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KINEMATICS STUDY AND WORKING SIMULATION OF THE SELF-ERECTION MECHANISM OF A SELF-ERECTING TOWER CRANE, USING NUMERICAL AND ANALYTICAL METHODS

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***Abstract**: In this paper the authors present a kinematics study of a self erection mechanism which is a component of a self erecting crane. The study was done, using several methods, all using the computer.*
The first is an analytical method, in which the computer is used to calculate the formulas resulted from applying the method.
The second method involves using dedicated software for the kinematics study of plane mechanisms, while the third one uses 3D CAD software for design and simulation.
***Keywords:** self-erecting cranes, kinematic analysis, analytical methods*

1. INTRODUCTION

The folding-unfolding mechanism of a self-erecting tower crane is presented in unfolded state in figure 1.

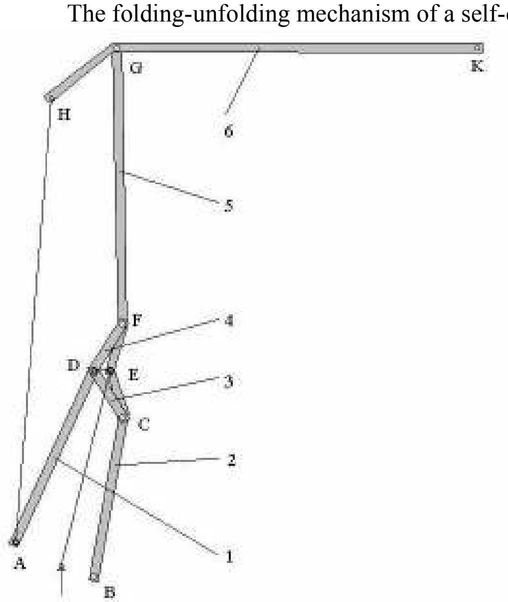


Figure 1 Self-erecting tower crane in unfolded state

Unfolding mechanism is done by using a tackle placed between D and E joints and is done in 2 stages, figure 3. In the first stage (the backstay fixed between A and H is loosened), by shorting the length of the tackle, the lower tower BCE rotates counter clockwise around the B joint and the rocker bar 1, through 3 and 4 bars, are pushing up the superior tower EFG along with the HGK boom and are rotating clockwise around the E joint. In stage 2, when the AH distance becomes equal with the backstay length, the HGK boom is rotating around G joint until GK becomes horizontal.

2. ANALYTICAL STUDY OF MECHANISMS KINEMATICS

2.1. Method overview

For the kinematics study was used the matrix method (geometric places method). This method is applied on dyads starting with the dyad linked to the end-effector. The coordinate system to which the mechanism relates has the origin in the fixed hinge A.

2.1.2. Positions study

Considering a RRR dyad related to a reference coordinate system and for which are known the positions of the external joints and the lengths of the bars, figure 2, can be written the following system:

$$\begin{cases}(x_3-x_1)^2+(y_3-y_1)^2=l_1^2\\(x_3-x_2)^2+(y_3-y_2)^2=l_2^2\end{cases} \tag{1}$$

By solving the system 2 solutions are given (x_3, y_3),

$$x_3 = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}; \qquad y_3 = \frac{D - (x_2 - x_1)x_3}{y_2 - y_1}, \qquad \textbf{(2)}$$

where:

$$\left.\begin{aligned} D &= \frac{x_2^2 + y_2^2 - x_1^2 - y_1^2 + l_1^2 - l_2^2}{2} \\ A &= (y_2 - y_1)^2 + (x_2 - x_1)^2 \\ B &= 2y_1(x_2 - x_1)(y_2 - y_1) - 2x_1(y_2 - y_1)^2 - 2D(x_2 - x_1) \\ C &= (y_2 - y_1)^2(x_1^2 + y_1^2 - l_1^2) + D^2 - 2y_1(y_2 - y_1)D \end{aligned}\right| \qquad \textbf{(3)}$$

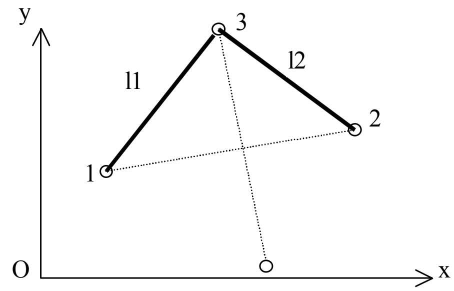


Figure 2 Geometric places method for a dyad

The real position of the interior joint is chosen according to the principle of position succession.

