STUDYING ROTATIONAL MOTION OF LUFFING BOOM CRANES WITH MAXIMUM LOAD USING SIMULATIONS

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Abstract: *Luffing Boom Cranes are type of cranes used for load carrying in building sites. They have complex structure with big dimensions and mechanisms. Their working usage is high. Main cycles of the work of Luffing Boom cranes are: lifting and lowering the working load, Boom luffing – upwards and downwards, rotation around vertical axes, and (if mobile type) translational movement forward and backwards. In this work, we are going to study the work of this crane while rotating with full loading. Study will be done using simulations with computer applications. The aim is to see the effects of dynamic forces and moments in the crane's main parts - metal construction, cables, and constraints during rotational work cycle, particularly at the start and end of the rotation. Also interest is to study the effects of load swinging in crane's stability. For this purpose, we modeled with software entire luffing boom crane. Crane is modeled from standard manufacturer, as a common model of luffing boom Crane.*

Keywords: LUFFING BOOM CRANE, ROTATIONAL MOTION, OSCILLATIONS, MODELING, SIMULATIONS

1. Introduction

The type of Crane taken for study is Liebherr 540 HC-l2 [2]. Properties of crane are: Length of the Boom - 60 m. Mass of the Boom – 140 t. Length of Mast – 53 m. Mass of mast – 160 t. Max carrying load Q_{max} = 6.6 t = 6600 kg . Crane rotation-angular speed: ω=0.6 rot/min. This is single rotational speed given by manufacturer [4].

During the rotation, crane's boom is in position at ψ = 15° with horizontal. There will be no luffing motion, nor lifting of load. Length of hoist cables is 20.5 m. Length of luffing cables is 20.7 m. Length of restraint cables is 28 m.

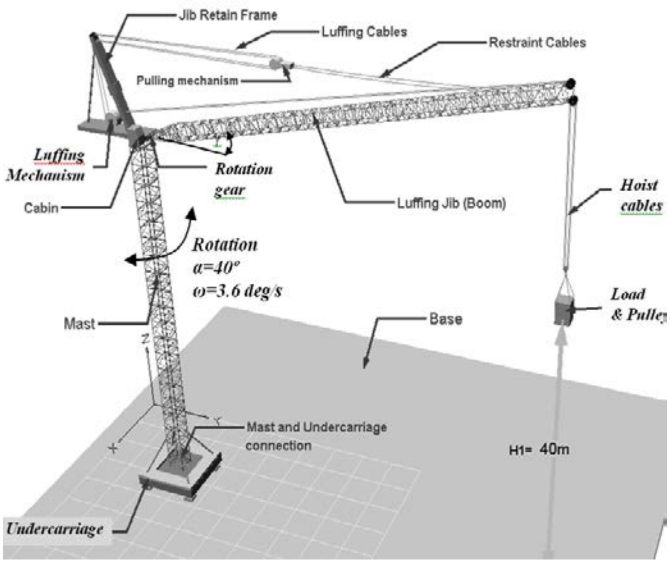

Fig.1. *Model of luffing boom crane*

Before simulations, weight Q (work load) is in the position of relative rest at the height H1=40 m (Fig.1). Simulation will be done for crane rotation with angular speed: ω=0.6 rot/min = 3.6 deg/s. Rotation will be simulated for angle of 40^o. Simulation has three phases [3],[5]:

First phase – initial position of relative rest with no motion. Load hangs on hoist cables. Starts at time 0 s <t < 1s.

Second phase – process of active rotation with speed ω=0.6 rot/min = 3.6 deg/s. Starts after first phase, between time 1 s <t < 14s.

Third phase - rotation stoppage. Crane will stop rotating, but load, pulley and hoist cables will continue to swing. Starts after second phase, between time 14 s < t < 20 s.

This form of simulation scenario is close to real work of crane and best for achievement of reliable results. All the graphs in this paper have time in second on horizontal axes, and in vertical axes they have studied component in their basic units, depending on the parameter studied.

2. Results of force (tension) in restraint cables

This is the force acting on restraint cables resulting from weight of boom, load hanging and swinging during crane rotation. There are 4 cables. Restraing and luffing cables lifts up or lowers the Boom, but for the case of rotation they carry the boom, load and lifting mechanisms (Fig.1). They are considered most loaded part of crane [3]. Dynamic forces that appear on these cables come from load swinging, hoist cables and boom oscillations. The diagram of tension force in these cables is shown in Fig.2.

