Scissor lift dynamic analysis and motion regulation for the case of lifting with maximum load

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Abstract: *This paper deals with Dynamic analysis of Scissor Lifts during the Load Lifting to determine their dynamic behavior, find the nature of oscillations, and the regulation of lifting to minimize these oscillations and optimize the work process. During the motion processes, the lift and its main parts undergo heavy forces, moments, and oscillations. The method of research is acquiring results through design, modeling, and simulations, comparing them with analytic calculations, and looking for the optimal motion regulation of the Load Lifting. The analysis will be acquired when the Scissor lift is carrying maximum Load. The study will be concentrated in the finding the nature of dynamic forces and stresses that acts on the main parts of the lift and the extent and the form of oscillations. Results will be shown in the form of diagrams and contour views as the solution results of the tested system. Modeling and simulations will be carried using software SimWise 4D, based on the type of the Scissor Lift taken from Standard Manufacturer. Conclusions of these analyses are useful for design considerations, dynamic behavior, and safety of these types of lifts.*

Keywords: SCISSOR LIFT, DYNAMIC ANALYSIS, LOAD LIFTING, OSCILLATIONS, REGULATION, MODELING, SIMULATIONS

1. Introduction

Scissor Lifts are Material Handling Machines, mainly used in warehouses and industrial facilities. Their primary use is lifting and lowering loads, and short horizontal traveling with or without load. The Scissor Lift taken for study is a type of Hydraulic Lift. The name comes from the form of bar's (Fig.1). It is an elevated work platform that consists of many parts used to lift people and other loads. Working with Scissor Lifts can lead to problems with load lifting due to the occurring oscillations, which can result in safety issues. It is important to find optimal scenario of lifting to minimize the oscillations. To do this, main kinematic and dynamic parameters of the motion must be found, which is difficult with instrumentation. The model of the Scissor Lift is designed and modeled with software SimWise 4D [2] (Fig.2). In Fig.1 is shown the Scissor Lift in the working environment.

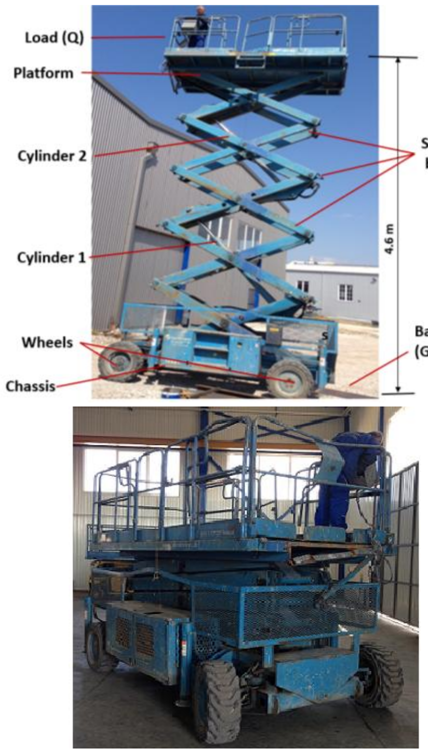

Fig.1. *Scissor Lift at highest position and lowest position [1],[13]*

Until now, authors have studied scissor lifts, with suggestions about design [4], [6], [7], dynamic stability [5], [13], [14], motion control and regulation [3], [11], [12], multibody dynamics [9],[10], oscillations [8], and simulations [3], [13], [14].

Scissor Lift is modeled based on the Lift *Type Genie® GS™-4390 RT* (Fig.1) [1]. It is used in one Local Factory near Prishtina City. Main parts of the Lift are: Chassis on 4 wheels, scissors bars, joints, hydraulic cylinders, and at the top is platform. Dimension of the Chassis are 4 m Length x 2.2 m Width. Total mass of the Lift is $m_L = 5849$ *kg*. Max lifting capacity is $Q_{max} = 6670.8\ N \approx 680\ kg$. Max lifting Height: $H_{max} = 13.1\ m$. Lifting velocity: $v = 0.35\ m/s$. Diameter of the wheels $D_w = 380\ mm$. Other dimensions are given in Fig.3 & Fig.4. Type of the Motor: Ford MSG 425 4-cylinder gas/LPG 75hp (56 kW) [1]. There are 2 hydraulic cylinders that lifts the load, mounted between the scissor bars. During this process, the lift is not moving horizontally. (Fig.2)

2. Modelling and simulations of Scissor Lift

Lift is modelled based on the Data from manufacturer [1] and then assembled to make the functional model. In Fig.2 is shown the model of the Scissor Lift created with software [2]. For the simulation purposes, flat ground is also modelled, where lift stands [3].

