

Analysis of kinematics and loads of the mechanical column lifts

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Abstract

Structure: Background/Aim: In this study presenting the problem of analysis load of the mechanical column lifts. A crane with two carrying columns was considered. The moving carrier of the consoles move along the inner belt of the carrying columns of this lift. In the first part of the paper, for the selected derived solution of the drive for lifting a motor vehicle, the principle of operation of the elements of the lifting mechanism is described. In the second part of the paper, the basics of static and kinematic analysis are given. The focus of the paper (key part) is the implementation of Finite Element Analysis (FEA) in the problem of moving load on mechanical column lifts. **Methods:** Finite Element Method (FEM), in Wolfram Mathematica language, the code was written. **Results:** Shown the numerical results (the force-time and moment-time 3D graphs for each node of the column) obtained. **Conclusion:** The foundations of dynamic analysis of the mechanical column lift during vehicle lifting are set.

1. Introduction

This paper discusses the problem of analysis load of the mechanical column lifts. This lifts are special type cranes. Characteristic types of mechanical column lifts are: single-column, two-column and quad-column (Figure 1). Due to

the existence of an analogy with these cranes, the subject problems will be presented on a two-post mechanical lift (Figure 2). For more details on mechanical column lifts, see [1-3].



(a)



(b)



(c)

Figure 1. If there are multiple panels, they should be listed as [2]: (a) Single-column; (b) Two-column; (c) Quad-column.

The moving load problem has been discussed in numerous scientific papers. Until the 60s of the 20th century, authors used an analytical approach in the formulation of the moving force problem [4-6]. The development of a new numerical method (FEM) has actualized the problem of moving force [7-9]. Olson [10] presented a review the moving force models with procedure for finite element analysis (FEA). The moving load problem considered to

the monograph by author Fryba [11]. In later scientific papers moving force problem was improved with moving problem mass by authors Riker, Lin and Tretheway [12], Wu [13] and other. Also, Wu [14] improved the moving load problem with three-dimensional framework. In general, the actuality of the moving load problem is also confirmed by recent papers (e.g. [15], [16]). In crane engineering, the latest papers on the study of this problem in the last 10 years are [17-23].

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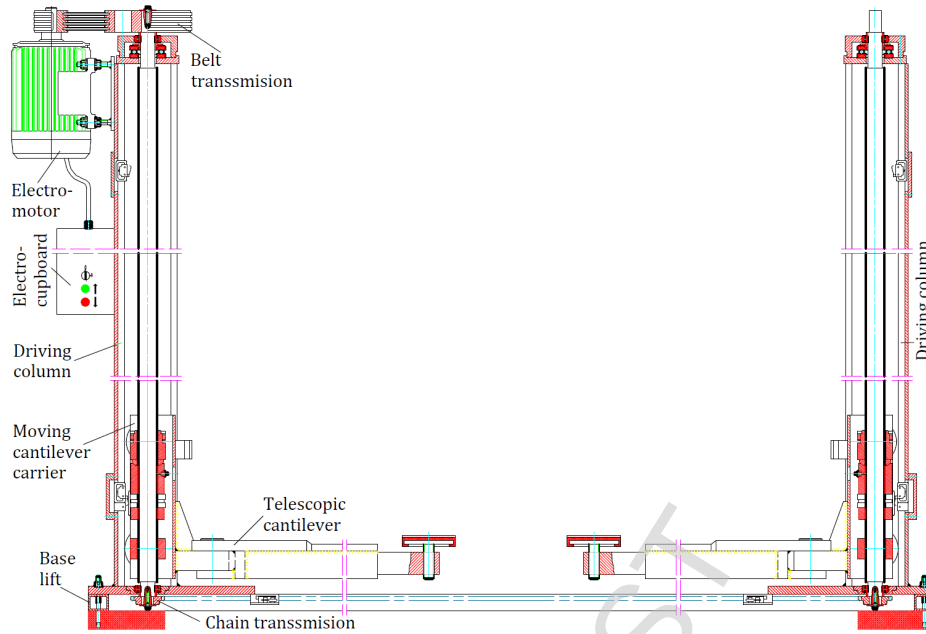


Figure 2. Mechanical two – column lift.

However, the subject of papers was exclusively the horizontal moving load problem, except in paper [24] – the vertical lifting vehicle. The author of this paper is not found literature with the problem of the analysis load of mechanical column lifts. To that effect, the kinematics of the lifting mechanism, the loads of the threaded spindles and the static loads of the columns of mechanical column lifts are defined first. Then, the nodal dynamic loads of column are defined by applying the finite element method (FEM). Definition of nodal forces at mechanical single-column lift in short form is communicated in [25].

2. Lifting mechanism

2.1. Kinematics of lifting mechanism

The kinematics of lifting mechanism is shown in Figure 3.

