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STRUCTURAL DESIGN OF A BOOM MOUNTING OF A MAST TYPE JIB CRANE FOR HANDLING SLUDGE PUMPS

Denis MOLNÁR[1*], Miroslav BLATNICKÝ[2], Ján DIŽO[2], Vadym ISHCHUK[2]

[1*] Faculty of Mechanical Engineering, Department of Transport and Handling Machines, University of Žilina, Univerzitná 8215/1, 010 26, Žilina, Slovakia, e-mail: denis.molnar@fstroj.uniza.sk
[2] Faculty of Mechanical Engineering, Department of Transport and Handling Machines, University of Žilina, Univerzitná 8215/1, 010 26, Žilina, Slovakia

Abstract: The paper is a continuation of the issue of the technical solution of a mast type jib crane for handling sludge pumps. It serves for the use in Building no. 900, Block V2, of the nuclear power plant Jaslovské Bohunice. It is an optimization of the original, in-service damaged handling device with manual control of lift and rotation. The overloading of the device has an insignificant effect on the lifting force on a crank handle. It was found that the lifting force permanently falls within the recommended range of 120 to 160 N for convenient operation by a single worker. Inasmuch as there is a complete absence of bearings in the slewing gear in the original design, it is the solution to this issue that is the subject of the paper. The problem of pulling out the sludge pumps, which was established in the course of using the jib crane, ingeniously provided the opportunities to further design changes on the original design. The solution offered was to scrap the original design of the carrier inserted into the support and replace it with a fixed mast on which the boom would rotate. Accordingly, it would potentially be feasible to increase the load capacity of the jib crane, and thus the issue of the sludge pumps attached to the tank bottom would be solved. Moreover, it is attainable to extend the scope of this crane in this way.

Keywords: mast type jib crane, handling, structural design, functional calculation, load capacity

1. INTRODUCTION

In olden times, human or animal power was used to transport loads, mainly by a direct action of this power. It was only with the passage of time that mechanical aids and various devices were developed to facilitate the transport of heavier loads which humans could not move without the aid of these devices [3,5,11]. The motion of these devices was ensured by human or animal power, and it was over time that energy of water (a mill) or wind energy began to be used to power some of the devices [4,6,12]. Mechanical power was achieved by means of a steam engine for the first time. Consequently, the first steam crane was introduced in the 18th century [1,2,6].

A crane is a lifting machine that works with the help of ropes and swivel platforms. It is primarily employed for lifting heavy loads and transporting them to other places. Cranes are valuable assets for the construction industry, since they work with heavy machinery and building materials [10,14].

Diverse types of cranes are known, each with a different design, mass, and load capacity for various types of applications. Cranes range in size from small ones, with a load capacity of several hundred kilograms, used in workshops, to huge ones with a load capacity of several hundred tonnes, used in the construction of oil platforms. Currently, the crane is the dominant device for handling loads and it is a crucial element for attaining the required productivity [3,7,13].

Modern cranes use a variety of motors and hydraulic systems that can deliver several times more force. Accordingly, they carry much heavier weights than manual cranes. Nevertheless, in some situations, it is still unnecessary to use motor-driven cranes for the reason that objects with low mass are easy to move even with the use of human power, and the use of a motor would unnecessarily increase the mass and cost of the equipment [9,10,14]. This is also the case of the lifting mechanism of the mast type jib crane designed (Fig. 1).

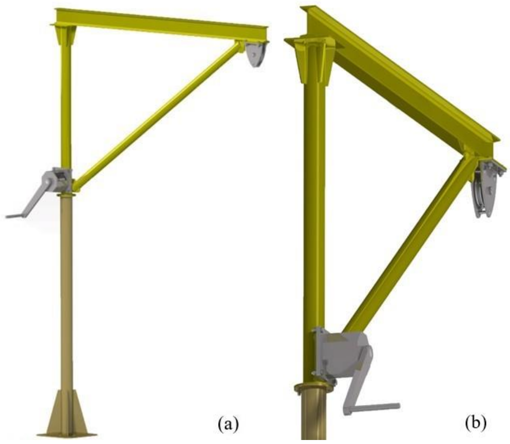

Fig. 1. 3D CAD model of the original mast type jib crane (a) and a view of this device from the winch (b)

The crane boom in question for the sludge pump handling is designed for a 250 kg load capacity, for the reason that it is not damaged in operation as the current one with a 120 kg load capacity. The paper sets out to solve the structural design of the bearing of the boom consisting of upper rolling-element bearing and lower journal bearing.

2. UPPER ROLLING-ELEMENT BEARING DESIGN

A roller bearing solution was chosen to support the upper part of the boom (Fig. 2).

