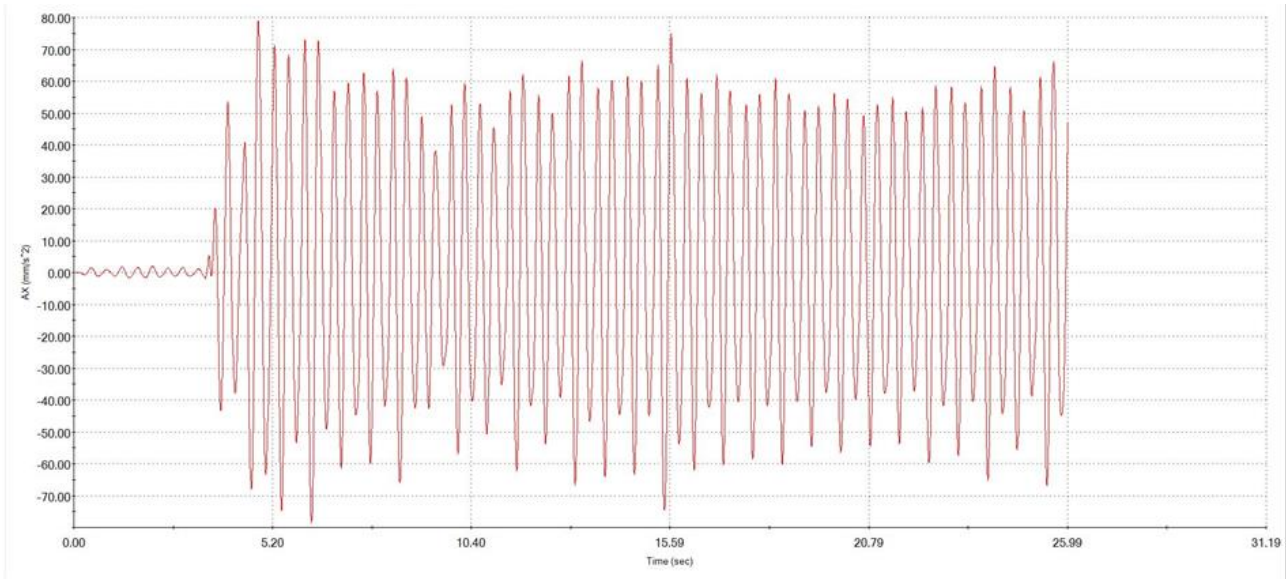


Figure 21. Acceleration on direction X during permanent regime

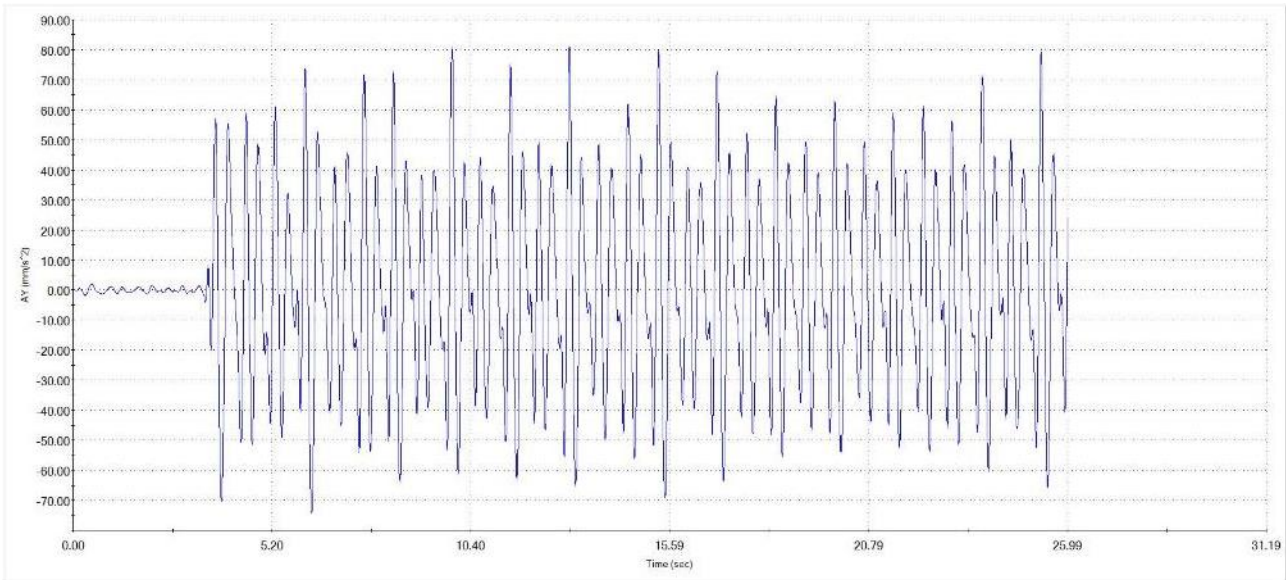


Figure 22. Acceleration on direction Y during permanent regime