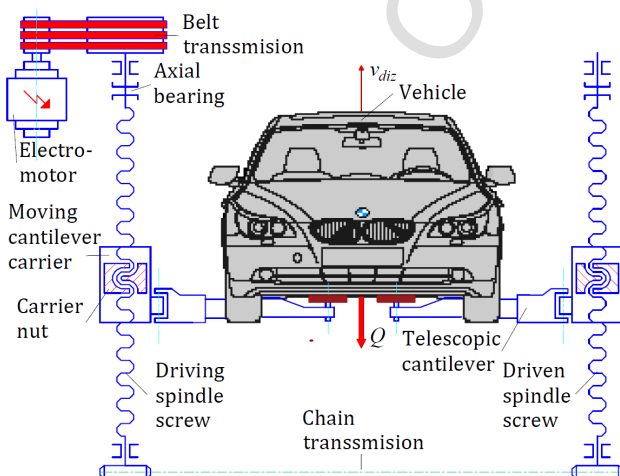


Figure 3. Kinematics scheme of drive of the mechanical two-column lift.

According to the principle of synchronization of the driving and follower screw spindle, the transmission ratio of the chain transmission must be $i_{CT} = 1$. The lifting speed is equal to the axial speed of the carrier nut.

For the number of revolutions of the threaded spindle n_{SS} and the thread stroke p , the axial speed of the carrier nut is defined by the formula:

$$v_l = n_{SS} \cdot p \quad (1)$$

2.2. Loads of spindle screws

Figure 4 shows the load distribution along the drive and follower screw spindles for axial force and torque. Threaded spindles are loaded with axial force, which is transmitted to them via the thread from the carrier nuts, on the variable part from the axial bearings to the carrier nuts.

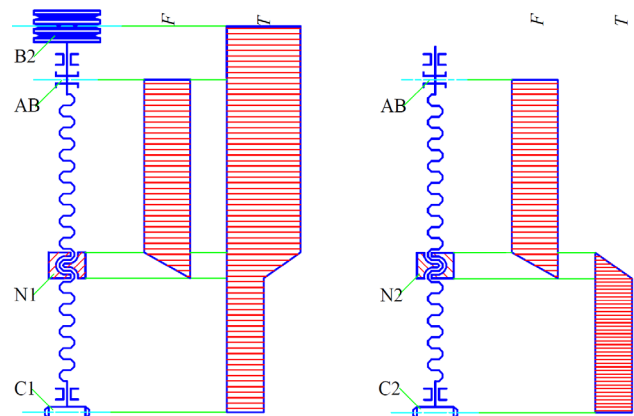


Figure 4. Scheme loads of spindle screws.

Along the nut under conditions of uniform load distribution on the threads, the tension force of the spindle decreases from F to a value of 0. 50% of the power, which the drive screw spindle receives from the driven pulley, is transmitted

to the carrier nut on the drive screw spindle, while the other 50% of the power is transmitted via the chain transmission to the carrier nut on the driven screw spindle.

The follower threaded spindle is loaded on the variable part from the driven chain to the carrier nut with a torque, which in the case of lifting the vehicle is:

$$T_{C2-N2} = \frac{m \cdot g}{2} \cdot \frac{d_2}{2} \tan(\varphi + \rho_n) \quad (2)$$

In the Equation (2) are: m the nominal mass, g the acceleration of gravity, φ the angle of slope of the screw thread, d_2 the average diameter and ρ_n the angle of friction in the screw thread.

The torque, which loads the drive threaded spindle on the variable part from the drive chain to the carrier nut, is equal:

$$T_{C1-N1} = \frac{T_{C2-N2}}{i_{CT} \cdot \eta_{CT}} \quad (3)$$

where η_{CT} is chain transmission efficiency.

The torque, which loads the drive screw spindle on the variable part from the carrier nut to the driven pulley, is:

$$T_{N1-B2} = \left(1 + \frac{1}{\eta_{CT}}\right) T_{C2-N2} \quad (4)$$

2.3. Static load of column

The weight of the motor vehicle mg is transferred from the screw spindle (tension) via an axial bearing in the top housing of the column system to the carrying column (compression).

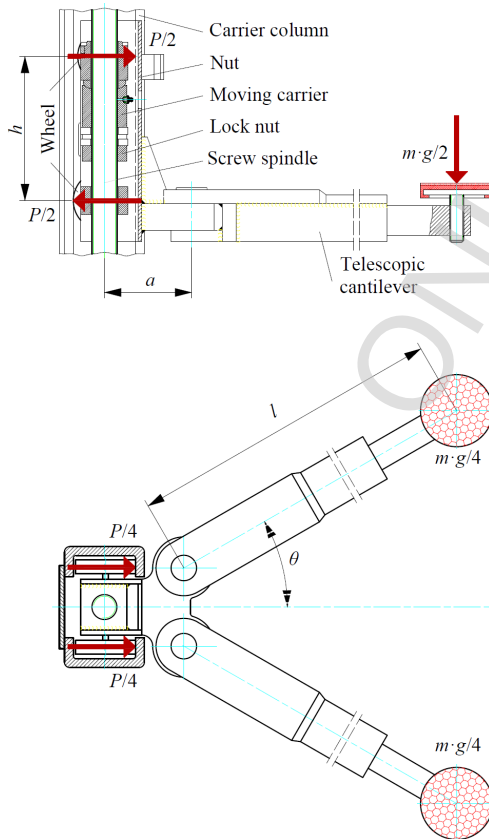


Figure 5. Reducing the bending moment to the coupling of forces.

