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Optimal Layout of the Head Drive for a Self-Supporting Bucket Elevator of High Productivity

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Abstract. The article deals with bucket elevators of high productivity. The demand for grain crops is growing worldwide, requiring transportation, transshipment, and storage in huge volumes. Based on this, it is urgent to solve the problem of increasing the productivity of bucket elevators in the self-supporting version. The problem is that increasing performance requires increasing the drive's power, leading to a significant weight increase. This imposes a limit on the height of the bucket elevator. A considerable weight at a high altitude significantly reduces the stability of the structure itself. For the most part, this problem was solved by limiting the height or productivity of the bucket elevator. The construction of a self-supporting bucket elevator, possible layouts of the head drive, and advantages and disadvantages were considered. Three bucket elevators with different heights, productivity, and belt width were selected to determine the optimal layout. Four drive options were calculated for each design, and a comparative analysis was carried out using a graphical method. The analysis showed that one of the biggest problems is the displacement of the center of mass relative to the central plane of the bucket elevator. As a result, means to ensure the smallest displacement coefficient relative to the vertical axis of the bucket elevator were presented. Advantages, disadvantages, and the possibility of constructive implementation of the layouts were also considered.

Keywords: drive arrangement, product innovation, high productivity, center of mass, rigidity.

1 Introduction

One of the strategic areas of our country's development is the agro-industrial sector. Among the directions of its operation is the preservation and transportation of grain products. In connection with the constant increase in the production of grain products and as a result of the increase in technological operations for its movement, storage, processing, and shipment to large-tonnage ships, the demand for bucket elevators of high productivity (up to 600 t/h) and height (up to 60 m) is increasing in self-supporting are performed.

The main requirements for bucket elevators in this version are energy efficiency (minimum losses from backflow), manufacturability (minimum grain injury), reliability (absence of even partial skidding in the belt-drum mechanism), and safety (compliance with current norms and standards).

Bucket elevators are designed to transport bulk products vertically in a continuous pulsating flow using many buckets fixed at periodic intervals on an endless belt. Bucket elevators work with cargo with a bulk mass from 0.1 to 1.5 t/m^3.

2 Literature Review

Characteristics and scope of application, classification of models, main components and functions, and loading and unloading methods of the bucket elevator are presented in the research work [1].

The research work [2] proposes a conceptual design and approach to service life prediction are presented for the design of the head shaft of a belt bucket elevator [3] for transporting grain to a height of 33.5 m and a capacity of 200 t/h.

An operational breakdown of a bucket elevator at a chemical plant was monitored in [4]. The improvement of the bucket elevator structure and the optimization effect of the model were achieved in the research work [5].

In [6], it was examined how a change in oil in the operating cycle of technological equipment leads to a change in its oil frequency.

The synthesis of fundamentally new relaxation dampers was carried out in the research work [7], the performance of which was not related to the pressure in the working cavity [8].

The research [9] analyzed the structure, principle of operation, and performance characteristics of the main components of bucket ship unloaders. The operational failure of a bucket elevator at a chemical plant was studied in [10].

A detailed analysis of the structural characteristics and main characteristics of the chain bucket mechanism and the ship transportation system was carried out in the research work [11].

The research [12] provided a detailed analysis of the general shape of the structure and composition of bulk ship unloaders. In [13], the material flow was simulated and computed in both shafts of the bucket elevator.

The research [14] presented continuous conveyor machines and their classification. Also, an innovative method for modeling the design and optimization of bucket elevators and other equipment, operating according to similar principles, was described in [15]. Finally, the research works [16, 17] analyzed static and dynamic loads in new structures and mechanisms.

Therefore, the article aims to solve the urgent problem of increasing bucket elevator productivity in the self-supporting version.

3 Research Methodology

Bucket elevators are divided into two types of execution according to the carrying capacity of the body: self-supporting and non-self-supporting (ordinary execution). A self-supporting bucket elevator can be installed as an independent device. It does not need a working tower.

To ensure vertical and wind resistance, the structure is fixed to the granary or with the help of stretchers. Also, the bucket elevator has a particular design and is equipped with platforms and stairs (Figure 1).