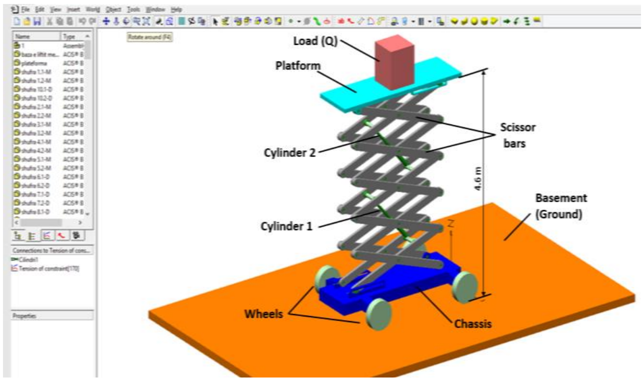

Fig.2. *Model of Scissor Lift in the software environment, at the highest position, created in the software SimWise 4d [2]*

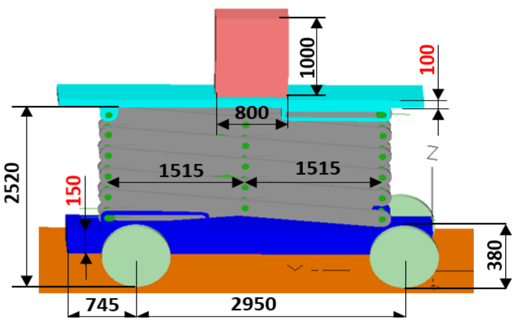

Fig.3. *Main dimensions (mm) of the Scissor Lift at its lowest and initial position (Left View)*

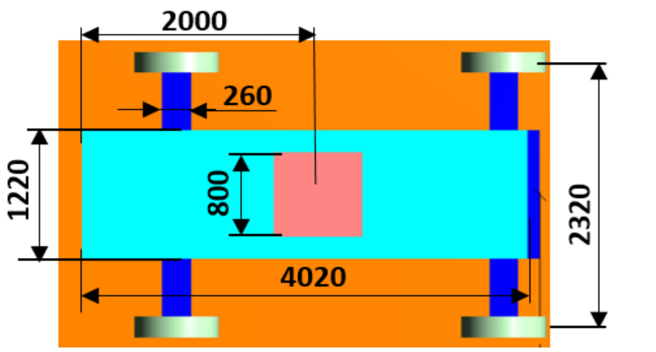

Fig.4. *Main dimensions (mm) of the Scissor Lift at its lowest and initial position (Top View)*

Load Q has prismatic form with dimensions 0.8m x 0.8m x 1m, laying on the platform. We consider that the best results will be achieved if the study is done with maximum loading capacity $Q_{max} = 680\ kg$ = 6670.8 N [14].

Before starting the simulations, lift stands in the position of relative rest, where platform and scissors are at initial lowest position (Fig.3 & Fig.4).

Simulation scenario of lifting is programmed close to real motion, which is important for achievement of reliable results. Platform (with Load Q) will start lifting from its initial lowest position (stowed) $H_1 = 1.8\ m$ up to the height $H_2 = 4.6\ m$. This means that platform will lift for $\Delta H = H_2 - H_1 = 2.8\ m$. Simulation has three phases [3],[13] (Fig.5):

First phase – initial position of relative rest with no lifting of Scissor Lift. Starts at time $0\ s < t < 0.5\ s$. Used to identify startup occurrences with no lifting.

Second phase – The process of lifting with the speed $v_l = 0.35\ m/s$ up to max height $H_2 = 4.6\ m$. Starts after first phase and occurs between time $0.5\ s < t < 8.5\ s$. Time of lifting is $t = 8\ s$.

Third phase - motion stoppage. Lifting will stop, but load Q, platform, bars, and other parts will continue to oscillate. Starts after second phase, between time sequence $8.5\ s < t < 9.5\ s$. Important for evaluation of the results after motion stoppage.