The horizontal forces P , at the point of contact between the wheels and the carrying column, are obtained by reducing the load on the cantilevers to the coupling of the forces on the carrying column, (see Figure 5 and Equation (5)).

$$P = \frac{m \cdot g}{2h} (a + l_{max} + \cos \theta) \quad (5)$$

In the Equation (5) are: h the spacing between the couple forces, l_{max} the maximum length of telescopic cantilever and θ the telescopic cantilever angle.

3. Definition of dynamic loads of column

3.1. Kinematics of vehicle lifting

The moving forces P represent the moving load i.e. horizontal couple forces P . On lifting and lowering the vehicle, the effect of the moving load on the carrying column occurs. At the start of the motion $t_0 = 0$, the bottom wheels of the moving carrier of the cantilevers are in the bottom end position $y(0) = 0$, while the top wheels are in the position $y(0) = h$. At the point of time t , the top and the bottom wheels will pass the track $y(t)$ (see Figure 6a). For practical analysis, usual use profile is trapezoidal profile of speed. Here, the used is a trapezoidal profile of the lifting speed (see Figure 6b).

The notations on the trapezoidal profile of lifting speed are: v the uniform lifting speed, t_a the acceleration time, t_d the deceleration time and t_l the lifting time (total time).

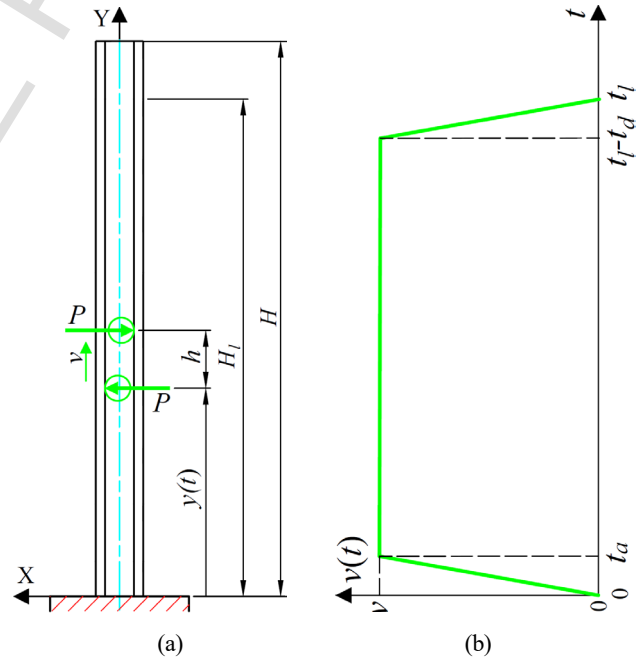


Figure 6. Moving load: (a) Column excited to a constant horizontal couple forces P moving along the column; (b) Trapezoidal speed profile.

The global position (relative to the bottom end position (BEP) of the column) of the couple forces P moving is defined by:

$$y_1(t) = y(t) = \begin{cases} \frac{v}{t_a} \int t \cdot dt, & 0 < t \leq t_a \\ v \int dt, & t_a < t \leq t_l - t_d \\ \frac{v}{t_d} \int (t_l - t) \cdot dt, & t_l - t_d < t \leq t_l \end{cases} \quad (6a)$$

$$y_{2t} = h + y(t) = h + \begin{cases} \frac{v}{t_a} \int t \cdot dt, & 0 < t \leq t_a \\ v \int dt, & t_a < t \leq t_l - t_d \\ \frac{v}{t_d} \int (t_l - t) \cdot dt, & t_l - t_d < t \leq t_l \end{cases} \quad (6b)$$

3.2. Formulation of node loads

The differential equation of dynamic equilibrium for the forced undamped column system with multiple degrees of freedom reads:

$$[\mathbf{M}] \cdot \{\ddot{\mathbf{U}}\} + [\mathbf{K}] \cdot \{\mathbf{U}\} = \mathbf{P}(t) \quad (7)$$

The notations in Equation (7) are: $[\mathbf{M}]$ the matrix of consistent masses of the column system, $[\mathbf{K}]$ the stiffness matrix of the column system, $\{\ddot{\mathbf{U}}\}$ the nodal acceleration vector, $\{\mathbf{U}\}$ the nodal displacement vector and $\{\mathbf{P}(t)\}$ the external nodal forces vector.