The main problem during the development of high-performance self-supporting bucket elevators is their mass characteristics. The mass of such bucket elevators can reach more than 10 tons, which imposes certain requirements on the strength of the structural elements and the stability of the structure itself.

Particular attention should be paid to the head of the bucket elevator. In self-supporting bucket elevators, the load from the head with the drive is transmitted through borehole pipes to the bucket elevator’s shoe and then to the foundation (Figure 1).

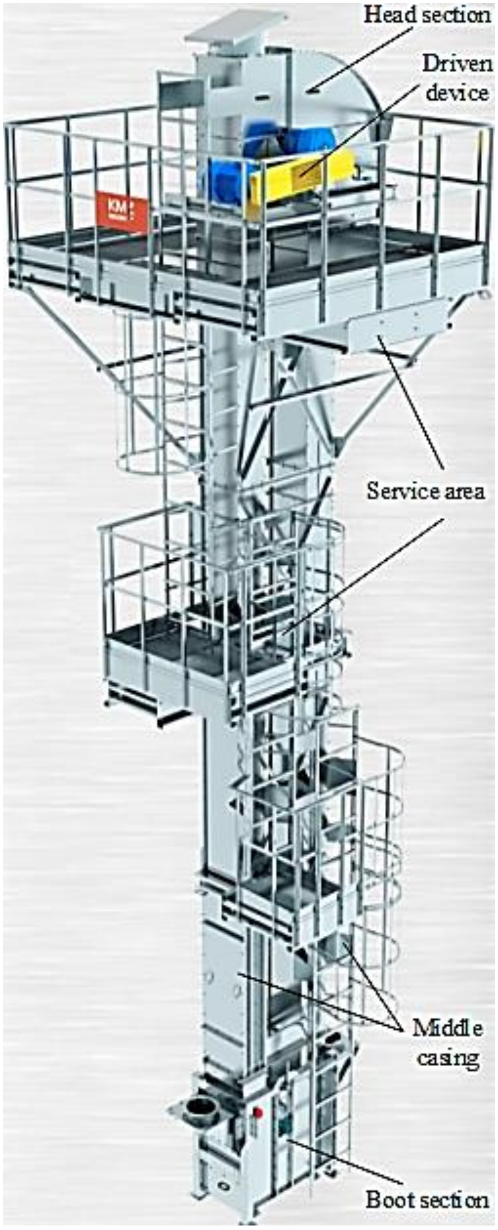


Figure 1 – Components of a bucket elevator

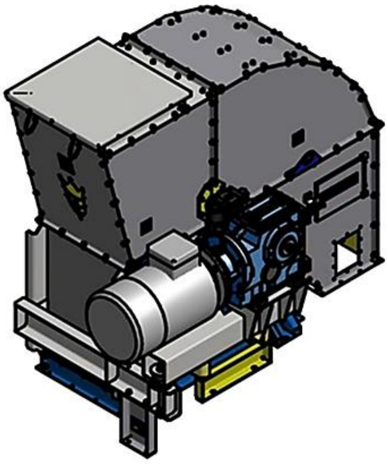
The peculiarity of the design is that the heaviest element – the bucket elevator head – is located at the highest point of the bucket elevator. This, in turn, leads to an unfavorable location, the center of gravity of the head, relative to the entire bucket elevator.

So, if it is necessary to increase the productivity of the bucket elevator in the self-supporting version, the designers are faced with problems that contradict each other:

- provision of the necessary power, which increases with increased height and productivity;
- keeping the center of gravity as close as possible to the vertical axis of the bucket elevator.

Considering the above, high-performance bucket elevators require high power, which translates into drive mass, which shifts the center of gravity of the head beyond the vertical axis of the bucket elevator. This factor makes it practically impossible to disassemble the bucket elevator without additional structures - the tower. Therefore, the research task is to compare the possible types of drive and determine the optimal layout of the elevator head.

Figure 2 presents the head with the drive and different layout types.



