Study on the dynamics of truck loader crane during cargo unloading using modeling and simulations

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***Abstract**: This article is a study on the work operation of a hydraulic crane installed on a heavy truck known as Truck Loader Crane. The crane is used to carry loads from the truck to the ground and vice versa. It usually is an integral part of the truck mounted behind the cabin or behind the cargo body, and there are cases when it is additionally mounted on the truck. The crane has several mechanical and hydraulic parts. It is controlled from the command panel attached to the crane or by using the remote panel. The work operation analyzed is cargo unloading from the truck body on the ground. It is a complex process consisting of attaching the cargo (load) to the boom, lifting the cargo from the truck body, transferring the cargo several meters, and lowering it on the ground. During this process, the crane undergoes heavy oscillations due to the motion and swinging of the load it carries. The type of analysis is dynamic analysis, and the methodology consists of 3D modeling of the crane and implementing simulations with SimWise4D software. Through this study, the aim is to identify the nature and extent of forces and stresses on the crane and its parts, the intensity of the swinging and oscillations of the cargo, and their effect on crane operation. High oscillations can cause parts failure and raise concerns about safety. Results will be shown in graphical form for the main influential parameters. Conclusions from this paper will be useful regarding the strength of crane materials, motion dynamics and motion control of crane and cargo, design of crane parts and safety during work. The Truck Loader Crane model is designed based on the data from the standard manufacturer.*

***Keywords**: TRUCK LOADER CRANE, CARGO UNLOADING, OSCILLATIONS, DYNAMIC ANALYSIS, MODELING, SIMULATIONS*

1. Introduction

The crane that will be studied is shown in Fig.1. It is a hydraulic type crane mounted on the heavy truck. The study example is from a local company in Prishtina City that handles transport of pallets and other loads. There are two main work activities of the Crane:

- Lifting the load from the ground and lowering it to the truck's cargo body.
- Taking the load from the truck and lowering it to the ground, to some platform or even to a certain height, depending on the request.

There are situations when the crane keeps the load steady at a certain height to stabilize it for a certain amount of time.

The height H of lifting is around 2 – 3 m from the ground, depending on the cargo (load) dimensions. Crane has a defined lifting velocity.

The cargo (load) can be in various forms, it is usually a pallet with various materials, various boxes, concrete structures – pipe or plate, metallic structures, cylindrical form material, etc.

Fig.1. Crane mounted on the truck in the working environment

The type of crane is Palfinger PK 11001 [1], [3], with maximum lifting capacity Q = 4000 kg. It is mounted on a Mercedes Benz 1317 heavy truck (Fig.1). Main technical data are taken from the manufacturer's manuals and notes placed on the crane, which are shown in Table.1.

Table.1. Technical features of the Palfinger Loader Crane [1]

Crane Specifications	
Model	PK 11001
Capacity-max	4000 kg to 2.5 m range
Capacity-min	340 kg to 18.8 m range
Load torque	109 kNm
Max manual outreach	23.4 m
Max hydraulic outreach	15 m
Slewing angle	420 °
Operating pressure	290 bar
Dead weight	1510 kg

The main parts of the crane are presented in Fig.2.

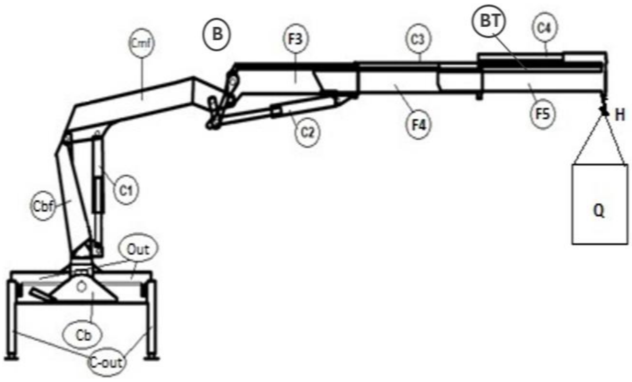

*Fig.2. Crane parts: **Out**-Outriggers; **C-out**- Outrigger cylinders; **Cb**- Crane base; **Cbf** – base frame, **B**- Boom with frames; **Cmf**- Middle frame; **F3, F4, F5** – Crane upper frames (beams), **C1, C2, C3, C4** – Crane cylinders; **BT**-Telescopic Boom; **Q** – Load (cargo) ; **H –** Hook [4]*

An electro- hydraulic system is used to move the crane. After the lifting command from the panel, the hydraulic oil is delivered by the gear pump to the oil cylinders, which pushes upwards its pistons. Then, the pistons move the Boom and load Q in various directions (Fig.2).