The equivalent nodal loads can be described on Figure 7. If column excited to a moving couple forces P , that present

$$\{\mathbf{P}(t)\} = \{0 \ 0 \ 0 \dots f_1^s(t) \ f_2^s(t) \ f_3^s(t) \ f_4^s(t) + f_1^{s+1}(t) \ f_5^s(t) + f_2^{s+1}(t) \ f_6^s(t) + f_3^{s+1}(t) \ f_4^{s+1}(t) \ f_5^{s+1}(t) \ f_6^{s+1}(t) \dots 0 \ 0 \ 0\} \quad (8)$$

The notations $f_i^{(s)} = f_i^{(s)}(t)$, $i = 2, 3, 5, 6$ and $f_i^{(s+1)} = f_i^{(s+1)}(t)$, $i = 2, 3, 5, 6$ in Equation (8) are equivalent nodal forces. The nodal forces are determined by formulas:

$$f_i^{(s)}(t) = P\{N^s\} \quad (9a)$$

$$f_i^{(s+1)}(t) = P\{N^{s+1}\} \quad (9b)$$

The notations N^s and N^{s+1} or

$$\{N^s\} = [N_2^s \ N_3^s \ N_5^s \ N_6^s]^T \quad (10a)$$

$$\{N^{s+1}\} = [N_2^{s+1} \ N_3^{s+1} \ N_5^{s+1} \ N_6^{s+1}]^T \quad (10b)$$

represent shape interpolation functions, which are represented by Hermitian polynomials [26]. The insert substitutions

$$\eta_1 = \frac{y_1(t)}{h} \quad (11a)$$

$$\eta_2 = \frac{y_2(t)}{h} \quad (11b)$$

in the shape functions [26], in this case the shape functions takes the final form:

$$\begin{aligned} N_2^s &= 1 - \eta_1^2 + 2\eta_1^3 \\ N_3^s &= h(\eta_1 - 2\eta_1^2 + \eta_1^3) \\ N_5^s &= \eta_1^2 + 2\eta_1^3 \end{aligned} \quad (12a)$$

the forces on all the nodes of the column are equal to zero except the nodes of elements s and $s + 1$ that is excited to couple forces P .

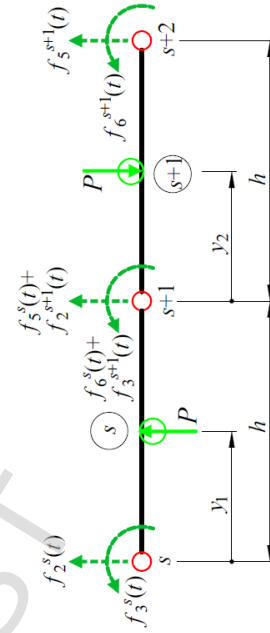


Figure 7. Nodal forces of the element s and $s+1$ excited to couple forces P .

In accordance with the Reference [26], the external forces vector for the column system is formulated:

$$\begin{aligned} N_6^s &= h(2\eta_1^2 + \eta_1^3) \\ N_2^{s+1} &= 1 - \eta_2^2 + 2\eta_2^3 \\ N_3^{s+1} &= h(\eta_2 - 2\eta_2^2 + \eta_2^3) \\ N_5^{s+1} &= \eta_2^2 + 2\eta_2^3 \\ N_6^{s+1} &= h(2\eta_2^2 + \eta_2^3) \end{aligned} \quad (12b)$$

In Equations (10a) and (10b) the notations $y_1(t)$ and $y_2(t)$ are local position coordinate (distance along the element to point action couple forces P) and h the spacing between the couple forces (equal sign length of finite element).

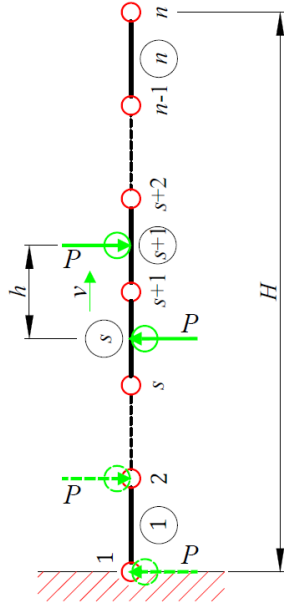


Figure 8. Couple forces P moving along a column.

The FE model of column is described on Figure 8. The column is divided into $n - 1$ elements (length h), with n nodes. As forming column excited by the coupling of moving forces P with speed $v(t)$.