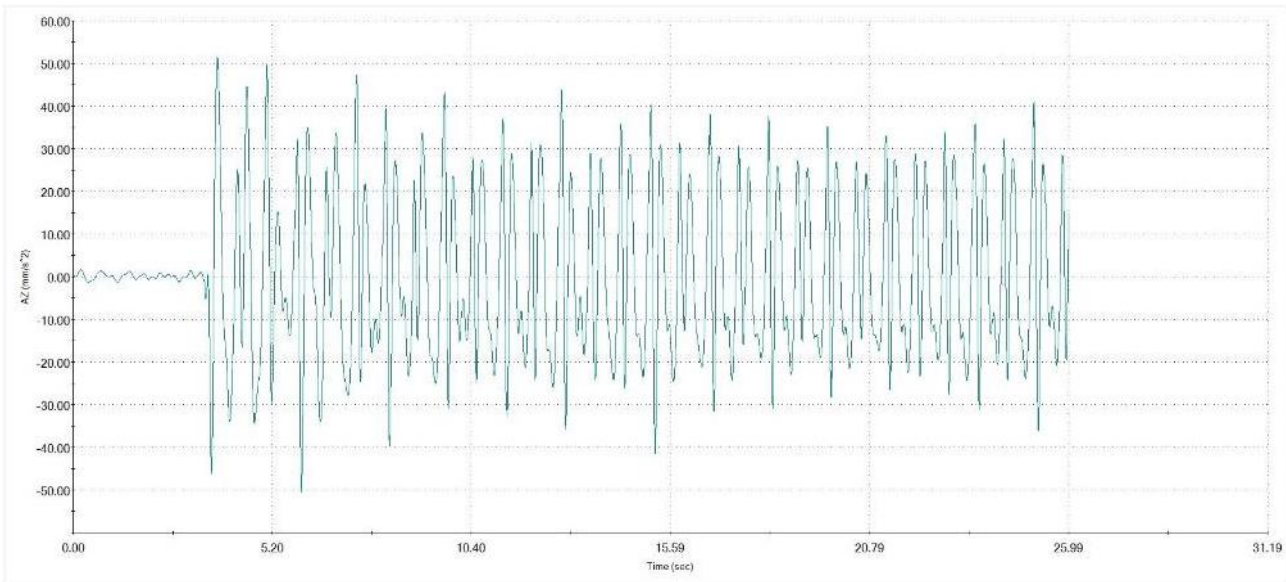


Figure 23. Acceleration on direction Z during permanent regime

Figures 24, 25 and 26 present the graphs of the oscillation amplitude of the boom on X, Y and Z directions during permanent excavation regime.