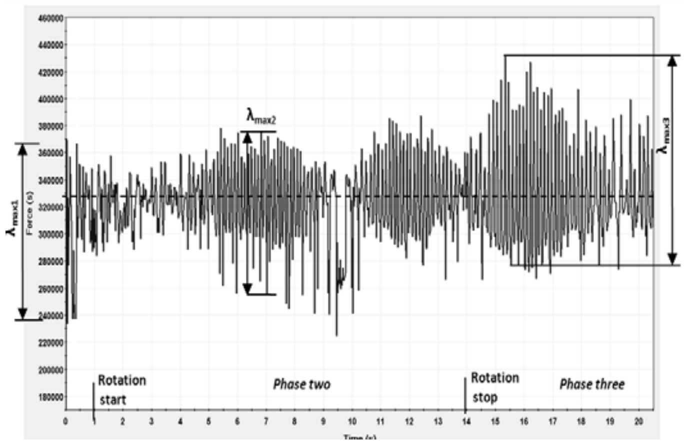

Fig 2. *Graph of Tension force on one of the Luffing cables – during Boom upwards motion*

Based on graph in Fig.2, medium value of tension force is F_{med} = 323000 N that is close to static value of force [3],[5], needed for calculation of dynamic coefficient [1],[2].

Phase one of the process – relative rest of Boom and load which is carried between times 0< t <1 s gives values of force that are dynamic in nature. Max value of force in this phase is F_{c1} = 362000 N. Value of amplitudes of force is high $\lambda_{max2} = (3.62\text{-}2.415)\cdot 10^5$ = 120500 N. Maximal frequency of oscillations is υ = 7 Hz. Phase one is usually called "load stabilization phase", before active motion.

Phase two – active rotation period - process of crane rotation is carried between times 1 s< t <14 s. Maximum value of the tension force is F_{c2} = 388000 N, in time t = 12.5 s. Value of max amplitude is $\lambda_{max2} = (3.888\text{-}2.765)\cdot 10^5$ = 112300 N. Maximal frequency of oscillations is υ = 9 Hz.

Phase three – rotation stoppage, between time 14 s< t <20 s. In this phase are achieved highest results of dynamic parameters for tension force. Maximum value is F_{c3} = 432000 N, in time t = 15.4 s. Value of max amplitude is λ_{max2} = $(4.32-2.77)\cdot10^5$ = 155000 N. Maximal frequency of oscillations is υ = 9 Hz.

Based on comments above, and Fig.2, we can conclude that highest dynamic values of force are in phase three, after stoppage rotation. In this phase are received maximal values of oscillations, and amplitudes.

If we find the ratio between max value of dynamic force gained from results (fig.2) and medium value of force, we can calculate dynamic coefficient [1],[2],[4]:

$$\Psi = \frac{F_{dynamic}}{Fstatic} = \frac{432000}{323000} = 1.337$$

This concludes that value of dynamic force is higher that of static force for 33.7%. This needs to be taken in when calculating cables and selection of safety factors for cables that will be implemented on these cranes.

Based on literature [2], for cranes with boom and class H1, value of dynamic coefficient is Ψ = 1.3. This means that value of tension force should not exceed F_c < 323000*1.3 = 419900 N. This value is complied in most of rotation process until t < 14.5 s, from Fig.2. But after this time value of Ψ exceeds three times, in t1 =15.4s, t2 = 16.1 s and t3=16.2 s. This is a matter of concern that requires attention.

Conclusion is that restraint and luffing cables are heavily loaded with oscillations that results in high amplitudes and high number or frequencies.

3. *Force in the rotation gear between upper platform and boom*

This connection is important part of these cranes for determining dynamic effects in crane's metallic construction. The gear is the motion mechanism and connection between two main parts. In fig. 4 is shown the graph of resultant force for the case of rotation.

Dynamic occurrences that appear come from load swinging, cables and boom oscillations, and thereafter will be passed to mast and basement. Results that will be required are resultant force F_{rmax} = $\sqrt{F_x^2 + F_y^2 + F_z^2}$ in this connection which is a restraint (Fig.3).

