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DYNAMIC ANALYSIS OF A BUCKET WHEEL EXCAVATOR BOOM USING FEA

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Abstract: *Bucket wheel excavators are the most widely used technology for lignite extraction and overburden removal in opencast mining. This is due to their high efficiency and ability to handle a wide range of geological conditions. The loads on the bucket wheel and dipper can vary significantly during excavation due to difficult-to-penetrate inclusions and the changing geological environment. This can lead to vibrations that can damage the excavator, especially the structural components directly or indirectly involved in the excavation. To investigate the effects on the main structural elements, it is essential to examine the natural frequencies. In this study, we investigate the natural frequencies and vibration modes of the boom structure of a bucket wheel excavator using a model developed in a previous study. The behavior of the structure is examined using a 3D finite element model under the action of loads and effects during use.*

Keywords: *bucket wheel excavator, boom structure, natural frequencies, mode shapes, finite element analysis, open-pit mining, lignite mining, overburden removal*

1. Introduction

Open-pit mining plays a crucial role in developed countries with advanced mining industries. It is the dominant method for producing construction raw materials and also plays a significant role in ore and mineral mining. In energy production, due to market competition, brown coal and lignite are almost exclusively produced by open-pit mining. The extraction of these low-calorific coals is only economical through open-pit mining, accounting for over 90% of production [1].

Lignite, as an energy source, still holds a significant share in the energy mix of many countries, both in Europe and worldwide. Sustainable lignite production requires cost reduction, increased production, and improved efficiency. To achieve this, production optimization is necessary, which can only be realized through modernization, revitalization, and maintenance of mining equipment [2].

In Europe, the traditional technology used for lignite extraction and overburden removal in open-pit mining is based on bucket wheel excavators. However, in recent years, the geological and rock environment in many European open-pit lignite mines has been deteriorating continuously.

Among the challenges are the values of the hauling force and energy requirements for waste rock or coal, their variability, and the dynamic effects that occur during excavation, as well as the resulting failures [3, 4].

Several studies have been conducted to investigate the phenomena described above, which can provide considerations for optimizing the sizing of steel structures in mining equipment [2, 5, 6, 7].

The research topic of this paper is the dynamic analysis of the boom structure of a bucket wheel excavator using the finite element method, which will be presented in detail within the framework of the paper.

2. Model geometry and loads of the boom

To investigate the behavior of the boom structure of a bucket wheel excavator under operational loads, a finite element model was developed using the FEM Design finite element software [8, 9, 10]. The model was based on the geometric characteristics of the bucket wheel excavator and incorporated the following assumptions:

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Material properties: The steel used for the boom structure was assumed to be linear elastic with a Young's modulus of 210 GPa and a Poisson's ratio of 0.3.

Boundary conditions: The boom structure was assumed to be fixed at the connection point to the main structure of the excavator.

Loads: The operational loads acting on the boom structure were considered to include the weight of the boom itself, the weight of the bucket wheel and its associated equipment, the weight of the excavated material, and the dynamic loads generated by the bucket wheel rotation.

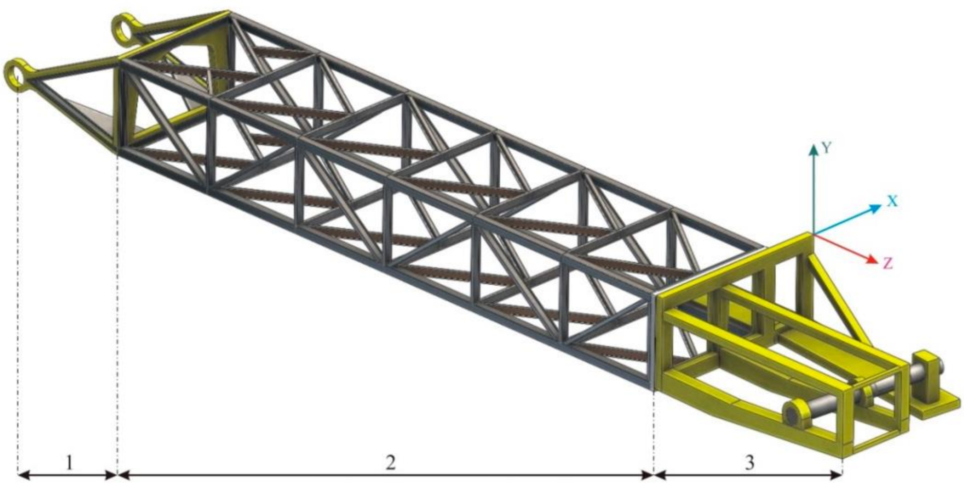

Fig. 1 Section of the BWE's boom [2]

The boom structure of the bucket wheel excavator can be modeled as a spatial truss structure, which can be further divided into three main structural units:

- Section 1: The hinged connection between the rest of the structure and the boom, which provides vertical lifting motion and allows for horizontal swinging motion.
- Section 2: The intermediate section, where the conveyor belt for discharging the excavated material is mounted.
- Section 3: The part that supports the bucket wheel, which carries not only the bucket wheel and its assemblies but also the elements of the bucket wheel drive and the attachment points for the boom lifting cables.

