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Research Article

Design of hydraulic lift system of technical equipment working in amusement industry

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Abstract: This paper examines the design and application of a telescopic hydraulic system for amusement industry equipment that experiences cyclic passenger loads. The system comprises three hydraulic cylinders, each with different diameters, which activate at various points as the device moves. To achieve static balance and lift the main beam from a horizontal to a vertical position, the forces exerted by the cylinders were calculated using static equilibrium equations. The system's design, including the length and angle of each cylinder, was based on the technical specifications of the equipment. Analytical and numerical methods were used to ensure the correct sizing of the cylinders and the system's overall effectiveness, resulting in a structure that operates safely and efficiently.

Keywords: Structural design; Technical device; Calculation; Analysis

I. INTRODUCTION

Nowadays, more than ever, it is noticeable that work comes first in life. Sadly, there is no time left for ordinary joy in life, so people should diversify their free time [1]. Relaxing from everyday worries is important in preventing psychological and physical problems brought about by such a hectic lifestyle [2-4]. Therefore, the contribution of the amusement industry and its technical facilities should not be negligible [5].

The historical development of technology used in the entertainment industry was analyzed in detail in works [1, 6], which was followed up in work [7], where the authors, among other things, also addressed the materials used in the construction of such devices [8-11], the design of the drive and units of the proposed device in question (**Fig. 1** to **Fig. 4**), carrying passengers, were presented.

Normative requirements that must be met in the design of technical equipment working in the amusement industry within the Slovak Republic were published in papers [12, 13]. In them, the proposed device was presented with geometry and individual structural units such as seats for passengers, gondolas carrying the seats, lattice structures carrying the gondolas, a drive mechanism, the main beam of the device and the movement possibilities of the proposed device. Structural proposals were supported by strength analytical and numerical calculations. The presented issue is a large-scale issue; therefore, the other two works [14, 15] were aimed at the research, design and calculation of other structural units of the device. The current work provides the results in a design of hydraulic cylinders used for positioning the given technical equipment [16-18]. The considered movement possibilities of the lifting mechanism are shown in **Fig. 3** and **Fig. 4**.

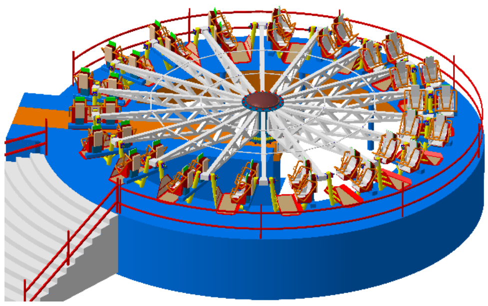

Figure 1. *A three-dimensional CAD model of the structural design of the technical device working in the amusement industry – Position No. 1*

Position No. 1 of the proposed device (**Fig. 1**) represents the rest state when the device is prepared for the boarding and exit of passengers to individual gondolas. As it was published in previous works, the gondola is designed for two passengers with a human weight of 100 kg (the gondola load safety coefficient required by the standard is 6) with a minimum required height of 135 cm (follows from the standard STN EN 547-3 + A1 due to safety of the mechanism). The number of gondolas is 18, representing 36 seated passengers spread over a wheel spacing of 5.73 m.

Position No. 2 of the proposed device (**Fig. 2**) represents the tilting of the gondolas in the direction of the acting centrifugal force, which is created by the effect of rotating the wheel at the proposed revolutions 14 min^{-1}, which will cause a maximum gravity acceleration of 2.2 g the passengers will feel. According to the STN EN 13814 standard, maximum of 6 g is allowed. The structure is rotated by an electric motor using a gear. More information about the designed device's operation principle can be found in the works [4-7].

Figure 2. *A three-dimensional CAD model of the structural design of the technical device working in the amusement industry – Position No. 2*

Figure 3. *A three-dimensional CAD model of the structural design of the technical device working in the amusement industry – Position No. 3*

Position No. 3 of the proposed device (**Fig. 3**) represents the engagement of the lifting mechanism in operation when the wheel with gondolas is raised using a hydraulic cylinder, i.e., from a horizontal position (**Fig. 2**) to a vertical one (**Fig. 4**). Here, the main component is the beam, whose load, geometry and principle of operation were solved by the authors in the paper [8].