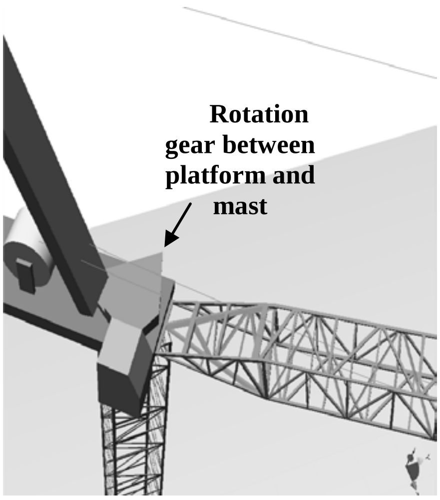

Fig.3. *Rotation gear between platform and mast*

Based on results in graph from Fig 4, we can conclude that curved line shows heavy dynamic nature of process that occurs in rotation gears. Value of max amplitudes are spread on entire graph (process), mainly during rotation period 8 s < t < 14 s, and after rotation stoppage 14 s < t < 15 s. Only after time t ≈ 17 s, oscillations have tendency of dropping down.

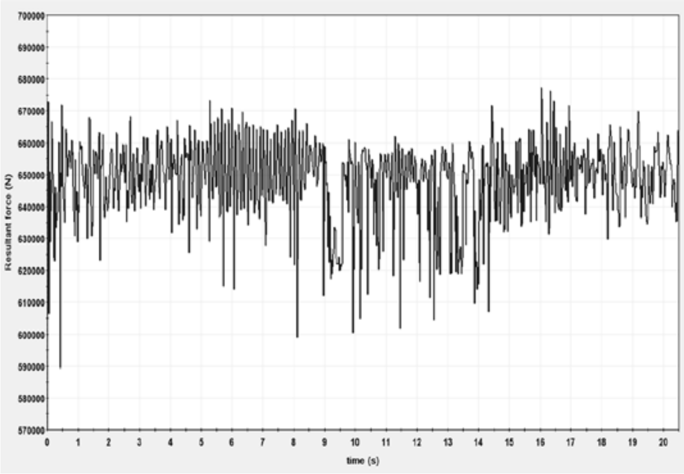

Fig.4. *Graph of Resultant force in the rotation gear of upper platform and mast during rotation*

Medium value of resultant force is F_{rmed} = 650000 N, which is close to static value. Maximum value of the resultant force is F_{rmax} = = 678000 N, in time t = 16.4 s. This value is gained after rotation stoppage. Compared to value of medium force, it is an increase of 4.3%. This is less than dynamic force - tension in restraint cables.

Max value of the frequency of oscillations is υ = 12 Hz, which occurs at time 6 s < t < 7 s. This is higher than frequency of restraint cables (υ = 9 Hz) for 33.3%.

4. *Force and momentum in the connection of mast and undercarriage*

These parameters are important for studying resultant force and momentum (torque) at the bottom of vertical mast and undercarriage and are important for studying stability of crane. This connection is a constraint that connects mast and basement of crane (fig. 5). Dynamic occurrences that appear here are passed from rotation gear and mast.

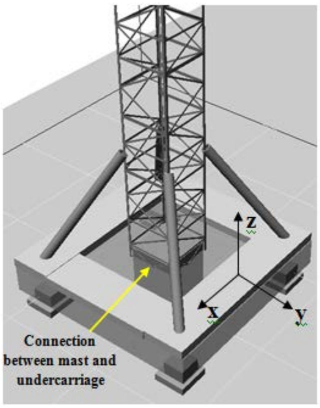

Fig.5. *Undercarriage and mast with local coordinative system*

In fig. 6 is shown the graph of resultant force for the case of rotation. Based on results from fig.6, we can conclude that graph shows heavy dynamic nature that occurs in bottom mast. Value of max amplitudes are spread on entire graph (process), mainly during active rotation between time 5 s<t<9 s, and after rotation stoppage 14 s<t<15 s. only after time t ≈ 18 s, oscillations have tendency of dropping down.

Medium value of resultant force is F_{rmed} = 806000 N, which is close to static value. Maximum value of the resultant force is F_{rmax} =

843000 N, in time t ≈ 17.2 s. this value is reached after rotation stoppage. Compared to value of medium force, it is an increase of 4.6%. This is close to dynamic force in rotation gear (paragraph 3). the curve of resultant force from fig.6 is similar to fig.4 of rotation gear. This proves that forces at bottom mast are directly passed from rotation gear through mast frame. max value of the frequency of oscillations is υ = 12 Hz, which occurs at time 6 s < t < 8 s.

