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DESIGN OF A MANIPULATOR OF A CONVEYOR FOR BULK MATERIALS – CALCULATION OF THE CENTER OF GRAVITY OF THE CONVEYOR

Summary. The predominant goal of the research presented in this paper is the design of a manipulator for a conveyor of bulk materials based on the given requirements. This issue is an emerging topical one mainly for the reasons of increasing efficiency and speed, as well as the safety of maintenance of machines and equipment. Especially, another essential aspect is the reduction of the physical strain on operators during service operations on the conveyor of bulk materials. The introductory part of this paper attends to the materials used for the production of steel structures, their technological processing, as well as different types of joining of their components. The practical part was set out to ascertain the mass and position of the center of gravity of the load itself – the conveyor. From

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the perspective of acting, it loads the entire proposed structure, although in different operating modes.

Keywords: steel structure, analytical calculation, center of gravity, technology, handling

1. INTRODUCTION

Today, steel structures (Figure 1) are exploited in technical practice in an extremely wide range of applications and represent a significant element not only in contemporary mechanical engineering but also in civil engineering and architecture. The area of construction of steel structures needs to be analyzed for design, legal standards and regulations, type of loading, construction material, and also from the perspective of the mechanical tests of the material used and its mechanical, physical, technological and chemical properties. Moreover, safety and reliability in long-term use in conjunction with the economy of the given construction are other essential aspects for the engineers of steel structures [1-4].

Today, an enormously wide range of different steels is produced, intended primarily for the manufacture of machinery, equipment, and construction engineering. Through the right selection of materials, it is possible to achieve the ideal service life of the structure under a given load, and at the same time, minimize costs. Accordingly, the economy of the project can be maximized [5-7].

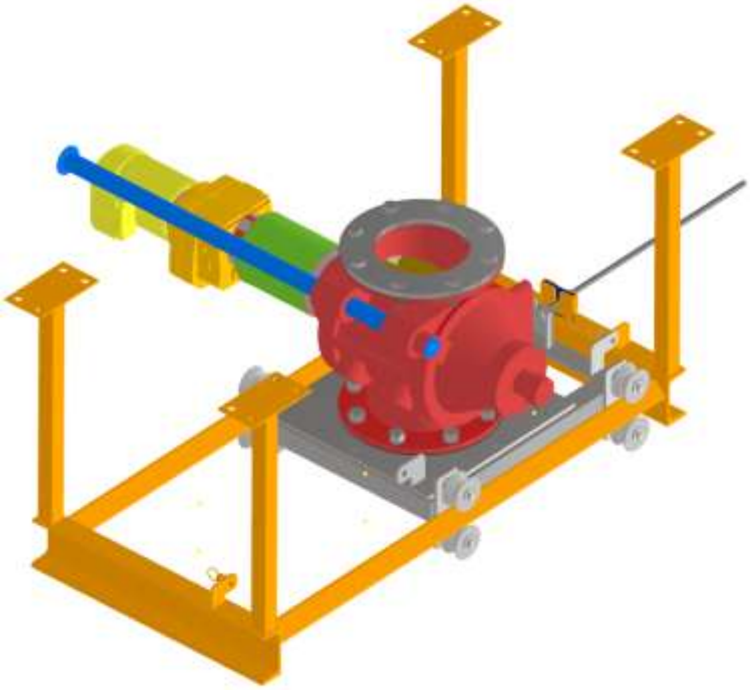

Fig. 1. The proposed steel structure – conveyor frame (orange) and trolley (gray) together with conveyor of bulk materials

All steels have their own specific properties, which result from their chemical composition and technologies used in processing (steelmaking) in the course of the actual production. Mechanical properties characterize how the material withstands the action of applied external force. Steels used in the construction of steel structures are commonly stressed in various ways. Thus, their mechanical properties are substantial. The mechanical properties are conclusively a decisive factor in selecting the appropriate material. Given the mechanics, if we apply an external force to an element of the structure, a deformation will occur. Moreover, if we reach the limit state, a fracture will occur and expand. The final shape change is the result of the interaction between the external and internal forces. The interaction acts against the induced deformation. In the case of the component returning spontaneously to its original shape after unloading, it is elastic deformation. Conversely, when the component does not return to its original shape after unloading and remains deformed in varying degrees, then it is a plastic deformation [8-12].

