Influence of trolley motion in the dynamic behavior of semi-portal cranes

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Abstract: *The paper presents dynamic analysis of the Semi-Portal Cranes for the case of Trolley motion travelling on Crane's Girders. Semi-portal cranes are mainly mounted in the industrial facilities, and they consist of metallic structures with big dimensions and many mechanisms that carry heavy loads. We will analyze the influence of the Trolley motion in the dynamic behavior of Semi-Portal Crane while carrying maximum Load, in particular the influence of Load swinging and oscillations. The method of analysis is acquiring experimental measurements and comparing those results with the results gained through modeling of crane, and carrying simulations. Designing the Crane's 3D model with software and motion simulations is the method applied in the paper to analyze dynamics and is important to explain the form and intensity of oscillations that can cause accidents, failures of parts, and other concerns about the safety. Analysis will be done for maximal and minimal speed of the Trolley. Conclusions from this paper will be useful about the design, dynamic response and safety of Semi-Portal Cranes. The analysis will be focused to find main kinematic and dynamic parameters influencing the crane dynamics, like forces, moments, speed (velocity), and Load swinging magnitude. The Crane is modeled based on the Data from standard manufacturer of Semi-Portal Cranes.*

Keywords: SEMI-PORTAL CRANE, TROLLEY MOTION, LOAD SWINGING, OSCILLATIONS, MODELING, SIMULATIONS

1. Introduction

Type of the Semi-portal Crane taken for the study is shown in Fig.1. Main work activities of Sem-Portal Cranes are: lifting and lowering of the load, Trolley backward and forward travel, Crane travel, and in some types rotation of the lifting system with the Load. The motion of Trolley with weight (load) on the rails in girders of the Semi-portal crane is considered a complex process followed with extreme load swinging, high oscillations of the structure and parts, high dynamic forces and moments that can create problems for crane's stability. This is mainly caused by swinging of the load during the work of crane. Therefore, the aim of this paper is to find the impact of the Trolley motion and Load swinging on the dynamic behavior of this type of Semi-Portal crane.

Fig.1. *Semi-Portal Crane in the working environment*

Study will be done for the Crane type SAM [1], shown in Fig. 1, manufactured in Italy, and mounted in one Factory in a Local Company [8]. It's main technical features are shown in Tab.1 It is a type of Semi-Portal Crane with Double girders, sometimes referred as Semi-Gantry Crane. In one side (Right) it has Support Leg with double Beam system with wheels moving on rails in the Basement, and in other side (Left) it has Girders mounted moving on wheels on the Rails attached to the Factory Wall. On the Main Girders is mounted Overhead Trolley which has its 4 wheels moving on the rails of the Main Girders, and in the Trolley is mounted the Electric Hoist system that Lifts and Lowers the working Load Q (Fig.2).

Table.1. *Technical features of the Semi-Portal Crane [1]*

Crane Features	Value
Max carrying Load	5000 kg
Trolley speed forward	8 - 18 m/min
Trolley travel Length	9 m
Diameter of Trolley wheels	160 mm
Trolley weight	4 [kN]
Crane Span	11 m
Height of Girders	6 m
Girders dimensions (L*W*H)	11.6*0.3*0.7 m
Crane Travel speed	10÷12 m/min
Crane Weight	23 [kN]
Power of trolley motor, kW	0.5 kW
Crane Rails Dimensions	30x30 mm x 20 m

Results of the research will be required for some main parts of semi-portal crane. Speed of the Trolley is considered main influential parameter in the Load swinging and intensity of forces in other parts [3], [5], [7]. To prove this, analysis will be carried for the case of two travel speeds of trolley, $v_{tmin} = 10\ m/min$ and $v_{tmax} = 18\ m/min$. Results will be presented with graphs and tables and then compared.

Authors have studied Overhead cranes and semi-portal cranes presented in the References, with studies about dynamic analysis [3], [7], [8], [10], simulations [3], [7], design [4], [6], [16], motion control and regulation [4], [9], [11], oscillations [5], [7], and Safety [15].

2. Modeling of Semi-portal crane and simulations

Semi-Portal Crane Modell is created with software SimWise 4D [2]. After the modelling, simulations will be carried to acquire results. They will be achieved with two numerical Methods, namely Finite Elements Method (FEM) and Numerical Kutta-Merson Method, which are part of the features of the software for the analysis purposes. Working load Q has a prismatic form with dimensions: *Length =1 m , Width= 1 m , Height = 1.2 m, Mass Q = 5000 kg,* connected on 4 carrying cables. These cables are connected upper with the Hook and Pulley system, and above them connects to the Drum with the four lifting cables. (Fig.2).