For total time T and time steps m , the time interval is chosen by $\Delta t = T/m$. For all the nodes ($i = 1 \dots n$) on the column at all time steps m , the force and moment vectors reads:

$$[F]_{m+1}^i = [F_{t=0}^i \ F_{t=1\Delta t}^i \ F_{t=2\Delta t}^i \ \dots \ F_{t=T}^i]^T \quad (13)$$

$$[M]_{m+1}^i = [M_{t=0}^i \ M_{t=1\Delta t}^i \ M_{t=2\Delta t}^i \ \dots \ M_{t=T}^i]^T \quad (14)$$

For at any time $t = r \cdot \Delta t$, (r takes values from 1 to m), the global position is determined by Equations (6a) and (6b). The number of element s (the point of contact: bottom wheels-column) and $s + 1$ (at the point of contact: top wheels-column) can be determined bay formulas:

$$s = \text{IntegerPart} \left[\frac{y_l(t)}{h} \right] + 1 \quad (15a)$$

$$s + 1 = \text{IntegerPart} \left[\frac{y_l(t) + h}{h} \right] + 1 \quad (15b)$$

Elements s and $s + 1$ there are per two nodes. In other words, nodes element s are s and $s + 1$, while nodes element $s + 1$ are $s + 1$ and $s + 2$. For elements s and $s + 1$, the nodal forces and moments when the couple forces P moving reads:

$$\begin{aligned} F_{t=r\Delta t}^s &= P \cdot N_2^s, & F_{t=r\Delta t}^{s+1} &= P \cdot N_5^s, \\ M_{t=r\Delta t}^s &= P \cdot N_3^s, & M_{t=r\Delta t}^{s+1} &= P \cdot N_6^s, \end{aligned} \quad (16a)$$

$$\begin{aligned} F_{t=r\Delta t}^{s+1} &= P \cdot N_2^{s+1}, & F_{t=r\Delta t}^{s+2} &= P \cdot N_5^{s+1}, \\ M_{t=r\Delta t}^{s+1} &= P \cdot N_3^{s+1}, & M_{t=r\Delta t}^{s+2} &= P \cdot N_6^{s+1}, \end{aligned} \quad (16b)$$

while, for $i = 1$ to n (i takes values from 1 to n) except s , $s + 1$ and $s + 2$ are equal zero e.i.

$$F_{t=r\Delta t}^i = 0, \quad M_{t=r\Delta t}^i = 0 \quad (17)$$

Equations (11a) and (11b) could be transform in terms of the the global position i.e. in following form:

$$\eta_1 = \frac{y_l(t) - (s - 1)h}{h} \quad (18a)$$

$$\eta_2 = \frac{y_l(t) - s \cdot h}{h} \quad (18b)$$

On the basis of illustrated procedure, the functions of time-load (time-force and time-moment) are defined for all the nodes of the column when is excited to couple forces P moving.

4. Numerical example

In this numerical example, the theoretical analysis of dynamic load in previous subsections will be applied on the derived solution of the mechanical column lift for the purpose of verification its correctness.

Couple forces of constant amplitudes moving from bottom end position do top end position of carrying column with speed profile (see Figure 6).

Given: Height of carrying column $H = 2$ m, amplitude of forces are 1 N, the spacing between the couple forces is $h = 0.25$ m, acceleration/deceleration time are 1 s, speed of moving couple forces in interval $t_l - (t_a + t_d)$ is constant $v = 0.05$ m/s and total time moving couple forces is $t_l = 36$ s.

Find: Determine the functions time-load of the column of the mechanical two-column lift due to the action of the couple forces P moving.

Solution: Column is divided into 8 identical finite elements. Defined are 9 nodes. The trapezoidal profile of lifting speed is graphic designed (Figure 9). Total time of 36 s is divided into 360 time steps.

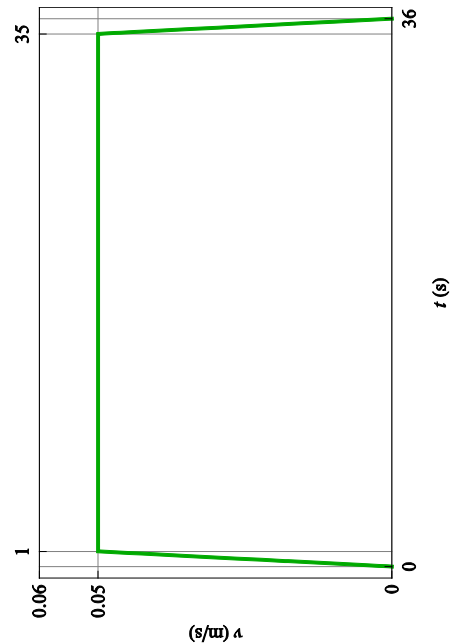


Figure 9. Speed – time diagram.

A software solution Wolfram Mathematica chosen to solve the problem set [27,28]. In Mathematica, the code was written based on the procedure given in the previous section.