The intermediate section (Section 2), which is defined as a spatial truss structure, can be further decomposed into planar truss elements based on mechanical considerations. These truss elements consist of interconnected rods at the nodes of the trusses [9]. In addition to bending stresses, shear forces, axial normal forces, and torsional forces act on the structure under investigation.

The discretization used in the construction of the 3D finite element model is as follows:

- Sections 1 and 2: The elements were assembled from rod elements in accordance with the actual geometric arrangement and dimensions.
- Section 3: This section, which is the main functional part of the excavation process, was modeled as a rigid body since it is not examined in detail in this study.

In the linear material model assigned to the elements in the model, an elastic modulus of E = 210000 MPa, a Poisson's ratio of $v = 0.3$, and a density of $\rho = 7.85$ g/cm3 were specified for structural steel. Thus, the model follows the properties of the real structure in both material and mass.

The supports of the boom structure were taken up on the one hand by the hinged connection at the beginning of Section 1 with the degrees of freedom according to the actual structural behavior, and on the other hand by the connection points of the lifting ropes at the junction of Sections 2 and 3.

vol. 30, selected papers from the 11th edition of
UNIVERSITARIA SIMPRO / 2024, pp. 51-55

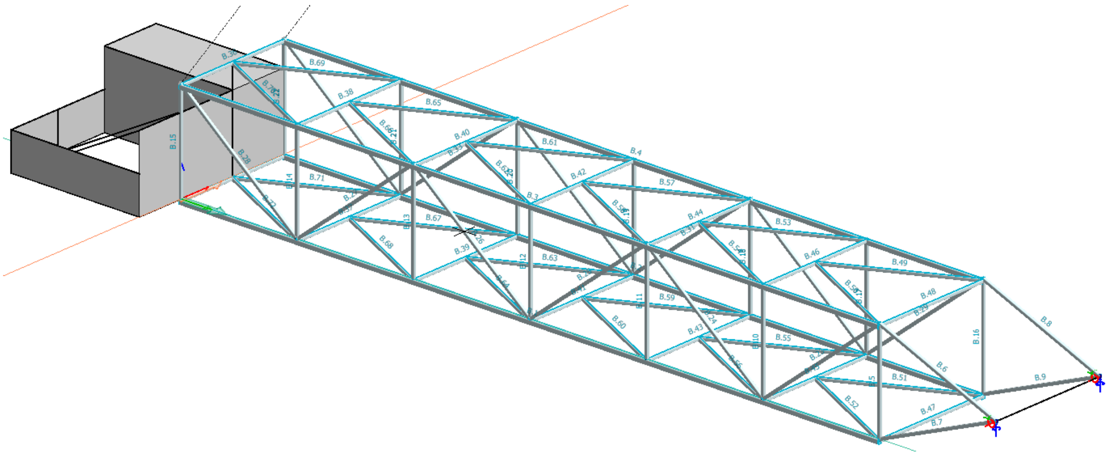

Fig. 2 FE model of the boom

The lifting rope pair used as support consists of 40 mm diameter galvanized steel wire ropes with WS40-6x36 construction. These were modeled as springs, each with an equivalent spring constant of 35000 kN/m, using a point-to-point connection element [8].

The following loads and effects act on the investigated part of the boom structure:

- The operating self-weight of the boom structure: This is automatically generated by FEM Design based on the properties of the specified material model.
- The load of the conveyor belt mounted inside the structure: These can be taken up according to technical specifications and standards.
- The loads of the bucket wheel drive system: These were taken into account using the following formulas: (cutting force; forward force; side force; force exerted by the mass of the excavated material)

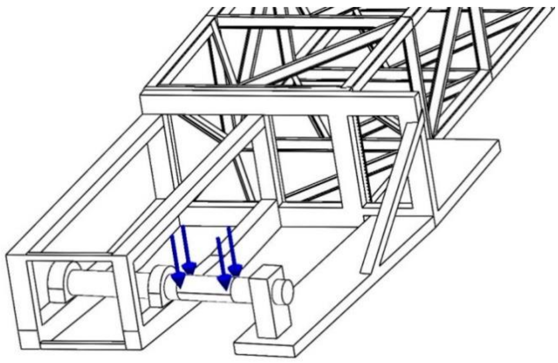

Fig. 3 Applying the force to the bucket wheel's shaft – Section 3 [9]

The self-weight of the structure is automatically generated by FEM Design based on the properties of the specified material model. The additional loads and effects described above were taken into account based on previous studies [6, 11, 12] and are detailed in Table 1.

