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Dynamic properties of large-sized steel bunkers for bulk materials

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Abstract. The article presents the results of a dynamic analysis of the structure of a large-sized steel bunker of the Kryvorizhstal plant (Ukraine). The overall dimensions of the bunker are 18 by 15 m in plan with a total height of about 9 m and a net volume of about 1000 m^3. The studies were carried out using the finite element method based on the construction-oriented software product SCAD (Ukraine). Variants of the dynamic analysis of an empty structure, as well as structures with a level of loading with bulk material of 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5% and 100% were considered. As a result, it was found that the frequency spectrum of the steel bunker is quite dense and quantitatively starts at a frequency of about 10 Hz. An increase in the level of bunker loading for every 25% of capacity leads to a decrease in the frequency spectrum by 20-30 % on average. This regularity makes it possible to develop and implement an automated system for controlling the frequency spectrum of unloading devices at the Kryvorizhstal plant.

1. Introduction

At present, the problem of interaction of bulk materials with steel containers for their storage, such as bunkers and silos, continues to be relevant. This is due to a number of significant problematic tasks, the solution of which remains a priority in the field of bulk mechanics [1]. In design practice, the imperfection of existing approaches and calculation methods leads to accidents and failures of structures of this type [2, 3]. The greatest difficulty is caused by the dynamic processes that occur during loading or unloading of containers. To be able to control these processes, one requires data on the dynamic characteristics of containers [4], which in turn depend significantly on the adopted design decision, on the one hand [5], and on the properties of the bulk material itself, on the other hand.

Another determining factor is the size of the container. Existing domestic research in this area is very fragmentary [6-8]. In fact, they are aimed at the analytical determination of the natural frequency spectrum of containers, but at the same time simplified shell systems are considered, which only approximately reflect the real geometric shape of containers. A rather similar situation is observed in foreign practice [9-11]. At the same time, the analytical results are even more narrowed and specific in nature.

Therefore, the task of correctly determining the dynamic properties of steel containers for bulk materials arises. This task actually includes two separate sub-tasks:

1) Determination of the intrinsic dynamic characteristics of a steel container without taking into account the effect of bulk material;
2) Determination of the forced dynamic characteristics of a steel container with consideration of

the effect of bulk material.

Thus, the main purpose of the research is to determine the range of dynamic characteristics of steel containers for bulk materials.

2. Methods

A large-sized steel bunker located at the Kryvorizhstal plant (Ukraine) was chosen as the object of research. The bunker is a pyramidal-prismatic with two openings for unloading bulk material. The total height of the structure is 8.88 m, with overall dimensions of 18×15 m. The total net volume of the bunker is about 1000 m^3.

The design of the bunker includes a supporting bent frame that separates two discharge openings. At the same time, this frame serves as a reinforcing element that improves the strength and deformation characteristics of the bunker (figure 1).

Due to its symmetry in two planes, the bunker operates according to the classical scheme, which allows for its arbitrary loading. The bulk material for storage is sinter, which is used in the steelmaking process. The material is loaded by gravity from railway wagons, which are delivered by train to the upper platform of the bunker gantry. A general view of the bunker gantry during loading is shown in figure 2.

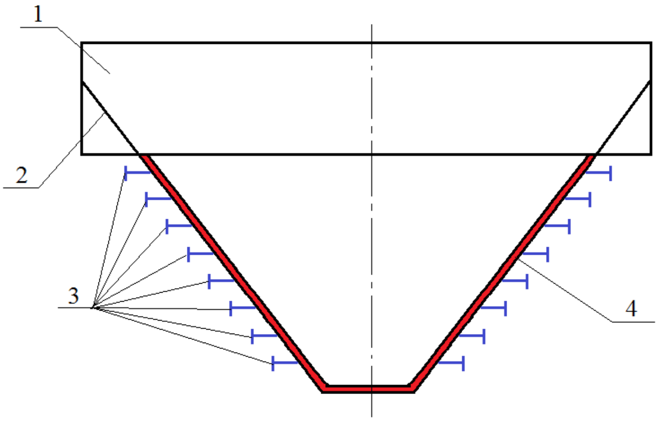

Figure 1. Reinforcing frame of a steel bunker at Kryvorizhstal: 1 – bunker beam; 2 – bunker wall; 3 – bunker ribs; 4 – supporting bent frame.