Based on the simulation of a numerical example, the equivalent nodal loads are illustrated using a 3D graphs (Figures 10-15). The code illustrates the principles of considering a carrying column 2 m high with $j = 1 \dots 9$ nodes. The nodes are evenly spaced along the column. The total vehicle lifting time of 36 s is divided into $q = 360$ time steps. The force-time 3D graphs for each node of the column are shown in Figures 10 and 11. Also, the moment-time 3D graphs for each node of the column are shown in Figures 12 and 13. At the end, the resultant force-time and resultant moment-time 3D graphs for each node of the column are shown in Figures 14 and 15. 3D graphs (Figures 10-13) show that the forces and the moments on each node are equal 0 (zero) for all times other except whilst the forces of the top and the bottom wheels are motion of translation (vertical) from the previous node to the next node. At the end, Figures 14-15 with 3D graphs, show that the resultant force and resultant moment on each node are equal 0 for all times other except whilst the forces of the top and the bottom wheels are motion of vertical from the previous two nodes to the next two nodes.

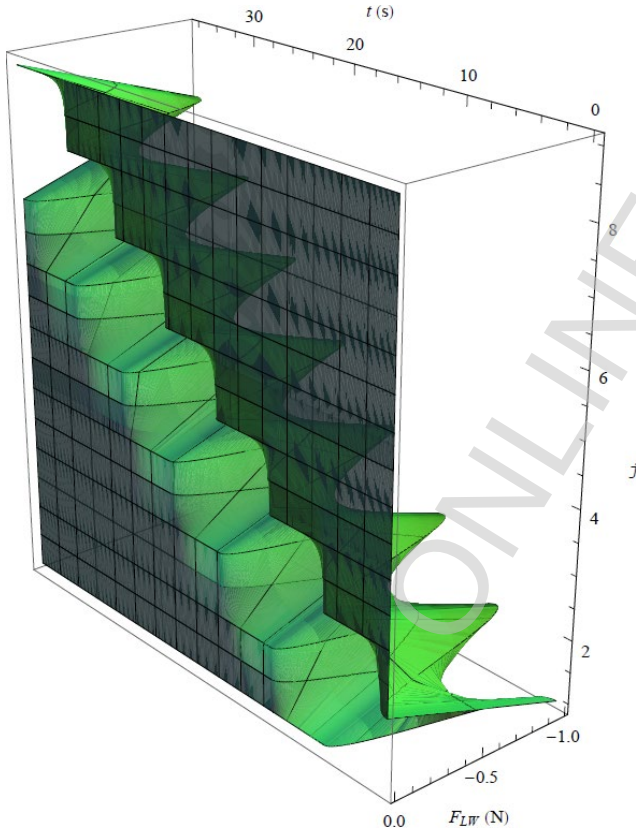


Figure 10. Force of the lower wheels – time 3D graph for each node of cantilever.

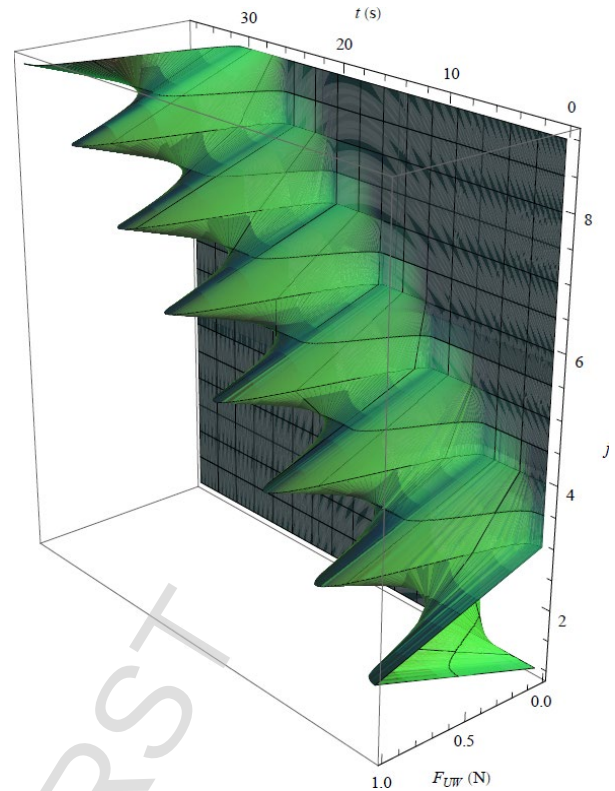


Figure 11. Force of the upper wheels – time 3D graph for each node of cantilever.