Steel structures consist of various steel elements made chiefly from metallurgical semi-finished products. For the sake of the simplification of transport, production as well as assembly, various joints are exploited in the creation of steel structures. The connections between the individual structural elements are realized through the mentioned joints. Based on the possibility of disassembling the structure after its assembly, we separate the joints into detachable and non-detachable [13-15].

The connected components interact with each other by action and reaction forces, which must be transmitted smoothly through the joints. When designing the technical parameters of metal structures, it is required to involve the condition of the resulting rigidity of the unit in the design requirement. This rigidity is ensured, moreover, through the connection of all the elements into one unit. Each commonly used joint has its own characteristics associated with the load-carrying capacity, stress distribution, and assembly procedure, in addition to the impact on the structural properties of the joined components. Every designer should be thoroughly acquainted with all the above-mentioned facts at an early stage of the design. It is crucial to consider the level of stress and the manner of the applied loads to determine what type of joint is suitable for a given purpose. Therefore, the designer must have accurate information about the cyclic stress and impact stress along with their impact on the structures [16, 17].

2. REQUIREMENTS IMPOSED FOR THE PROPOSED STEEL STRUCTURE

The equipment is dedicated to being integrated into an existing production line for packing milk powder into bags. The device is located on a supporting structure above the milk powder filling machine. The structure must not interfere with the operation of the filling line. For this reason, it must be anchored to the ceiling at a height of 4.20 m above the floor. The design of the device needs to be adapted to the requirement to be able to wash the tank. For the sake of installation of the equipment in a food business, it is desirable to make the supporting structure from stainless steel.

The primary element of the device is a rotary feeder, which ensures the following three requirements:

- to separate, using pressure, the buffer hopper compartment, which is pressurized by a bag filler, in which a required atmospheric pressure is,
- to prevent the transfer of explosion and flame from the hopper compartment to the bag filler in case of an explosion of milk powder in the buffer hopper. In this case, it concerns the occupational safety of the workers operating the bag filler,

- to ensure the uniform supply of milk powder into the bag filler, which has a great influence on the accuracy of a bag filler weighing.

The rotary feeder is required to be ATEX certified, which guarantees the applicability of the rotary feeder for the separation of two spaces in the event of an explosion. The materials used for the production of all parts of the rotary feeder that come into contact with the material to be conveyed need to be certified for direct contact with foodstuffs. In addition, the electric gearbox of the rotary feeder shall be adapted for speed control using a frequency converter to regulate the power as per the needs of the milk powder filler to bags.

The rotary feeder is connected to the intermediate hopper by a short stainless steel pipe and a fabric compensator, which minimizes the transmission of vibrations from the buffer hopper to the bag filler. For this reason, the influence on the strain gauge weight sensors is minimized. The compensator is rated for a reduced blast pressure to match the resistance of the buffer hopper.

Based on the above requirements, a manually operated manipulator of bulk material conveyor will be designed along with a structure for its anchoring and travel. The mentioned manipulator and its travel need to be installed for the sake of service or maintenance interventions, moreover, for the reason of cleaning the conveyor itself as well as the interconnecting pipe joining the hopper of the product (milk powder) to the equipment employed for packaging the milk powder. There is plenty of options for dealing with such servicing operations, for example, handling with external manipulators, hoists, and mechanical or electric forklifts. Nevertheless, through the food operation, the high demands on cleanliness, the weight of the conveyor itself together with its drive of approximately 230 kg, as well as the economy of the solution itself, it is evidently the optimal solution. This is further elaborated in this paper. Because of the acting of relatively small passive resistances during the movement of the manipulator (trolley) on the travel, it will be manipulated through pushing by the operator. The conveyor, in this case, is considered only as a load acting on the structure, given the fact that it is supplied as a whole by an external company.