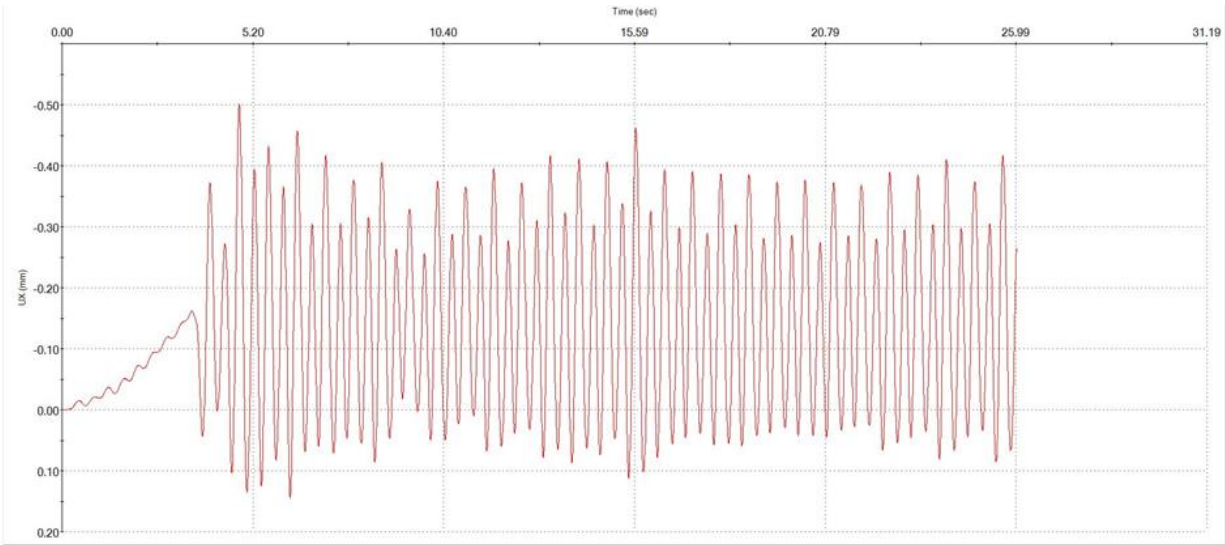


Figure 24. Oscillation amplitude on direction X during permanent regime

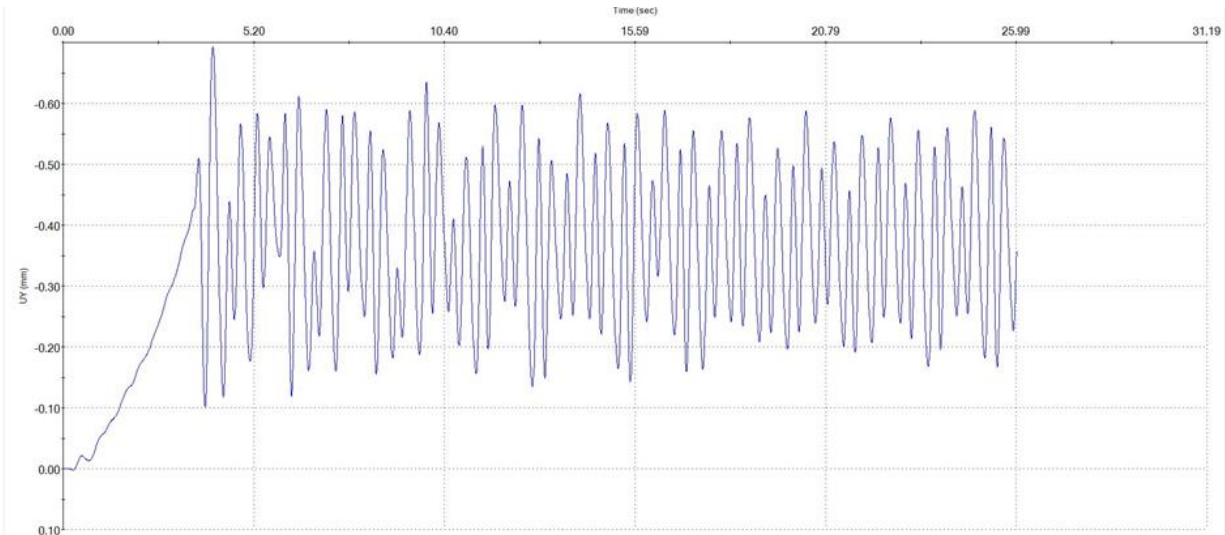


Figure 25. Oscillation amplitude on direction Y during permanent regime

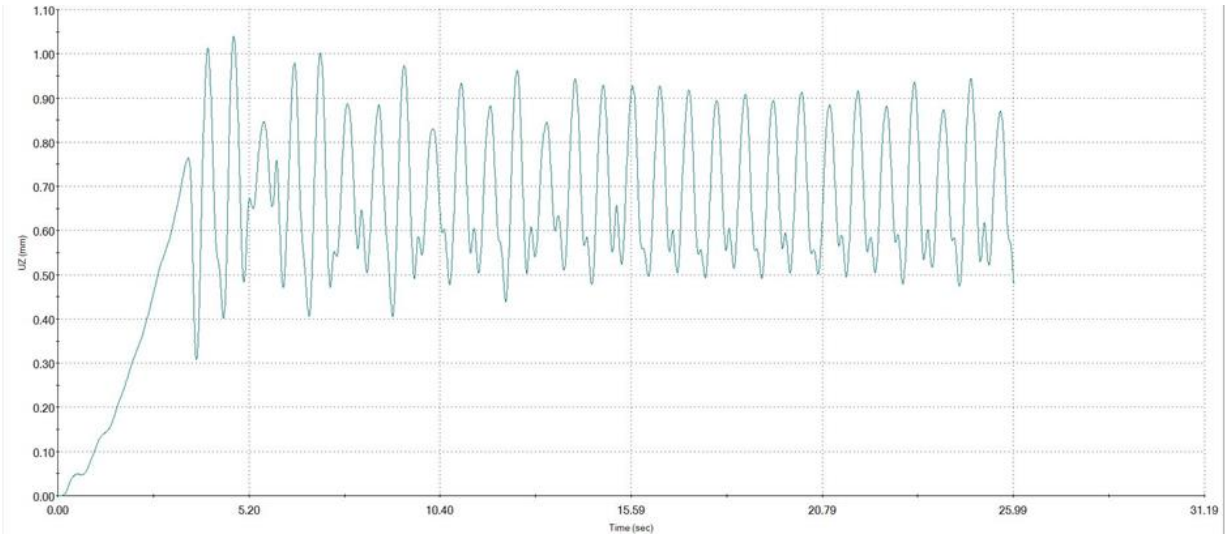


Figure 26. Oscillation amplitude on direction Z during permanent regime

4.3. Dynamic time response analysis during a shock

The dynamic time response analysis was performed in case of a shock, when the buckets hit a hard material inclusion during excavation. Figures 27, 28 and 29 show the graphs of the accelerations on direction X, Y and Z in this case.