The main beam will be raised using a hydraulic system with a telescopic cylinder, while the geometry of the mechanism resulted in the lengths of the cylinders l_{v1} = 1.4 m, l_{v2} = 1.6 m, l_{v3} = 1.8 m and the total length of extension from the point of attachment of the cylinders will be l_{vc} = 6.96 m. The CATIA V5 software was used to determine the angles at which the cylinders would push into the beam.

Figure 4. *A three-dimensional CAD model of the structural design of the technical device working in the amusement industry – Position No. 4*

II. Determination of the Necessary Lifting Forces of Hydraulic Cylinders

The cylinder No. 1 starts to push the structure at the angle of α_1 = 50° (**Fig. 5**). In the given figure, point 1 indicates the attachment point of the telescopic system in the anchoring of the device, the thick lines are the intended beam (length from the rotary link to the holder of the telescopic system), the dashed lines depict the length of the cylinders' extension, before the start of pushing to the final position of the device. The values α_1 = 50°, α_2 = 46.88°, α_3 = 53.484° and α_4 = 67.689° are the angles at which the telescopic system pushes at different positions of the beam, β_1 = 23.301° and β_2 = 51.032° are the angles at which the device lifts. In previous publications, the values of F_k = 304,210.65 N (load from the weight of the wheel structure) and F_m = 16,196.31 N (load from the weight of the electric motor with accessories used to rotate the wheel with nacelles) were determined. Thus, to determine the force exerted by the cylinders, adding the beam F_n itself is necessary, which can be written as a continuous load q_n (see Eqs. (1-2)). This load can be obtained according to Eq. (2) if the mass of the beam m_n = 10,058.57 kg (Eq. (1)) and the height of the beam section h = 1.3 m are known:

$$F_n = m_n \cdot g\,, \tag{1}$$

$$F_n = 10,058.57 \cdot 9.81 = 98,674.57 \text{ N}\,,$$

$$q = \frac{F_n}{h}\,, \tag{2}$$

$$q = \frac{98,647.57}{1.3} = 75,903.52 \text{ N} \cdot \text{m}^{-1}\,.$$

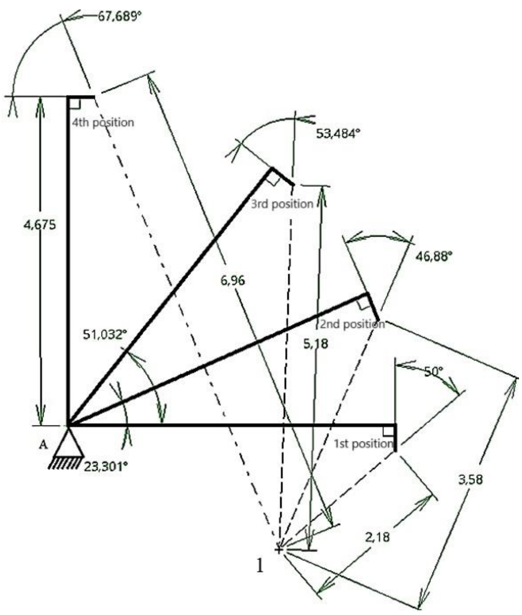

***Figure 5.** A designed geometry of the extrusion of individual cylinders*

Length dimensions of the beam according to **Fig. 6** are a = 4.675 m (a distance from a rotary coupling to a cylinder attachment), b = 0.375 m (a distance from a beam axis to a horizontal axis of a cylinder attachment), k = 3.325 m (a distance from a wheel axis to a hydraulic cylinder attachment axis), l = 8.566 m (a total length of the beam).

