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CAM-spring mechanisms for pantographs of electrically propelled vehicles

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Abstract. The process of current collection with a non-autonomous power source used for electric motors of a rolling stock occurs in a contact pair: pantograph's skid (head) - contact wire. The main indicator of the quality of current collection is the contact pressure, which depends on many factors. The dominant factor is static pressure generated by spring mechanisms of the pantograph. The pressure is a result of dynamic and other random factors. It is difficult to keep it constant. One of the solutions for optimizing contact pressure can be a cable cam-spring mechanism installed in the lifting unit of the contact part of the pantograph. Due to the special cam shape, it is possible to stabilize forces of the contact insert. Static pressing does not depend on its altitude. Dynamic forces can be smoothed.

1. Introduction

Contact pressure has static, dynamic and random components. The static component is normalized and taken into account when designing pantographs. The dynamic part is determined from the reduced mass due to accelerations. The random component is determined by amplitude-frequency properties of the system and its connections with the external environment. In all cases, the change in contact pressure is due to the movement of the contact insert. By artificially compensating for the forces arising from movements of the insert, it is possible to stabilize the contact pressure. At the same time, it is possible to improve the quality of current collection: to eliminate or minimize sparking and arc processes in contact, to reduce wear of contacting elements and the number of heads leaving the wire in one lever pantographs, etc.

2. Devices creating constant forces

Let us consider the option when the cable driving the cams [2, 3] into rotation leaves it at γ to the vertical (Fig. 1). The design scheme is shown in Fig. 2.



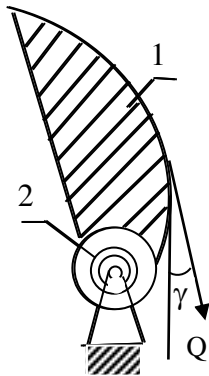


Figure 1. The cam with a coil spring

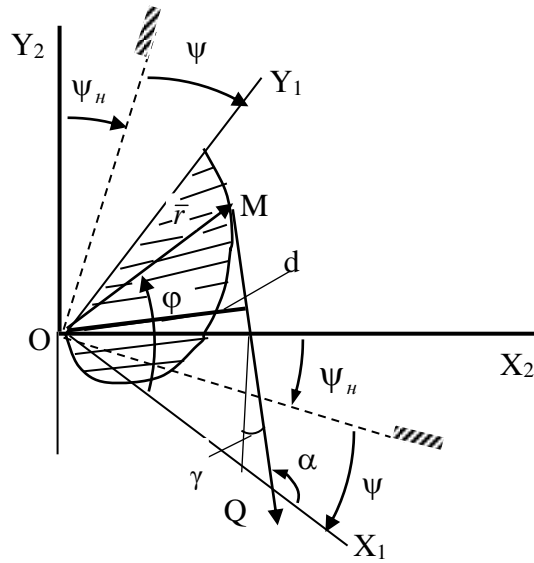


Figure 2. The design scheme

Under the action of force Q , cam 1 rotates, spiral spring 2 is compressed. ψ_h - angle of rotation of the cam at a given load $Q = Q_0$ where Q_0 - preliminary effort.

Rigidly bind the cam coordinate system $X_1 O Y_1$. In this coordinate system, we find the coordinates of point M of the cable release from the cam. We neglect the mass of the cam and resistance forces. We will look for such a shape of the cam which ensures a constant force $Q = Q_0$ of its further movement. That is, the cable pulling force will remain constant throughout the cam rotation. To fulfill this requirement, it is necessary that at each moment of time:

$$Q_0 \cdot d = c(\psi_h + \psi), \quad (1)$$

where c - coil spring stiffness, $N \cdot m$, d - perpendicular from the coordinate origin to the line of the cable, ψ - angle of rotation of the cam, measured from the starting angle ψ_h .

From Fig. 2 and formula (1) we have

$$d = r \cdot \sin(\alpha - \varphi) = d_0 \cdot (1 + \psi / \psi_h) \quad (2)$$

where r - radius is a vector drawn from the origin to point M of the cable exit from the cam, φ - angle between radius r and axle $O X_1$, α - angle between the cable and axle $O X_1$, equal to $\alpha = \pi / 2 + (\psi_h + \psi) + \gamma$, $d_0 = c \cdot \psi_h / Q_0$.

Let us calculate the differential of expression (2):

$$dr \cdot \sin(\alpha - \varphi) + r \cdot \cos(\alpha - \varphi) \cdot (d\alpha - d\varphi) = d_0 \cdot d\psi / \psi_h \quad (3)$$

Taking into account that $d\alpha = d\psi$, from $\frac{dy_1}{dx_1} = \tan(\alpha)$ we have $\frac{dr}{d\varphi} = \frac{r}{\tan(\alpha - \varphi)}$,

from (3) we have

$$r = \frac{d_0}{\psi_h} \cdot \frac{1}{\cos(\alpha - \varphi)} \quad (4)$$

This formula can be written as

$$r = \sqrt{d^2 + (d_0 / \psi_h)^2} = d_0 \sqrt{\left(1 + \frac{\psi}{\psi_h}\right)^2 + \frac{1}{\psi_h^2}} \quad (5)$$

Let us calculate $d = d_0(1 + \frac{\psi}{\psi_h})$, and angle φ :

$$\varphi = \alpha - \arcsin\left(\frac{d}{r}\right) \quad (6)$$

Let us calculate the coordinates of point M of the release of the cable from the cam:

$$x_1 = r \cdot \cos(\varphi), \quad y_1 = r \cdot \sin(\varphi) \quad (7)$$

(5) implies that in case of the vertical cable release from the cam ($\gamma = 0$), the distance from the point M of the cable exit to the horizontal line OX2 remains constant throughout the rotation of the cam and is equal to $h = d_0 / \psi_h$.