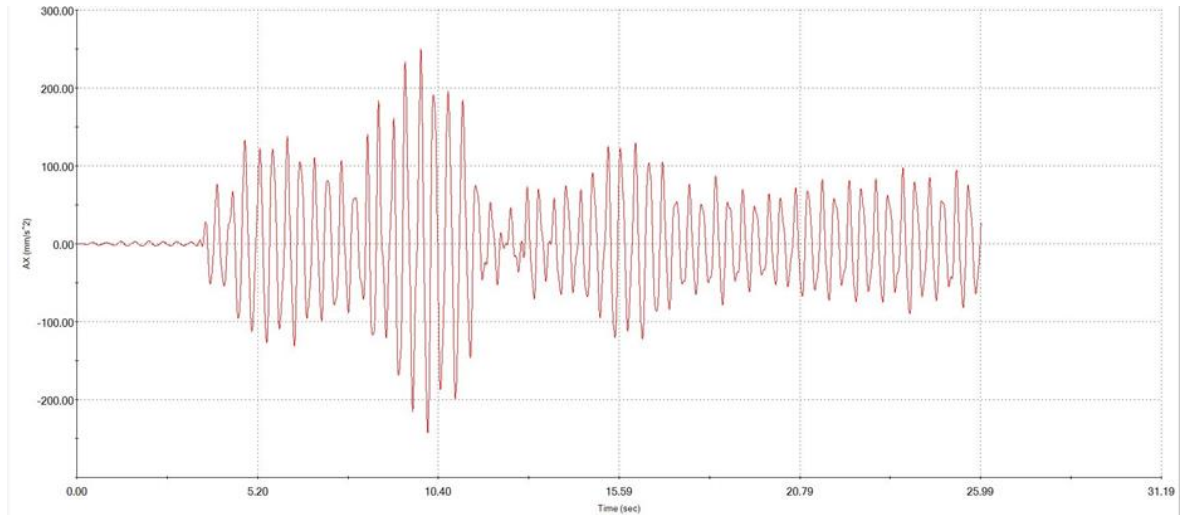


Figure 27. Acceleration on direction X in case of a shock

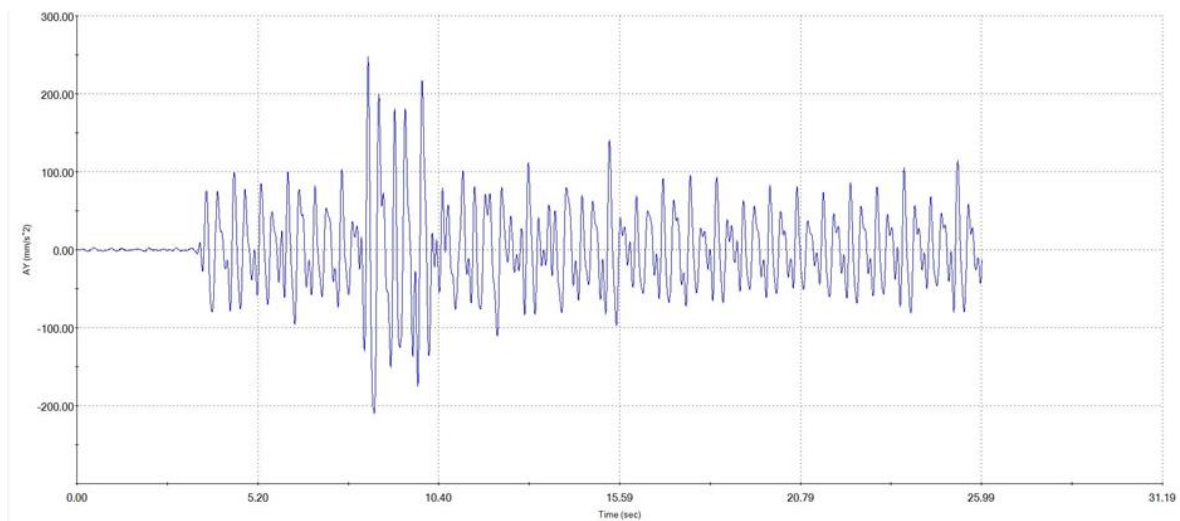


Figure 28. Acceleration on direction Y in case of a shock

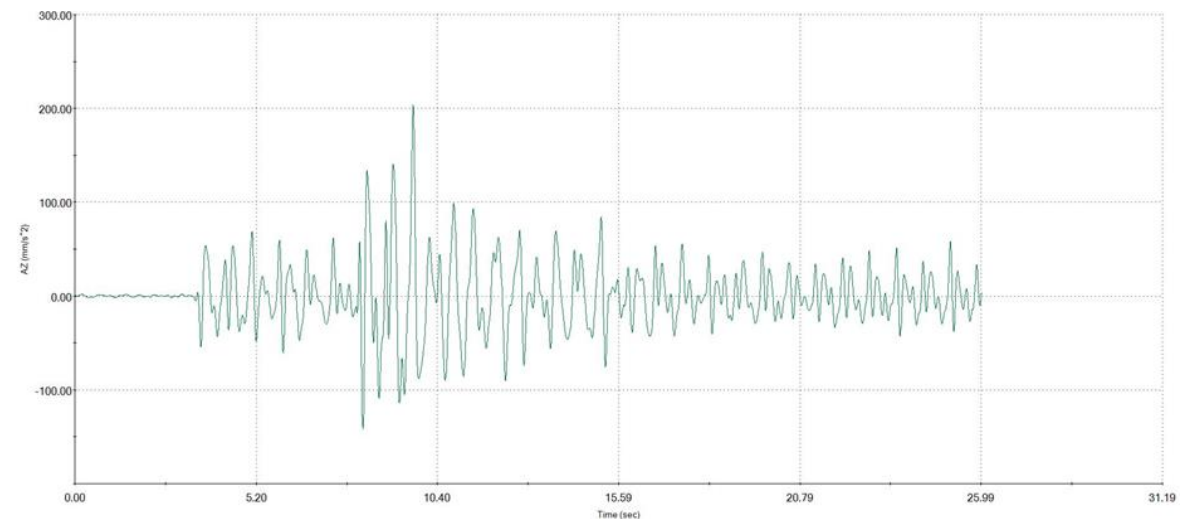


Figure 29. Acceleration on direction Z in case of a shock

Figures 30, 31 and 32 present the graphs of the oscillation amplitude of the boom on X, Y and Z directions in the case of a shock due to hard material inclusions during excavation.

