

# Braking mechanism for profile rolling mill cooling bed. Analysis and operation

M Ardelean, E Ardelean, A Josan and V Socalici

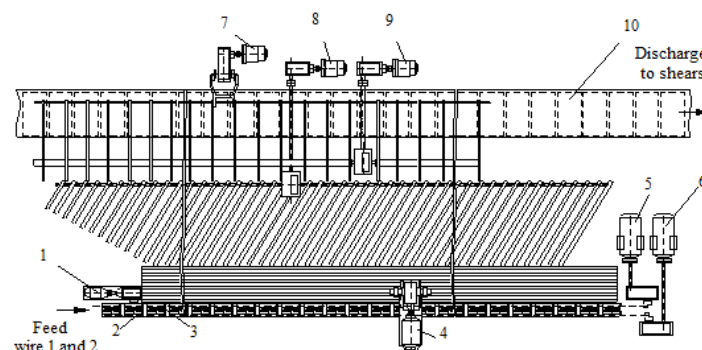
Politehnica University of Timisoara, Department of Engineering and Management,  
5 Revolution Street, Hunedoara, 331128, Romania

E-mail: [marius.ardelean@fih.upt.ro](mailto:marius.ardelean@fih.upt.ro)

**Abstract.** This paper presents the braking mechanism which are part from construction of rake tip cooling bed for small rolled product, and it is analyzed the kinematics of this mechanism. Purpose of this study it was to determine the movement law and other kinematics parameters of effector elements of brake mechanism. This is required because in operation of the cooling bed, several mechanisms operate simultaneously, so it can must be optimized the operation of this complex equipment. Mechanism has two effector the elements, first effector element that elevates laminate of cooling bed surfaces, respectively, the second effector element that moves transversely laminate to the cooling bed. Through these movements, rolled products are moved step by step, towards to delivering live roller table.

## 1. General considerations

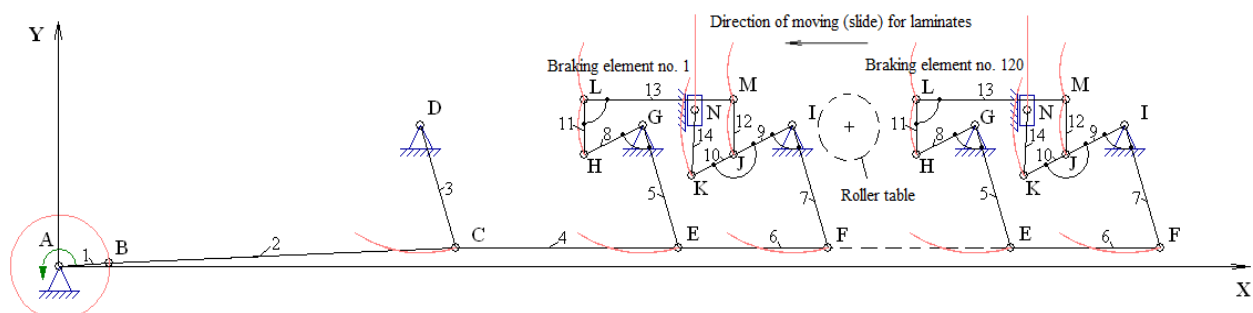
Cooling bed provides cooling for hot laminate arrived from the last rolling stand to the cool temperature adjustment. This temperature must satisfy the conditions for processing and handling further in the technological flow and is usually between 60 and 100°C. Simultaneously, the cooling bed is used to transport laminates to the adjustment department, and in some constructions prevents deformation due to thermal stress, or makes straightening bent laminates. Some of the more complex cooling beds can be found in the case of small section rolling mills, Figure 1.