Table 1. Loads on the stuctures

No.	Loads	Magnitude [kN]	Type
1	Structure's Self-Weight	FEM Design Generated	Constant
2	Conveyor Belt	250	Reduced
3	Drive System	295	Distributed
4	Bucket wheel	396	Point Load

3. FEA analysis of the boom

After the 3D finite element model of the structure was assembled in FEM Design and the loads and effects acting on the structure were defined, dynamic analyses were performed. The analyses determined the natural frequencies, vibration modes, and nodal displacements associated with each vibration mode. The software-based analysis provided the opportunity to determine the natural frequencies and vibration modes that can be

vol. 30, selected papers from the 11th edition of
UNIVERSITARIA SIMPRO / 2024, pp. 51-55

calculated under the influence of static loads per unit modal mass, which may be important for subsequent analyses.

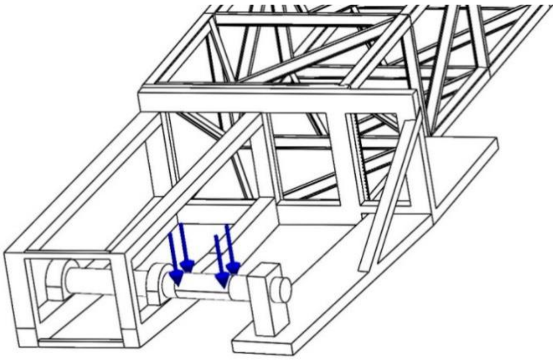

Fig. 4 Boom deformation in Mode Shape 2 (1.775 Hz)

The calculations were carried out for the case where the lifting force of the lifting rope pair was taken into account. As a result of the modal analysis, natural frequencies and associated vibration patterns were determined. The eigenvalue problem was solved using FEM Design software, where the individual vibration patterns can also be displayed graphically (Figure 4). The calculated natural frequencies and periods are summarized in Table 2.

Table 2. Natural frequencies and periods of the boom considering the lifting effect of cable pairs

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
f [Hz]	0.260	1.775	2.319	4.468	5.067	5.455	6.701	7.822	7.961	7.990
t [s]	3.853	0.563	0.431	0.224	0.197	0.183	0.149	0.128	0.126	0.125

Based on the results, it can be concluded that the model we developed can be run to simulate the behavior of real structures. It clearly demonstrates the behavior of the lifting rope pair used as a support as a spring model, as well as the allowable vertical displacement and horizontal swinging of the hinged support at the beginning of Section 1.

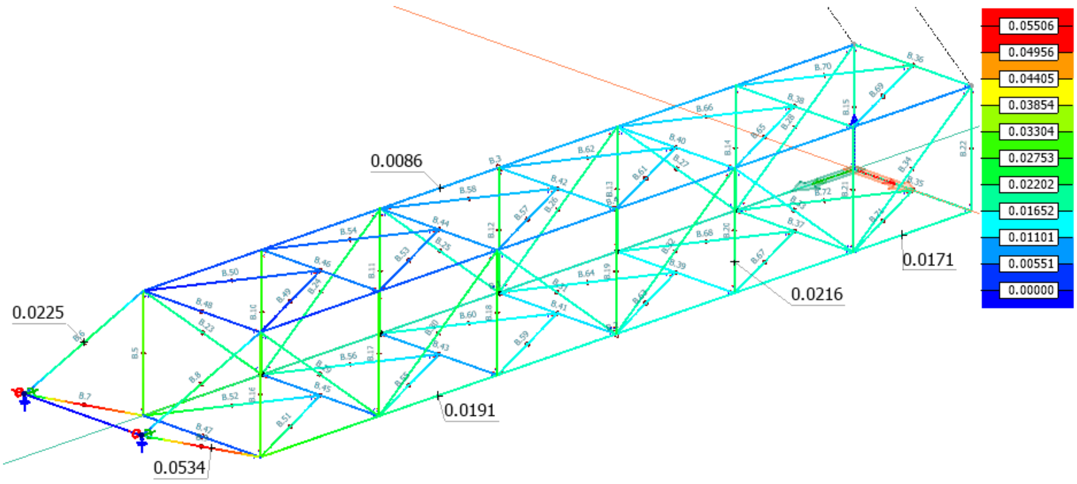

Fig. 5 Boom Deformation in Mode Shape 2 (1.775 Hz) [Rad]

4. Conclusions

The analysis of steel structures in mining machinery has become more complex due to the availability of advanced design tools. In this study, we developed a finite element model of Sections 1 and 2 of the boom structure of a bucket wheel excavator using the FEM Design finite element software for dynamic analysis of the structure under operational loads.

The vibration analysis performed on the excavator's supporting structure provided a comprehensive overview of the evolution of the boom's natural frequencies in the modeled environment. This information can also be useful for analyzing similar space truss structures.

In addition to the analyses conducted so far, it is important to consider that the loads of the bucket wheel and dipper can vary abruptly during excavation due to hard-to-excavate inclusions and the variable geological environment. The stresses can act in a highly repetitive manner. In the following stages of the research, we intend to address additional dynamic effects, their modeling and analysis, and simulation studies. As part of this, we incorporate non-linear material properties into the model and simulate different types of failures for which the experience gained in this study can be particularly beneficial.

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