The angles that the bars have with the OX axis measured counter clockwise are determined with the equation

$$\alpha_i = arctg\frac{y_2 - y_1}{x_2 - x_1}, \qquad \textbf{(4)}$$

where x_1, y_1, x_2, y_2 represents the coordinates of the bar i.

2.1.3. Velocities study

Deriving in relation with time the system of equations (2)

$$\begin{cases} (x_3 - x_1)(\dot{x}_3 - \dot{x}_1) + (y_3 - y_1)(\dot{y}_3 - \dot{y}_1) = 0 \\ (x_3 - x_2)(\dot{x}_3 - \dot{x}_2) + (y_3 - y_2)(\dot{y}_3 - \dot{y}_2) = 0 \end{cases} \qquad \textbf{(5)}$$

Knowing the projections of the external joints velocities of the dyad related to the reference coordinate system chosen previously $\dot{x}_1$, $\dot{y}_1$, $\dot{x}_2$, $\dot{y}_2$ and then the internal joint's velocities components are uniquely determined $\dot{x}_3$, $\dot{y}_3$ with the equations

The velocity vector is written

$$\bar{v}_3 = \dot{x}_3\bar{i} + \dot{y}_3\bar{j} \qquad \textbf{(6)}$$

and its magnitude

$$v_3 = \sqrt{\dot{x}_3^2 + \dot{y}_3^2} \qquad \textbf{(7)}$$

Bars angular velocities are determined using the Euler equation for velocities.

From equation $\bar{v}_2 = \bar{v}_1 + \bar{\omega} \times \bar{r}$ by writing the vectors in analytical form and after writing the cross product, the angular velocity is then determined by equalling the magnitudes of the vectors

$$\omega = \sqrt{\frac{(\dot{x}_2 - \dot{x}_1)^2 + (\dot{y}_2 - \dot{y}_1)^2}{(x_2 - x_1)^2 + (y_2 - y_1)^2}}. \qquad \textbf{(8)}$$

2.1.4. Accelerations study

Deriving in relation with time the system of equations (5)

$$\begin{cases} (x_3 - x_1)(\ddot{x}_3 - \ddot{x}_1) + (\dot{x}_3 - \dot{x}_1)^2 + (y_3 - y_1)(\ddot{y}_3 - \ddot{y}_1) + (\dot{y}_3 - \dot{y}_1)^2 = 0 \\ (x_3 - x_2)(\ddot{x}_3 - \ddot{x}_2) + (\dot{x}_3 - \dot{x}_2)^2 + (y_3 - y_2)(\ddot{y}_3 - \ddot{y}_2) + (\dot{y}_3 - \dot{y}_2)^2 = 0 \end{cases} \qquad \textbf{(9)}$$

and knowing the projections of the external joints accelerations of the dyad related to the reference coordinate system chosen previously $\ddot{x}_1$, $\ddot{y}_1$, $\ddot{x}_2$, $\ddot{y}_2$, then the internal joint's accelerations projections are determined $\ddot{x}_3$, $\ddot{y}_3$ and the magnitude

$$a_3 = \sqrt{\ddot{x}_3^2 + \ddot{y}_3^2} \qquad \textbf{(10)}$$

Bars angular accelerations are determined by using the Euler equation for accelerations.