**Figure 1.** Location the cooling bed mechanisms of small sections rolling mill [1], [2]  
1- mechanism of separation; 2,3 - feed roller table wire 1 and 2; 2, 4- drive mechanism for mobile rake; 5, 6 - braking mechanisms of the wires 1 and 2; 7, 9 – grouping-evacuation mechanism; 8 - drive mechanism of table angled roller; 10 - delivering live roller table

When leaving the finishing train, rolled bars are taken over by a supply roller table, in the first part of it are mounted two rotating shears that cut the rolled bar in the rolling flow to the desired size, [3]. Behind these rotating shears, starts cooling bed with feed roller table, separation and braking mechanisms. The speed of rolled product at the exit from the last rolling stand is between 4...14m/s. The length of the cooling bed is 120m. The role of the braking device, Figure 2, is to stop the laminate in motion and put it in the delivery trough. The operation of the braking device on both wire is made by a DC motor via a crankshaft and drawbar [4].

Electric control is done independently for both wires and separately for lifting and lowering. The commands for raising and lowering of the braking device requires, so that the bars (rakes) can stop at the same level as the cooling bed [1].

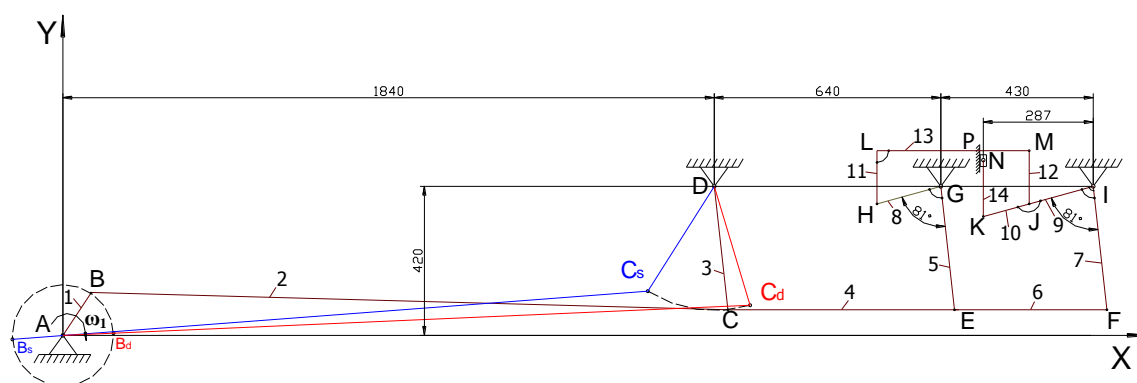


**Figure 2.** Diagram of the braking mechanism (wire 1) [5]

The braking device is located along straightener with rakes and bring further material on rakes. In the case of brake mechanism [6], the first part is mobile, achieving braking of the laminate due to friction, by lifting its, and the second part is fixed and gets next rolled sections [2], [4].

## 2. Kinematic scheme of the mechanism

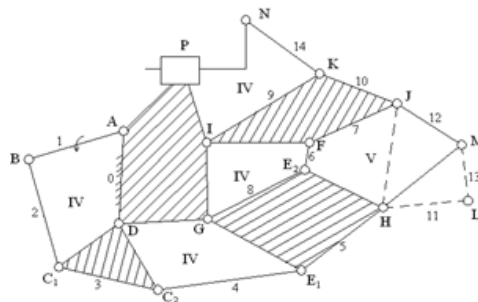
Kinematic scheme, in principle, of the mechanism is shown in Figure 3. The mechanism is related to plan reference system, with origin fixed joint in A, having OX axis oriented parallel to the direction of fixed couplers D, G, I [5].



**Figure 3.** Kinematic diagram of mechanism [2]

This is planar mechanism, consisting of 11 mobile cinematic elements and 15 kinematic rotation couplers of class V (forming quadrilateral A, B, C, D; dyad C, E, G; dyad E, F, I, dyad H (L) MJ; dyad K, NN) and a translational coupler. Structure diagram (kinematic chain) of the mechanism [7] is shown in Figure 4.

From Figure 4 results the mechanism contains a V rank element, two elements of rank IV (quaternary), an element of the rank III (ternary) and eight elements of rank II (binary), which form five deformable closed contours (loops) four of which is class IV and one of class V. Joints C and E are double couplers. Element 0 is the fixed element and element 1 is the driving element (motor) [5].