Dimensions of the cargo body of Mercedes Truck are Length: 7.3 m, width: 2.3 m. Cargo body of the truck is 1.5 m up from the ground.

Fig.3. Rear view foto of the main Crane Parts

Results of the research will be acquired for some main parts of the crane. Forces, torque, stresses and oscillations of the cargo-load during the cargo lowering from the truck body to the ground are considered main influential parameters for measuring strength and strain of crane [4], [5], [6]. The analysis will be carried out for the cargo-load capacity Q = 1500 kg, which is the lifting capacity for the crane based on the crane specifications and Load Q carrying distance that will be around 7 m [1]. Maximal motion speed of the crane can reach $v_{cmax} = 0.7\ m/s$. Results will be presented with graphs and then discussed.

Regarding the Literature review, some authors in their papers have studied Truck loader cranes, shown in the References, with studies regarding the crane dynamic analysis [4], [5], [7], modelling [5], [8], [11], simulations [5], [6], [11], [12], theory of dynamic analysis [7], [12], motion control and regulation [6], [9], [10] and crane safety [13].

2. Modeling of the Truck Loader crane and simulations scenario

Modell of the Truck Loader Crane is designed with software *SimWise 4D* [2]. The model contains Mercedes Truck and Loader crane with its important parts, Basement and Load Q.

Working load Q as a cargo to be carried has a box form with dimensions: *Length =1 m, Width= 1 m, Height = 1 m, Mass Q = 1500 kg*. It is placed on the Truck cargo body, ready to be moved. (Fig.4).

Loader crane has its outriggers extended for stability purposes. Distance of the outrigger from Crane Base is 2.1 m.

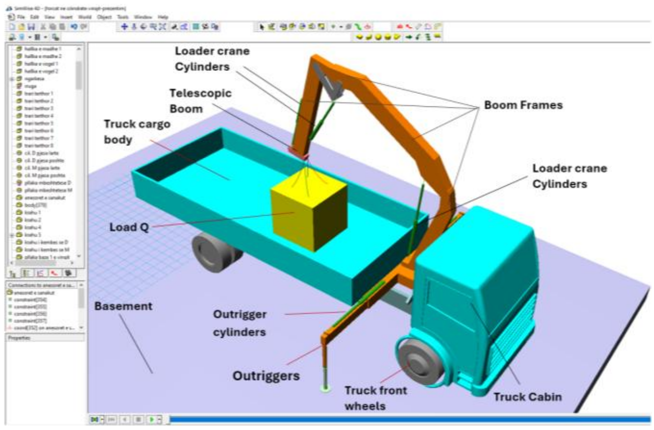

Fig. 4. Model of the Truck and Loader Crane with main parts in the software environment, in the initial position [2]

After completion of the model, simulations will be carried out to get results. Analysis with simulations will be acquired using two numerical Methods, namely Finite Elements Method (FEM) and Numerical Kutta-Merson Method, which are part of the software modules.

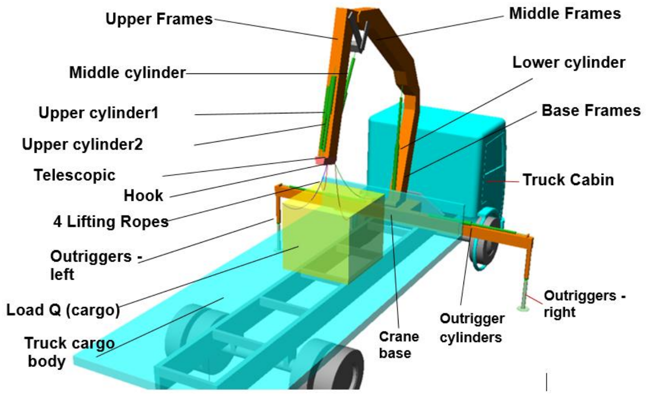

Fig.5. Modelled main parts of the Crane mounted on the truck (Rear view)

For the proper analysis of the load lowering, simulations will be organized as close as to real occasions [6]. The plan is to unload the load Q in the distance around D = 7 m from the Crane base (center). This distance is selected randomly. There are five phases of continuous Crane and Load motion identified:

- *Phase 1*: The Crane's Boom in its initial position is linked with the Load Q through the Hook and the Lifting ropes, which are not restrained (loose). Load Q stands on the cargo body at the height of 1.6 m from the ground. (Fig.4 & Fig.5).