Initial distance of the Load from the basement is 0.9 m. It is positioned on the right part of the crane's work span. (Fig.2). The lifting system is a double pendulum system of load lifting and carrying.

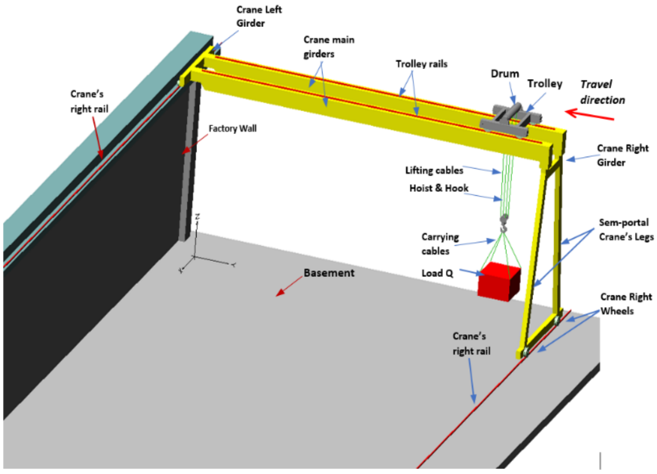

Fig. 2. *Model of the Portal Crane with main parts in the software environment [2]*

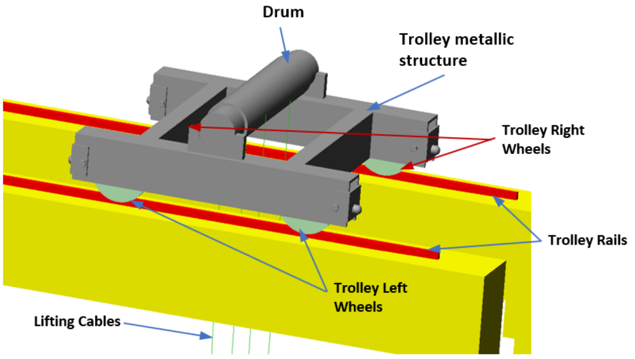

Fig.3. *Model of the Trolley and its parts*

For the proper analysis of Trolley motion, simulations will be organized as close as to real occasions, with the planning and programming of the Step Function for the motion in the form of :

if(t<25 s, step2(0,1 s,-0.166, 3.0 s),0) m/s for $v_{tmin} = 10\ m/min$

if(t<25 s, step2(0,1 s,-0.3, 3.0 s),0) m/s for $v_{tmax} = 18\ m/min$

Simulations will start without Trolley motion from t=0 until time t = 1 s. This is done to achieve the initial relative static stability of the Load Q hanging on lifting cables. For the case of minimum speed $v_{tmin} = 10\ m/min$, after $t=1\ s$, the travel of Trolley will start, with the increasing speed from $v_{tr} = 0$ m/min to $v_{tr} = 10\ m/min$ ($v_{tr} = -0{,}166\ m/s$) until time $t=3\ s$ (Fig.4). Negative value means travel in the opposite direction of the Y axes. This is planned for the smooth travel of Trolley. After this time, the speed will remain constant, until the end of travel. Travelling will stop in time $t = 25\ s$. The length of travel will be $L_{tr} = 3.325\ m$. For accurate analysis of the occurrences after travel stoppage, simulation will continue until time $t = 30\ s$. We consider that simulating the occurrences before, during the motion and after stoppage is the best method to analyze the Trolley motion [3], [7].