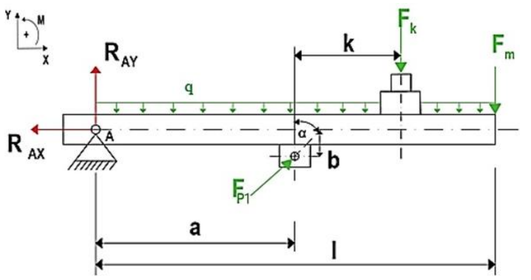

***Figure 6.** A calculation scheme of the hydraulic cylinder No. 1 – the 1st position*

The initial force acting from the hydraulic cylinder No. 1 can be expressed using Eq. (3):

$$\begin{aligned} &\sum_i M_{iA} = 0 \quad \Rightarrow \\ &F_{P1} \cdot \cos\alpha \cdot a + F_{P1} \cdot \sin\alpha \cdot b - \\ &-F_m \cdot l - F_k \cdot (k+a) - \frac{q \cdot l^2}{2} = 0. \end{aligned} \tag{3}$$

The angle α = 50° applies for the cylinder No. 1 needed to generate the force of the first cylinder. Then, it is get (Eq. (4)):

$$F_{P1} = \frac{F_m \cdot l + F_k \cdot (k+a) + \dfrac{q \cdot l^2}{2}}{\cos\alpha \cdot a + \sin\alpha \cdot b} \tag{4}$$

and after substituting, we get F_{P1} = = 1,627,186.68 N.

The obtained force is considered only at the beginning of the first cylinder pushing. Logically, further forces must decrease until the final position of the stroke. When cylinder No. 1 extends by 1.4 m, the telescopic system starts to push out the second cylinder. According to **Fig. 7**, the action of the forces against the beam changes due to lifting; therefore, it is necessary to construct another balance equation when the beam is no longer in a horizontal position. To begin with, the calculation can be simplified by choosing a local coordinate system.

There are considered the obtained force only at the beginning of pushing the cylinder No. 1. Logically, further forces must decrease until the final position of the stroke. When cylinder No. 1 extends by 1.4 m, the telescopic system starts to push out the cylinder No. 2. It can be seen, according to **Fig. 7**, that the action of the forces against the beam changes due to lifting; therefore, it is necessary to construct another equation of equilibrium, when the beam is no longer in a horizontal position. To begin with, the calculation can be simplified by choosing a local coordinate system.

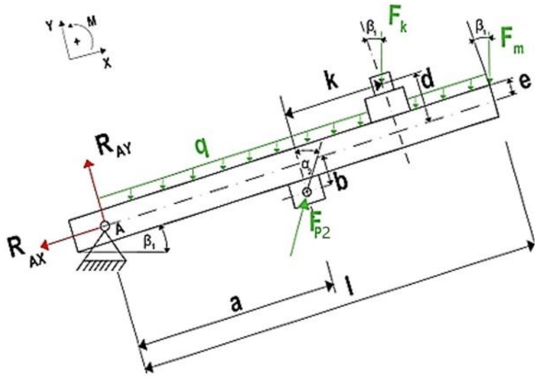

***Figure 7.** A calculation scheme of the hydraulic cylinder No. 2 – the 2nd position*

The angle, by which the beam is lifted, will be β_1 = = 23.301° and the angle at which the second cylinder pushes will be α_2 = 46.88°. Since the forces F_k and F_m are not normal to the axis of the beam, the forces for the x axis must also be considered. The center of gravity, to which the force F_m acts, is distance from the main axis of the beam marked as e and it has a value of e = 0.125 m, and the distance d = 1.171 m applies to the force F_k. Then, according to **Fig. 7**, it is possible to compile the moment equation to the point A for which applies (Eq. (5)):

$$\begin{aligned} &\sum_i M_{iA} = 0 \quad \Rightarrow \quad -\frac{q \cdot l^2}{2} \cdot \cos\beta_1 - \\ &-F_m \cdot [\cos\beta_1 \cdot l - \sin\beta_1 \cdot e] - \\ &-F_k \cdot [\cos\beta_1 \cdot (a+k) - \sin\beta_1 \cdot d] + \\ &+F_P \cdot [\cos\alpha_2 \cdot a + \sin\alpha_2 \cdot b] = 0. \end{aligned} \tag{5}$$