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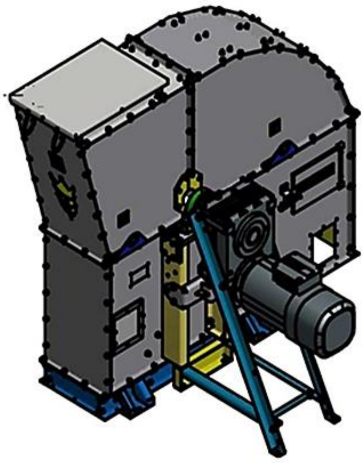

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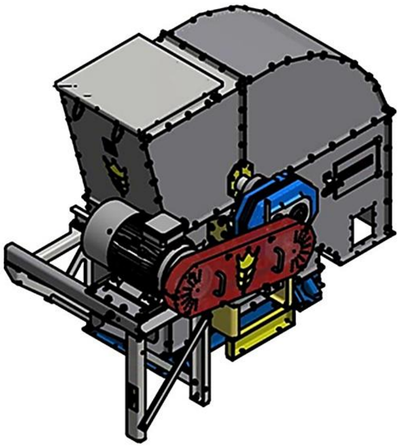

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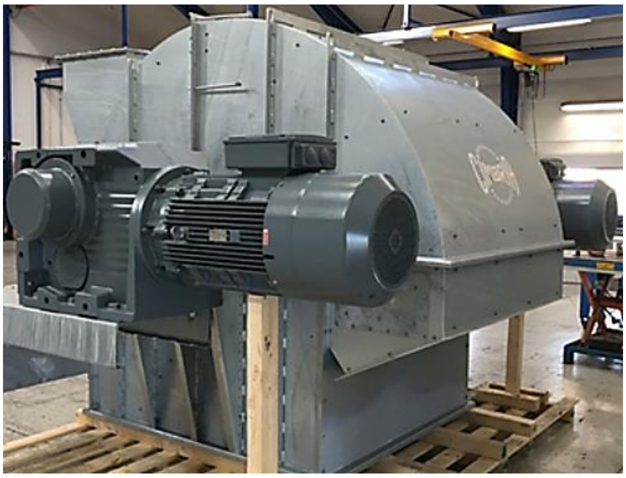

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Figure 2 – Layout types for the head with the drive: a – conical-cylindrical, monoblock reducer (CCM); b – cylindrical, monobloc reducer (CM); c – cylindrical gearbox, V-belt (CGV); d – two conical-cylindrical reducers, monoblock (2CCM)

Let’s consider the main types of drive location relative to the head of a high-performance bucket elevator (Figure 2) and consider the advantages and disadvantages (Table 1) of using these solutions.

Table 1 – Advantages and disadvantages

Type of the drive	Advantages	Disadvantages
CCM	The compact size of the head.	High drive cost.
	High efficiency of the reducer.	
	Ease of maintenance.	Increased wear of the bevel gear.
	The center of gravity of the head is not strongly shifted.	
CM	Optimal cost of the drive.	Increased size of the head.
	The highest gearbox efficiency.	The center of gravity of the head is not strongly shifted.
	Ease of maintenance.	Picky about the quality of installation.
CGV	The compact size of the head.	Needs regular maintenance.
	The center of gravity of the head is not strongly shifted.	Low efficiency due to belt transmission.
	Ease of repair.	
2CCM	The compact size of the head.	High cost of drives.
	The center of gravity of the head is not shifted.	Requires additional power reserve (+ 30 % for asynchronous operation).
	Convenience in service.	It requires a device to synchronize the operation of drives.

For the following analysis, the criteria were defined, according to which we are comparing:

– the weight of the head assembly with the drive; nominal torque on the drum shaft;

– mass of motor-reducer;

– the price of the head considering the drive;

– coefficient of displacement for the center of mass.

An example of the location of the bucket elevator head at the center of gravity is presented in Figure 3.