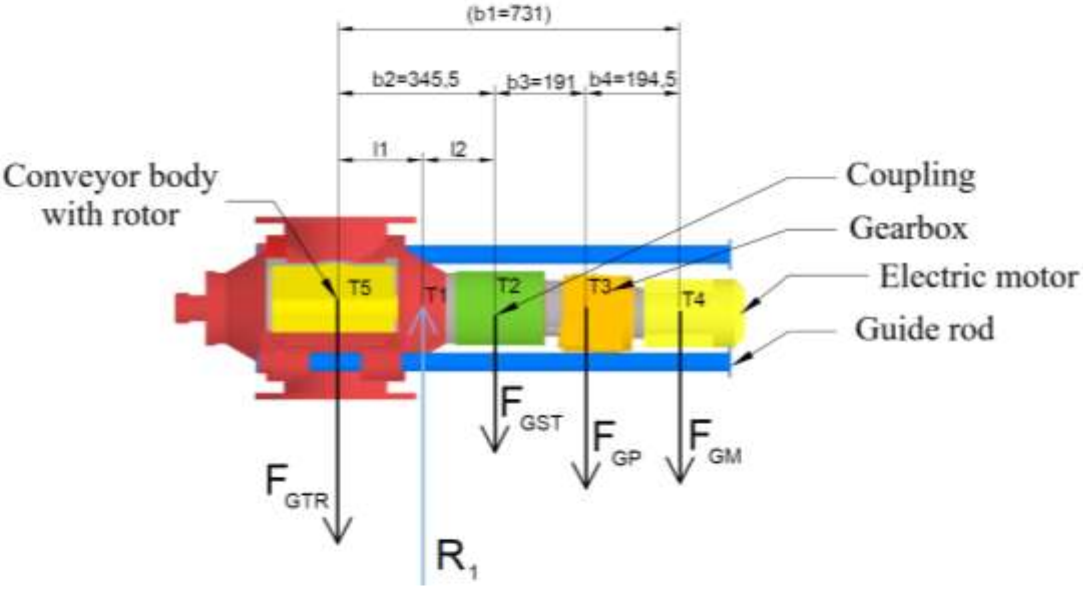

Fig. 2. 2D model of a conveyor of bulk materials in a retracted state with the individual components marked and the distances of their centers of gravity considered

For the solution, the first point of the issue is to deal with the load itself, that is, the conveyor (Figure 2). It loads the whole structure. Individual quantities and dimensions marked in Figure 2 are as follows: F_{GTR} – gravitational force of the lid, body and rotor of the conveyor, R_1 – total reaction force sought in the arrangement when the rotor is retracted, F_{GST} – gravitational force of the coupling of the drive with the guide rods, F_{GP} – gravitational force of the gearbox of the drive, F_{GM} – gravitational force of the electric motor of the drive, b_1 – distance between the center of gravity of the body with the rotor and the center of gravity of the motor, b_2 – distance between the center of gravity of the body with the rotor and the center of gravity of the coupling, b_3 – distance between the center of gravity of the coupling and the center of gravity of the gearbox, b_4 – distance between the centers of gravity of the gearbox and the motor, l_1 – searched distance between the center of gravity of the body with the rotor and the center of gravity of the system, l_2 – searched distance between the center of gravity of the coupling with the rods and the center of gravity of the system, T_1 – the center of gravity of the system of conveyor with the rotor retracted, T_2 – the center of gravity of the coupling, T_3 – the center of gravity of the gearbox, T_4 – the center of gravity of the electric motor, T_5 – the center of gravity of the body of the conveyor with rotor.

It is indispensable to determine the position of the center of gravity (dimensions l1, l2 in Figure 2) of the conveyor itself along its length (*z*-axis). Additionally, to determine the position of the center of gravity within the frame of the *z*-axis in different operating modes of the device, or at the most unfavorable condition for stresses on the trolley structure and the supporting structure. Furthermore, it will be necessary to calculate the center of gravity of the trolley-conveyor system, which will jointly load the proposed support structure. Due to the rotational symmetry of the conveyor used, it is not required to attend to the calculation of the center of gravity in the *x*-axis and *y*-axis.

3. CALCULATION OF THE CENTER OF GRAVITY OF THE CONVEYOR

Because it was not possible to obtain a functional CAD model of the conveyor used and the manufacturer did not indicate the position of the center of gravity of this device, it was essential to divide the device into several parts. Accordingly, to ascertain the center of gravity of the whole system based on their masses and positions of the centers of gravity (Figure 2). The system is made up of an extension lid, a rotor, guide rods, a conveyor body, a coupling, a gearbox and a drive electric motor. The centers of gravity of the individual parts were determined in two ways. First is rough modeling in Autodesk Inventor and the subsequent determination of the center of gravity through this program. While the second is estimation regarding the known geometry and knowledge of the internal arrangement of the components. The length dimensions were determined from the measurements of the model, as supplied by the company, in the Autodesk Inventor environment. As aforementioned, primarily, it is decisive to attend to the position of the center of gravity of the conveyor within the frame of the z-axis in the condition with the rotor and lid retracted, that is, in the operating position.