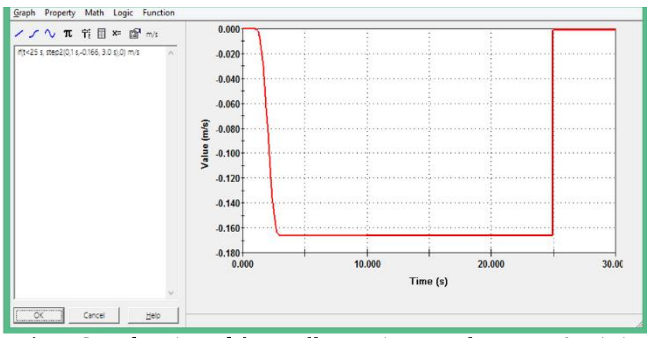

Fig.4. *Step function of the Trolley motion speed $v_{tmin} = 10\ m/min$*

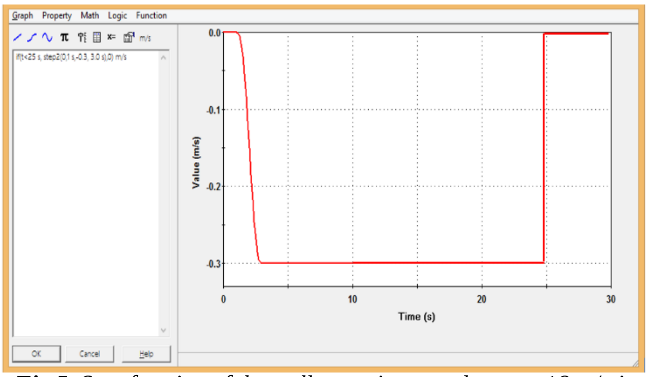

Fig.5. *Step function of the trolley motion speed $v_{tmax} = 18\ m/min$*

In Fig. 5 is given the Step Function for the Simulation scenario for the case of maximum speed $v_{tmax} = 18\ m/min$. The form of function is similar then perious. Travelling will stop also in time $t = 25\ s$, but the length of travel will be $L_{tr} = 7.5\ m$ due to higher speed of the Trolley (Fig.5).

3. Experimental On-Site measurements

Some experimental measurements in crane are done in the place of work, to achieve the accuracy and validation of results. The measured parameter is Tensile force in the 4 lifting cables: $\boldsymbol{F_{lc}}$. In this crane there are 4 lifting cables connected between the pulley system and the Drum. The tensile force comes as a results of hanging load Q and Pulley System which swings during the Trolley motion. For this case, these cables usually don't lift or lower the load, but carry the Load during the travel (Fig.2 & Fig.3) [13].

Type of Lifting Cables are wire ropes type 6X19, with diameter $d_c = 10\ mm$ [13]. Other properties are: Modulus of elasticity: $E = 400\ MPa$ [14], Minimum breaking strength $F_b = 54.3\ kN$, Safe Load $F_s = 10.9\ kN$ [1], [14]. Tensile force was measured with Dynamometer type *Dini Argeo* attached to the Hook [12], during the motion of the Trolley (Fig.6).

There were 5 measurements carried. First measurement is done at first phase (relative rest), measurements 3,4,5, are done during telpher motion (second phase), measurement 6 is done after motion stoppage (third phase). Results are shown in Table.2.

Measure-ment No.	Time of Trolley motion (s)	Tensile Force in all lifting cables F_{lc} (N)	Force in each branch of lifting cables (F_{lc}/4) (N) (aprox.)
1	0	50200	12676.77
2	5	51100	12904.04
3	10	51350	12967.17
4	18	50650	12790.4
5	27	51900	13106.06

Table 2. *Results of F_{lc} with dynamometer in hanging cables*

Fig.6. *Type of the Dynamometer and measurements during the motion of the trolley [12]*

4. Results of the analysis

Results of the analysis will be presented in the form of Graphs for main dynamic and kinematic parameters for some main parts of crane: Tensile Force in the Lifting Cables, Forces in the Trolley, Forces and moments in the Girders, swinging and oscillations of the Load.

4.1. Tensile Force on the Lifting cables

This is the Tension Force acting on lifting cables - F_{lc} resulting from Load hanging and swinging during the Trolley motion. Nature of this force is axial force – Tension. There are 4 branches of lifting cables, which lifts and lowers the load. Length of each Cable branch from the Pulley to the Drum is 3.3 m. Maximal load in one branch of Lifting cables is [15], [16]:

$$F_{lcmax} = \frac{Q}{m \cdot \eta_{ho}} = \frac{51}{4 \cdot 0.99} = 12.878 \text{ [kN]} \qquad (3.1)$$

Q = 5200 kg = 5200·9,81 N = 51 kN (*Mass of load+aprox.mass of lifting devices+mass of cables*):

η_{ho} = 0.99 - working coefficient of hoist; [16]

m = 4 – number of cable branches participating in the lifting/hanging of the Load.

Results of the simulation are shown in Fig.7 and Fig.8, for one branch of the cables. The curve of Tensile Force for other cable branches are similar (although not the same), and due to limitations in this paper will not be shown.

In the Fig.7 is given the graph of Tensile Force for the case of minimum speed of Trolley v_{tmin} = *10 m/min*. According to the simulation plan (Chapter 2), between the time $0 \le t \le 1$ *s* there is no motion, and force on cables is close to static value (3.1). After time *t = 1 s*, tension force will change. Between the intervals $1 \text{ s} \le t \le 25 \text{ s}$ there is a motion of Trolley, and after *t=25 s* Trolley will stop moving.

The curve of the Force in cables F_{cl} is in the form of sinusoid with swinging and with amplitudes and oscillations at almost entire travel process, from the start to the end, and after the halt of travel. Oscillations within swinging of the cable are small. After the travel stop on time *t=25 s* and further, amplitudes are even higher. Swinging and oscillations of cables will continue for a long time even after *t = 30 s,* due to the Load swinging. Conclusion is that lifting cables are heavy loaded with swinging and oscillations that results in high amplitudes and high frequencies. Maximum value of force is achieved after travel stoppage at time *t = 27 s*. Medium value of the force is $F_{cl} \approx 12800$ *N*.