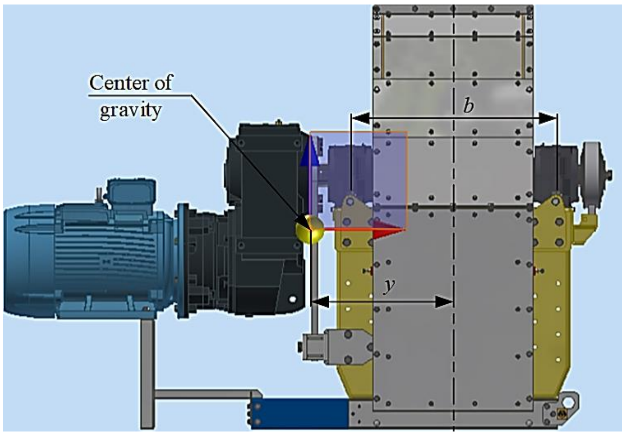


Figure 3 – An example of the location of the center of gravity of the bucket elevator head

The coefficient of displacement of the center of mass was determined relative to the central plane of the bucket elevator head:

$$k_y = \frac{2y}{b}, \quad (1)$$

where b – the distance between the bearing units; y – the distance from the center of mass to the central plane of the bucket elevator head; $k_y > 1$ – the center of gravity is outside the bearing nodes; $k_y = 0$ – the center of gravity, located on the central plane of the bucket elevator head.

4 Results

To determine the optimal layout of the head, we will conduct a comparative analysis of several bucket elevators (Tables 2–4) under the following conditions:

– the transportation material – wheat with a bulk density of 0.75 t/m^3;

– humidity – 14 %;

– execution of the bucket elevator – self-supporting;

– unloading type – centrifugal.

Table 2 – Parameters of bucket elevators

Productivity, t/h	300			
Height, m	38			
Tape width, mm	450			
Bucket volume, dm^3	7.48			
Rows of buckets on the belt	1			
Type of drive	CCM	CM	CGV	2CCM
Power, kW	55	55	55	2×30
Nominal moment, N·m	5930	5870	5870	2×3200
Weight of motor-reducer, kg	730	695	745	2×432
Price without VAT, UAH	268 720	207 568	232 568	349 210
Belt speed, m/s	3.05	3.05	3.05	3.05
Weight of the head, kg	1470	1400	1550	1620
Coefficient k_y	0.76	1.4	0.74	0.00

Table 3 – Parameters of bucket elevators

Productivity, t/h	300			
Height, m	38			
Tape width, mm	800			
Bucket volume, dm^3	2×5.08			
Rows of buckets on the belt	2			
Type of drive	CCM	CM	CGV	2CCM
Power, kW	55	55	55	2×30
Nominal moment, N·m	7490	7570	7570	2×3820
Weight of motor-reducer, kg	890	859	910	2×550
Price without VAT, UAH	383 310	303 325	333 325	385 360
Belt speed, m/s	2.71	2.68	2.75	2.91
Weight of the head, kg	2210	2140	2360	2650
Coefficient k_y	0.51	0.68	0.46	0.00

Table 4 – Parameters of bucket elevators

Productivity, t/h	400			
Height, m	38			
Tape width, mm	900			
Bucket volume, dm^3	2×7.48			
Rows of buckets on the belt	2			
Type of drive	CCM	CM	CGV	2CCM
Power, kW	75	75	75	2×45
Nominal moment, N·m	8580	9110	9110	2×5720
Weight of motor-reducer, kg	939	909	960	2×580
Price without VAT, UA	404 610	324 625	354 625	388 696
Belt speed, m/s	3,22	3,06	3.1	3
Weight of the head, kg	2360	2280	2590	2780
Coefficient k_y	0.62	0.82	0.55	0.00

It can be seen from the obtained graphs that in all cases (Figure 4), the arrangement of the CM with a cylindrical reducer is the most appropriate. In almost all parameters, it has the best indicators.

However, it has the most significant displacement coefficient of the center of mass. In the first case (Figure 4 a), the displacement coefficient is 1.4, i.e., the center of mass is located far behind the bearing units, significantly affecting the bucket elevator's stability. In the second and third cases (Figures 4 b, c), due to the use of the middle casing with a much larger cross-section, the center of mass is located within the bearing nodes – 0.68 and 0.82, respectively.