First, it is essential to determine the forces acting in the system from the known values of the masses and the gravitational acceleration in line with equations (1 - 4):

$$F_{GTR} = \left(m_{TE} + m_R + m_V\right) \cdot g \tag{1}$$

$$F_{GST} = \left(m_S + m_T\right) \cdot g \tag{2}$$

$$F_{GP} = m_p \cdot g \tag{3}$$

$$F_{GM} = m_m \cdot g \tag{4}$$

where m_{TE} [kg] – mass of the conveyor body m_{TE} = 130.2 kg, m_R [kg] – mass of the conveyor rotor m_R = 11 kg, m_V [kg] – mass of the conveyor lid m_V = 22.8 kg, m_S [kg] – mass of the coupling of the drive m_S = 6 kg, m_T [kg] – mass of the two guide rods m_T = 2.10 kg, m_P [kg] – mass of the gearbox of the drive m_P = 26 kg, m_m [kg] – mass of the motor of the drive, g [m·s^{-2}] – gravitational acceleration g = 9.81 m·s^{-2}. Substituting the values into the equations (1-4) and solving the equations, we obtain:

- F_{GTR} = 1 608.84 N,
- F_{GST} = 255.06 N,
- F_{GP} = 255.06 N,
- F_{GM} = 137.34 N.

Based on the detected weights, it is possible to exploit the equilibrium condition (5) to determine the value of the reaction at the center of gravity of the whole system T_1 (Figure 2):

$$\sum F_{iy} = 0;\ \ F_{GTR} + F_{GST} + F_{GP} + F_{GM} - R_1 = 0 \tag{5}$$

By virtue of the force and length parameters, we determine the position of the center of gravity of the conveyor in the operating position. It can be seen from Figure 2 that the sum of $l_1 + l_2$ = 345.5 mm. Employing the moment equilibrium condition (6), we can determine the dimension l$_1$ sought:

$$\begin{gathered}\sum M_{iT5} = 0; \\ -R_1 \cdot l_1 + F_{GST} \cdot \left(l_1 + l_2\right) + F_{GP} \cdot (l_1 + l_2 + b_3) + F_{GP} \cdot \left(l_1 + l_2 + b_3 + b_4\right) = 0\end{gathered} \tag{6}$$

Subsequently, we can calculate the dimension l_2 using the equation (7):

$$l_2 = b_2 - l_1 \tag{7}$$

Substituting the values into equations (5 - 7) in conjunction with solving the equations, we obtain:

- R_1 = 2 255.86 N,
- l_1 = 144.31 mm,
- l_2 = 201.19 mm.

Based on the calculated center of gravity in the z-axis, it emerges that there is no extreme change in the center of gravity position despite the considerable distance of the overhang of the conveyor drive. This phenomenon occurs because the drive with guide rods is balanced through the ultra-heavy cast iron body of the conveyor.

Further, it was required to calculate the position of the center of gravity of the conveyor in the position with the rotor extended. This mode is applied in cases where from the hygiene perspective, it is demanded to clean the inside of the conveyor or to perform other types of maintenance. In this case, identical masses as in the previous calculations have been certainly assumed. In addition, the same position of the center of gravity of the motor-gearbox-clutch system as in the previous case has been deemed because there is no movement (Figure 3). Individual quantities and dimensions are as follows: F_{GRV} – gravitational force of the conveyor lid and rotor, F_{GT} – gravitational force of the guide rod, F_{GO} – gravitational force of the middle part of the conveyor body, F_{GS} – gravitational force of the coupling, F_{GP} – gravitational force of the drive gearbox, F_{GM} – gravitational force of the electric motor of the drive, c_1 – distance between the center of gravity of the lid with the rotor and the center of gravity of the guide rods, c_2 – distance between the center of gravity of the guide rods and the center of gravity of the conveyor body, c_3 – distance between the center of gravity of the body and the center of gravity of the coupling, c_4 – distance between the centers of gravity of the coupling and the gearbox, c_5 – distance between the center of gravity of gearbox and the center of gravity of the motor, l_3 – searched distance between the center of gravity of the guide rods and the center of gravity of the system, l_4 – searched distance between center of gravity of the system and center of gravity of the body, T_{11} – center of gravity of the conveyor lid with rotor, T_{12} – center of gravity of the guide rods, T_6 – center of gravity of the conveyor system with the rotor extended, T_7 – center of gravity of the conveyor body, T_8 – center of gravity of the coupling, T_9 – center of gravity of the gearbox, T_{10} – center of gravity of the electric motor, R_2 – total reaction sought in the system with the rotor extended.