Out of the equation

$$\bar{a}_2 = \bar{a}_1 + \bar{\omega} \times (\bar{\omega} \times \bar{r}) + \bar{\varepsilon} \times \bar{r} \qquad \textbf{(11)}$$

Writing the vectors in analytical form and after writing the cross product

The angular acceleration is then determined by equalling the magnitudes of the vectors

$$\varepsilon = \sqrt{\frac{[\ddot{x}_2 - \ddot{x}_1 + \omega^2(x_2 - x_1)]^2 + [\ddot{y}_2 - \ddot{y}_1 + \omega^2(y_2 - y_1)]^2}{(x_2 - x_1)^2 + (y_2 - y_1)^2}}. \qquad \textbf{(12)}$$

The algorithm for using the method on the considered mechanism in order to determine the velocities and accelerations is the same as to the positions study.

2.2. Applying the method

The algorithm for applying the method follows:

a) knowing the positions of the D_3 and B joints and D_3C and BC lengths the position of the joint C is determined;
b) the position of joint E_2 is determined by knowing the positions of B and C joints and BE and CE lengths;
c) the position of joint F is determined by knowing the positions of D_4 and E_5 joints and DF and EF lengths;
d) the position of joint G is determined by knowing the positions of E and F joints and EG and FG lengths;
e) For the first stage of unfolding the position of joint H is determined according to the positions of F and G joints and FH and GH lengths and in the 2^{nd} stage of the unfolding the AHG dyad is considered (backstay AH is stretched) and the position of the joint H is determined according to the positions of the A and G joints and AH and GH lengths;
f) The position of the joint K is determined according to the positions of G and H joints and GK and HK lengths.

2.3. Obtained results

By following the algorithm paragraph 2.2 and using the formulas in paragraph 2.1 a computer program was written using a high level programming software.

The results can be presented both graphical and in tables. In this paper the results are presented in graphs. Due to limited space and large amount of date to be shown, the data is presented for one element which is the boom of the tower crane.

In figure 3a is presented the variation graph of the joint G and the angle between the boom and abscissa. In figure 3b is presented the variation graph of absolute velocity of joint G its components and the angular velocity of the boom. In figure 3c is presented the absolute acceleration of the G joint, its components and the angular acceleration.