Only one kinematic data of lifting we have from manufacturer for the lifting purpose, and that is the speed of lifting $v_l = 0.35\ m/s$ [1]. Regulation of lifting is done with the adjustment of hydraulic power given from two cylinders to have the required lifting speed $v_l = 0.35\ m/s$. For this purpose, a step function is implemented to represent a real scenario of lifting simulation (Fig.5). The value of piston speed in cylinders that accurately represents required lifting speed of platform is $v_{cyl} = 0.077\ m/s$. This is determined through numerous simulations (iterations). Definition of this function and its form was done to enable 'smooth' lifting and minimize oscillations in the lift. This is the most important process of motion regulation of scissor lifting in this paper [3],[13].

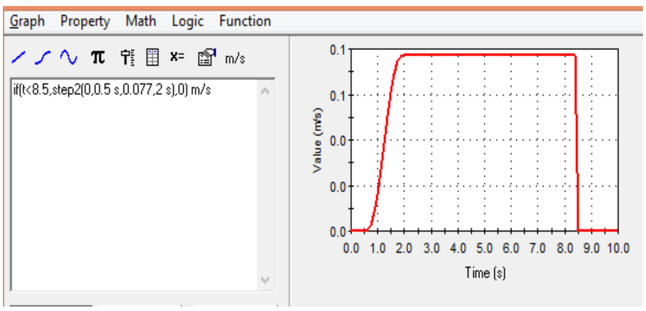

Fig.5*. Step function of the lifting speed*

Dynamic and kinematic parameters investigated for results are: forces, oscillations as part of acceleration, motion length, stresses that act in main parts of the lift. Results will be achieved using Numerical methods (Kutta-Merson) and Finite Elements Method (FEM), supported by software, in order to achieve accurate results [2], [13].

3. Results on the lifting cylinders

Hydraulic cylinder (actuator) is the device that lifts and lowers the load using hydraulic power of fluid. There are 2 cylinders mounted inside Scissors. Main parameter for analysis is finding the Force F_{cyl} acting on cylinder while it lifts the Load and upper parts of the lift. The force on cylinders depends on the dimensional and positional parameters of scissor bars and pistons (Fig.6|).

3.1. Calculation of Forces acting on the cylinders

Weight of parts lifted by cylinders is:

$Q_u = 20 \cdot Q_b + 2 \cdot Q_{cyl} + Q_{pl} + Q = 20 \cdot 100 + 2 \cdot 100 + 750 + 860 = 3710$ [kg] = 36395.1 [N]

Where:

Q_u – Weight of upper parts of the lift,

Q_b = 100 kg = 981 [N] – Weight of one scissor bar, out of twenty,

Q_{pl} = 750 kg = 7357.5 [N] – weight of the platform,

Q_{cyl} = 100 kg = 981 [N] – weight of one cylinder, out of two,

Q = 860 kg = 8436.6 [N] – maximal carrying load.

Force acting on the cylinder is based on the position of cylinder as in Fig.6 and referred to the literature [6], [7], and will be calculated considering the forces and reactions in two bars, where in the *Bar1* is connected (mounted) the cylinder.

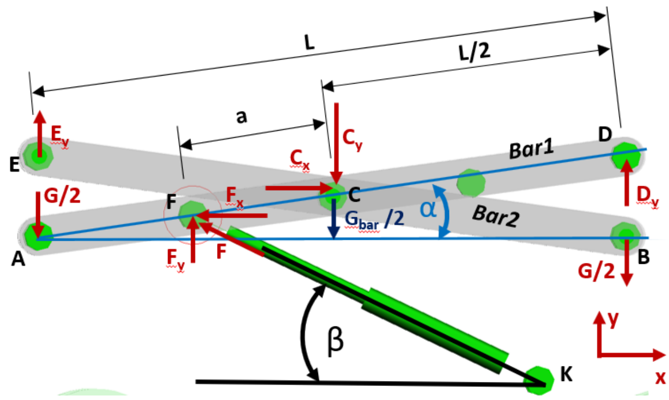

Fig.6. *Parameters of force acting on cylinders*

According to the diagram (Fig.6), we have [6], [7]:

$$D_y = E_y = \frac{G + G_{bars}}{2} \qquad [1]$$

$$G = Q_{pl} + Q \ ;\ G_{bars} = 20 \cdot Q_b + 2 \cdot Q_{cyl} \qquad [2]$$

$F_x = F \cdot \cos\beta$; $F_y = F \cdot \cos\beta$ - Force components in cylinder

α – Angle between the scissor bar and chassis,

β - Angle between the cylinder(s) and chassis.