- *Phase 2*: Crane cylinders will start the lifting from the time $t_1 = 0\ s$. Initially, they will lift unrestrained 4 ropes, and then the Load Q. Lifting will continue slowly, until the height of load 2.23 m from the ground, until the time $t_2 = 5$ s.

- *Phase 3*: Next motion is Right turning of the Boom with load Q, until time $t_3 = 21$ s. The time is longer in order to minimize the excessive load swinging.

- *Phase 4*: In this phase is the horizontal extension of Telescopic Boom and upper cylinders with load Q, to reach the unloading position in final the distance D ≈ 7 m. During this phase, the load moves horizontally to the right direction. This phase lasts until time $t_4 = 40\ s$.

- *Phase 5*: In this phase is the lowering of the load on the ground. It lasts until the time $t_5 = 43\ s$. This is the final motion process when the load Q is unloaded on the ground (Fig.6).

After the time $t_5 = 43\ s$ there is no motion, but the simulation will continue until the time $t_s = 47\ s$ to monitor the occurrences on the crane after the end of the load motion [6].

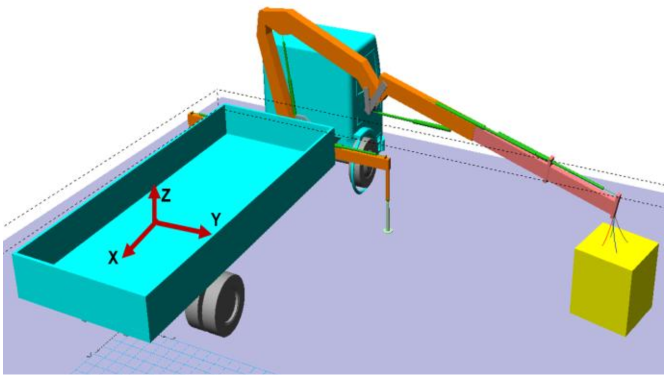

Fig.6. Final position of the simulation - Load Q is unloaded on the ground

3. Results of the unloading

Results of the Load motion and unloading will be presented in the form of graphs for influential dynamic parameters for some main parts of the crane and for the load Q. These parameters are kinematic and dynamic in nature: Forces in the cylinders, Resultant Force and Torque in joints, Stress in the crane frame; Load Q motion, speed and swinging.

3.1. Force in the Cylinders

There are four cylinders in the Boom Frames of the Loader crane that will be analyzed (Fig.7). The parameter that will be measured is the force in the pistons of the cylinders while moving the load. The nature of this force is pressure force.

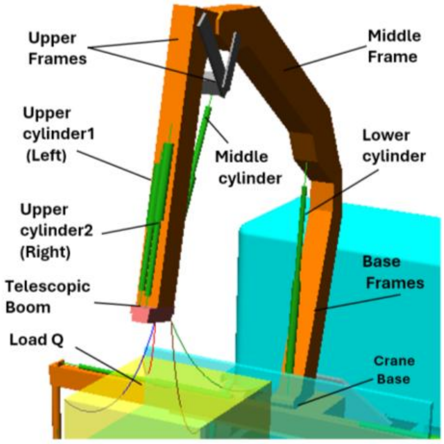

Fig.7. View of the Boom cylinders

- *Force in the Lower Cylinder*. In Fig.8 is the graph of the Pressure force F_{p1} in the piston of the lower cylinder. This cylinder is connected on the bottom side with the Crane Base and on the upper side with a Middle frame. Based on the graph, the piston of this cylinder is heavy loaded part. The force has negative values, while it is a pressure force.