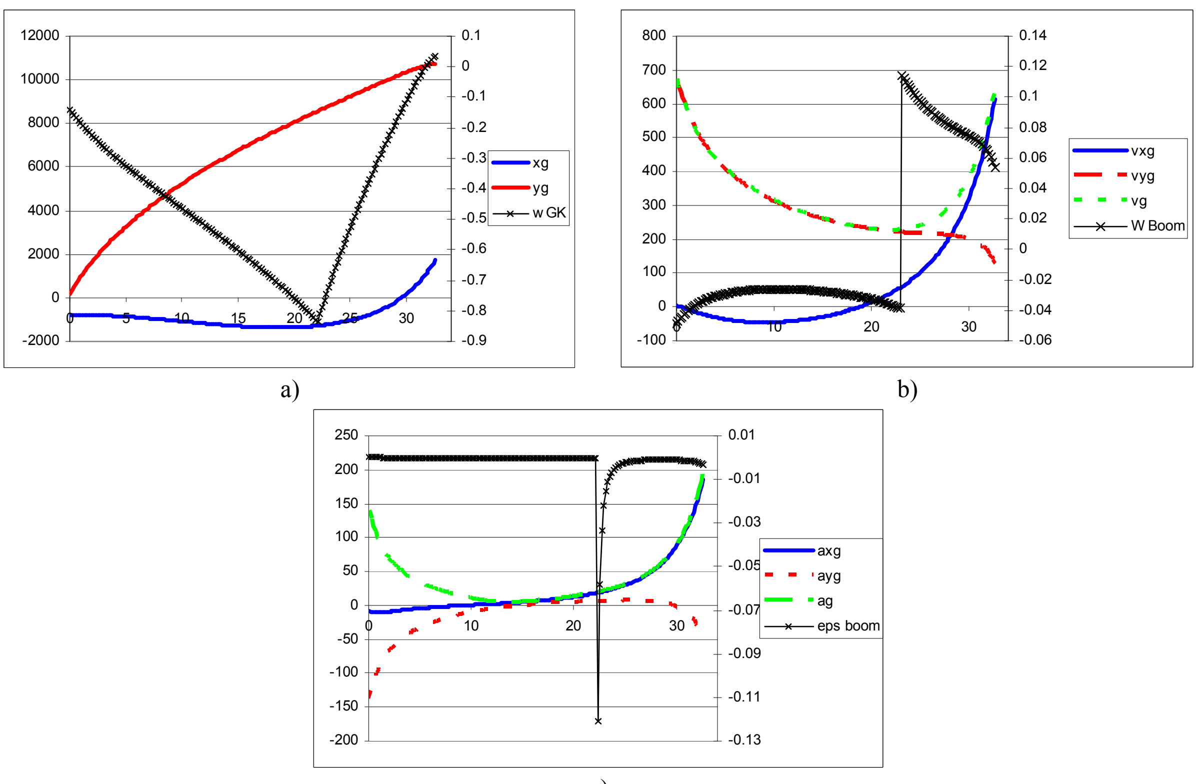


Figure 3 Obtained results using the analytical method for the joint G on the boom of the self erecting tower crane; a) joint G coordinates on X axis and Y axis and rotation of the boom; b) joint G velocities, absolute velocity and components on X axis, Y axis and angular velocity of the boom; c) joint G accelerations, absolute acceleration and components on X axis, Y axis and angular acceleration of the boom;

3. KINEMATIC STUDY USING DEDICATED SOFTWARE FOR PLANE MECHANISMS

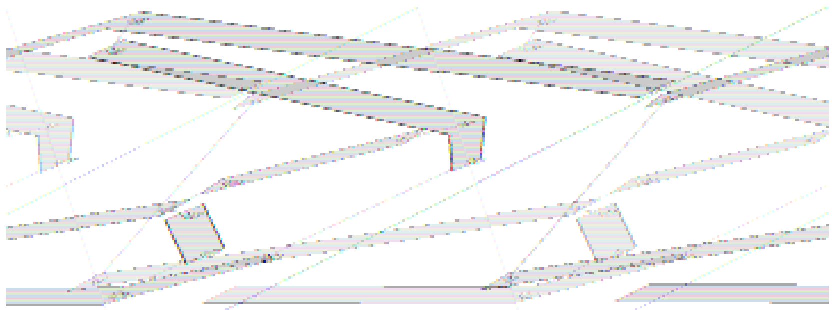
There are companies in the software market that have created dedicated software for kinematic and dynamic studies for plane mechanisms.

Such software involves creating a scale 2D model of the studied mechanism and specifying the constraints between the kinematic elements. The software writes automatically the equations system, and solves it using numerical methods. The obtained results are presented in graphics and tables.

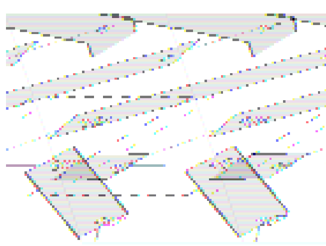
The self erection mechanism of the self erecting tower crane was studies with such software.

3.1. Using the software

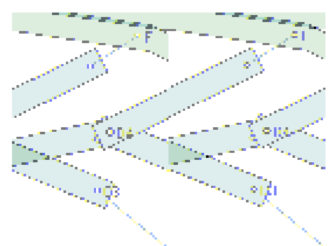
For the self erecting mechanism kinematic elements were built on 1:1 scale in bar shape (figure 1) and then the constraints between the kinematic elements were specified and the mechanism was brought to the initial position. By specifying the motion to the driving element, the software calculates the kinematic and dynamic parameters and the working simulation of the studied mechanisms.



a)



b)

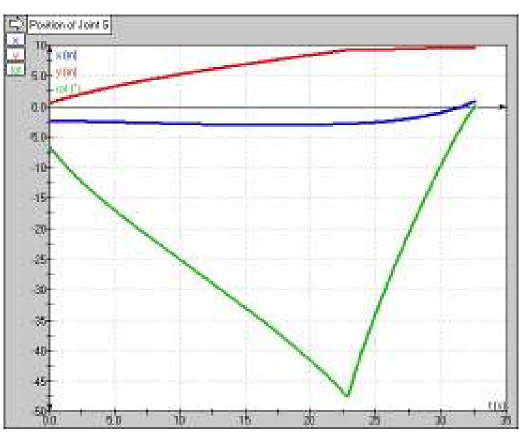


c)