C - Reaction force in the center of the bar's connections,

Equations of equilibrium in ***Bar1*:**

$$\sum X_i = 0 \ ;\ C_x - F_x = 0 \ \rightarrow C_x = F_x = F \cdot \cos\beta$$

$$\sum Y_i = 0 \ ;\ -G/2 + F_y - C_y - G_{bars}/2 + D_y = 0$$

$$-G/2 + F_y - C_y - G_{bars}/2 + (G+G_{bars})/2 = 0 \ \rightarrow C_y = F_y = F \cdot \sin\beta$$

$$\sum M_D = 0 \ ;\ G/2 \cdot L \cdot \cos\alpha + G_{bars}/2 \cdot (L/2) \cdot \cos\alpha - F_y \cdot \cos\alpha \cdot (L/2+a) + C_y \cdot L/2 \cdot \cos\alpha + F_x \cdot \sin\alpha \cdot (L/2+a) - C_x \cdot L/2 \cdot \sin\alpha = 0$$

Using factorization and trigonometry identities, we get:

$$G/2 \cdot L \cdot \cos\alpha + G_{bars}/2 \cdot (L/2) \cdot \cos\alpha - F \cdot \sin\beta \cdot \cos\alpha \cdot (L/2+a) + C_y \cdot L/2 \cdot \cos\alpha + F \cdot \cos\beta \cdot \sin\alpha \cdot (L/2+a) - C_x \cdot L/2 \cdot \sin\alpha = \mathbf{0}$$

$$\rightarrow \quad L \cdot \cos\alpha \cdot (G/2 + G_{bars}/4) - F \cdot \sin\beta \cdot \cos\alpha \cdot (L/2+a) + F \cdot \sin\beta \cdot L/2 \cdot \cos\alpha + F \cdot \cos\beta \cdot \sin\alpha \cdot (L/2+a) - F \cdot \cos\beta \cdot L/2 \cdot \sin\alpha = \mathbf{0}$$

$\rightarrow \quad L\cdot\cos\alpha\cdot(G/2+G_{bars}/4)+F\cdot[\sin\beta\cdot\cos\alpha\cdot(-L/2-a+L/2)+$
$+\cos\beta\cdot\sin\alpha\cdot(L/2+a-L/2)]=\mathbf{0}$

$\rightarrow \quad L\cdot\cos\alpha\cdot(G/2+G_{bars}/4)+F\cdot[-a\cdot\sin\beta\cdot\cos\alpha+a\cdot\cos\beta\cdot\sin\alpha]=\mathbf{0}$

$\rightarrow \quad L\cdot\cos\alpha\cdot(G/2+G_{bars}/4)-F\cdot a\cdot[\sin\beta\cdot\cos\alpha-\sin\alpha\cdot\cos\beta]=\mathbf{0}$

$\rightarrow \quad L\cdot\cos\alpha\cdot(G/2+G_{bars}/4)-F\cdot a\cdot\sin(\beta-\alpha)=\mathbf{0}$

$$\rightarrow \quad F=\frac{L\cdot\cos\alpha\cdot\left(\frac{G}{2}+\frac{G_{bars}}{4}\right)}{a\cdot\sin(\beta-\alpha)}=\frac{L\cdot\cos\alpha\cdot\left(\frac{Q_{pl}+Q}{2}+\frac{20\cdot Q_b+2\cdot Q_{cyl}}{4}\right)}{a\cdot\sin(\beta-\alpha)}$$

For our task, the parameters are:

L = 1.515 [m] – Length of one scissor bar (Fig.3 & Fig.6),

a = 0.745 [m] – Distance between the center of scissor bars joint (C) and restraint point of the cylinder (F) (Fig.6)

n = 2 – Number of cylinders. We assume that power is distributed equally between two cylinders.