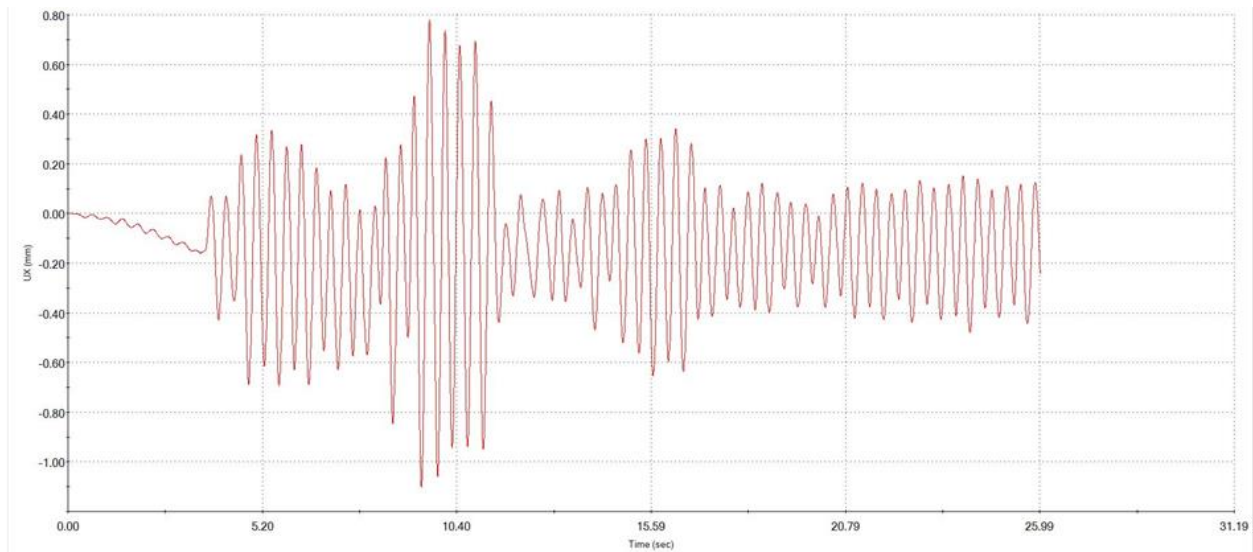


Figure 30. Oscillation amplitude on direction X in case of a shock

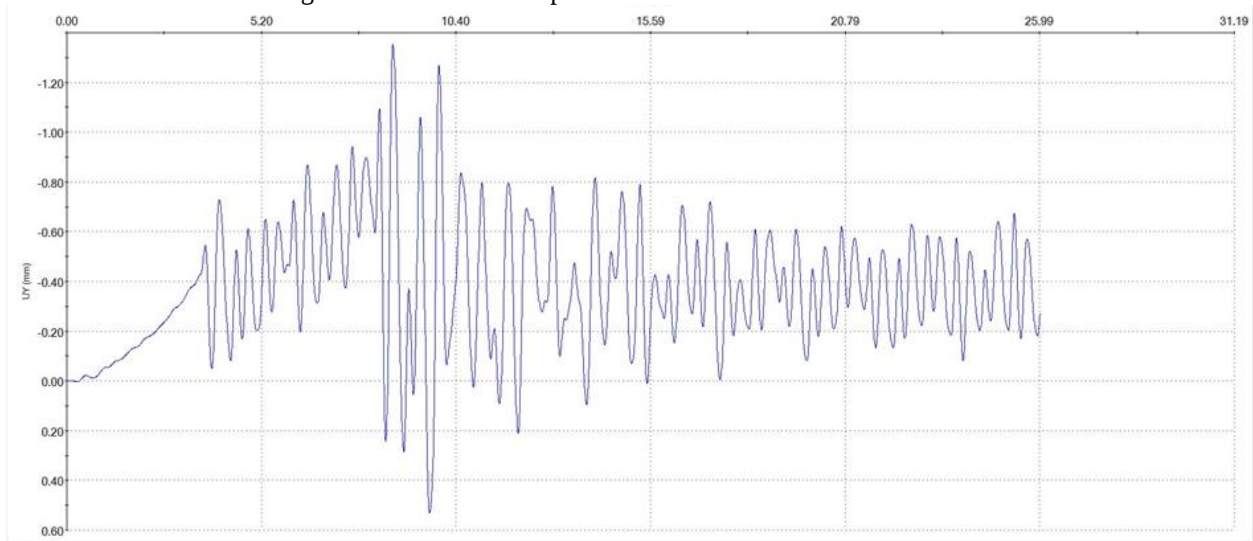


Figure 31. Oscillation amplitude on direction Y in case of a shock

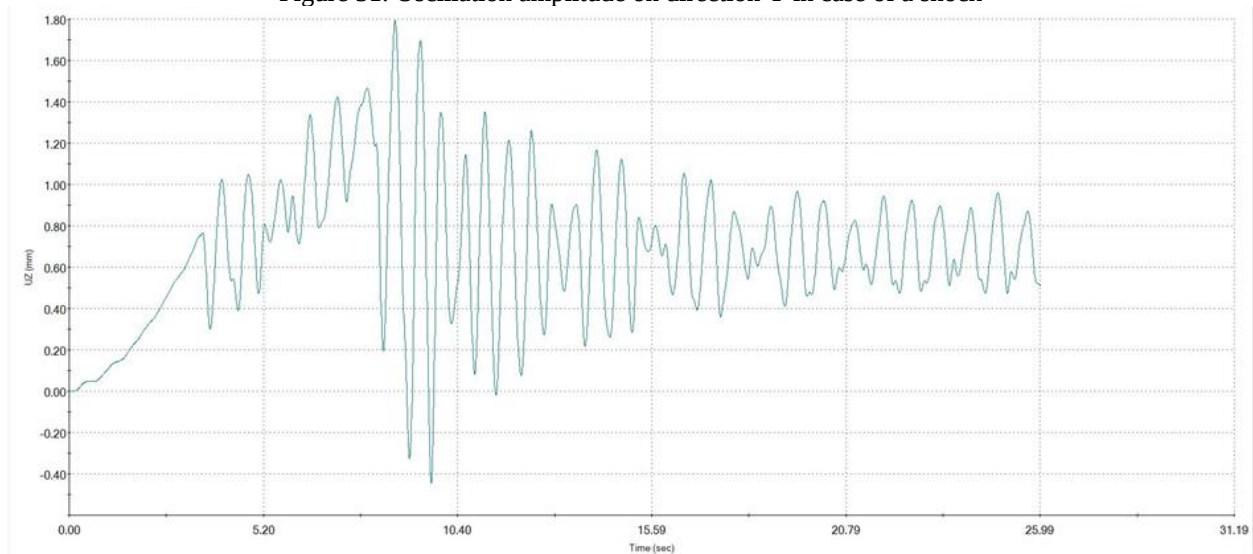


Figure 32. Oscillation amplitude on direction Z in case of a shock

5. Conclusions

A virtual model of boom of the ERc 1400-30/7 BWE was created in order to perform the time response analysis under the action of the excavation forces. The mathematical model of the resultant excavation forces was defined as the main source of vibration of the boom and the static loads acting on the boom were also determined.

In both scenarios considered, first the excavation of homogenous material and second a shock produced by the sudden appearance of hard material formations, the dynamic time response analysis performed for a global damping of 2% of the critical damping, is characterized by:

- Transient period caused by the beginning of the excavation process;
- Transient period caused by the sudden appearance of harder formations of material;
- Permanent regimes corresponding to the excavation of homogeneous material.

Analyzing the acceleration variation graphs it can be concluded that:

- The accelerations are variable in time having an oscillating character;
- The highest values of acceleration are obtained for the X and Y directions;
- The acceleration variation graphs for all directions are symmetrical about the time axis.

From the point of view of the deformations in dynamic regime, the following conclusions result:

- The deformations are variable in time and have an oscillating character;
- The largest deformations are obtained for the Z direction.

In general practice, expressing the vibrations in the form of deformations is suitable for low frequencies, while expressing of vibrations in the form of accelerations is suitable for high frequencies. The BWE boom model adopted in this paper, allows a good approximation of both approaches, deformations or accelerations, and can be quickly adapted for other types of BWE.

The results obtained from the simulation are comparable with the measurements performed in-situ for this type of excavator [10]. The concordance between the simulation results on the virtual model and the acceleration measurements performed, validates the adopted model.

Both the in-situ measurement results and the simulation results, show that the vibrations generated by the excavation process do not cause accelerations in the main operator cabin that exceed the vibration levels regulated by law, regarding the vibration exposure transmitted to the body of the BWE operator:

- 1.15 m/s^2 (8 hrs / day) - the limit value of daily professional exposure;
- 0.5 m/s^2 (8 hrs / day) - value of the daily exposure from which the action is triggered [11].

However, an important future direction of research, which will be disseminated in a future research paper, is to find vibration damping solutions applicable to the BWE operator cabin. These would cause a smoothing of the oscillation variation curves, especially those that take place in the dominant (vertical) direction, thus leading to increased comfort.

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