Figure 2. Loading of steel bunkers at Kryvorizhstal.

One of the most common methods of modern structural mechanics, the finite element method, was chosen as a research method [12-16]. For its practical implementation, the design and computing complex SCAD (Ukraine) was used, which was specially developed for the construction industry [17, 18]. The research used special techniques for modelling spatial structures developed and presented in [19-25].

The constructed finite element design model of the steel bunker at the Kryvorizhstal plant is shown

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in figure 3. The model includes about 55 thousand elements and 54 thousand assemblies, which together form a stiffness matrix of 323 thousand equations. The accuracy of the finite element breakdown was chosen to allow for the first 32 forms of oscillations of the bunker structure to be taken into account. Also, for a more detailed analysis of the dynamic properties of the structure, a model of a single bunker was considered. The combined effect of individual bunkers of the gantry was not taken into account.

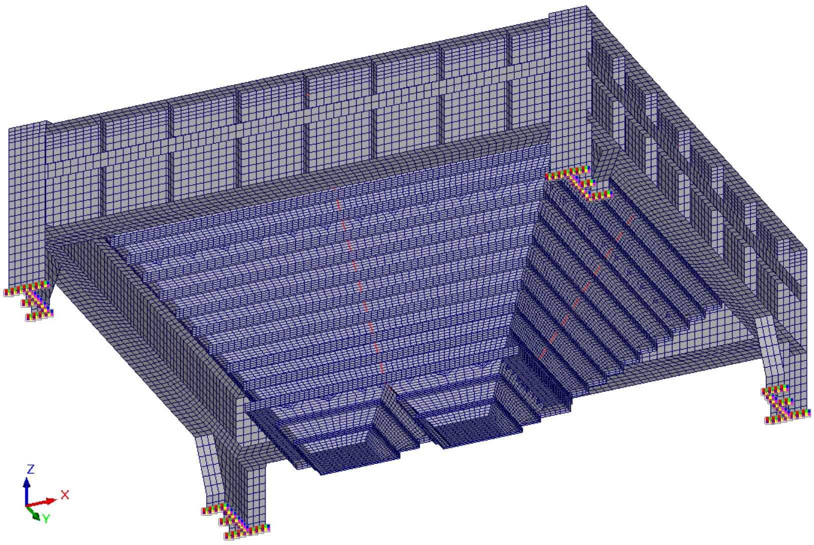

Figure 3. A design model of a steel bunker at Kryvorizhstal.

In the course of the research, a modal analysis was performed on an empty bunker tank, as well as on tanks with load levels of 1/8 (12.5%) + 2/8 (25.0%) + 3/8 (37.5%) + 4/8 (50.0%) + 5/8 (62.5%) + 6/8 (75.0%) + 7/8 (87.5%) + 8/8 (100.0%) of the total volume.

3. Results and discussion

The spectrum of natural and forced dynamic characteristics of the steel bunker at the Kryvorizhstal, obtained on the basis of modal analysis, is presented in table 1. For all nine levels of loading, the first 16 partial frequencies are shown as the most characteristic. Figure 4 and figure 5 graphically show the nature of changes in the lower 8 most important partial frequencies depending on the loading level of the steel bunker. The resulting modes of oscillations for these partial frequencies are presented in figure 6.

As can be seen from the above results of the modal analysis, the obtained frequency spectrum is quite dense. The qualitative change in the spectrum depending on the level of loading of the steel bunker with bulk material has a clearly expressed nonlinear character and remains the same for the entire lower frequency spectrum considered.