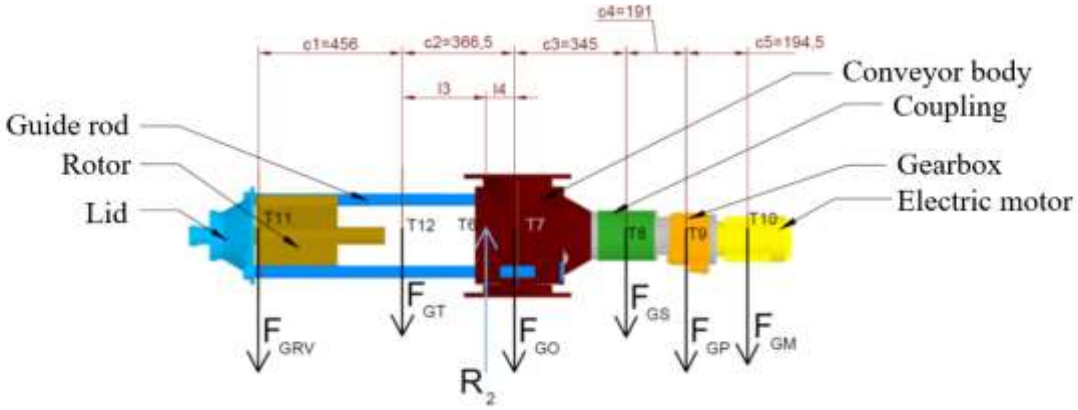

Fig. 3. 2D model of a conveyor of bulk materials in an extended state with the individual components marked and the distances of their centers of gravity considered

For equations (8 - 11), we determine the forces acting in the system, whereby the symbols from the previous calculation are retained:

$$F_{GRV} = (m_V + m_R) \cdot g \tag{8}$$

$$F_{GO} = m_{TE} \cdot g \tag{9}$$

$$F_{GT} = m_T \cdot g \tag{10}$$

$$F_{GS} = m_S \cdot g \tag{11}$$

Substituting the values into the given equations in conjunction with solving the equations, we obtain:
- F_{GRV} = 331.58 N,
- F_{GO} = 1 277.26 N,
- F_{GT} = 98.1 N,
- F_{GS} = 58.86 N.

Because the identical mass of the whole system as is in the previous case, the value of the reaction $R_2 = R_1$ was considered following the equation (5). Based on the given knowledge, it is feasible to determine the position of the center of gravity of the conveyor in the operating position using the moment equilibrium condition (12), when we determine the searched dimension l_3 as:

$$\begin{gathered}\sum M_{iT11} = 0; \\ 2 \cdot F_{GT} \cdot c_1 - R_2 \cdot \left(c_1 + l_3\right) + F_{GO} \cdot \left(c_1 + l_3 + l_4\right) + F_{GS} \cdot \left(c_1 + l_3 + l_4 + c_3\right) + \\ + F_{GP} \cdot \left(c_1 + l_3 + l_4 + c_3 + c_4\right) + F_{GM} \cdot \left(c_1 + l_3 + l_4 + c_3 + c_4 + c_5\right) = 0\end{gathered} \tag{12}$$