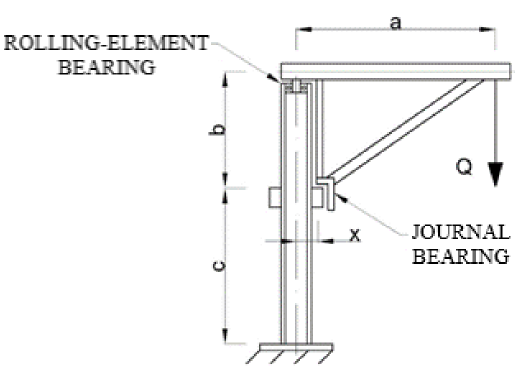

Fig. 2. Schematic design of the structure

In order to select the bearing, it was necessary to know chiefly its inner diameter. This diameter was determined from the required dimension of the pin that connects the bearing to the boom (Fig. 3).

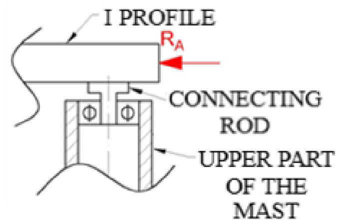

Fig. 3. A detail of the schema of the upper rolling-element bearing

It can be seen from Fig. 3 that the connecting pin will be stressed predominantly in shear due to the R_A force analysed in paper by Blatnický, et al [2]. Therefore, it is crucial to size a minimum diameter of the pin in this step. Formula (1) was used for this process:

$$\tau_{SD} = \frac{R_A}{S}, \tag{1}$$

where τ_{SD} (MPa) is the maximum permissible shear stress, R_A (N) is the loading force, S (mm^2) is the cross-sectional area of the pin. For structural steel of grade STN 11 500 (E295), the values of a purely pulsating shear stress according to the engineering tables are in the range τ_{SD} = 55 ÷ 85 MPa. In terms of our case, a value of 60 MPa was selected. After adjusting Formula (1) and substituting the values, the minimum cross-sectional area (2) is:

$$S = \frac{R_A}{\tau_{SD}} = \frac{3\ \ 322}{60} = 55.36\ \text{mm}^2. \tag{2}$$

Further, the minimum pin diameter (3) needs to be calculated:

$$S = \frac{\pi \cdot d_p{}^2}{4}, \tag{3}$$

where d_p (mm) is the diameter of the pin. By adjusting Formula (3) and substituting the values, it is possible to obtain the minimum pin diameter:

$$d_p = \sqrt{\frac{S\cdot 4}{\pi}} = \sqrt{\frac{55.36\cdot 4}{\pi}} = 8.4\ \text{mm}. \tag{4}$$

For the sake of safety, k = 1.5 and visual proportionality, it was concluded to use a pin with diameter d_p = 20 mm. A single row angular contact ball bearing type 7304 B 20x52x15 from the ZVL Slovakia catalogue [15] was chosen for the selected diameter. Subsequently, a safety calculation was carried out in accordance with the formula of ZVL company (5):

$$s_o = \frac{C_{or}}{P_{or}}, \tag{5}$$

where s_o (-) is the static safety factor, C_{or} (N) is the basic radial load rating and P_{or} (N) is the static equivalent radial load. The basic radial load rating is a tabulated value. The value of C_{or} for the selected type 7304 B 20x52x15 is 9.6 kN. The static equivalent radial load P_{or} amounts to R_A = 3 322 N [2]. The static safety factor value is subsequently calculated according to Formula (5) as:

$$s_o = \frac{9.6 \cdot 10^3}{3\ \ 322} = 2.89\ (\text{-}).$$

On the basis of Table 1 of the ZVL Slovakia company [15], the value of s_o for ball bearings is 1.5. Inasmuch as the calculated value of static safety factor, specifically 2.98, is higher than the value of 1.5, it can be stated that the safety condition is met.

Tab. 1. Values of static safety factor

Static safety factor s_o			
Bearing motion	Type of load, bearing running requirements	s_0 ball bearing	s_0 cylindrical, needle, spherical, and tapered roller bearings
swinging	Large swing angle with low frequency and approximately periodic loading	1.5	2.5

After designing the dimensions of the pin and bearing, the individual dimensions of a bearing housing unit were designed. The standardized dimensions of the ball bearing, bearing snap ring and bearing-housing seal in accordance with the engineering tables had to be taken into account. The bearing is pressed into the housing and secured by means of the retaining ring. The whole bearing housing unit is fitted with clearance into the mast and welded all round (Fig. 4).