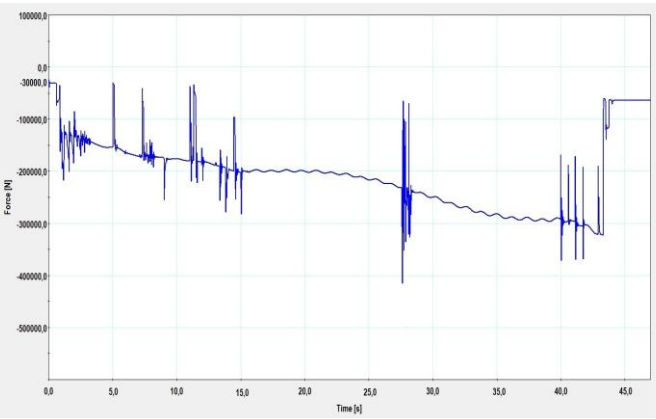

Fig. 8. Force on the piston of the Lower Cylinder

Based on the graph Fig.8, at the start of the lifting, piston force is smaller, around $F_{p10} \approx -30000$ *N*. On time t = 1 s it reaches the value $F_{p11} \approx |-130000|$ *N*. With the continuation of the lifting process, until time t = 14 s, the piston force increases up to $F_{p12} \approx |-200000|$ *N*. Between the time t = 14 s until t = 22 s the intensity of force does not change significantly, almost constant, with some oscillations. This is the time when cylinder holds steadily the lower and middle frame, while other cylinders move the upper frames with the load Q. Next, between the time t = 22 s until t= 43 s the value of force is increasing up to $F_{p13} \approx |-320000|$ *N*. On time t = 43 s the load is lowered on the ground. The piston force decreases significantly, to the value of $F_{p14} \approx |-65000|$ *N*, while it carries only the weight of the frames and Telescopic Boom of the crane.

During the entire process, the piston is heavily loaded with pressure force, with high oscillations that result in intense amplitudes. In some moments of the process, there are short timed high jumps of force values as a result of intense oscillations. These are particularly present at the start of the process, between the time t = 1 s ÷ 3 s, between the time t = 27 s ÷ 28 s and t = 40 s ÷ 43 s.

- *Force in the Middle Cylinder*. In Fig.9 is the graph of the Pressure force F_{p2} in the middle cylinder. This cylinder is connected on one side with the Middle Frame and on another side with upper frame. Based on the graph, the piston of this cylinder is also heavy loaded part. At the start of the lifting, piston force is around $F_{p20} \approx -7000$ *N*. On time t = 1 s it reaches the value $F_{p21} \approx |-50000|$ *N*. During the lifting process, until the time t = 14 s, the piston force increases up to $F_{p22} \approx |-110000|$ *N*. Also in this cylinder, between the time t = 14 s until t = 22 s the intensity of force is almost constant, but with some oscillations. Next, between the time t = 22 s until t= 43 s the value of force increases up to $F_{p23} \approx |-225000|$ *N*. After time t = 43 s, the load is lowered on the ground, so the piston force decreases significantly, to the value of $F_{p2} \approx |-28000|$ *N*, while it carries only the weight of the Upper frames of the crane.

For this piston, the conclusion is that it is heavily loaded with pressure force during the entire process, but with less intensity of the force compared with Lower cylinder. There are high oscillations that result in intense amplitudes. In addition, there are short timed high jumps of force values because of intense oscillations.

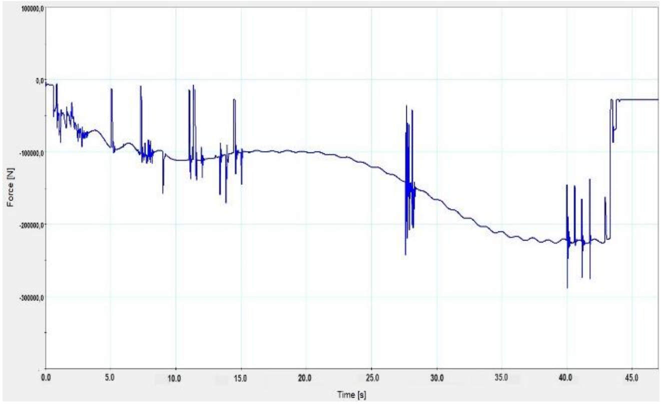

Fig. 9. Force on the piston of the Middle cylinder

- *Force in the Upper cylinder1*. In Fig.10 is the graph of the Pressure force F_{p3} in the upped cylinder 1 (left) (Fig.7). This is one of the two cylinders connected with Telescopic Boom used mainly to push or pull the load Q. Based on the graph, the piston of this cylinder is also heavy loaded part, but with less intensity of the force compared with two previous cylinders.