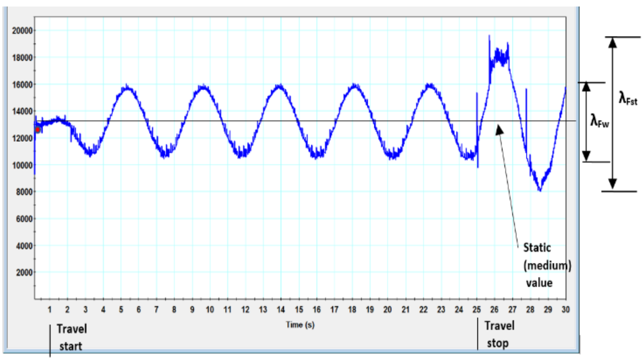

Fig. 7. *Tension force on one branch of the lifting cable for the trolley speed* v_{tmin} *= 10 m/min*

In the Fig.8 is given the graph of Tensile Force for the case of maximum speed v_{tmax} *= 18 m/min*. Maximum value of force is achieved after travel stoppage at time *t = 29 s*.

Results in the Fig.7 & Fig. 8 also gives the results of the Static value, or medium value of the F_{cl} . They are close to the results of experimental measurements in Chapter 3.

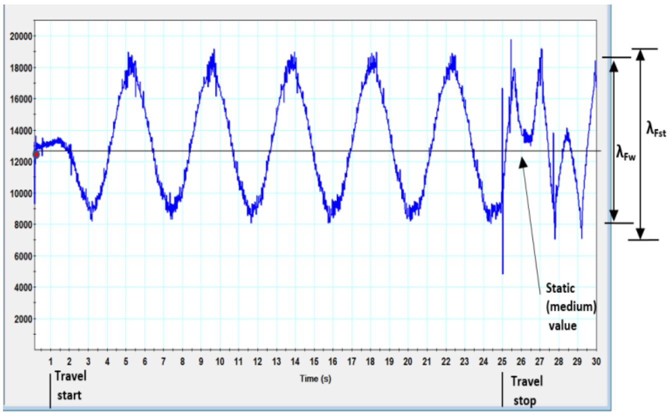

Fig. 8. *Tension force on one branch of the lifting cable for the trolley speed* v_{tmax} *= 18 m/min*

Table 3. *Results of Tensile force on the lifting cables*

Parameters of cables	speed v_{min} = 10 m/min	speed v_{max} = 18 m/min	Difference in %
Average tension Force F_{clst} (close to static)	≈12800 N	≈12800 N	≈ 0
Max tensile force F_{maxc} **- In Motion (t<25 s)** **- After stoppage**	 16000 N 19000 N	 19000 N 19300 N	 +18.7% +1.5%
Dynamic coefficient: ψ = F_{max} / F_{clst} **- In Motion (t<25 s)** **- After stoppage**	 1.25 1.484	 1.484 1.51	 18.7 % 1.75 %
Peak-to-peak amplitude of tensile force **- In Motion (t<25 s)** λ_{FW} **- After stoppage** λ_{Fst}	16000-10500 = 5500 N 19000-8000 = 11000 N	19000-8500 = 10500 N 19300-7000 = 12300 N	90.9 % 11.8 %

In the Table 3 are given the results and comparison of Tensile force in the lifting cables for two different speeds of Trolley v_{tmin} = *10 m/min* and v_{tmax} *= 18 m/min*. Important parameter for the analysis and comparison is *Peak-to-peak amplitude λ*. It can be concluded that difference in speed gives different values in all parameters. Also, results are different for the part *In Motion (t<25 s)* of Trolley, and after stoppage time. It is important to emphasize the Max tensile force part *In Motion* of Trolley which is 18.7% higher for the motion with v_{max} = 18 m/min compared to v_{tmin} *= 10 m/min*. Also there is a big difference in the parameter of Peak-to-peak amplitude of the Tensile force. It is 90.9% higher for travel with v_{max} *= 18 m/min* compared to v_{min} *= 10 m/min*. This concludes that speed is main influential parameter in the dynamic behavior of trolley. The higher the speed, intenser is the dynamics of motion which also results in the increased swinging of the Load and intenser oscillations.

According to the results and value in Table.3, maximal value of Tensile Force is F_{cmax} = 19300 N, for the case of v_{tmax} *= 18 m/min*, after stoppage time. Comparing to the Minimum breaking strength F_b *= 54.3 kN* from the cable Properties in Chapter 3 [14], we can conclude that $F_{cmax} < F_b$. Lifting cables can withstand the intensity of max Tensile Force.