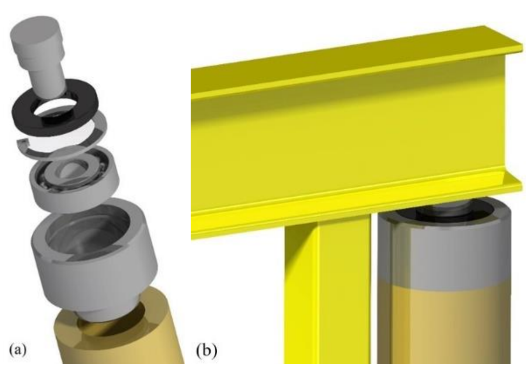

Fig. 4. 3D CAD model of the used components of the designed roller-element bearing (a) and display of a rolling bearing of the boom in working condition (b)

3. LOWER JOURNAL BEARING ASSEMBLY DESIGN

The design of the bottom bearing was based on the condition to transfer the vertical forces from the boom along with the forces from a stiffener into this part [3]. Another condition was to place the entire mechanism of the proposed electrical rotation in this part. First, the supporting part had to be sized, which is connected to the mast in a non-rotatable way and on which the boom moves by means of sliding bearings. Additionally, the gearing of the rotating mechanism is mounted here.

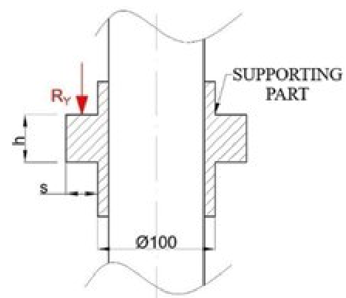

Fig. 5. Schematic representation of the supporting part

Because of the further pressing of the journal bearings as well as the gear wheel, it was necessary to produce a cylindrical component with precise external dimensions which will be welded to the mast (Fig. 5, Fig. 6).

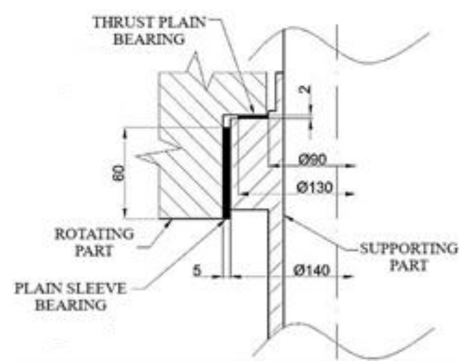

Fig. 6. Schematic representation of a geometry of the proposed journal bearing assembly

It is evident from the schema (Fig. 6) that the supporting part will be stressed predominantly in shear from force R_y. The bending stress was neglected to the extent that the dimension s proved to be excessively small for the R_y force to exert a bending stress on it, even after the final design. First, it was essential to ascertain the size of the area subjected to shear stress according to Formula (6):

$$\tau_{S_{max}} = \frac{R_y}{S_k}, \tag{6}$$

where τ_{Smax} (MPa) is the maximum permissible shear stress, R_y (N) is the force generating the shear stress and S_k (mm^2) is the critical cross-sectional area. Structural steel STN 11 500 (E 295) was selected, whose values of the purely pulsating shear stress are within the range τ_{SD} = 55-85 MPa. The maximum value of 85 MPa was chosen. After adjusting Formula

(6) and substituting values into the formula, the minimum critical cross-sectional area was obtained:

$$S_k = \frac{R_y}{\tau_{S_{max}}} = \frac{2\,452.5}{85} = 28.85.$$

Further, it was possible to calculate the minimum height *h* (Fig. 5) according to Formula (7):

$$S_k = \pi \cdot d \cdot h,$$
$$h = \frac{S_k}{\pi \cdot d} = \frac{28.85}{\pi \cdot 100} = 0.09 \text{ mm}, \tag{7}$$

where *d* (mm) is the diameter of the cylindrical surface area and *h* (mm) is the height of the cylindrical surface area. Thus, the minimum height *h* for a given material and a given load was 0.09 mm. It is an extremely small value which implies that the resulting shape will be designed with safety greater than k = 1.5 (-).

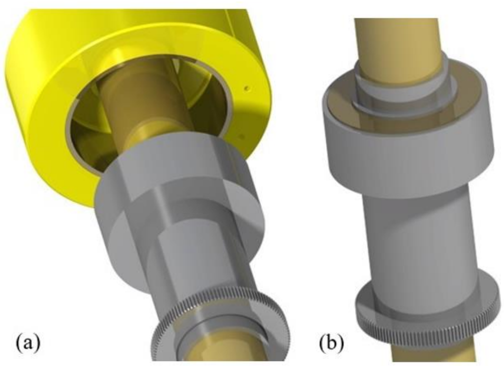

Fig. 7. Rotating (yellow) and non-rotating (grey) part of the journal bearing assembly (a) and depiction together with the journal bearings in working condition (b)

Subsequently, the most suitable dimensions of the journal bearings were selected from the ISB catalogue [8] and with respect to these dimensions, the further design was derived (Fig. 6, Fig. 7).