At the start of the lifting, piston force is around $F_{p30} \approx 2500$ *N*. It is a push force, has a positive value, while the cylinder is pushing the telescopic Boom. On time t = 1 s it reaches the value $F_{p31} \approx 16500$ *N*. During the pushing process, until the time t = 14 s, the piston force drops to $F_{p32} \approx -800$ *N*. Between the time t = 14 s until t = 41 s the intensity of force is almost constant, around $F_{p33} \approx -800$ *N*, but with oscillations in form of sinusoids. After time t = 43 s, the load is lowered on the ground, so the piston force decreases up to $F_{p34} \approx 500$ *N*, carries no load.

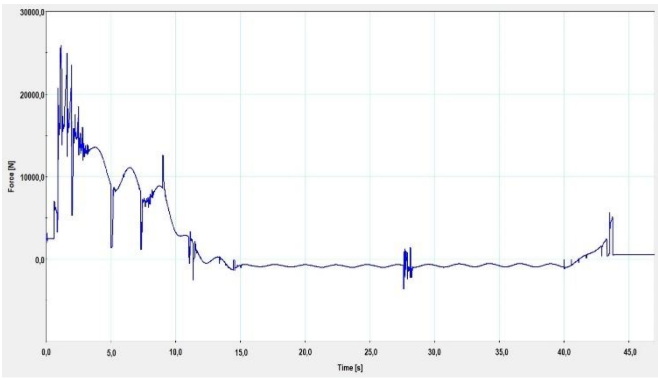

Fig. 10. Force on the piston of the Upper cylinder 1 (left)

- *Force in the Upper cylinder2*. In Fig.11 is the graph of Pressure force F_{p4} in the Upper cylinder 2 (right) (Fig.7). This is the second of the two cylinders pushing the Telescopic Boom, used mainly to push and pull the load Q. The piston of this cylinder is also heavy loaded part, but with less intensity of the force compared with the first two cylinders.

Based on the graph, there are similarities of the piston force in this cylinder compared to Upper Cylinder 1, in terms of intensity and oscillations.

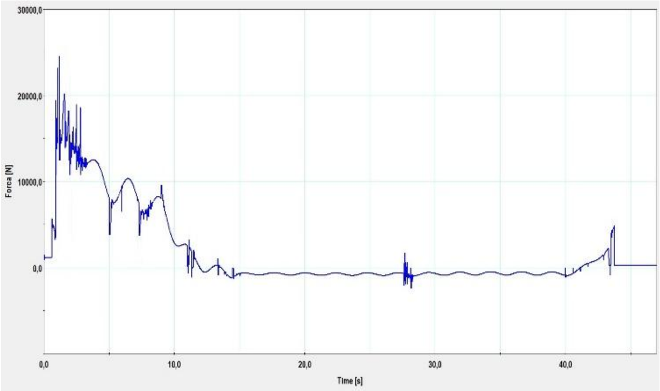

Fig. 11. Force on the piston of the Upper cylinder 2 (right)

3.2. Forces in connections (joints)

Connections or joints between crane parts are heavy loaded parts. There can be different types of connections in form of joints that represent the connection between parts in the form of restraints. Typical types can be Rigid joints, Revolute joints, Rigid Joints on slot, etc. We will present one significant joint between main parts of the crane ***C****onnection-joint between Crane Base and Base frame* (Fig.12). It is a type of Revolute joint.