Finally, force in the cylinder(s) is calculated by the formula:

$$F_{cyl}=\frac{L\cdot\cos\alpha\cdot\left(\frac{w}{2}+\frac{w_{bars}}{4}\right)}{n\cdot a\cdot\sin(\beta-\alpha)}=\frac{L\cdot\cos\alpha\cdot\left(\frac{Q_{pl}+Q}{2}+\frac{20\cdot Q_b+2\cdot Q_{cyl}}{4}\right)}{2\cdot a\cdot\sin(\beta-\alpha)}$$

Calculations of the Force are done for three positions of lifting height:

Position 1 – Lowest position of the platform. Height is H_1 = 1.8 m. Parameters, as in Fig.6, are: α= 4.42° , β = 14.896° , a = 0.745 m , L = 3.03 m. Time t = 0.2 s. Value of the Force in the cylinders is:

$$F_{cyl1}=\frac{3.03\cdot\cos(4.42^{\circ})\cdot\left(\frac{750+860}{2}+\frac{20\cdot100+2\cdot100}{4}\right)}{2\cdot0.745\cdot\sin(14.896^{\circ}-4.42^{\circ})}=15177.92$$

[kg] = **148895.38 [N]**

Position 2 - Middle height of the platform. Height is H_2 = 3.36 m. Parameters are (Fig.6): α= 10.367° , β = 32.827° , a = 0.745 m , L = 3.03 m. Height of platform H_2 = 3.36 m. Time t = 4.5 s. Value of the Force in the cylinders is:

$$F_{cyl2}=\frac{3.03\cdot\cos(10.367^{\circ})\cdot\left(\frac{750+860}{2}+\frac{20\cdot100+2\cdot100}{4}\right)}{2\cdot0.745\cdot\sin(32.827^{\circ}-10.367^{\circ})}=7094.97$$

[kg] = **69601.7 [N]**

Position 3 - Highest position of the platform. Height is H_3 = 4.6 m. Parameters are: α= 15.258°, β = 44.04°, a = 0.745 m, L = 3.03 m. Time t = 8.4 s. Value of the Force in the cylinders is:

$$F_{cyl3}=\frac{3.03\cdot\cos(15.258^{\circ})\cdot\left(\frac{750+860}{2}+\frac{20\cdot100+2\cdot100}{4}\right)}{2\cdot0.745\cdot\sin(44.04^{\circ}-15.258^{\circ})}=5526.4$$

[kg] = **54214.05 [N]**

Results of these calculations will be compared with graphical result for accuracy and validity of results.

3.2. Graphical results of the Force acting on cylinders

In Fig. 7 is given the graph of acting Force F_{cyl1} in the Hydraulic Cylinder 1. The process of lifting ends in time t = 8.5 s.

Based on the graph in Fig.7, we can conclude that force in the cylinder is close to the calculated values from the paragraph 3.1, which are shown with red dots. This validates the graphical results with simulations. Force F_{cyl} is dynamic in nature. At the start of the lifting process, in the interval $0.2\ s< t <1\ s$, it shows high frequencies up to $\upsilon \approx 11\ Hz$ and amplitudes $\lambda \approx 78000\ [N]$. Maximum value of force is achieved in time $t = 0.3\ s$, with the value $F_{cyl1} = -149000\ [N]$. Negative values denote pressure. After time $t=1\ s$, oscillations are low, until the start of phase 3, when there are more oscillations after stoppage, but with lower amplitudes.

This is important part of regulation, where oscillations are high at the beginning of the lifting, but later they decrease significantly.

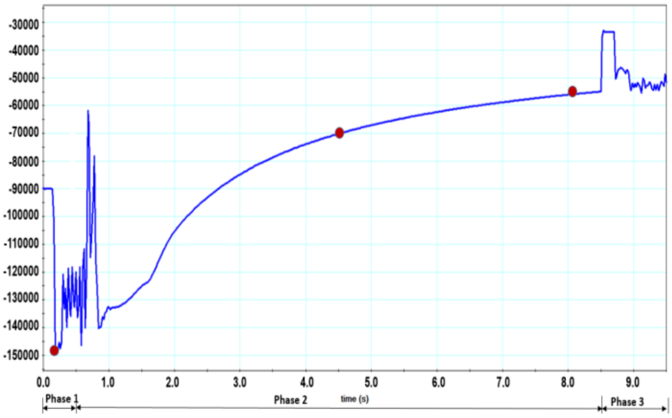

Fig. 7. *Force F_{cyl1} in the hydraulic Cylinder 1*

In Fig. 8 is the graph of the linear incerasing length of the cylinder's piston during the process of lifting. Cylinder will extend from 1.84 m to 2.4 m.