In quantitative terms, as the steel bunker is loaded with bulk material, the values of the partial frequencies decrease by an average of 20-30 % for every 25% increase in the level of loading. In this way, it becomes possible to adjust the values of the operating frequencies of the vibration device, which facilitates the gravity release of bulk material, while unloading the structure. Based on the data obtained, such a device should be able to change the frequency spectrum to ensure safe unloading of the structure. In this case, a possible option is to create a special functional complex for automatically monitoring the level of load of the steel bunker, the start and end time of its unloading. This makes it possible to automatically adjust the frequency of operation of the unloading device, adjusting it to the spectrum of partial frequencies of the structure determined in the course of these studies, thus increasing the efficiency of unloading bulk material. The proposed functional diagram of the automated system is shown in figure 7.

Table 1. Oscillation frequency spectrum of the steel bunker of the Kryvorizhstal plant.

Frequency number	Partial frequency (Hz) at the container loading level, %								
	0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0
1	10.32	9.86	8.31	6.14	4.72	3.80	3.17	2.70	2.43
2	10.62	10.19	8.78	7.42	6.22	5.24	4.03	3.70	3.22
3	11.66	11.65	11.35	9.13	7.35	6.13	4.68	3.73	3.30
4	15.47	14.63	11.36	9.44	8.17	6.14	4.91	4.51	4.06
5	15.87	14.64	11.59	9.45	8.23	7.11	5.33	4.94	4.38
6	16.05	15.08	11.77	9.85	8.31	7.40	5.76	5.14	4.54
7	16.51	15.35	11.87	9.87	8.54	7.48	6.76	5.88	5.13
8	17.82	15.40	11.90	10.51	8.63	7.64	6.79	5.97	5.21
9	17.84	15.79	13.02	11.00	8.93	7.79	6.86	6.27	5.59
10	17.85	16.02	13.38	11.09	9.58	7.80	7.06	6.29	5.83
11	17.90	16.20	13.45	11.11	9.69	8.71	7.11	6.54	5.88
12	18.24	17.68	13.71	11.62	9.72	8.72	7.19	6.56	5.90
13	18.25	17.82	14.29	13.03	11.57	9.28	7.37	6.63	6.03
14	18.47	17.84	16.68	13.97	11.77	9.39	7.93	6.80	6.15
15	18.53	17.85	16.95	14.11	12.17	10.13	7.97	6.86	6.16
16	18.65	18.15	17.00	14.12	12.28	10.28	8.01	7.33	6.31

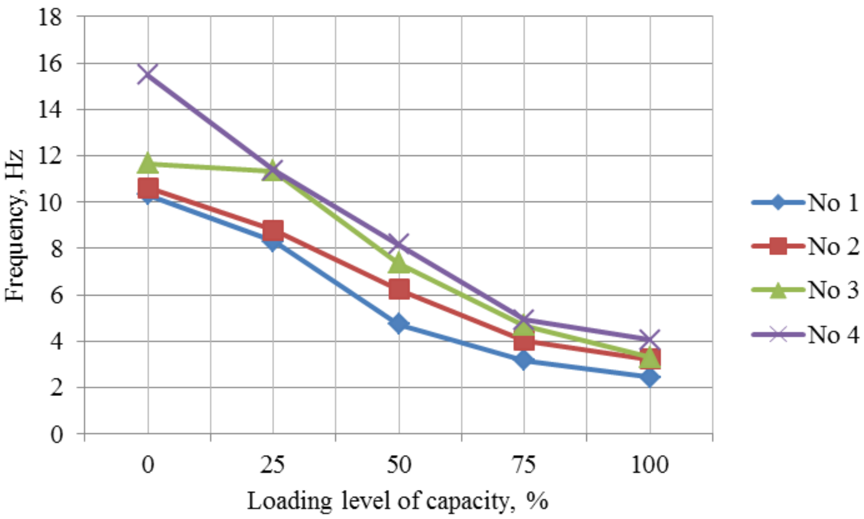

Figure 4. Partial frequencies (No 1- No 4) of natural oscillations of the steel bunker container of the Kryvorizhstal plant (table 1).