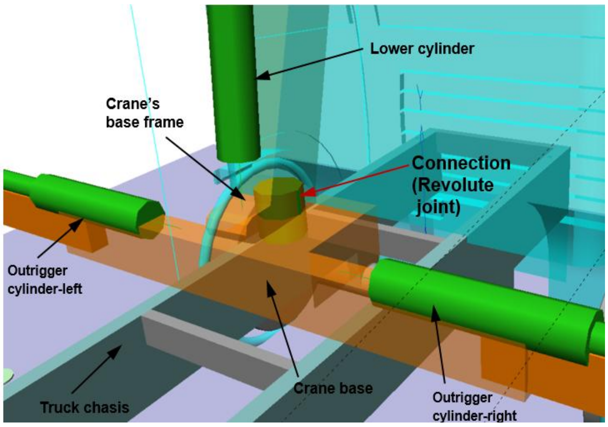

Fig.12. Connection-joint between Crane Base and Base frame

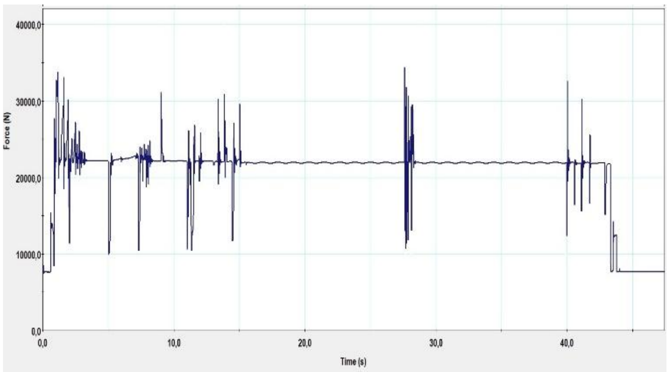

Fig. 13. Force in the connection between Crane Base and Base frame

In Fig. 13 is given the graph of Resultant Force F_{r1} in the connection. At the start of the lifting, resultant force is smaller, around $F_{r1} \approx 8000$ *N.* The medium value of this force for entire process is $F_{rm} \approx 22500$ *N*. At the end of the motion, after the Load is unloaded on the ground the Resultant force drops significantly, around $F_{r1} \approx 8000$ *N* There are short timed high jumps of Resultant force values because of intense oscillations. These are particularly present at the start of the process, between the time t = 1 s ÷ 2.5 s and repeat several times during the process. Conclusion is that this connection is heavily loaded with reaction force and with oscillations in entire motion process.

In Fig. 14 is the graph of resultant torque (Force moment) in the joint. At the start of the lifting, torque is small, around $T_1 \approx 11000$ *Nm*. On time t = 1 s it reaches the value $T_2 \approx 50000$ *N*. With the continuation of the lifting process, until time t = 12 s, the torque increases up to $T_3 \approx 80000$ *Nm*. Between the time t = 12 s until t = 22 s the value of torque does not change significantly in intensity, but has oscillations. Next, between the time t = 22 s until t= 43 s the value of torque is increasing up to $T_4 \approx 119000$ *Nm*. There are also short timed high jumps of torque values as a result of intense oscillations. After time t = 43 s, when the load is lowered on the ground, the torque decreases significantly up to the value of $T_1 \approx 20000$ *Nm*, while it carries only the weight of the frames and Telescopic Boom.

We can conclude that this joint (connection) is heavily loaded during the entire process, with high oscillations that also result in intense amplitudes.

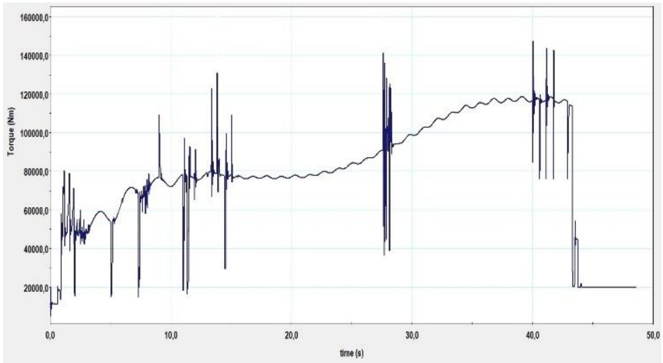

Fig. 14. Torque in the joint – connection between Crane Base and Base frame

3.3. Motion and Speed of the Load Q

In this paragraph will be presented the motion of the Load Q, its swinging and oscillations, and its speed. In Fig.15 is given the movement trajectory of the Load Q in three axes of directions, based on coordinate system shown in Fig.6. According to the curves of the graph in Fig.15, we can see the motion trajectory and swinging of the Load Q.

Note: The position of Load Q represents the position of its Center of mass, which is 500 mm (0.5 m) inside from its edges.