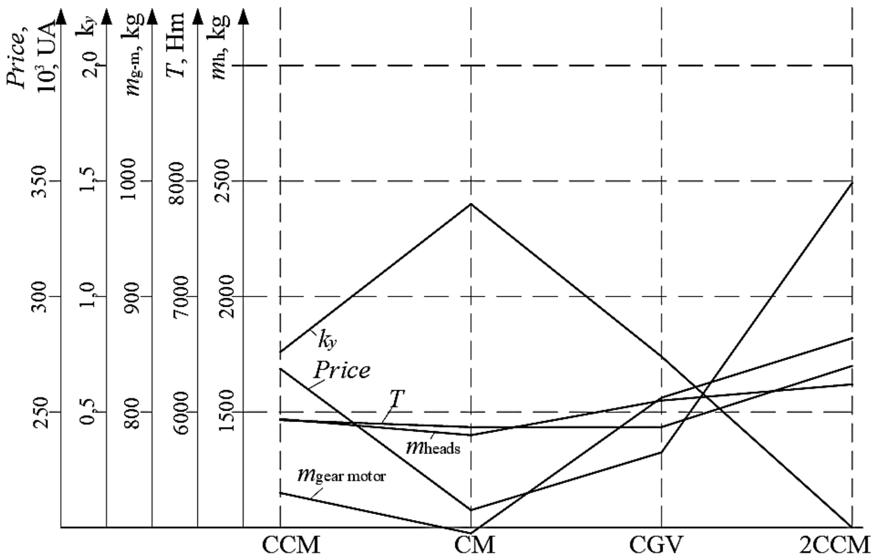
The arrangement with the bevel-cylindrical gearbox CCM has optimal parameters, except for the price.

It can be seen from the graph (Figure 4 a) that this layout is optimal for the bucket elevator in the first version.

In the case of two 2CCM conical-cylindrical gearboxes, we get the best coefficient of displacement of the center of mass, but the high cost and mass of two drives limit the use of similar design solutions.

The layout with a cylindrical reducer and a V-belt transmission of the CGV has suitable parameters, but implementing large capacities through a belt transmission is quite challenging.

As a result, possible variants of the layout for the head are summarized in Figure 5.



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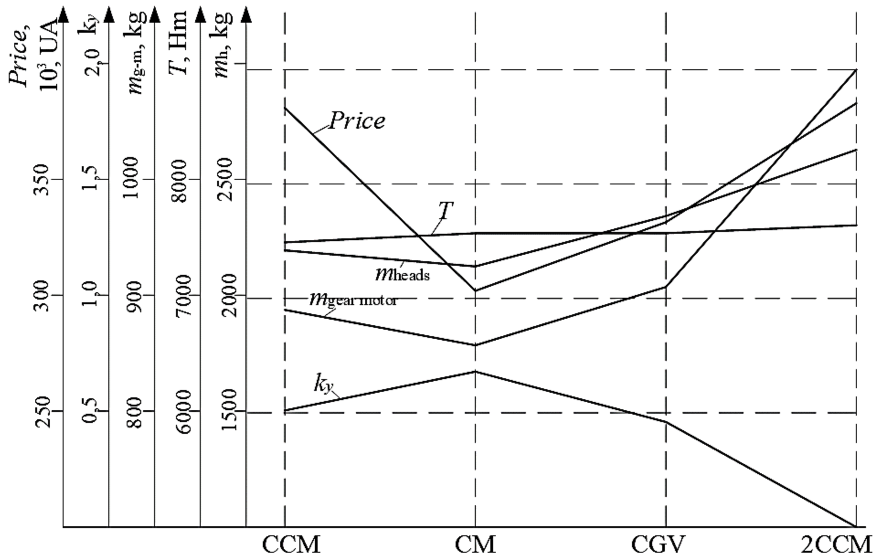