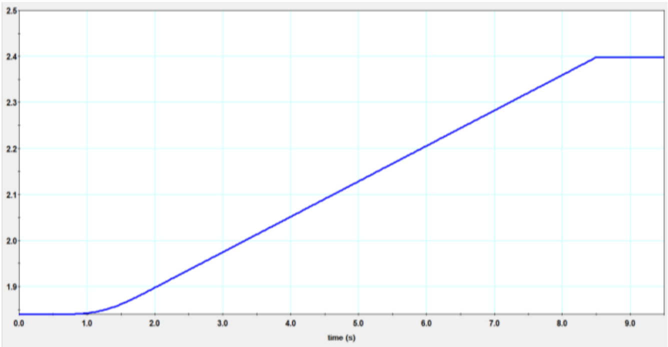

Fig. 8. *Length of hydraulic piston in Cylinder 1 during lifting*

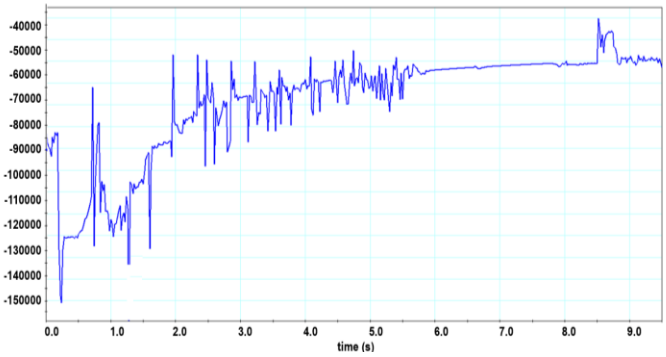

Fig. 9. *Force F_{cyl2} in the hydraulic Cylinder 2*

In Fig. 9 is given the graph of the Force F_{cyl2} in the Hydraulic Cylinder 2. The values are similar that of Cylinder 1, but the dynamic occurrences are intense, with more oscillations and frequencies than in Cylinder1, particularly in the time period 2.5 s <t< 6 s.

4. Oscillations in the Lifts Platform and Chassis

In the Fig. 10 is given the graph of acceleration ***a*** (m/s^2) in the platform of the lift. This is the parameter used to define the oscillations during the lifting.

Based on Fig. 10, we can conclude that platform undergoes heavy oscillations with high amplitudes up to $\lambda \approx 3.3\ (m/s^2)$ and frequencies up to $\upsilon \approx 13\ Hz$ at the start of the lifting to time $t = 2\ s$.

After time $t = 5.7$ *s*, amplitudes and frequencies tend to decrease. Based on the graph, medium value of acceleration is a ≈ 2.5 (m/s^2). Maximal value is $a_{max} \approx 6.5$ (m/s^2) at time t = 5.7 s.

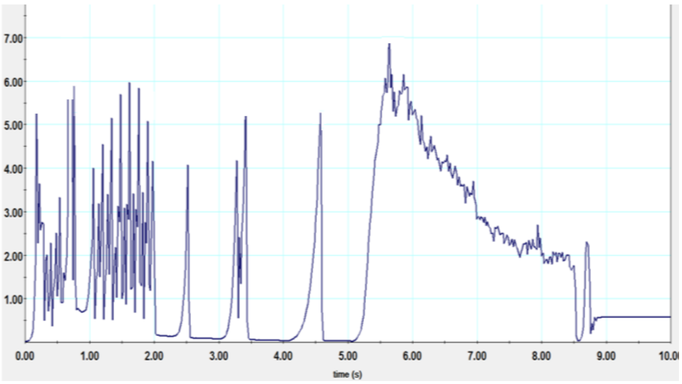

Fig. 10. *Oscillations on the platform, measured through acceleration* (m/s^2)

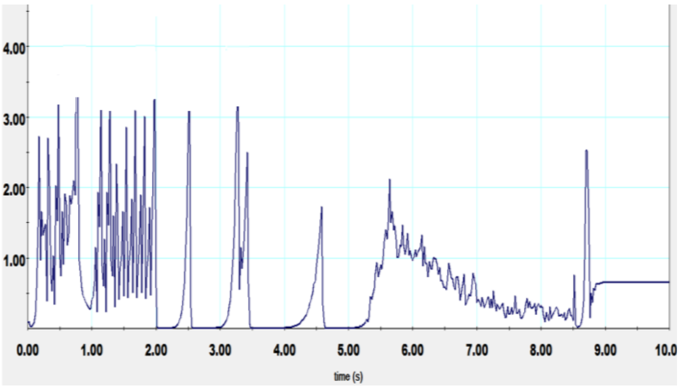

Fig. 11. *Oscillations on the chassis, measured through acceleration* (m/s^2)

In Fig. 11 is given the graph of acceleration ***a*** (m/s^2) in the chassis of the lift. We can conclude that chassis undergoes heavy oscillations, similarly to the platform, but intensity of accelerations is lower. Based on the graph, medium value of acceleration is a ≈ 1.2 (m/s^2) and maximal value is $a_{max} \approx 3.3$ (m/s^2) at time $t = 0.8$ *s*.