Figure 3 shows that the sum of $l_3 + l_4$ = 366.5 mm. Employing the acquired knowledge, we are able to determine the distance between the center of gravity of the system and the center of gravity of the body in the extended state. The calculation of the dimension l_4 is then given by equation (13):

$$l_2 = b_2 - l_1 \tag{13}$$

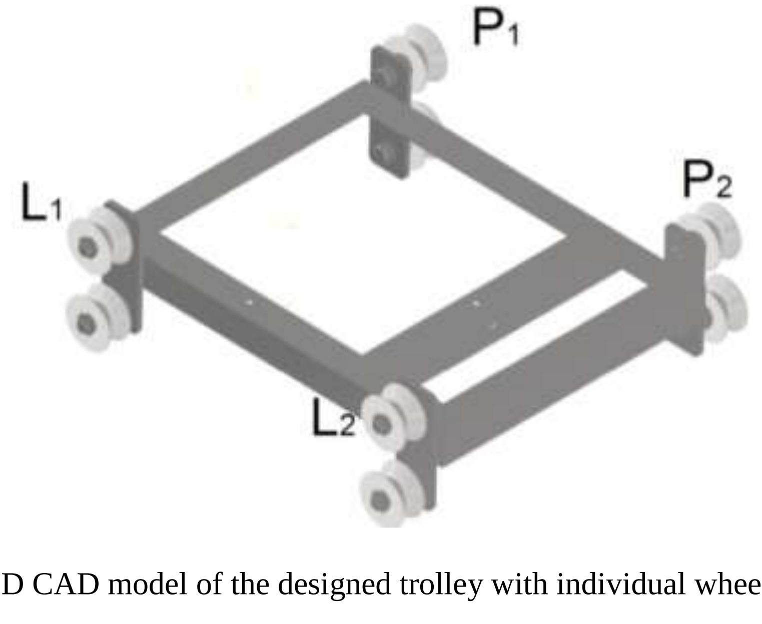

Fig. 4. A 3D CAD model of the designed trolley with individual wheel markings

Substituting the values into equations (12) and (13) and solving the equations, we obtain:
- l_3 = 327.97 mm,
- l_4 = 38.53 mm.

Thus, the position of the center of gravity of the conveyor is ascertained. A conceptual design of the trolley (Figure 4) emerges from the geometry of the conveyor. The trolley will be part of the proposed manipulator and it will function as a conveyor carrier. After the preliminary design of the shape of the trolley, it will be possible to determine the longitudinal and transverse position of the center of gravity of the entire conveyor trolley through further calculations. This assembly will load the proposed supporting steel structure - a track of the manipulator. Because the original design of the trolley is created in Autodesk Inventor, it was possible to determine directly in this software the position of the center of gravity of the trolley itself in both the transverse and longitudinal directions. The software determined the weight of the trolley based on the model as $m_{VO} = 23$ kg.

The selected material for the trolley is steel EN X5CrNi18-10 with yield strength $R_e = 180$ MPa. The total weight of the conveyor including flanges, rubber seals and fasteners in the form of bolts, nuts and washers (Figure 5) is $m_{GTP} = 255.91$ kg. Individual components are listed in Table 1.