4. RESULTS AND DISCUSSION

4.1. Comparison of the original and modified structures

In previous papers, the problem was clearly defined based on the applied research of inspecting the damaged equipment (no photos are allowed in the nuclear power plant; therefore, no photos are available). Among other things, the attachment of the pump to the bottom of the tank was scrutinized. This phenomenon caused excessive stresses on the structure resulted in the repeated damage to the structure. In other words, the damage occurred for the reason that the force required to lift the pump stuck to the bottom of the tank was in excess of 750 N. The mast type jib crane was no longer designed for such a large force, inasmuch as the original structure had a load capacity of 50 kg and the design did not take into account the effect of the sludge pump. Further, from the investigation of the sludge pump sticking to the bottom of the tank, it was concluded that this was a normal phenomenon that could not be dealt with. Thus, changes in the design of the mast type jib crane were performed in order to ensure a sufficient load capacity of the crane. The partial result referred to in the paper is related to this issue.

The original design did not include any bearings in the rotating mechanism. The swivel support of jib was inserted into the carrier. The modified structure is made up of the support mast which the slewing boom is mounted on, the structure including upper and lower boom mountings. Moreover, the design of the boom is the same as that of the original jib crane. This design provides a gain in the load capacity of the mast type jib crane to 250 kg and ensures an elimination of the problem of the sludge pump sticking to the bottom of the tank (Tab. 2).

Tab. 2. Characteristic properties of the original and modified designs of the mast type jib crane

Mast type jib crane	Original structure		Modified structure	
Parameter	Value	Unit	Value	Unit
Tensile force in the rope – pump is not stuck to the bottom	412.02	N	412.02	N
Tensile force in the rope – pump stuck to the bottom	750	N	750	N
Load capacity of the device	50	kg	250	kg
Maximum tensile force in the rope	490.5	N	2452.5	N
Permissible bending stress	110	MPa	150	MPa
Bending stress	121.5	MPa	198	MPa

It was found that the operator would appreciate a change of the concept from manual to electric slewing of the crane boom, which will be the subject of further research, design, and calculations. A comparison of the results of the original and modified designs of the mast type jib crane can be seen in Table 2.

5. CONCLUSIONS

The paper is a continuation of the research and design of the optimal hanging and handling device employed in the nuclear power plant in Jaslovské Bohunice. This device has served and will serve for the handling of sludge pumps. Thus far, a description of the original solution has been made and the problems that arose in practice have been defined. The calculation of the acting force on the crank handle of the winding device needed to lift the load was carried out. Because of a requirement to design a given mast type jib crane with electric rotation, it was primarily indispensable in this paper to design the boom bearing. This is partly due to the unsatisfactory condition of the original design. The problem of the load capacity of the crane, which emerged in practice during the solution of the work, provided an opportunity to incorporate the solution of this problem into the content of the work.

The solution consisted of a dimensional design of a new supporting mast, as it was logically considered that the defect of the original structure was mainly the excessive bending stresses just at the locations of the vertical parts of the structure. The design of the original boom remained the same. After sizing the new supporting mast, the bearing design presented in this article was continued. The upper bearing of the boom was solved by means of the rolling-element bearing, which was made up of a rolling bearing embedded together with a retaining ring and seal in the bearing housing attached to the upper part of the mast. The lower bearing was designed to form a common block containing both the boom bearing itself and the mechanism for rotating the boom. The design resulted in a load-bearing non-rotating structure attached externally to the mast, capable of transmitting forces from the boom to the mast, incorporating a thrust plain bearing and a fixed gear wheel. The other part of the block consists of a rotating part connected to the boom, carrying a sleeve plain bearing. The gear wheel will be addressed in the further solution of the issue as part of the rotating mechanism. This is the subject of ongoing research.

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Biographical notes

Denis Molnár received his M.Sc. degree in Mechanical Engineering (specialization: Vehicles and engines) from the University of Žilina in 2021. Then he started his PhD studies at the Faculty of Mechanical Engineering at the Department of Transport and Handling Machines, the University of Žilina. His scientific interests focus on issues related to transport and handling machines, designing, FEM simulations as well as welding.

Miroslav Blatnický received his M.Sc. and PhD degrees in Mechanical Engineering from the University of Žilina, respectively. He is currently teaching at the Faculty of Mechanical Engineering, the University of Žilina. His area of research is focused on functional and strength calculations and FEM analyses in the field of transport and handling machines, hoisting machinery and steel structures.

Ján Dižo received his B.Sc., M.Sc. and PhD degrees in Mechanical Engineering from the University of Žilina, respectively. He is currently teaching at the Faculty of Mechanical Engineering, the University of Žilina. Mr. Dižo's research interest mainly focuses on the creation of MBS models and analysing dynamic structural properties of transport and handling machines.

Vadym Ishchuk received his M.Sc. degree in Mechanical engineering from the University of Žilina in 2022. Since 2022, he has been a graduate student at the Department of Transport and Handling Machines at the University of Žilina. His scientific interests focus on problems concerning the dynamics of railway rolling stock and wheel-rail interaction.