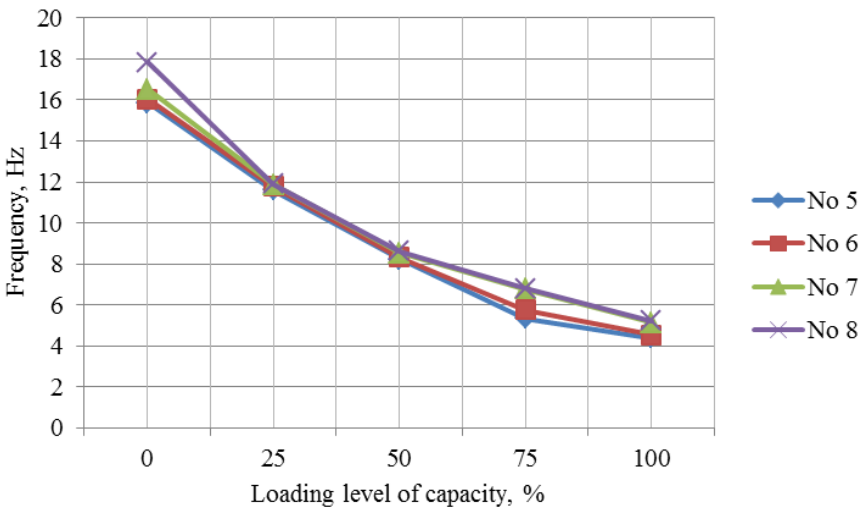

Figure 5. Partial frequencies (No 5- No 8) of natural oscillations of the steel bunker container of the Kryvorizhstal plant (table 1).