The force for the hydraulic cylinder No. 2 is possible to get by a modification of Eq. (5), (see Eq. (6)):

$$\begin{aligned} F_{P2} = &\frac{F_m \cdot \cos\beta_1 \cdot l}{\cos\alpha_2 \cdot a + \sin\alpha_2 \cdot b} - \\ &-\frac{F_m \cdot \sin\beta_1 \cdot e + F_k \cdot \cos\beta_1 \cdot (a+k)}{\cos\alpha_2 \cdot a + \sin\alpha_2 \cdot b} - \\ &-\frac{F_k \cdot \sin\beta_1 \cdot d + \frac{q \cdot l^2}{2} \cdot \cos\beta_1}{\cos\alpha_2 \cdot a + \sin\alpha_2 \cdot b}. \end{aligned} \tag{6}$$

and after substituting, it will be F_{P2} = = 1,377,410.81 N.

The initial force for the cylinder No. 3 can be expressed similarly to the cylinder No. 2 according to Eq. (5) because only the angles at which the forces act will change (**Fig. 8**). The values of the angles are β_2 = 51.032° and α_3 = 53.484°:

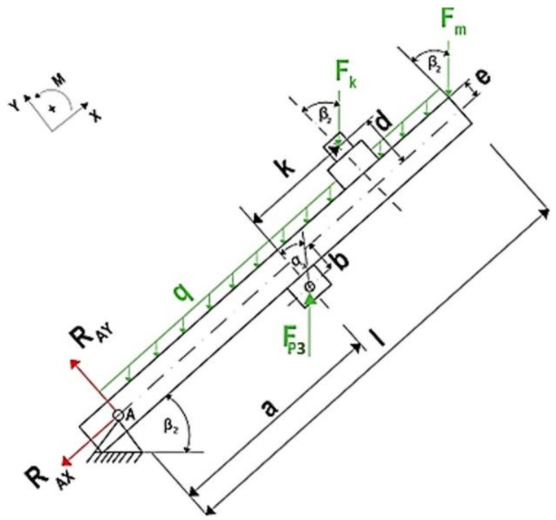

Figure 8. *A calculation scheme of the hydraulic cylinder No. 3 – the 3rd position*

Then, the force for the cylinder No. 3 will be given in Eq. (7):

$$\begin{aligned} F_{P3} = &\frac{F_m \cdot \cos\beta_1 \cdot l}{\cos\alpha_3 \cdot a + \sin\alpha_3 \cdot b} - \\ &-\frac{F_m \cdot \sin\beta_2 \cdot e + F_k \cdot \cos\beta_2 \cdot (a+k)}{\cos\alpha_3 \cdot a + \sin\alpha_3 \cdot b} - \\ &-\frac{F_k \cdot \sin\beta_2 \cdot d + \frac{q \cdot l^2}{2} \cdot \cos\beta_2}{\cos\alpha_3 \cdot a + \sin\alpha_3 \cdot b} \end{aligned} \tag{7}$$

and after substituting F_{P3} = 1,002,363.57 N.

After determining all three initial forces, it is clear that the force with which the telescopic system needs to be pushed on the beam decreases. The beam tilting helps to it. This means there is a certain dependence between the force required to lift the beam and the length of extension of the cylinders. This dependence can be written down graphically. However, firstly, it is necessary to determine the final force from the cylinders so that the dependence can be shown throughout the stroke. The forces acting on the device in the vertical position are, therefore, according to **Fig. 9**, where the force from the cylinders acts at an angle α_4 = 67.689°. It is possible to set, based on **Fig. 9**, the moment equation to point A, for which it is valid (see Eq. (8)):

$$\begin{aligned} &\sum_i M_{iA} = 0 \quad \Rightarrow \quad F_m \cdot e + F_k \cdot d + \\ &+F_{P4} \cdot \cos\alpha_4 \cdot a + F_{P4} \cdot \sin\alpha_4 \cdot b = 0. \end{aligned} \tag{8}$$

Modification and substituting lead to the force from the telescopic cylinders in the vertical position of the amusement device F_{P4} = - 168,851.77 N.