4.2. Swinging and Oscillations of the Load Q

During the motion of Trolley, the Load Q as a carried Workload will swing and oscillate and this will have effect on entire construction of the crane. Load Q is connected above with 4 carrying cables, Pulley system, lifting cables, Drum and Trolley

(Fig.1 & Fig2). It is important to find the extent and magnitude of swinging and oscillations of the Workload. In Fig.10 is given the graph of swinging and oscillations of the workload for v_{tmin} = *10 m/min*. Blue solid curve represents swinging around X axes, and Red dotted curve represents swinging around Y axes. They are measured in degrees of swinging towards local coordinate system (°) (Fig.9).

In Fig.11 is given the graph of speed (velocity) of the workload for v_{tmin} = *10 m/min*. Blue solid curve represents speed towards X axes, and Red dotted curve represents speed towards Y axes. It is noticeable that the velocity of the Workload Q is dynamic with high amplitudes, in a form of sinusoid.

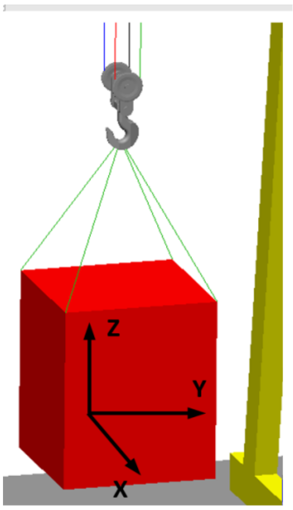

Fig.9. *Workload Q and Pulley in the Local coordinate systems*

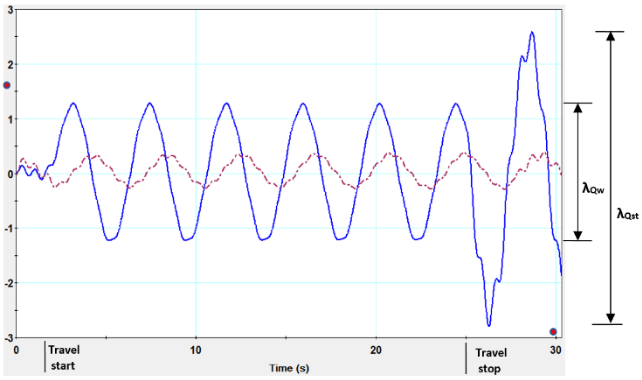

Fig.10. *Angle of Swinging and oscillations of the workload Q around **X** and **Y** axes, and max amplitude for In Motion λ_{Gw}, and after stoppage λ_{Gst} ,for V_{min} = 10 m/min.*

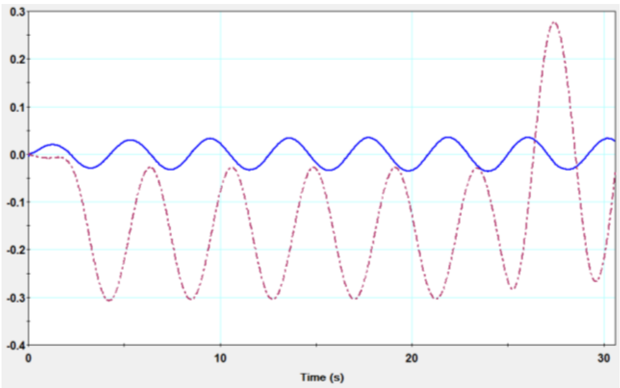

*Fig.11. Speed (Velocity) of the workload Q towards **X** and **Y** axes and max amplitude for In Motion λ_{Gvw}, and after stoppage λ_{Gvst} for V_{min} = 10 m/min = 0.166 m/s.*

In Fig.12 is given the graph of swinging and oscillations of the workload Q for v_{tmax} = *18 m/min* and in Fig.13 is given the graph of speed (velocity) of the workload Q for v_{tmax} = *18 m/min*.