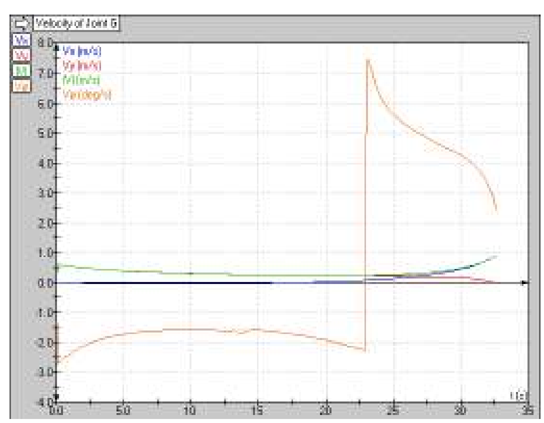
Figure 4 a) Built kinematic elements with connecting points, placed in position to apply the geometric constraints; b) applying constraints between kinematic elements (selection of the points); c) the created constraint between the kinematic elements

3.2. Obtained results

Using this software the results are obtained easily by specifying to the software the studied kinematic element and its parameters (positions, velocities, accelerations, etc.). In figure 5 are presented the results for the same kinematic element presented in the first method (par 2.3)



a)



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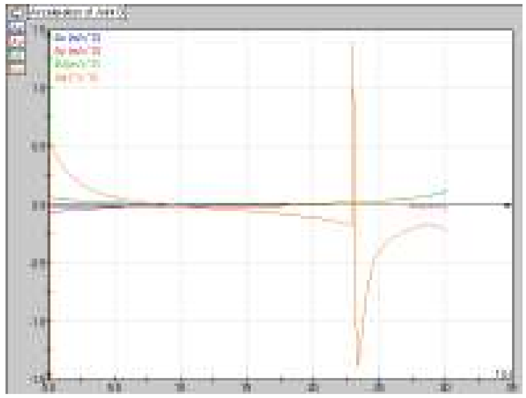

c)

Figure 5 Obtained results using a 2D dedicated software for kinematic and dynamic analysis for the joint G on the boom of the self erecting tower crane; a) joint G coordinates on X axis and Y axis and rotation of the boom; b) joint G velocities, absolute velocity and components on X axis, Y axis and angular velocity of the boom; c) joint G accelerations, absolute acceleration and components on X axis, Y axis and angular acceleration of the boom;

4. KINEMATIC STUDY USING 3D CAD SOFTWARE

In the past years, some of the producers of 3D CAD software have attached modules for kinematic and dynamic simulation for assembly studying. To build the assembly, first the parts have to be built in 3D and then the geometric constraints are placed between the parts, so the assembly is created. To every part its geometric and physical characteristics are specified.

4.1. Using the software

The kinematic elements of the folding unfolding mechanism have been built one at a time following the dimensions and geometric shape of the part, figure 6. For every element, the associated material was specified. By placing the position constraints between the parts, the assembly is obtained, figure 6.By transferring the assembly into the dynamic simulation module, the geometric constraints are transformed into kinematic couples thus resulting the 3D mechanism.

a) b)

Figure 6 a) Built parts of the mechanism, placed in position to apply the geometric constraints; b) applied constraints between kinematic elements;

4.2. Obtained results

In this situation too the results can be obtained fairly easily by specifying the studied kinematic element, a point that belongs to the element, or a kinematic couple between 2 elements and the kinematic parameters to study. Same as 2D software, the data can be presented in tables and graphically.

In figure 7 are presented the results for the kinematic element which was presented previously.

5. CONCLUSION

Regarding the first method, a program written in a high level programming language using analytical equations deducted by the authors, the following conclusions:

- The method is very precise because of the analytical equations; eventual errors may exist solely by the CPU precision (negligible).
- Assumes a laborious work in order to determine the analytical equations before the program is written;
- Any mechanism can be studied for which the transfer function can be determined in analytical way.