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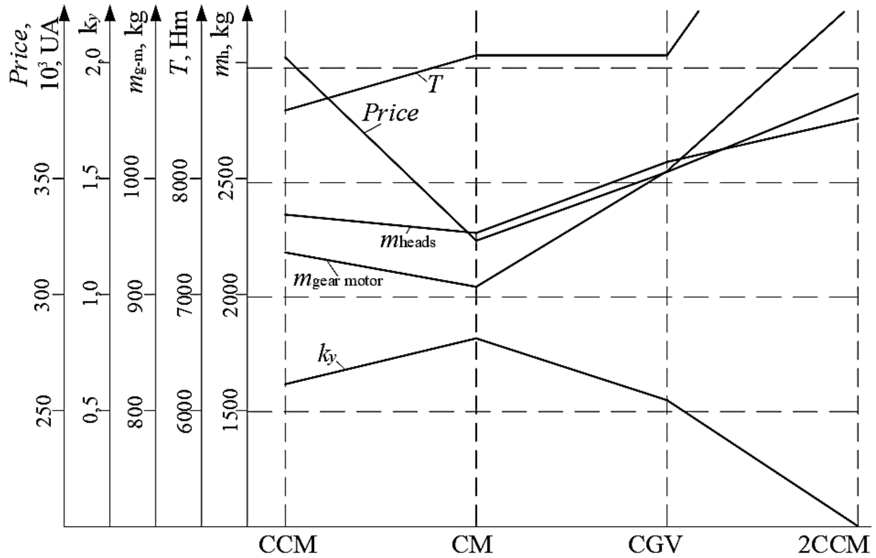

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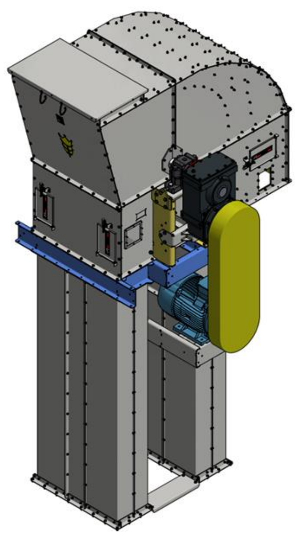
Figure 4 – Charts comparing the criteria of bucket elevators according to Tables 1 (a), 2 (b), and 3 (c), respectively



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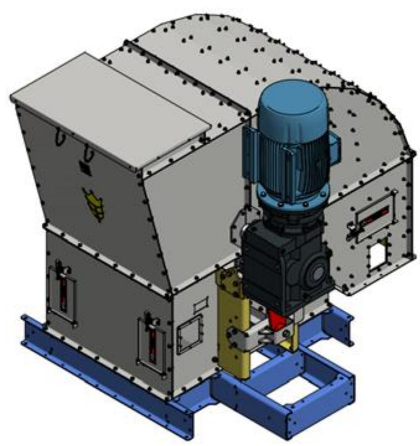

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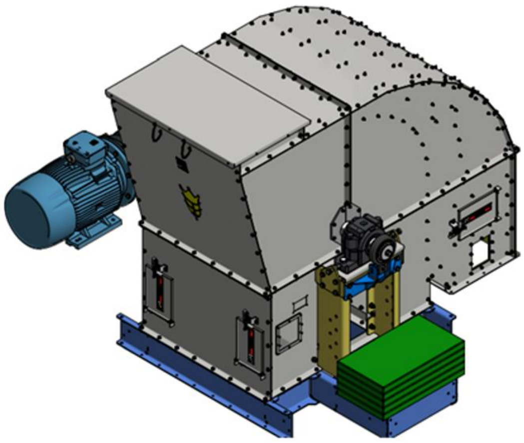

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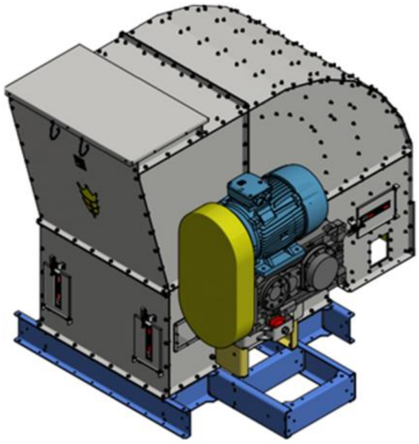

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Figure 5 – Layout types for the head with the drive: a – conical-cylindrical, monoblock reducer (CCM); b – cylindrical, monobloc reducer (CM); c – cylindrical gearbox, V-belt (CGV); d – two conical-cylindrical reducers, monoblock (2CCM)

5 Discussion

Based on the previous analysis, in order to solve this problem, it is necessary to consider possible variants of the layout of the head (Figure 5), which will provide the smallest displacement coefficient relative to the vertical axis of the bucket elevator:

First, the cylindrical reducer is installed vertically on the drive shaft, and the electric motor is installed between the pipes of the middle casing, which are connected using a V-belt transmission (Figure 5 a). The advantages are compact dimensions of the head and optimal center of gravity. The disadvantages are as follows:

– inconveniences in servicing are related to the location of the electric motor;

– the need to organize an additional site for service;

– to place the electric motor between the pipes (it is necessary to place it below the level of the service platform; if the service platform is lowered below, then it will not be possible to service the gearbox, bearings, and pressure relief valve);

– limitation of the size of the electric motor (the distance between the pipes is 600 mm, the size of the electric motor of 45 kW is 465 mm, 55 kW – 520 mm, and 75 kW – 570 mm).