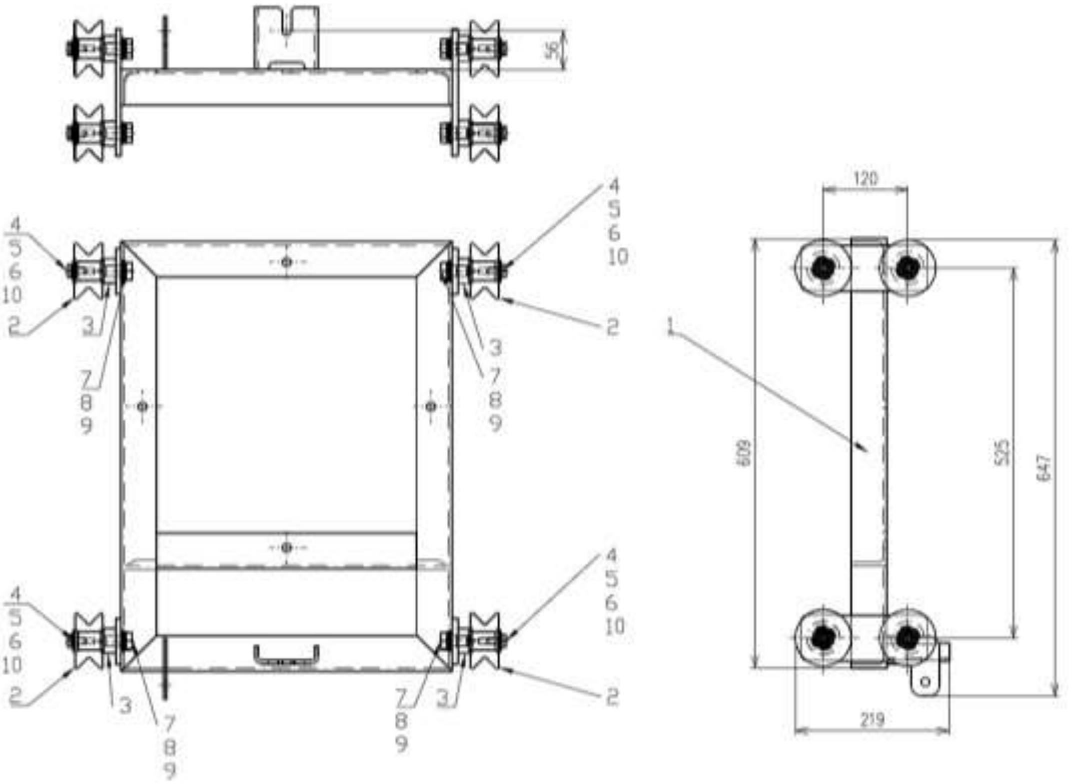

Fig. 5. Technical drawing of the conveyor trolley

Tab. 1

A list of items of the conveyor trolley

Item	Description	Drawing - standard	Material	Qty	Weight [kg]
1	Trolley frame	VT 213 132	DIN 1.4301	1	12.882
2	Wheel	VT 313 116	DIN 1.4301	8	0.857
3	Axle pin	VT 313 117	DIN 1.4301	8	0.257
4	Bolt M10x20	DIN 933	DIN 1.4301	8	0.024
5	Washer Ø10	DIN 128	DIN 1.4301	8	0.002

6	Washer Ø10	DIN 9021	DIN 1.4301	8	0.012
7	Bolt M16x28	DIN 933	DIN 1.4301	8	0.081
8	Washer Ø16	DIN 128	DIN 1.4301	8	0.008
9	Washer Ø16	DIN 125	DIN 1.4301	8	0.011
10	Bearing PTFE 25x35	–	PTFE	8	0.002

Based on the known distance, we can assume that the sum of the values of distances of the individual forces from the central center of gravity is equal to the value of distance of 108 mm, that is, $l_5 = l_6 + l_7 = 108$ mm. In the case of the longitudinal position of the center of gravity, we consider the distance between the centers of gravity of the conveyor with flanges and the trolley is $l_5 = 108$ mm, based on the model in Autodesk Inventor (Figure 6). Dimensions and quantities are as follows: F_{GTP} – gravitational force of the conveyor with flanges and fasteners, F_{VO} – gravitational force of the trolley, l_6 – longitudinal distance between the center of gravity of the conveyor and the center of gravity of the trolley-conveyor system, l_7 – longitudinal distance between the center of gravity of the system and the center of gravity of the trolley, l_5 – longitudinal distance between the center of gravity of the conveyor and the center of gravity of the trolley, T_{13} – center of gravity of the conveyor-trolley system in the longitudinal direction, T_{14} – center of gravity of the conveyor with flanges and fasteners in the longitudinal direction, T_{15} – center of gravity of the trolley in the longitudinal direction, R_3 – total reaction sought in the center of gravity of the trolley-conveyor system.

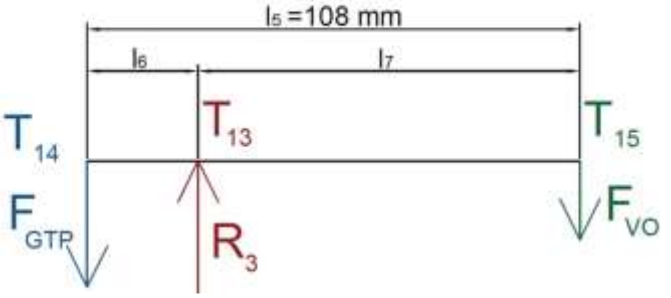

Fig. 6. A longitudinal center of gravity of a system of the conveyor with trolley

First, it is essential to determine the forces acting in the system from the known values of the masses and the gravitational acceleration in line with formulas (14) and (15):

$$F_{GTP} = m_{GTP} \cdot g \tag{14}$$

$$F_{VO} = m_{VO} \cdot g \tag{15}$$

where m_{GTP} [kg] - mass of the conveyor with flanges and fasteners $m_{GTP} = 255.91$ kg, m_{VO} [kg] - mass of the trolley $m_{VO} = 23$ kg, g [m·s^{-2}] - gravitational acceleration $g = 9.81$ m·s^{-2}.