**Figure 4.** Structure diagram (kinematic chain) of the mechanism [2], [5]

It should be noted that the mechanism is complex, and to reach to the real scheme we used the conventional sign reproducing a rigid binary, ternary, quaternary and so on. Thus, in Figures 3 and 4 it is shown that the elements 5 and 8 are of the same rigid, as well as the elements 7, 9 and 10 [1].

The mechanism has two effector elements:

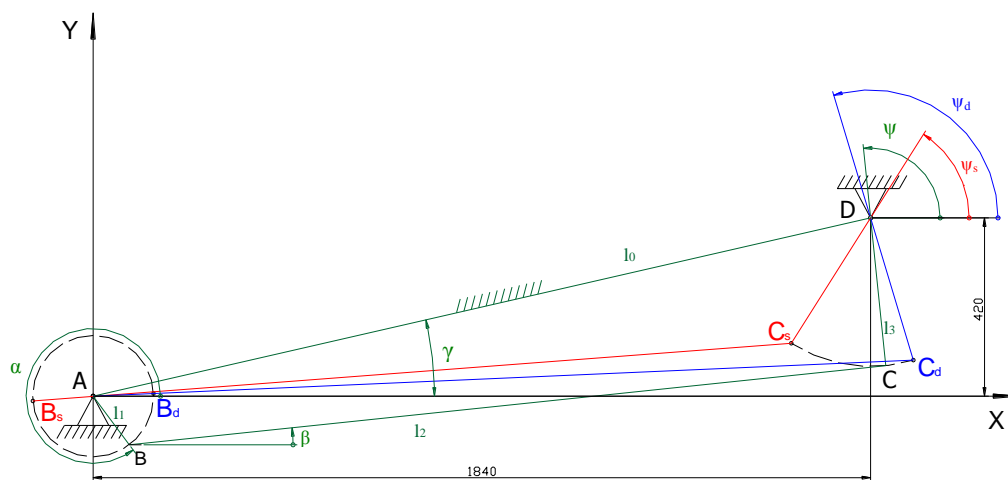
- the first element is the element effector H(L)M for the braking phase (when it brakes laminate by friction). Movement of the effector is obtained from EGH and IJF elements whose movements are in phase;
- the second effector element (for the lifting phase of the laminate and delivery to the mechanism with bar rakes for straightening) is KNN dyad with sliding rod 14. Movement of the effector 14 is obtained from the element 10. This provides lifting and overturning of the laminate, handing it to straightening grate with rakes through rod throwers (piston) from the joint N of dyad KNN (KNP).

### 3. Structural analysis of the mechanism

#### 3.1. Kinematic analysis of four bar mechanism ABCD

Contour vector equation is written by giving of the mechanism side's sign [7], Figure 5.

$$\vec{l}_1 + \vec{l}_2 + \vec{l}_3 = \vec{l}_0 \quad (1)$$



**Figure 5.** Positional analysis of the four bar mechanism ABCD

By projecting equation contour on the axis of the reference system [7], we obtain the following scalar equations:

$$\begin{cases} l_1 \cdot \cos \alpha + l_2 \cdot \cos \beta + l_3 \cdot \cos \psi = l_0 \cdot \cos \gamma \\ l_1 \cdot \sin \alpha + l_2 \cdot \sin \beta + l_3 \cdot \sin \psi = l_0 \cdot \sin \gamma \end{cases} \quad (2)$$

In these equations  $\beta$  and  $\psi$  angles are not known, the angle  $\gamma$  has a known value and the angle  $\alpha$  is known as the independent variable with values between  $\alpha_d$  and  $\alpha_s$ .