Second, the conical-cylindrical motor-reducer (monoblock) is installed vertically on the drive shaft, with the motor facing up (Figure 5 b). The advantages are as follows:

– the compact head size;

– the center of gravity is close to the central plane of the bucket elevator.

The disadvantage is the need to organize an additional platform for maintenance (since the length of the motor-reducer, at the capacities presented, is greater than the distance from the axis of the head to its base, to which the maintenance platform is attached).

Third, the conical-cylindrical motor-reducer (monoblock), installed on the drive shaft horizontally or at a certain angle to the base of the bucket elevator head, on the opposite side, to compensate for the weight, a counterweight is installed (Figure 5 c). The advantages are compact dimensions of the head, optimal position of the center of gravity, and ease of service.

The disadvantage is the excess weight of the bucket elevator head, which contributes to a decrease in the stability of the bucket elevator.

Fourth, the conical-cylindrical gearbox is paired with an electric motor installed above the gearbox and connected by a V-belt transmission (Figure 5 d). The advantages are as follows:

– the compact size of the head;

– the center of gravity is close to the central plane of the bucket elevator.

The disadvantage is the inconvenience related to the location of the electric motor in maintenance.

Moreover, using a drum motor, the electric motor is in the middle of the drum. The advantages are the compact dimensions of the head and the optimal center of gravity.

The disadvantage is the impossibility of ensuring the operating temperatures of the electric motor and ensuring safety standards for explosion protection.

6 Conclusions

The analysis of the presented material shows that one of the biggest problems is the displacement of the center of mass relative to the central plane of the bucket elevator, which significantly affects the stability of the bucket elevator. From the layout options presented, it is clear that there is no universal solution. The layout of the CGV (Figure 2 c) will not ensure adequate operation at large capacities. The layout of the 2CCM (Figure 2 d) has an excessively high cost and significantly greater weight than other layouts.

For further work, it is advisable to consider the layouts of CCM and CM (Figures 2 a, b), depending on the width of the pipes of the middle case.

For a bucket elevator with a narrow belt (Table 2), it is optimal to use the CCM layout. In this case, the displacement coefficient of the center of mass is 0.76, half as much as that of the CM layout – 1.4.

For bucket elevators with a wide belt (Tables 3, 4), due to the use of pipes in the middle body of a larger cross-section, it is advisable to use the layout of the CM, which has the best indicators in terms of price (20 % cheaper) and efficiency.

Two possible layouts were identified during the analysis, and promising layouts were proposed. Further research will contribute to the development of high-performance bucket elevators.