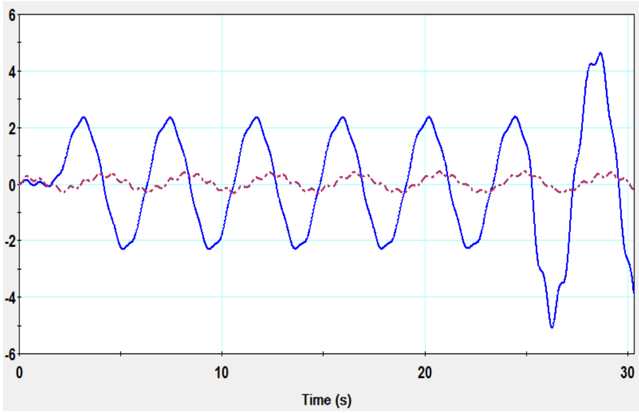

Fig.12. *Angle of swinging and oscillations of the Workload Q around **X** axes and **Y** axes Max amplitude for In Motion λ_{Gw}, and After Stoppage λ_{Gst} for v_{min} = 18 m/min*

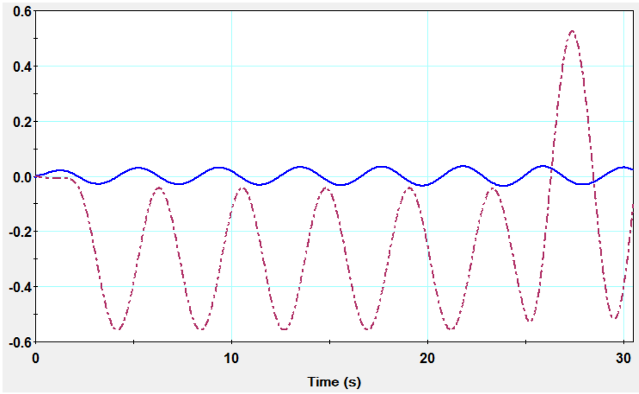

Fig.13. *Speed (velocity) of the Workload Q towards **X** and **Y** axes and Max Amplitude for In Motion λ_{Gvw}, and After Stoppage λ_{Gvst} for v_{max} = 18 m/min = 0.3 m/s.*

In Table.4 are given results and comparison for swinging and speed (velocity) of the workload Q for two Trolley speeds. Based on the values and difference given in %, the results of the parameters from the speed V_{tmax} = *18 m/min* are much higher than those from the speed V_{tmin} = *10 m/min*.

Table 4. *Results of swinging and oscillations of the workload Q*

Results of swinging and speed of workload	**Trolley speed v_{min} = 10 m/min**	**Trolley speed v_{max} = 18 m/min**	**Difference in %**
Max value of swinging (°)	|-2.9|	|-4.6|	58.6 %
Max Amplitude of swinging λ_G, (°) (Peak-to-peak) (X axes) **In Motion (t<25s)** λ_{GW} **After stoppage** λ_{Gst}	1.33 – (-1.2) = 2.5 ° 2.7 – (-2.9) = 5.6 °	2.2 – (-2.2) = 4.4 ° 4.4 – (-4.6) = 9 °	+14.2% +76% +60%
Max value of speed (velocity) (m/s)	0.27 m/s	0.67 m/s	+148%
Max Amplitude of Speed (Velocity) λ_{deg}, (°) (Y axes) **In Motion (t<25s)** λ_{GVw} **After stoppage** λ_{GVst}	-0.02 – (-0.3) = 0.28 m/s 0.28 – (-0.28) = 0.56 m/s	-0.02 – (-0.56) = 0.54 m/s 0.55 – (-0.55) = 1.1 m/s	+92.8% +96.4%

4.2. Resultant Force acting on the Trolley

Dynamic Forces acting on the Trolley are passed from the drum and initially coming from the swinging of the Load Q and Lifting cables. Their Resultant force is measured in the constraints between the Drum and Trolley (Fig.14). In Fig. 15 and Fig.16 are given the graph of the Resultant Force in the Trolley F_{Rt} for both taken speeds. This is the Resultant force of all acting forces – tensile, bending and torsion components. Nature of this force is dynamic with amplitudes and oscillations.

For the case of speed v_{tmin} = *10 m/min*, maximal value of the Resultant Force *In Motion* is F_{Rmaxm} = *6100 N* and after stoppage time F_{Rmaxs} = *7100 N*, which occurs in time $t \approx 27$ s (Fig.15). Based on the graph, Medium value, which is Static Force is $F_{Rst} \approx 4800$ *N*. This concludes that the value of Dynamic Force in the Trolley is for 47.9% higher than the Static force, F_{Rmaxs}/F_{Rst} = 7100 N/4800 N = 1.479.