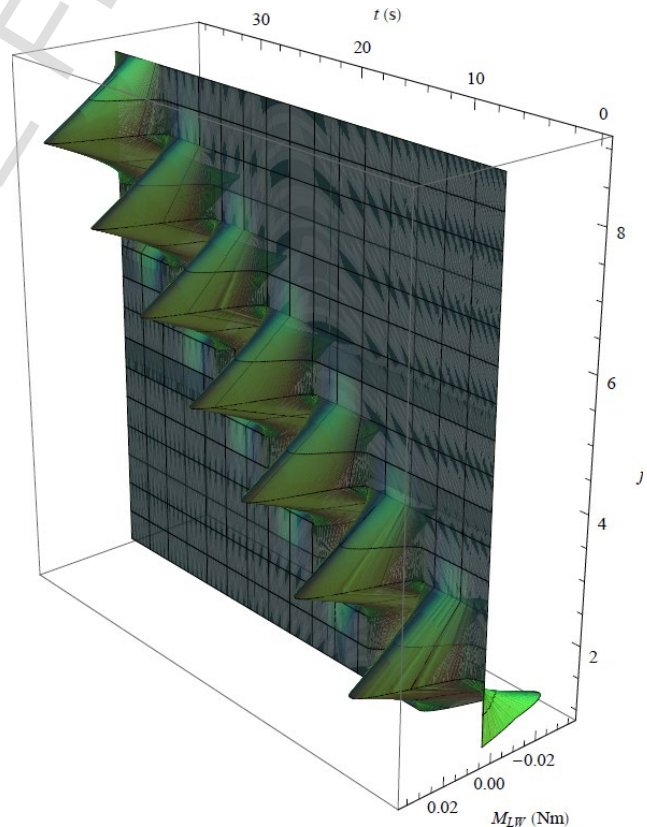


Figure 12. Moment of the lower wheels – time 3D graph for each node of cantilever.

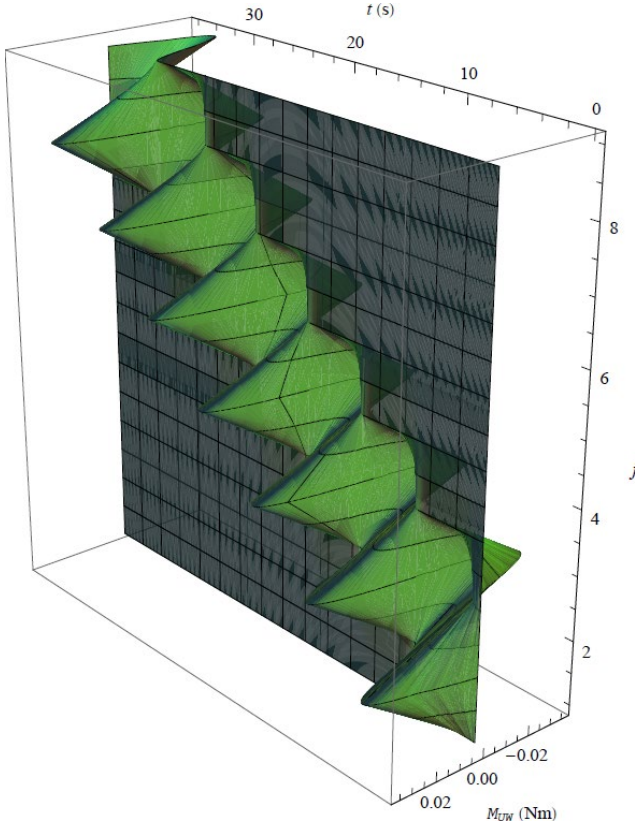


Figure 13. Moment of the upper wheels – time 3D graph for each node of cantilever.

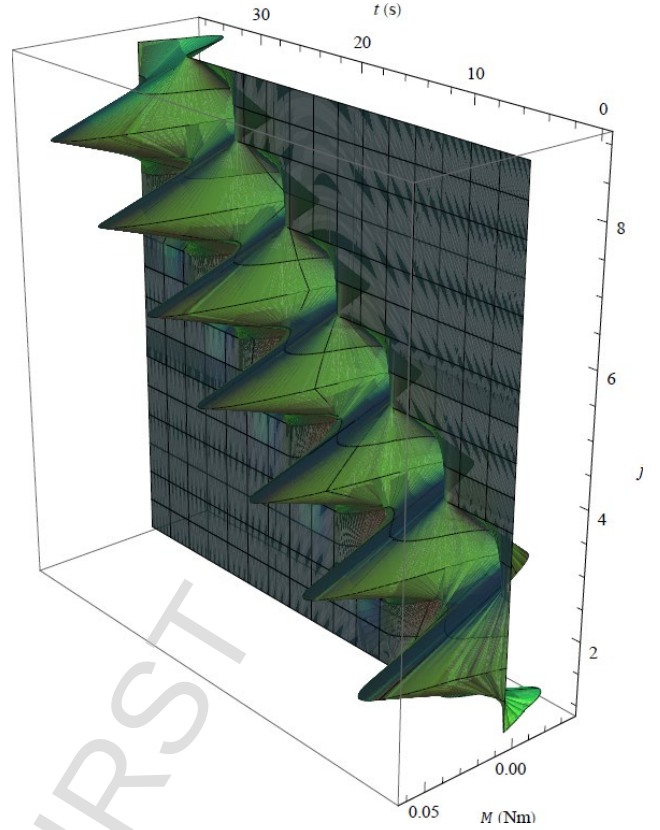


Figure 15. Resultant moment – time 3D graph for each node of cantilever.