5. Results of the Scissor bars

Scissor bars are the part of the lift that passes the force from cylinders to the raise of the platform. They are one of the heaviest loaded parts. We will present the forces that act on their joints, and stresses. For this case, we will take one Scissor bar (Fig.14), considering that other bars will undergo similar forces and stress.

In the Fig.12 is shown the joint of Scissor bar: *Bar1*, taken for analysis, which is a revolute joint. In Fig.13 is given the result of Resultant Force in this joint. Medium value of resultant force (close to static) in the *Bar1* is $R_{b1} \approx 140000$ *[N]*, and maximal force (dynamic force) is $R_{b1max} \approx 250000$ *[N]* *(t = 1.5 s)*. Value of dynamic Force is for 78% higher, which is a matter of concern. Based on the curve of Resultant Force, we can conclude that Scissor bars undergo heavy dynamic loads, with high amplitudes and frequencies until time $t \approx 7$ *s*. After that, dynamic occurrences decrease significantly.

In Fig.14 is shown the Contour spread of Stresses in Scissor *Bar1*. In this figure we can see the discretization of *Bar1* in FEM volume Elements. Based on the contour colors, we can conclude that highest value of stress is in the right joint of the bar.

In the Fig.15 is given the graph of stresses in the *Bar1*. Stress result is the type of Von Misses Stress. Stress curve changes in high dynamic oscillations, with high frequencies and amplitudes. Dynamic occurrences are intense at the start of the process, and after $t=3$ *s* start to decrease. Maximal value of stress is $\sigma \approx 476$ *MPa* $= 4.76 \cdot 10^8$ at time $t \approx 1.4$ *s*.