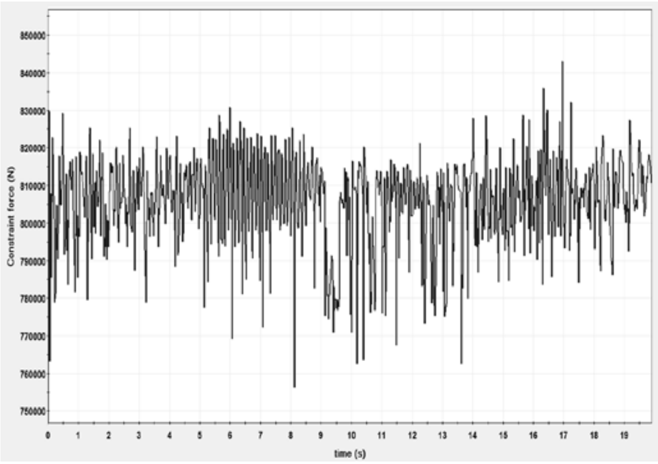

Fig.6. *Graph of resultant force in the constraint between mast and undercarriage*

In fig. 7 is shown the graph of momentum (torque) for the case of rotation. This is important parameter for calculating crane's stability from overturning. There are 4 curves shown in graph: three for each local axes of mast, and forth is resultant torque M.

Based on results from graph in fig.7 we can conclude that curved line shows heavy dynamic nature of moments-torque with high frequencies and oscillations that occurs in bottom mast, which are being passed to undercarriage and basement of crane. medium value of resultant torque is M_{rmed} = 8500000 Nm, which is close to static value.

Oscillations of torque around **y axes** are low at the beginning of rotation until t < 9 s, and almost with constant value close to static value. after time t > 9 s, values of torque increase (in negative value) due to rotation. oscillations also increase, with increasing amplitudes and frequencies that reach up to υ = 10 Hz. amplitudes of torque can reach up to $\lambda = -(6.2-4.2)\cdot10^6 = -2\cdot10^6$ Nm.

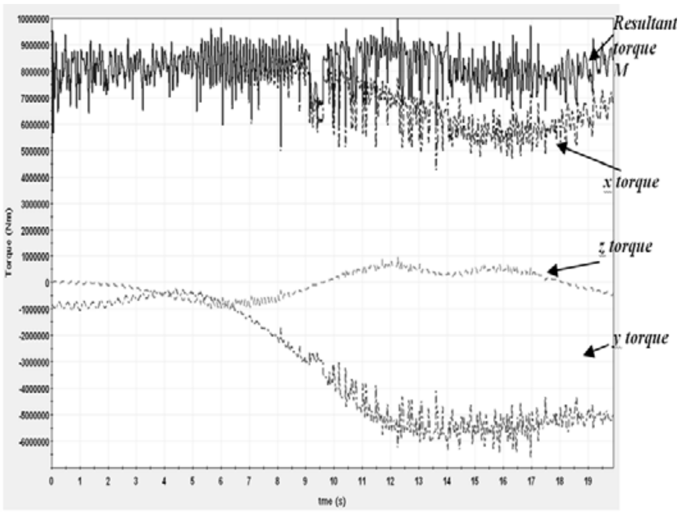

Fig.7. *Torque (momentum) in the constraint between mast and undercarriage*

Oscillations of torque around **x axes** are of high dynamic nature from start to the end of rotation process. Frequencies reach up to υ = 12 Hz (6 s<t<7 s). Amplitudes of torque can reach up to $\lambda = (9-5)\cdot10^6 = 4\cdot10^6$ Nm. This value is double higher than the value around **y axes**. This concludes that crane undergoes higher dynamic forces and moments around its **x axes,** compared to values around y axes and z axes. Oscillations of torque around **z axes** are of lower dynamic nature than other two previous cases. This means that moments around vertical z axes have little influence on crane.