Substituting the values into the equations (14) and (15) in conjunction with solving the equations, we obtain:

- $F_{GTP} = 2\,510.477$ N,
- $F_{GVO} = 225.06$ N.

Second, based on the detected weights, the longitudinal position (l_6, l_7) of the center of gravity T_{13} can be determined using both the equilibrium condition (16) and equation (17) (Figure 6):

$$\sum M_{iT14} = 0;\ -R_3 \cdot l_6 + F_{VO} \cdot l_5 = 0 \tag{16}$$

$$l_7 = l_5 - l_6 \tag{17}$$

Substituting the values into equations (16), (17) and subsequently solving the equations, we obtain:

- $l_6 = 8.91$ mm,
- $l_7 = 99.1$ mm.

A case of the transverse center of gravity is deemed as the most negative case. In other words, it is the case in which the center of gravity of the conveyor is the most distant from the center of its body (Figure 7), that is, the transverse center of the trolley. Quantities and dimensions marked in Figure 7 are as follows: F_{GTP} – gravitational force of the conveyor with flanges and fasteners, F_{VO} – gravitational force of the trolley, l_8 – a transverse distance between the center of gravity of the conveyor and the center of gravity of the trolley-conveyor system, l_9 – a transverse distance between the center of gravity of the system and the center of gravity of the, l_1 – a transverse distance between the centers of gravity of the conveyor and the trolley, T_{16} – center of gravity of the conveyor-trolley system in the transverse direction, T_{17} – center of gravity of the conveyor with flanges and fasteners in the transverse direction, T_{18} – center of gravity of the trolley in the transverse direction, R_3 – the total reaction sought in the center of gravity of the trolley-conveyor system. Such an instance occurs when the conveyor rotor is retracted into the body. We consider the trolley as a transversely symmetrical body.

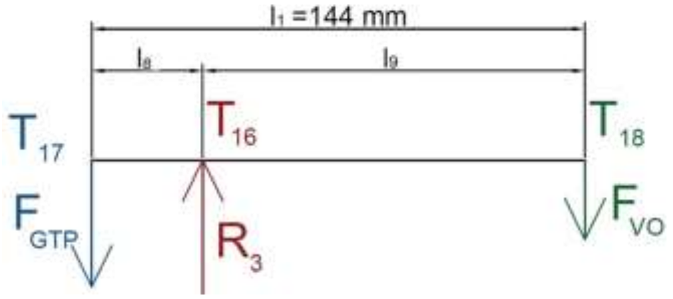

Fig. 7. A transverse center of gravity of the system of the conveyor with trolley

Based on the weights (remain same as for the longitudinal direction), the longitudinal position (l8, l9) of the center of gravity T_{16} can be determined using the equilibrium condition (18) and equation (19) (Figure 7):

$$\sum M_{iT17} = 0;\ -R_4 \cdot l_8 + F_{VO} \cdot l_1 = 0 \tag{18}$$

$$l_9 = l_1 - l_8 \tag{19}$$

Substituting the values into equations (16) and (17) and solving the equations, we obtain:
- l_8 = 11.88 mm,
- l_9 = 132.4 mm.

4. CONCLUSION

This paper focused on the analytical quantification of the masses and the center of gravity positions of the conveyor of bulk materials. The conveyor will load the proposed structure in operation in diverse operating modes. Because it was not feasible to obtain a functional CAD model of the conveyor (supplied by an external company) and the manufacturer did not even indicate the position of the center of gravity of this device, it was necessary to divide the device into several parts and determine the center of gravity of the whole conveyor based on their masses and positions of the centers of gravity. After considering the geometric and mass parameters of the conveyor, a trolley was designed to move the conveyor in operation. Ultimately, the determined sub-target can be regarded to have been met.

Future research needs to be on calculations of reactions of the conveyor track from the trolley transmitted through the prismatic wheels. Subsequently, it will be attainable to determine the bending moments induced on the supporting structure (track of the trolley) and to calculate the resistances acting against the movement of the trolley. These will then be needed in the design of the conveyor´s manipulator.

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