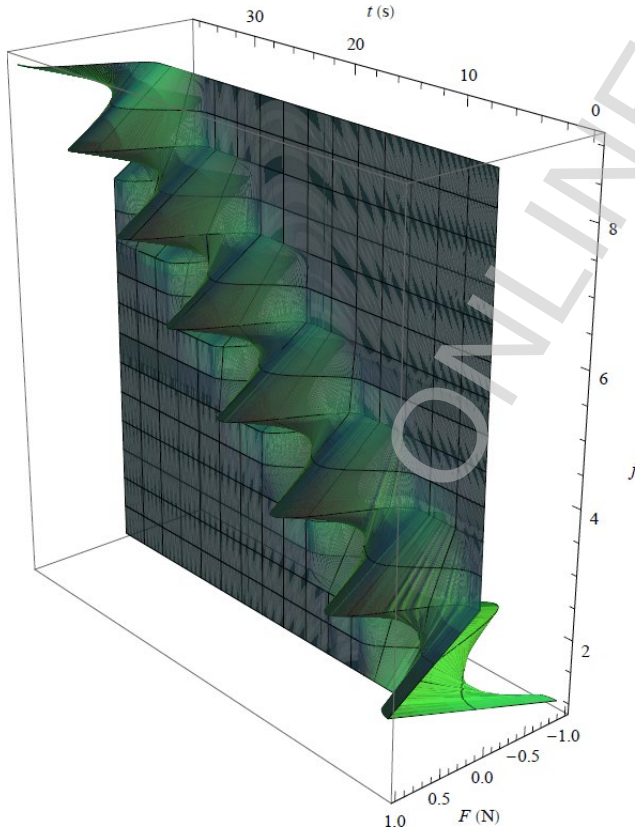


Figure 14. Resultant force – time 3D graph for each node of cantilever.

Consideration of forced oscillations with a finite number of degrees of freedom is carried out via Equation (7). By extracting the values for force F and moment M (Equations 16a and 16b) for each node ($j = 1 \dots 9$) and implementing them in equation (7), it is possible to obtain the response of the carrying column of the crane due to the moving force. The response fully captures the variability of the load position and the dynamic characteristics of the forced. Also, the values for force F and moment M for each node can be implemented on the model, corresponding to the crane column model in Figures 7 and 8, in an adequate software solution (e.g. SAP2000, RFEM6, ANSYS, ...).

5. Conclusion

Load of mechanical two-column lifts is analysed in this research. The focus of the paper is the problem of moving loads in the dynamic analysis of mechanical two-post lifts using the finite element method. The method of consistent masses is used. The coupling of forces is moving with a trapezoidal speed profile.

For want of literature on mechanical column lift, the analysis load of mechanical two-column lift is given in the first part. Generality, this paper focused on the formulation of nodal forces of the column (main part).

Equivalent nodal couplings of forces and moments for initial parameters were obtained. Using code written in the language of Wolfram Mathematica, the force-time and moment-time 3D graphs for each node of the column can be drawn. Techniques for describing the moving load problem in the vertical plane are shown. It is enabled to understand the moving load action at the mechanical column lifts. The

basis of dynamic analysis of the mechanical column lift during vehicle lifting is set.

The obtained results can provide valuable guidance and insights into solving the same or similar problems that might appear in various types of mechanical column lifts.

The additional aim of this paper is the extend literature of the lifts for lifting vehicles, as well as of problem moving load.

This paper offer valuable insights for further study of column mechanical cranes and suggests opportunities for additional research into the kinematics and dynamics of these lifts.

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Analiza kinematike i opterećenja mehaničke stubne dizalice

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Apstrakt

Structure: Uvod/Cilj: U ovoj studiji predstavlja se problem analize opterećenja mehaničkih stubnih dizalica. Razmatrana je dizalica sa dva noseća stuba. Pokretni nosač konzola kreće se duž unutrašnjeg pojasa nosećih stubova ove dizalice. U prvom delu rada, za izabrano izvedeno rešenje pogona za podizanje motornog vozila, opisan je princip rada elemenata mehanizma za podizanje. U drugom delu rada date su osnove statičke i kinematičke analize. Fokus rada (ključni deo) je implementacija konačno elementne analize (KEA) u problemu pomičnog opterećenja na mehaničkim stubnim dizalicama. **Metode:** Metoda konačnih elemenata (MKE), u programskom jeziku Wolfram Mathematica, napisan je kod. **Rezultati:** Prikazani su dobijeni numerički rezultati (3D grafikoni sila-vreme i moment-vreme za svaki čvor stuba). **Zaključak:** Postavljeni su temelji dinamičke analize mehaničke stubne dizalice tokom podizanja vozila.

Originalni naučni rad

mašinstvo, računarske nauke, mehanika, matematika

Ključne reči:

mehanička stubna dizalica; stub; pokretno opterećenje; opterećenja čvorova; KEA