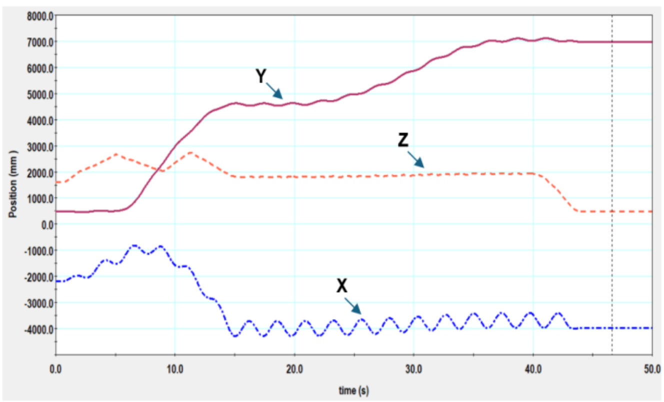

Fig. 15. Position and motion of the Load Q (mm).

The trajectory towards Y axis, in red color, full line, shows the motion in the right direction and starts from initial position of $Y = 500\ mm$ to the final distance $Y \approx 7000\ mm\ (7\ m)$. Between t= 0 s and t ≈ 6 s there is no motion towards Y axis (flat line), while during this time there is a vertical lifting of the load towards Z axis and some oscillations towards X axis. Between time t ≈ 6 s and t ≈ 15 s there is a rotation of the load to the right, and after time t ≈ 15 s there is a horizontal motion of the Load Q in the right direction.

Trajectory towards Z-axis, in orange color, dashed line, shows vertical motion of the Load Q. It starts from initial position of $Z = 1600\ mm$ to the final distance on the Ground $Z \approx 500\ mm$. Between time t=15 s and t ≈ 40 s there is no vertical motion towards Z axes (flat line), while during this time there is only horizontal motion of the load Q.

Trajectory towards X axis, in blue color, dash-dot line, shows the motion that starts from initial position of $X = -2000\ mm$ to the final position $X \approx -4000\ mm$. Based on this curve, the load has intense swinging and oscillations towards X axes at entire motion process. The amplitudes of swinging can be up to $A_L \approx 300\ mm$.

In Fig.16 is given the Resultant Speed of the Load Q. Based on the speed curve we can conclude that load undergoes intense oscillations of the motion speed at entire process. Highest amplitudes of speed appear on times t = 2 s to t = 15 s which is the process of lifting and rotation of the load Q. Maximal value of the speed is $v_{max} = 1.23\ m/s$ at time t ≈ 14 s. After the time t = 15 s the oscillations of resultant speed have lower intensity, almost same amplitudes but high frequencies, and continue until the end of the motion t_{end} = 43 s, when the load Q is lowered on the ground.

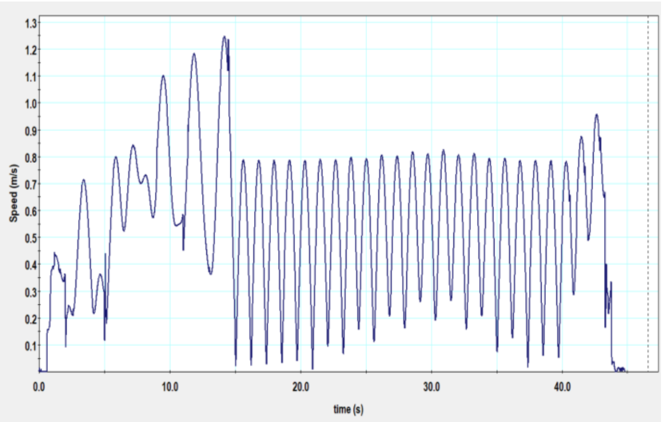

Fig. 16. Resultant speed of the Load Q (mm/s).

3.4. Stress on the Crane frame

We will present the stress of one part of the Crane that is heavily loaded, the Base frame. The type of stress is Von Misses stress. In Fig.17. is given the graph of stress.