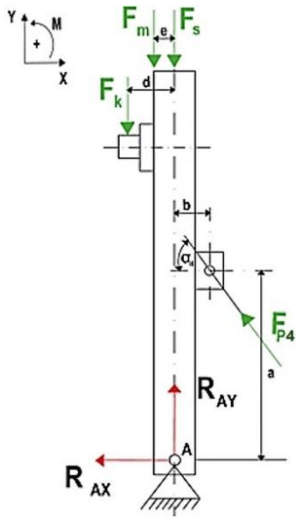

Figure 9. *A calculation scheme for the vertical position – the 4th position*

The force for the vertical position of the amusement device came out in the negative direction, because the forces F_m and F_k are located behind the pivot point of the beam. Thus, at a certain

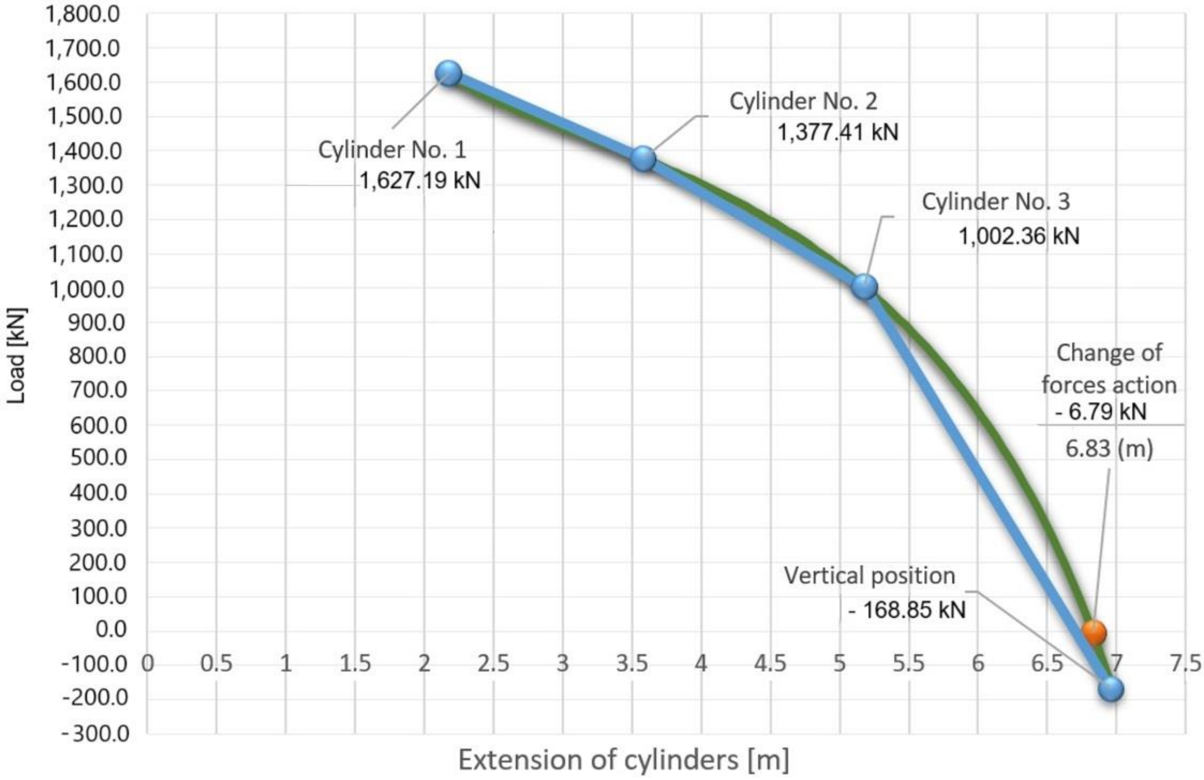

Figure 10. *A dependence of the load on the extension of cylinders*

point of tilt, these forces stop creating a moment against the $F_{PIEST\,4}$ force, but they begin to support this force and help it rotate the device around the rotational coupling. Then, the load's dependence on the cylinders' extension is shown in **Fig. 10**.

The first, a blue curve, is created from 4 points connected by linear lines, which means the curve considers only the cylinders' initial forces in the places where they start to push to the final value. The second curve, shown by a green curve, represents the function processed using the relation (6), where the results of the forces were graduated by 5 cm and thus 97 results were processed, from which a more accurate hyperbolic function is obtained. According to these results, it can be concluded that the proposed device reaches beyond the axis of rotation approximately at a length of 6.8 m measured from the mount of the telescopic system.