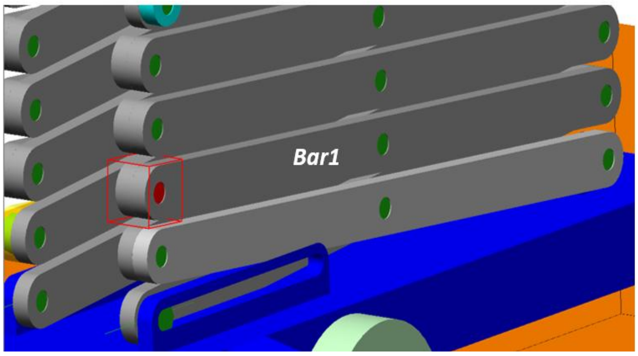

Fig.12. *Scissor Bar Joint taken for force calculation.*

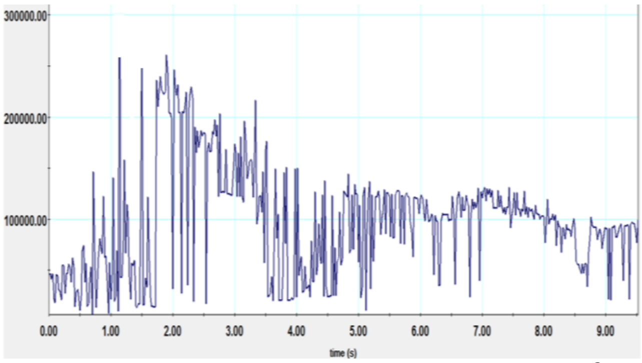

Fig.13. *Resultant Force acting on one of Scissor bars,* m/s^2

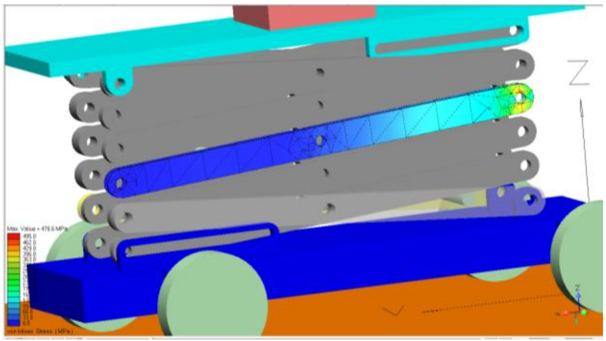

Fig.14. *Contour spread of Stresses in one of Scissor Bars - Bar 1*

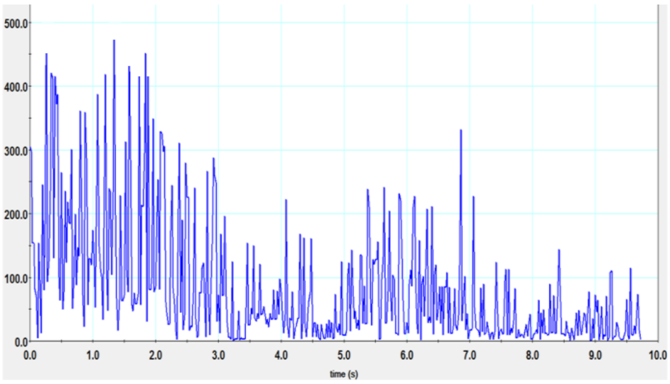

Fig.15. *Stress in one of Scissor Bars - Bar 1, MPa*

6. Forces in the Wheels

Wheels of the lift are connected in chassis and enables travel of the lift. In Fig.16 is given the graph of the Resultant Force R_w in the joint of front-left wheel. Based on the curve of Resultant Force, we can conclude that forces on the wheels are heavy dynamic in nature, with changes in amplitudes and frequencies until time t ≈ 5 s. After that, dynamic occurrences decrease significantly. Medium value of the resultant force (static force) after time $t=1$ *s* is $R_w \approx 31000$ *[N] s*, and maximal value of the dynamic force is $R_{wmax} \approx 42000$ *[N]* *(t = 1.5 s)*. This is a difference of 35%, which is a matter of concern. As a conclusion, during the lifting there should be additional outriggers from the chassis to the basement to increase the stability of the lift.

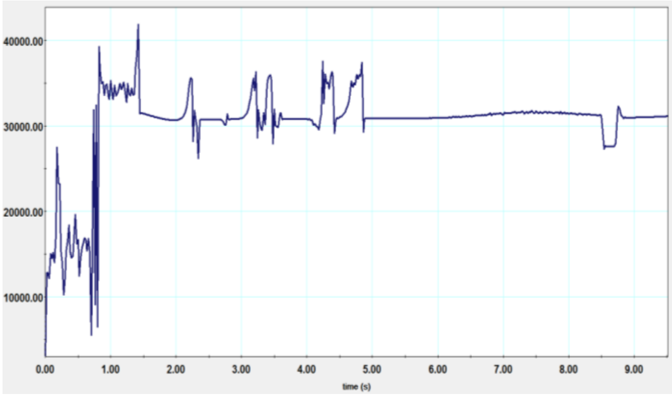

Fig.16. *Resultant Force acting on one of the Wheels.*

7. Conclusions

In this paper we have analyzed a Scissor Lift in the process of lifting to determine its dynamic behavior during load lifting, and the methodology to implement motion regulation through modeling and simulations with software. Modelling and simulations helps determining lift's behavior and its main parts. For the proper analysis and motion regulation it is important to develop accurate models to describe the lift dynamics [10], [12]. This can help also in further analysis for lifts regulation and optimization.

Dynamic analysis was carried after modelling and simulation of the scissor lift. The analysis proved the dynamic nature of the process and showed importance for the regulation to have less oscillations. Results of the forces in cylinder(s) are calculated analytically to determine the acting forces, then presented graphically using simulations, and then compared. Other results of kinematic and dynamic parameters in other parts of lift are presented graphically, analyzed, and commented.

Main issues in the lifting process are oscillations that are intensive in some parts of the lift. Their occurrence is irregular, with high amplitudes and frequencies. The form and influence of oscillations in the scissor lift can explain causes of parts failures, materials fatigue, and stability problems [8], [10]. These oscillations are difficult to be measured with actual instruments, so the methodology of analysis with simulations and comparison with analytical calculations helps to identify the dynamic occurrences in the scissor lift during the load lifting and leads to actions to be taken to minimize them and increase the safety of working with such a device.

Conclusions in this paper are important for safety and design considerations of these types of hydraulic lifts [3] and similar ones. They can be used also for analysis of other work processes, like lift travel in stowed or raised position.

8. References

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