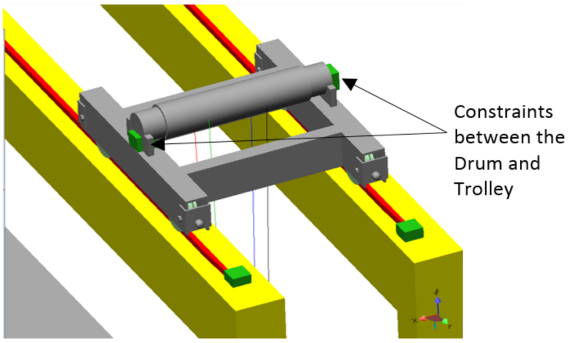

Fig. 14. *Measured constraints between the Drum and Trolley*

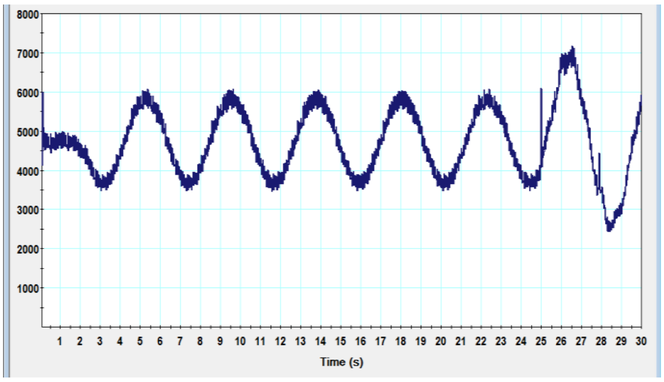

Fig. 15. *Resultant Force acting on Trolley for the speed* v_{tmin} = *10 m/min*

For the case of the speed v_{tmin} = *18 m/min*, maximal value of dynamic Force *In Motion* is F_{Rmaxm}= *7000 N* and after stoppage time F_{Rmaxs} = *8650 N*, which occurs in time $t \approx 26.5$ s (Fig.16). Based on the graph, Static value of force is $F_{Rst} \approx$ *4800 N*. This concludes that the value of Dynamic Force in the trolley is for 80.2% higher than the static force, F_{Rmaxs}/F_{Rst} = 8650 N/4800 N = 1.802.

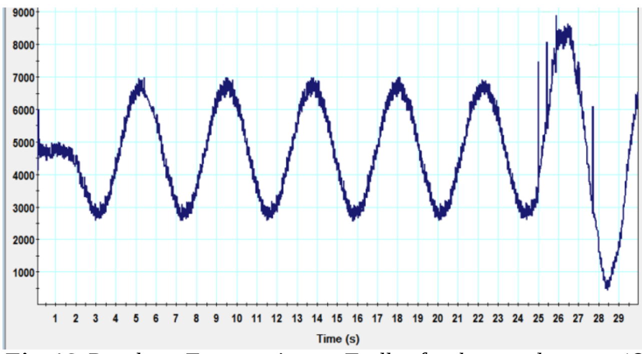

Fig. 16. *Resultant Force acting on Trolley for the speed* v_{tmax} = *18 m/min*

4.4. Moments and Forces in Main girders

Girders are the part of crane that carries most of the loading and forces coming from the Trolley motion. There are two main girders. We will present the Resultant Forces and Moments (Torque) acting on the Front Main Girder, in the Left Constraint (Rigid Joint on Slot) and Right Constraint (Rigid Joint) (Fig.17). Results of forces and moments are shown graphically in Fig.18 to Fig.21 for the taken speeds.

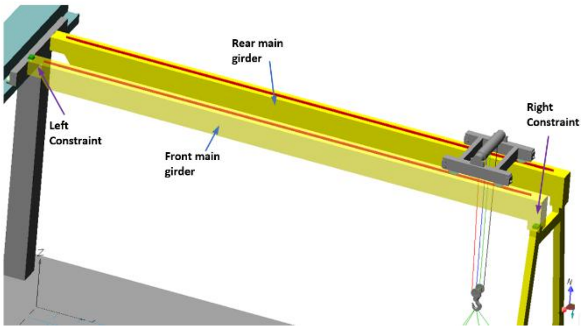

Fig. 17. *View of Left and Right Constraints in Front Main Girder*

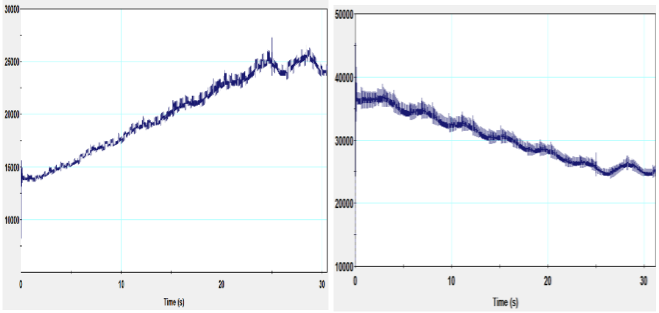

Fig. 18. *Resultant Force acting on Front Main Girder for the speed* v_{tmin} = *10 m/min, in the Left Constraint and Right Constraint*