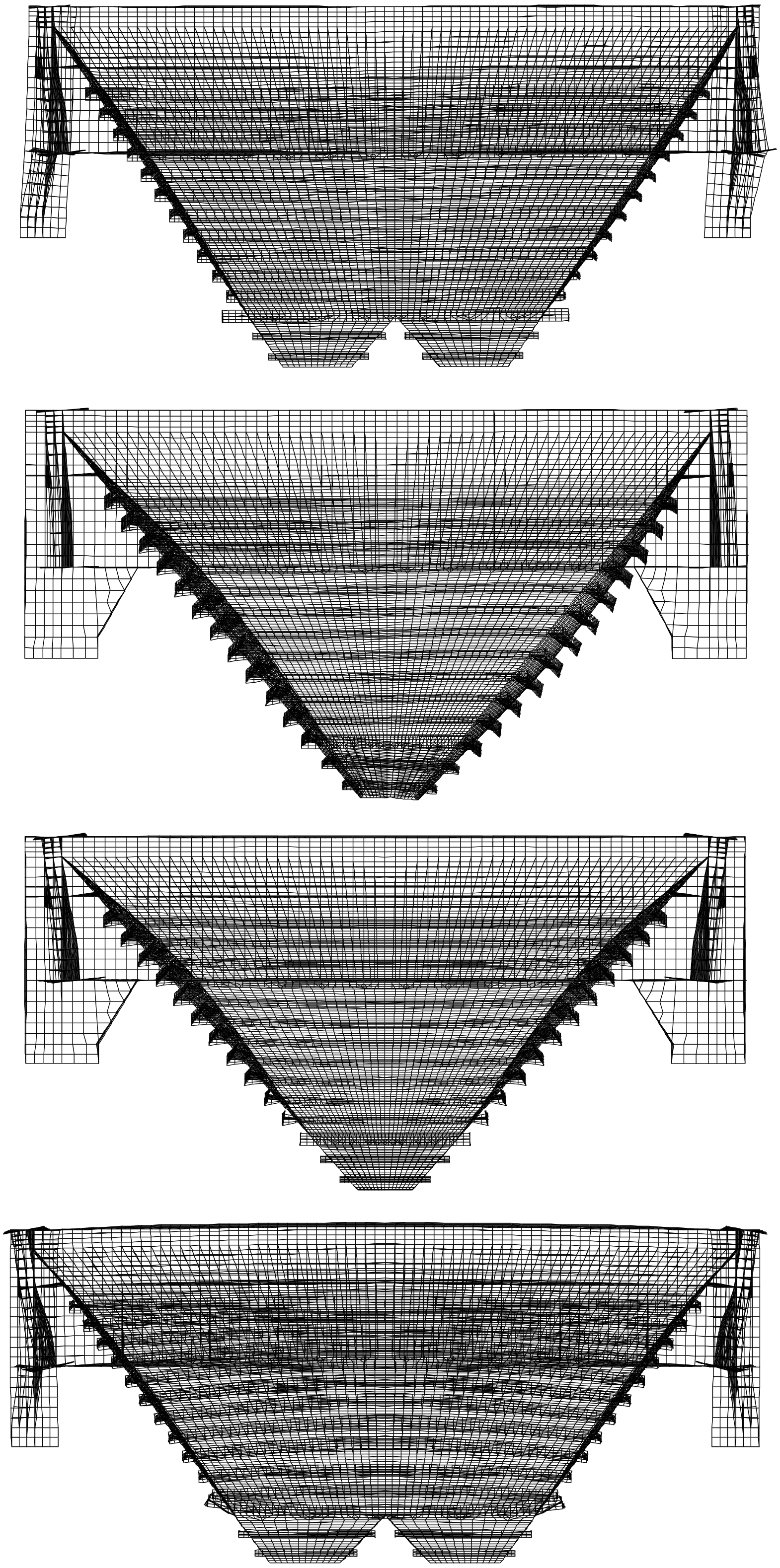

Figure 6. Partial modes of natural oscillations of the steel bunker container of the Kryvorizhstal plant: a – No 1; b – No 2; c – No 3; d – No 4 (table 1).

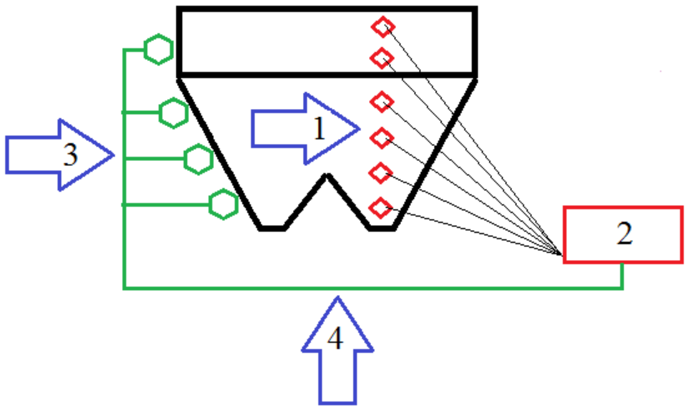

Figure 7. Diagram of the automated system for monitoring the load level of the steel bunker of the Kryvorizhstal plant: 1 – load level sensors; 2 – processing device; 3 – unloading devices; 4 – control channel for unloading devices.

4. Conclusions

Based on the results of the analysis of dynamic characteristics of large-sized steel bunker for bulk materials of the Kryvorizhstal plant, the following should be stated:

1. The spectrum of natural and forced partial frequencies (frequency spectrum) of the bunkers of the considered type is quite dense.
2. The frequency spectrum of the bunkers of the considered type starts from a frequency of about 10 Hz.
3. The frequency spectrum of the bunkers of the considered type qualitatively and quantitatively significantly depends on the level of loading of the bunker with bulk material and on average decreases by 20-30 % for every 25 % increase in the loading level of the structure.
4. The determined regularity of changes in the frequency spectrum can be used to develop and implement a specialized automated system for controlling the frequency spectrum of unloading devices. Such a system provides for an automatic change in the frequency level of the devices depending on the level of bulk material in the bunker structure.

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