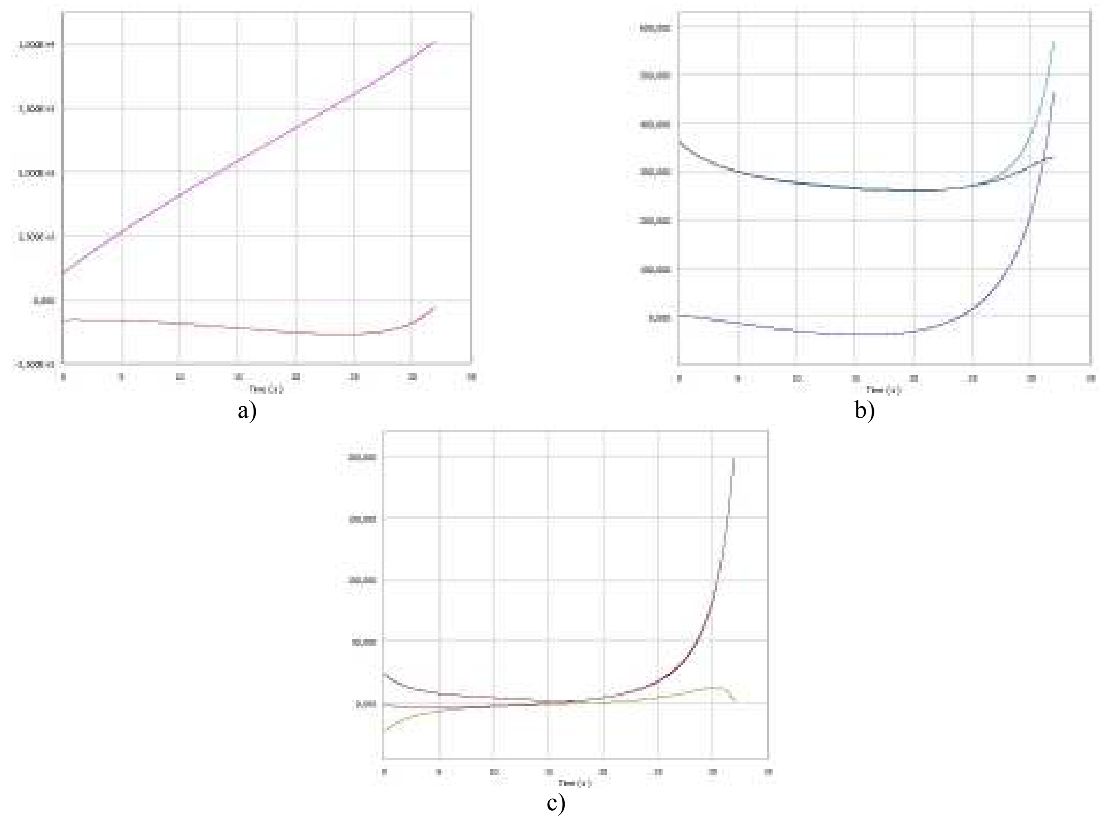

Figure 7 Obtained results using a 3D CAD software with kinematic and dynamic analysis module for the joint G on the boom of the self erecting tower crane; a) joint G coordinates on X axis and Y axis of the boom; b) joint G velocities, absolute velocity and components on X axis, Y axis of the boom; c) joint G accelerations, absolute acceleration and components on X axis, Y axis of the boom;

In case of the dedicated software for 2D mechanisms the conlusions follow::

- The 2D model is built fairly easy ;
- The equations system which describes the motion of the mechanism is solved numerically, and the precision of the results is influenced by the presion of the numerical method to solve the system;
- Not any plane mechanism can be studied but only those for which the software has defined the types of kinematic elements and constraints;
- The results are obtained easy;

Regarding the third method we can see that:

- The 3D model is fairly difficult to build;
- There aren't yet flexible kinematic elements so not any mechanism can be studied;
- The precision of the results depends of the used numerical method for solving the equations motion system;
- Obtaining the results is easy.

6. REFERENCES

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