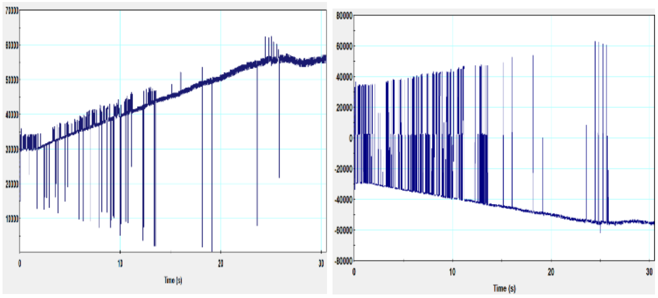

Fig. 19. *Moment (Torque) acting on Front Main Girder for the speed* v_{tmin} = *10 m/min, in the Left Constraint and Right Constraint*

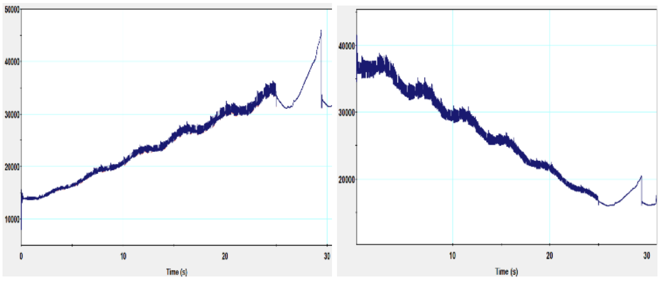

Fig. 20. *Resultant Force acting on Front Main Girder for the speed* v_{tmax}= *18 m/min, in the Left Constraint and Right Constraint*

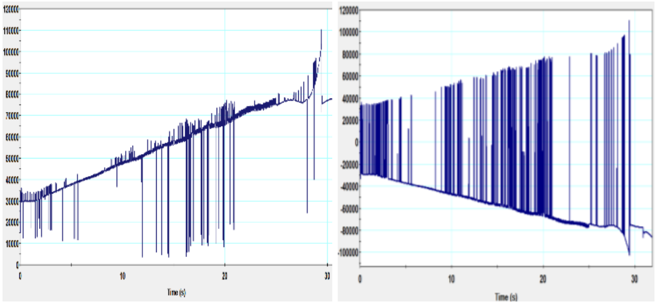

Fig. 21. *Moment (Torque) acting on Front Main Girder for the speed v_{tmax} = 18 m/min, in the Left Constraint and Right Constraint*

Based on the Results of Graphs from Fig.18 to Fig.21, it can be noticed that values of Forces and Moments are higher for the speed v_{tmax} = *18 m/min* in the Left Constraint (Rigid Joint on Slot) for about 48%. In the Right Constraint (Rigid Joint) values are similar in the Intensity, but for the case of speed v_{tmax} = *18 m/min*, amplitudes of oscillations are higher.

In both cases, values of Moments (torque) show high amplitudes and frequencies during the entire process, which is a matter of concern.

Values for Rear (Second) main girder are similar, therefore are not shown here. It can be concluded that Main girders undergo heavy dynamic loading with high frequencies of oscillation's.

5. *Conclusions*

In this paper we analyzed the dynamics of the Semi-portal crane for the process of Trolley motion, through modeling and simulations with software. For the proper analysis and motion simulation of the trolley, the process was planned to be as close as real occasions. Also, this simulation planning of the motion enables regulation of trolley travel in order to minimize the oscillations and swinging of the Load. For the proper dynamic analysis, it is important to develop accurate 3D models to describe the semi-portal crane dynamics [7]. For the analysis reliability, results of simulations were compared with some experimental measurements. The analysis proved the dynamic nature during the trolley motion and the importance for the regulation to have less oscillations.

Results acquired were for the main parts of crane, and included parameters as Forces, Moments, Angle of Load swinging and Speed (Velocity). The analysis was carried for two speeds of the Trolley, minimal and maximal speed, and then comparing the results from them. After the resulted analysis, we conclude that main parameter of influence during the trolley motion is the intensity of trolley speed that effects load swinging and intensity of Forces and moments in other parts of crane.

Main issues during the trolley motion are oscillations that are intensive in some time frames of the process. Their occurrence is irregular, with high amplitudes and frequencies. The form and influence of oscillations in the Trolley and entire Semi-portal crane can explain causes of parts failures and stability problems [3], [4]. Load swinging and oscillations during the process are difficult to be measured with existing measuring devices and instruments, so the methodology of analysis with simulations and comparison with experimental measurements helps to identify the dynamics of semi-portal crane and measures to be taken to minimize the safety issues during the work.

Conclusions in this paper can be useful for the safety and design of semi-portal cranes, and for other work processes like load lifting and crane's motion.

6. *References*

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