$$\psi = 2 \cdot \arctg \left[ \frac{A_\psi \pm \sqrt{A_\psi^2 + B_\psi^2 - C_\psi^2}}{B_\psi - C_\psi} \right] \quad (3)$$

$$A_\psi = 2 \cdot l_1 \cdot l_3 \cdot \sin \alpha - 2 \cdot l_3 \cdot l_0 \cdot \cos \gamma \quad (4)$$

$$B_\psi = 2 \cdot l_1 \cdot l_3 \cdot \cos \alpha - 2 \cdot l_3 \cdot l_0 \cdot \cos \gamma \quad (5)$$

$$C_\psi = l_1^2 - l_2^2 + l_3^2 + l_0^2 - 2 \cdot l_1 \cdot l_0 \cdot \cos(\alpha - \gamma) \quad (6)$$

$$\beta = 2 \cdot \arctg \left[ \frac{A_\beta \pm \sqrt{A_\beta^2 + B_\beta^2 - C_\beta^2}}{B_\beta - C_\beta} \right] \quad (7)$$

$$A_\beta = 2 \cdot l_1 \cdot l_2 \cdot \sin \alpha - 2 \cdot l_2 \cdot l_0 \cdot \cos \gamma \quad (8)$$

$$B_\beta = 2 \cdot l_1 \cdot l_2 \cdot \cos \alpha - 2 \cdot l_2 \cdot l_0 \cdot \cos \gamma \quad (9)$$

$$C_\beta = l_1^2 + l_2^2 - l_3^2 + l_0^2 - 2 \cdot l_1 \cdot l_0 \cdot \cos(\alpha - \gamma) \quad (10)$$

The speed of the element 3 has following form:

$$\omega_3 = \frac{l_1}{l_3} \cdot \frac{(l_3 \cdot \sin(\alpha - \psi) - l_0 \cdot \sin(\alpha - \gamma))}{(l_1 \cdot \sin(\alpha - \psi) + l_0 \cdot \sin(\psi - \gamma))} \cdot \omega_1 \quad (11)$$

$$\omega_3 = R_1 \cdot \omega_1 \quad (12)$$

Method to obtain the angular velocity of element 2 is similar to that of the element 3, thus the speed is obtained from the following equation:

$$\omega_2 = \frac{l_1}{l_2} \cdot \frac{(l_2 \cdot \sin(\alpha - \beta) - l_0 \cdot \sin(\alpha - \gamma))}{(l_1 \cdot \sin(\alpha - \beta) + l_0 \cdot \sin(\beta - \gamma))} \cdot \omega_1 \quad (13)$$

$$\omega_2 = R_2 \cdot \omega_1 \quad (14)$$

To obtain the acceleration of the element 3 will be derived expression of speed versus time, under the same conditions, and angular acceleration of the element 3 has the expression (15).

$$\varepsilon_3 = \frac{l_1 \cdot l_3 \cdot (1 - R_1)^2 \cdot \cos(\alpha - \gamma) - l_1 \cdot l_0 \cdot \cos(\alpha - \gamma) - l_3 \cdot l_0 \cdot R_1^2 \cdot \cos(\psi - \gamma)}{l_1 \cdot l_3 \cdot \sin(\alpha - \psi) + l_3 \cdot l_0 \cdot \sin(\psi - \gamma)} \cdot \omega_1^2 \quad (15)$$

$$\varepsilon_3 = P_1 \cdot \omega_1^2 \quad (16)$$

Similar to manner of obtaining the angular acceleration of the element 3, angular acceleration of the element 2 has the following expression:

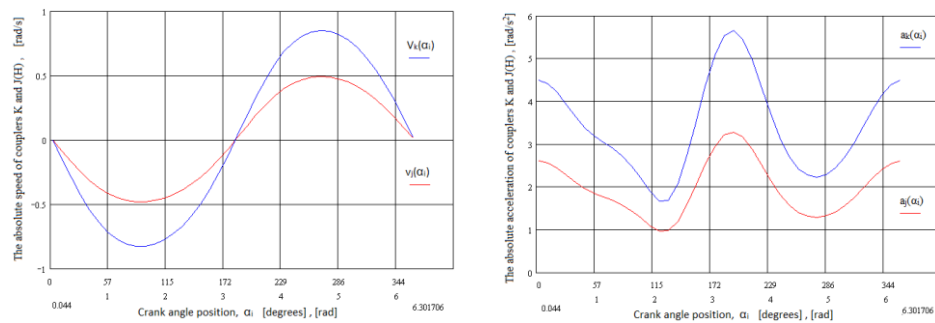
$$\varepsilon_2 = \frac{l_1 \cdot l_2 \cdot (1 - R_2)^2 \cdot \cos(\alpha - \gamma) - l_1 \cdot l_0 \cdot \cos(\alpha - \gamma) - l_2 \cdot l_0 \cdot R_2^2 \cdot \cos(\beta - \gamma)}{l_1 \cdot l_2 \cdot \sin(\alpha - \beta) + l_2 \cdot l_0 \cdot \sin(\beta - \gamma)} \cdot \omega_1^2 \quad (17)$$

$$\varepsilon_2 = P_2 \cdot \omega_1^2 \quad (18)$$

Due to the constructive particularities of mechanism the segment 3 is equal and parallel to 5 and 7, and segment 8 is equal and parallel to segment 9 [1].

Effector element H(L)MJ (braking segment) will have a translational movement with motion parameters of the points H and J.

Movement of the H and J and therefore of the effector element is carried out on same radius circle, with centres in G and I, radius circle are equal and parallel with elements 8 and 9 ( $8 = 9 = 187\text{mm}$ ).



**Figure 6.** The variation of the speed and acceleration of couplers J(H) and K depending on the AB crank angle position

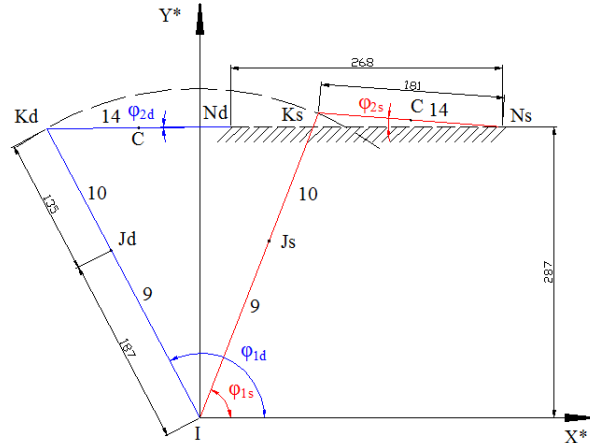
Angular speeds of elements 8 and 9 are equal to  $\omega_3$ . Acceleration of points H and J are composed acceleration and have the expressions of the form:

$$|\bar{a}_J| = IJ \cdot \sqrt{\omega_3^4 + \varepsilon_3^2} \quad (19)$$

$$|\bar{a}_H| = GH \cdot \sqrt{\omega_3^4 + \varepsilon_3^2} \quad (20)$$

### 3.2. Kinematic analysis of crank-piston mechanism

The extreme positions of the crank-piston mechanism, a component of the brake mechanism of the wire 1 and the dimension of the mechanism [1], are presented in Figure 7.



**Figure 7.** The extreme positions of the piston-crank mechanism

To facilitate the analysis of the mechanism, the system of reference axes XOY reorients (rotates  $90^\circ$ ) and becomes  $X^*OY^*$ , with  $OX^*$  axis oriented in the direction of N coupler. Is denoted  $e=287\text{mm}$  - eccentricity of mechanism, and  $r=IK=322\text{mm}$ ,  $l=KN=181\text{mm}$ ,  $a=KC$ ,  $(l-a)=NC$ .

$$\lambda = \frac{r}{l}, \quad \kappa = \frac{a}{l}, \quad \nu = \frac{e}{l} \quad (21)$$

The crank angle position for limit positions left and right are:

$$\varphi_{1s} = \psi_s + 90^\circ, \quad \varphi_{1d} = \psi_d + 90^\circ \quad (22)$$