III. DESIGN OF THE CYLINDER DIAMETERS ACCORDING TO THE INITIAL FORCES

The correct diameters of the cylinders of the telescopic system must be determined to lift the proposed technical device safely. These diameters can be quantified using simple relationships when the initial cylinder lift force and feed fluid pressure are known. The pressure in the system will be set to p = 35 MPa. Therefore, Eq. (9) is valid for the cylinder No. 1:

$$F_{P1} = p \cdot S_1 \quad \Rightarrow \quad S_1 = \frac{F_{P1}}{P}$$
$$S_1 = \frac{1{,}627{,}186.68}{35} = 46{,}491.02 \text{ mm}^2. \tag{9}$$

Then, the radius of the cylinder No. 1 r_1 is (see Eq. (10)):

$$S_1 = \pi \cdot r_1^2 \quad \Rightarrow \quad r_1 = \sqrt{\frac{S_1}{\pi}}$$
$$r_1 = \sqrt{\frac{46{,}491.05}{\pi}} = 121.65 \text{ mm} \tag{10}$$

at which, the active diameter of the hydraulic cylinder D_1 is given by Eq. (11):

$$D_1 = 2 \cdot r_1 = 2 \cdot 121.65 = 243.3 \text{ mm} \tag{11}$$

A normalized cylinder with the diameter D_1 = 245 mm was chosen. Similarly, it is possible to determine the diameter of the cylinder No. 2 D_2 using Eqs. (12-14):

$$F_{P2} = p \cdot S_2 \quad \Rightarrow \quad S_2 = \frac{F_{P2}}{P}$$
$$S_2 = \frac{1{,}337{,}410.81}{35} = 39{,}354.59 \text{ mm}^2. \tag{12}$$

The radius of the cylinder No. 2 r_2 is (see Eq. (13)):

$$S_2 = \pi \cdot r_2^2 \quad \Rightarrow \quad r_2 = \sqrt{\frac{S_2}{\pi}}$$
$$r_2 = \sqrt{\frac{39,354.59}{\pi}} = 111.92 \text{ mm} \tag{13}$$

at which, the active diameter of the hydraulic cylinder No. 2 is given by Eq. (14):

$$D_2 = 2 \cdot r_2 = 2 \cdot 111.92 = 223.84 \text{ mm}, \tag{14}$$

therefore, the normalized cylinder with the diameter D_2 = 245 mm was chosen.

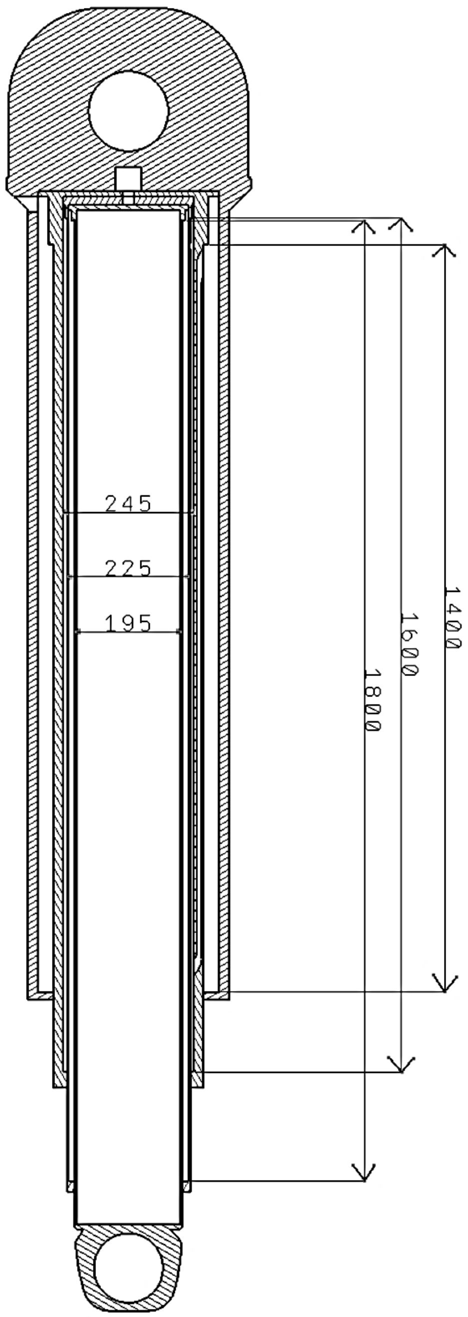

Figure 11. *The main dimensions of the designed telescopic system*

Finally, Eqs. (15-17) serve to calculate the diameter of the cylinder No. 3:

$$F_{P3} = p \cdot S_3 \quad \Rightarrow \quad S_3 = \frac{F_{P3}}{P}$$
$$S_3 = \frac{1,002,363.57}{35} = 28,638.96 \text{ mm}^2. \tag{15}$$

The radius of the cylinder No. 3 is (see Eq. (16)):

$$S_3 = \pi \cdot r_3^2 \quad \Rightarrow \quad r_3 = \sqrt{\frac{S_3}{\pi}}$$
$$r_3 = \sqrt{\frac{28,638.96}{\pi}} = 95.48 \text{ mm} \tag{16}$$

and the active diameter of the hydraulic cylinder No. 3 is given by Eq. (17):

$$D_3 = 2 \cdot r_3 = 2 \cdot 95.48 = 190.96 \text{ mm} \tag{17}$$

Based on the previous calculation, the normalized diameter of the hydraulic cylinder No. 3 is chosen with the diameter of D_3 = 195 mm. According to the observed diameters of individual hydraulic cylinders, it is possible to set up a telescopic system with corresponding diameters, as depicted in **Fig. 11**.

IV. Conclusion

The paper discussed the research on a structural design of a telescopic hydraulic system implementable in a technical equipment cyclically stressed by the variable load from passengers. Overall, many publications on this issue focused on normative analytical and numerical solution methods. The beginning of the research consisted of the analysis of the historical development of the entertainment industry from the beginning to the present day, together with the presentation of the main components used in constructing such facilities and their material base. Here, information resulting from valid procedures and standards such as STN EN 13814 and STN EN 13814-1 was fully utilized. In the following solution to the problem, the proposed type of amusement device was presented together with the technical specifications and the place of an implementation, where the maximum number of passengers was 18 and other parameters of the device were normatively derived accordingly. The research was further devoted to creating a 3D CAD model with the help of the CATIA V5 software , which was logically based on derived dimensional calculations. After designing the geometry of the individual components, analytical and numerical methods were used to accurately design the selected structural units as a gondola assembled for two passengers and adapted to the main dimensions of the body according to the STN EN 547-3 + A1 standard, with the maximum load capacity of 100 kg per passenger. Further calculations focused on the design of the truss structure and the hollow shaft, verified using analytical and numerical methods. During the design, attention was also paid to the specific calculation of the electric motor's power, which resulted in an electric motor with a conical-frontal gearbox with an output of 90 kW, together with the gear transmission design. The main beam of the amusement device was checked for the required deflection according to the STN EN 13814 standard using analytical calculations, and the numerical method was also checked in the ANSYS software. All these steps resulted in the presented work in the possibility of determining the dependence of the load on the extension of the cylinders of the telescopic system, and a suitable diameter of the individual cylinders was proposed. This system will consist of three hydraulic cylinders with different diameters, and each cylinder starts pressure at a different device position. However, this was preceded by quantifying the forces with which the cylinders will act on the main beam to achieve static equilibrium and lift it to the desired position (from horizontal to vertical). This, the forces were determined using the static equilibrium equations. The geometry of the cylinders (length, angles at which the cylinders begin to act on the beam) was chosen based on the parameters of the proposed technical device resulting from previously published research work.

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AUTHOR CONTRIBUTIONS

M. Blatnický: Conceptualization, Methodology, formal analysis, writing – original draft preparation.

J. Dižo: Software, Validation, Writing – original draft preparation, Project administration.

A. Lovska: Supervision, Review and editing, Project administration, Data curation, supervision, Investigation.

V. Ishchuk: Software, Visualization, Data curation, Resources.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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