Maximum value of the resultant torque $M=\sqrt{M_x^2+M_y^2+M_z^2}$ is M_{max} ≈ 10000000 Nm, in time t ≈ 12.5 s. This value is achieved during phase two, but it occurs only once. Most of extreme values of torque are around M_{max} ≈ 9200000 Nm. Compared to value of medium torque, it is an increase of 8.3%.

5. *Swinging of load and pulley*

Pulley system with load is main system that passes swinging and oscillations through cables on the metal construction of crane. Pulley with load and their according local coordinative system are shown on fig.8. On fig.9 are given swinging and oscillations of load based on local coordinate axes y (full line) and axes x (dotted line) from fig.8. Oscillations and swinging are measured in degrees (º). Based on figure 9, swinging of load reaches maximum values around **y axes** with max angle β_y ≈ -11.578º in time t≈12 s, and around **x axes**, with max angle of swinging β_x = 11.37º in time t ≈ 21 s.

Amplitude of swinging increases in time due to the swinging of load. Max amplitude of load swinging is $\boldsymbol{\lambda}_{deg(max)}$ = 24º - (-24º) = 48º, between time 4 s< t <12 s. Swinging of load is best parameter for measuring influence carried from working load to the metal construction of crane. Simulation is carried until t = 26 s.

Based on literature [2], angle of load swinging should not exceed 15º. Maximum vale that we got is β ≈ -11.578º. If we consider wind on boom cranes, it should be added 3 % of load, or value of resultant force [2]. This concludes that crane will have no stability issues resulting from load swinging, even with a presence of wind.

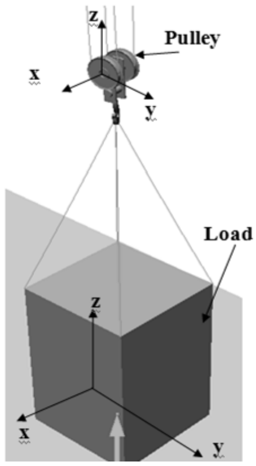

Fig.8. *Load and pulley. Local coordinate system of load*

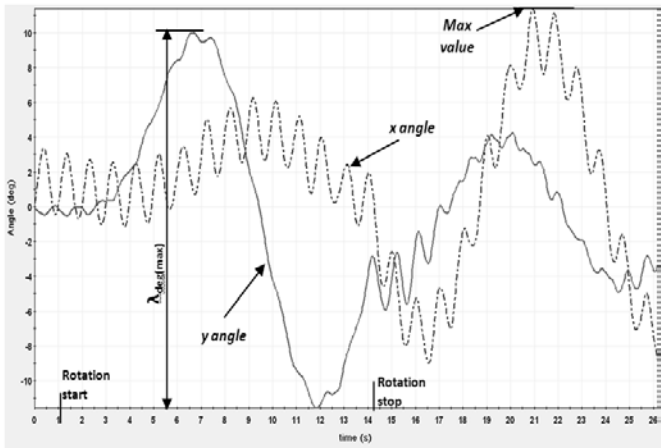

Fig.9. *Graph of Swinging of working load around* ***y axes*** *and* ***x axes***

6. *Conclusions*

Studying rotational motion of luffing boom cranes proved the dynamic nature of this process. Applying simulations with software [6] is a good method to find crane's acting dynamic forces, and determining dynamic stability. These forces and moments should be calculated for each major part and constraint, as it is done in this paper, in order to have best picture of occurrences in machine parts and components, in this case on luffing boom cranes. Main issues of crane rotation are intensive oscillations with high frequency and high amplitudes, mostly with irregular occurrence.

Results are shown for some crucial parts of these cranes, and they are commented for each case. Most complex work periods are motion start and stoppage. Most of crane metal parts can handle dynamic occurrences, based on their material and properties [4] and tables in literature [2],[1]. But in some cases, like tension force in restraint cables, the values gained exceeds the limitations, which are matter of concern. These oscillations, that might be difficult to measure with actual instruments can explain causes of stability problems, parts failure and materials fatigue. They are mainly induced by load swinging that produces forces in hoist cables, boom, mast and other parts. Influence in crane's stability have oscillations of other cables in crane, also oscillations of metallic construction and motion of mechanisms.

Based on these conclusions, proper restraints in crane basement should be done with high priority in order to prevent crane overturning. Speed of rotation should be kept as lower as possible, in order to minimize negative effects of load swinging, strain on parts of crane and problems with safety.

7. *References*

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