Position angle of the connecting rod:

$$\varphi_2(\varphi_1) = \arcsin(\lambda \cdot \sin \varphi_1 - \nu) \quad (23)$$

Rod position (point N) at a time:

$$S_N(\varphi_1) = x_N(\varphi_1) = l \cdot \cos \varphi_2 + r \cdot \cos \varphi_1 \quad (24)$$

Simplified relation for determining movement of the rod N:

$$S_N(\varphi_1) = X_N(\varphi_1) = r \cdot f_N(\varphi_1) \quad (25)$$

$$f_N(\varphi_1) = \cos \varphi_1 + \frac{1}{\lambda} \cdot \sqrt{1 - (\lambda \cdot \sin \varphi_1 - \nu)^2} \quad (26)$$

The speed of the rod 14 is obtained by the relation:

$$v_N(\varphi_1) = \omega_1^* \cdot r \cdot f_N'(\varphi_1) \quad (27)$$

$$f_N'(\varphi_1) = -\sin \varphi_1 + \frac{1}{\lambda} \cdot (\lambda \cdot \sin \varphi_1 - \nu) \cdot \varphi_2'(\varphi_1) \quad (28)$$

$$\varphi_2'(\varphi_1) = \frac{\lambda \cdot \cos \varphi_1}{\sqrt{1 - (\lambda \cdot \sin \varphi_1 - \nu)^2}} \quad (29)$$

Acceleration of the rod 14 is:

$$a_N(\varphi_1) = \frac{dv_N(\varphi_1)}{dt} = \frac{d}{dt}(\omega_1^* \cdot r \cdot f_N'(\varphi_1)) = r \cdot \varepsilon_1^* \cdot f_N'(\varphi_1) + \omega_1^{*2} \cdot r \cdot f_N''(\varphi_1) \quad (30)$$

Where  $\omega_1^*$  and  $\varepsilon_1^*$  are angular velocity and acceleration of driving element FIK, identical with EGH and CD elements by constructive reasons.

The function  $f_N''$  has the form:

$$\begin{aligned} f_N''(\varphi_1) &= \frac{d}{dt} \left( -\sin \varphi_1 + \frac{1}{\lambda} \cdot (\lambda \cdot \sin \varphi_1 - \nu) \cdot \varphi_2'(\varphi_1) \right) = \\ &= -\cos \varphi_1 + \cos \varphi_1 \cdot \varphi_2'(\varphi_1) + \frac{1}{\lambda} \cdot (\lambda \cdot \sin \varphi_1 - \nu) \cdot \varphi_2''(\varphi_1) \end{aligned} \quad (31)$$

where function  $\varphi_2''$  has form:

$$\varphi_2''(\varphi_1) = \frac{-\lambda \cdot \sin \varphi_1 + (\lambda \cdot \sin \varphi_1 - \nu) \cdot \varphi_2'^2(\varphi_1)}{\sqrt{1 - (\lambda \cdot \sin \varphi_1 - \nu)^2}} \quad (32)$$

Angular velocity of connecting rod is:

$$\omega_2^*(\varphi_1) = \frac{d\varphi_2(\varphi_1)}{dt} = \frac{d\varphi_2'(\varphi_1)}{d\varphi_1} \cdot \frac{d\varphi_1}{dt} = \omega_1^* \cdot \varphi_2'(\varphi_1) = \omega_1^* \cdot \frac{\lambda \cdot \cos \varphi_1}{\sqrt{1 - (\lambda \cdot \sin \varphi_1 - \nu)^2}} \quad (33)$$

Angular acceleration of connecting rod is:

$$\begin{aligned} \varepsilon_2^*(\varphi_1) &= \varepsilon_1^*(\varphi_1) \cdot \frac{\lambda \cdot \cos \varphi_1}{\sqrt{1 - (\lambda \cdot \sin \varphi_1 - \nu)^2}} + \omega_1^{*2}(\varphi_1) \cdot \frac{1}{\sqrt{1 - (\lambda \cdot \sin \varphi_1 - \nu)^2}} \cdot \\ &\quad \cdot (-\lambda \cdot \sin \varphi_1 + (\lambda \cdot \sin \varphi_1 - \nu) \cdot \varphi_2'^2) \end{aligned} \quad (34)$$