References

1. Ma, Y., Cui, R. (2024). Bucket Elevator. *In: Tao, D., Yan, Y., Dong, D., Zhang, D. (Eds.) Handbook of Port Machinery*. Springer, Singapore. https://doi.org/10.1007/978-981-99-4848-2_21.
2. Chen, Z. (2024). Bucket Chain Ship Unloaders. *In: Tao, D., Yan, Y., Dong, D., Zhang, D. (Eds.) Handbook of Port Machinery*. Springer, Singapore. https://doi.org/10.1007/978-981-99-4848-2_26
3. Chikelu, P.O., Nwigbo, S.C., Obot, O.W., Okolie, P.C., Chukwuneke, J.L. (2023). Modeling and simulation of belt bucket elevator head shaft for safe life operation. *Scientific Reports*, Vol. 13, 1083. https://doi.org/10.1038/s41598-022-26060-x
4. Gelnar, D., Zegzulka, J. (2019). Bucket Elevator Filling and Discharge. *In: Discrete Element Method in the Design of Transport Systems*. Springer, Cham. https://doi.org/10.1007/978-3-030-05713-8_4
5. Gurudath, B., Kumawat, K.K., Tejaswi, V., Sondar, P.R., Rakshan Kumar, J.K., Hegde, S.R. (2021). Failure analysis of a bucket elevator shaft. *Journal of Failure Analysis and Prevention*, Vol. 21, pp. 563–569. https://doi.org/10.1007/s11668-020-01101-7
6. Ma, F., Xiong, F., Li, G. (2019). Key structure innovation and optimization design of bucket elevator. *In: Wang, K., Wang, Y., Strandhagen, J., Yu, T. (Eds.) Advanced Manufacturing and Automation VIII. IWAMA 2018. Lecture Notes in Electrical Engineering*, Vol 484, pp. 623–627. Springer, Singapore. https://doi.org/10.1007/978-981-13-2375-1_78
7. Kurgan, V., Sydorenko, I., Bovnegra, L., Pavlyshko, A., Kirkopulo, K. (2023). Stabilization of natural frequency oscillation equipment when changing its weight. *In: Tonkonogyi, V. et l. (Eds.) Advanced Manufacturing Processes IV. InterPartner 2022. Lecture Notes in Mechanical Engineering*, pp. 455–464. Springer, Cham. https://doi.org/10.1007/978-3-031-16651-8_43
8. Sydorenko, I., Semenyuk, V., Lingur, V., Bovnegra, L., Kirkopulo, K. (2022). Relaxation shock absorbers with additional mechanical control circuit. *In: Tonkonogyi, V. et al. (Eds.) Advanced Manufacturing Processes III. InterPartner 2021. Lecture Notes in Mechanical Engineering*, pp. 655–663. Springer, Cham. https://doi.org/10.1007/978-3-030-91327-4_63
9. Gelnar, D., Zegzulka, J. (2019). *Basic Description of Bucket Elevators. In: Discrete Element Method in the Design of Transport Systems*. Springer, Cham. https://doi.org/10.1007/978-3-030-05713-8_3
10. Zheng, J. (2024). Bucket Wheel Ship Unloaders. *In: Tao, D., Yan, Y., Dong, D., Zhang, D. (Eds.) Handbook of Port Machinery*. Springer, Singapore. https://doi.org/10.1007/978-981-99-4848-2_33
11. Park, F.C., Kim, J.W. (1999). Singularity analysis of closed kinematic chains. *Journal of Mechanical Design*, Vol. 121(1), pp. 32–38. https://doi.org/10.1115/1.2829426
12. Li, Y. (2024). Catenary Chain Bucket Ship Unloaders. *In: Tao, D., Yan, Y., Dong, D., Zhang, D. (Eds.) Handbook of Port Machinery*. Springer, Singapore. https://doi.org/10.1007/978-981-99-4848-2_27
13. Li, S. (2024). En Masse Ship Unloaders. *In: Tao, D., Yan, Y., Dong, D., Zhang, D. (Eds.) Handbook of Port Machinery*. Springer, Singapore. https://doi.org/10.1007/978-981-99-4848-2_28
14. Gelnar, D., Zegzulka, J. (2019). The Optimization of Bucket Discharge to Maximize the Transported Volume and to Minimize Material Fall Down the Shaft. *In: Discrete Element Method in the Design of Transport Systems*. Springer, Cham. https://doi.org/10.1007/978-3-030-05713-8_13
15. Ma, Y., Chen, L. (2024). Introduction to Port Continuous Conveying Machinery. *In: Tao, D., Yan, Y., Dong, D., Zhang, D. (Eds.) Handbook of Port Machinery*. Springer, Singapore. https://doi.org/10.1007/978-981-99-4848-2_15
16. Gelnar, D., Zegzulka, J. (2019). Conclusion. *In: Discrete Element Method in the Design of Transport Systems*. Springer, Cham. https://doi.org/10.1007/978-3-030-05713-8_14
17. Woo, S. (2023). Engineering (Dynamic) Load Analysis. *In: Design of Mechanical Systems. Springer Series in Reliability Engineering*. Springer, Cham. https://doi.org/10.1007/978-3-031-28938-5_2