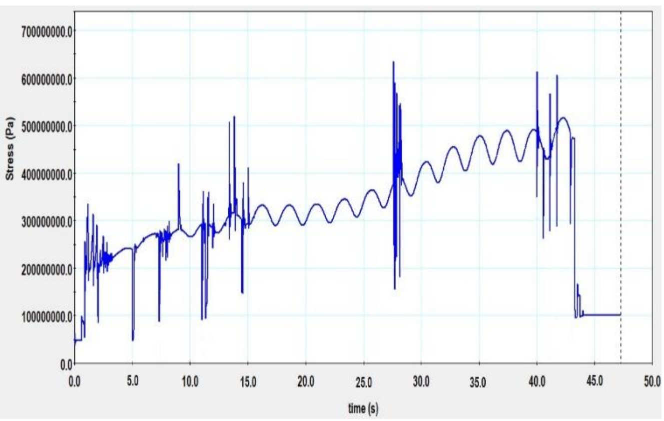

Fig. 17. Graph of Stress on the Base Frame of the Crane Boom (Pa)

Based on the graph Fig.17, at the start of the lifting, stress on the Base Frame is around $\sigma_0 \approx 50000000\ Pa = 5{\cdot}10^7 Pa$. On time t = 1 s it reaches the value $\sigma_1 \approx 2{\cdot}10^8\ Pa$. Until time t = 14 s, the Stress increases up to $\sigma_2 \approx 3.15{\cdot}10^8\ Pa$. Between the time t = 14 s until t = 22 s the intensity of Stress does not change significantly and has heavy oscillations. Between the time t = 22 s until t = 43 s the value increases up to $\sigma_3 \approx 5.15{\cdot}10^8\ Pa$.

After time t = 43 s, when the load is lowered on the ground the value of stress decreases significantly, to the value of $\sigma_4 \approx 1{\cdot}10^8 Pa$, while it carries only the weight of the frames and telescopic Boom of the crane.

Conclusion is that Base frame is heavily loaded part with dynamic stress in entire motion process. Also, based on Fig.19, there are short timed high jumps of stress values as a result of intense oscillations. These stress value jumps are a matter of concern regarding material durability, while in short time and in some periods of motion, it can exceed the tensile stress of the material [13].

In Fig.18 is shown an example of stress dispersion in the Base frame on its entire volume, in the time t ≈14 s. The part is meshed and calculated using Finite Elements Method (FEM). Based on the color contrast on the volume, the values of stress are not equally dispersed. Maximal values of stress are in the lower part, at the joint between the Base frame and Crane base.

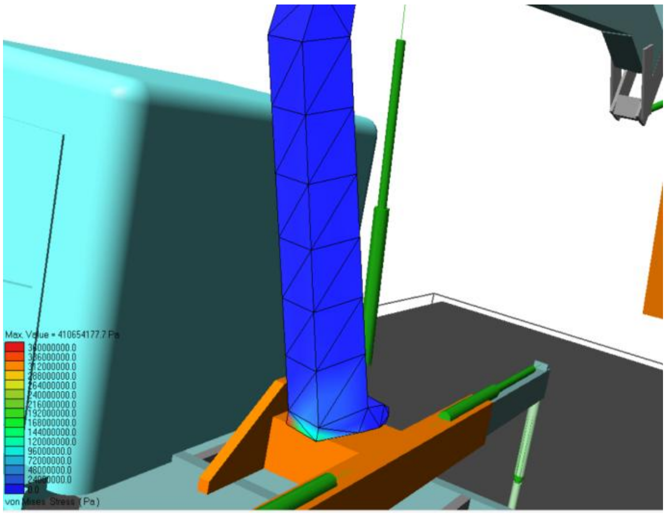

Fig. 18. Sample of dispersion of the Stress on the Base Frame in the time moment t = 14 s

4. Conclusions

In this study, we analyzed lowering of the load by the Truck Loader crane and analyzed the dynamics of this work operation. Analysis was focused on some main parts of the Loader crane: Main frames of the Boom, cylinders that move the boom frames and the load, main joint in crane base and motion of the Load Q.

Based on the analysis and results, we can conclude that during the load lowering the crane is heavily loaded with dynamic occurrences and oscillations that are present on entire duration of the process. Matter of concern are some temporary jumps of forces, torque intensity and stresses during the motion that can be short in time, but with high values. This can lead to safety issues; therefore, it is important to have slow speed of the Load Q. In addition, the motion needs to be controlled so that the Load Q does not swing and oscillate heavily, which can lead to problems in the crane and truck stability.

The dynamic parameters selected for analysis best represent the dynamics of the motion, and these are forces, torque, stresses and the motion of the Load Q. Results of the parameters are shown in graphical form and discussed, and conclusions are given for each case.

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