The coordinates of any point on the rod 14 denoted by C (can be and center of gravity) can be determined depending on angle  $\varphi_1$  and  $\varphi_2$ .

$$\begin{cases} X_c(\varphi_1) = r \cdot \cos \varphi_1 + a \cdot \cos \varphi_2(\varphi_1) \\ Y_c(\varphi_1) = e + a \cdot \sin \varphi_2(\varphi_1) \end{cases} \quad (35)$$

Speed has form:

$$\begin{cases} v_{cx}(\varphi_1) = r \cdot \omega_1^* \cdot \left( \frac{\kappa}{\lambda} \cdot (\lambda \cdot \sin \varphi_1 - \nu) \cdot \varphi_2'(\varphi_1) - \sin \varphi_1 \right) \\ v_{cy}(\varphi_1) = r \cdot \omega_1^* \cdot \frac{\kappa}{\lambda} \cdot \cos \varphi_1 \end{cases} \quad (36)$$

The absolute speed of point C is:

$$v_c(\varphi_1) = \sqrt{v_{cx}^2(\varphi_1) + v_{cy}^2(\varphi_1)} = \omega_1^* \cdot r \cdot \sqrt{f_{cx}'^2(\varphi_1) + f_{cy}'^2(\varphi_1)} \quad (37)$$

Acceleration of point C is obtained through its projections on the reference system axes. Components after the two axes of the reference system has expressions:

$$a_{cx}(\varphi_1) = \varepsilon_1^* \cdot r \cdot f_{cx}'(\varphi_1) + \omega_1^{*2} \cdot r \cdot f_{cx}''(\varphi_1) \quad (38)$$

$$a_{cy}(\varphi_1) = \varepsilon_1^* \cdot r \cdot f_{cy}'(\varphi_1) + \omega_1^{*2} \cdot r \cdot f_{cy}''(\varphi_1) \quad (39)$$

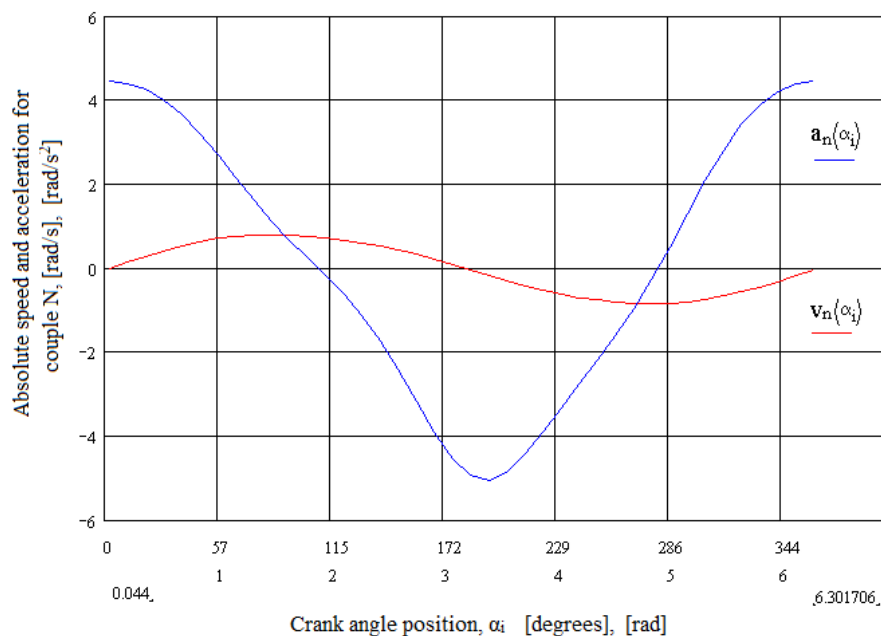
Where functions  $f_{cx}''$  and  $f_{cy}''$  has form:

$$f_{cx}''(\varphi_1) = -\cos \varphi_1 + \kappa \cdot \cos \varphi_1 \cdot \varphi_2''(\varphi_1) + \frac{\kappa}{\lambda} \cdot (\lambda \cdot \sin \varphi_1 - \nu) \cdot \varphi_2'(\varphi_1) \quad (40)$$

$$f_{cy}''(\varphi_1) = -\kappa \cdot \sin \varphi_1 \quad (41)$$

Absolute acceleration has form:

$$a_c(\varphi_1) = \sqrt{a_{cx}^2(\varphi_1) + a_{cy}^2(\varphi_1)} \quad (42)$$



**Figure 8.** The variation of the speed and acceleration of couple N

#### 4. Results and conclusions

This cooling bed is one of the most complicated rolling mills cooling beds, it is necessary to correlate the operation of several mechanisms component of cooling bed, including the laminates brake mechanism [8].

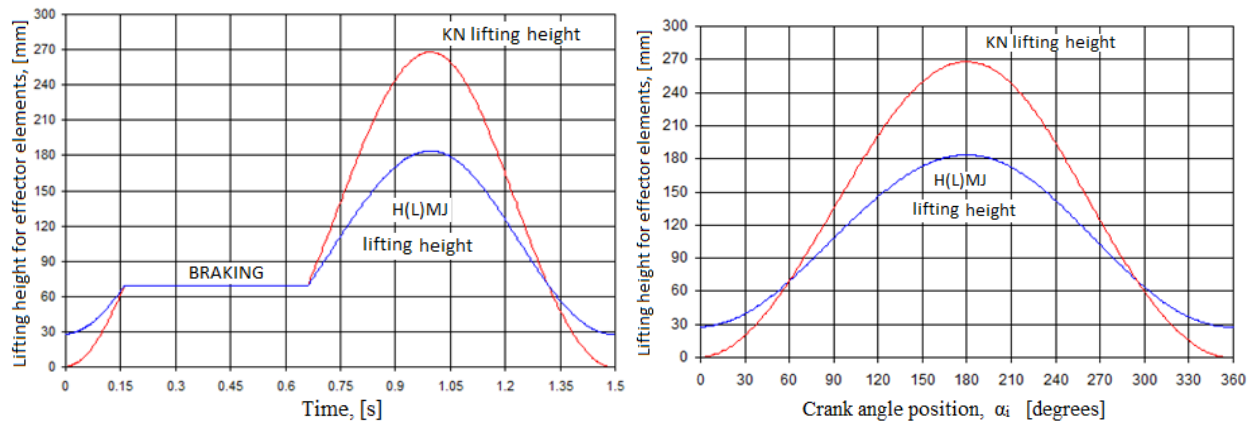
The present mechanism works in two phases, the first phase when laminate it is braked by friction from the effector element (mobile trough) H(L)M, respectively the second phase when the laminate is lifted by the second effector element 14 and is pushed towards to the delivery rakes.

Theoretical displacements of both effector elements are shown in figures above, showing the crank angle at which the mechanism can be stopped for braking of the laminate.

For crank angle position lower than  $60^\circ$ , the position of coupler N is below the position of coupler M. This angle corresponds to the pause position, corresponding to the first phase of the working mechanism (braking of laminates).

Acceleration of point C is obtained through its projections on the reference system axes. Components after the two axes of the reference system has expressions:

For angles position of the crank exceeding  $60^\circ$ , the mechanism enters in the second phase of working when the laminate is lifted and transported to the next position in fixed rake.



**Figure 9.** The real displacements of the two effector elements depending on time (left) and Theoretical displacements of the two effector elements depending on the crank angle position (right)

All of the graphical dependencies were made in Mathcad software, were was made computational routines for analytical calculation of all kinematic parameters of studied mechanism.

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