If instead of a spiral spring we take a linear spring, formula (5) will take the form:

$$r = \sqrt{d^2 + (d_0 / \lambda)^2 R_0^2} = d_0 \sqrt{\left(1 + \frac{\lambda}{R_0} \psi\right)^2 + \left(\frac{\lambda}{R_0}\right)^2},$$

where λ - initial deformation of the spring at a given force Q_0 .

Example.

Let for the force $Q_0 = 5 \text{ N}$ the initial angle $\psi_h = 35^\circ$ with the stiffness of the spiral spring is equal $c = 0.0117 \text{ N} \cdot \text{m}$

Using formulas (5) - (7), we can calculate the profile of the cam that ensures the constant force $Q = 5 \text{ N}$ when the cam rotates (Fig. 3).

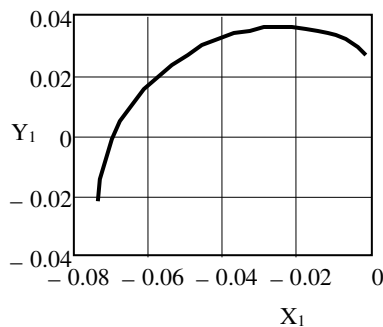


Figure 3. The profile of the cam with a spiral spring

3. Spring-cam mechanism for trolleybus pantographs

Consider the possibility of using a spring-cam mechanism for a trolleybus [4]. The kinematic diagram of the trolleybus current collector is shown in Fig. 4.

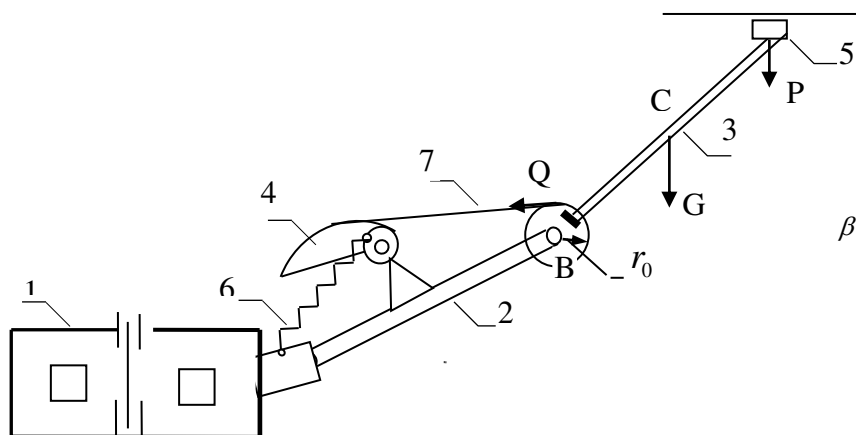


Figure 4. Kinematic diagram of a trolleybus pantograph

The mechanism contains housing 1, lower rod 2, upper rod 3, cam 4, contact head 5, spring 6, and cable 7.

Consider the static state of the device. The initial position of cam 4 corresponds to its rotation at ψ_n . The cam rotates through this angle at force Q_0 . The spring gets deformation λ . From this position we calculate the working angle of the cam rotation ψ , that is, the working range of the cam rotation angle will be $0 \leq \psi \leq \psi_s$. The angle ψ_s will be determined below, it corresponds to the maximum lowering of contact head 5 with the contact wire.

Let us find the cam profile that ensures constant force Q . The design scheme is shown in Fig. 5.

As follows from the geometry of Fig. 5, the relationship between the angles is as follows $\alpha = \nu_0 - \psi + \beta$.

$$\text{In addition } d = r \cdot \sin(\varphi - \alpha) = L \cdot \sin \beta, \quad (8)$$

where L – distance between the drum axes and the block.

For the constant force $Q = Q_0$ the following moments should be equal

$$Q \cdot d = c(\lambda + R_0 \cdot \psi) \cdot R_0 = c \cdot \lambda \cdot R_0 \cdot (1 + R_0 \cdot \psi / \lambda). \quad (9)$$

c – spring rate, R_0 – drum radius, λ – initial deformation of the spring at $Q = Q_0$.

At $\psi = 0$ $Q_0 \cdot d_0 = c \cdot \lambda \cdot R_0$, (9) implies that the length of the perpendicular dropped from the origin to the line of the thread must change according to the law

$$d = d_0 \cdot (1 + R_0 \cdot \psi / \lambda) = L \cdot \sin \beta \quad (10)$$

From (8) taking into account (10) we have

$$\varphi = \nu_0 + \beta - \left(\frac{\lambda}{R_0} \right) \cdot \left[\left(\frac{L}{d_0} \right) \cdot \sin \beta - 1 \right] + \arcsin \left(\frac{L}{r} \cdot \sin \beta \right) \quad (11)$$

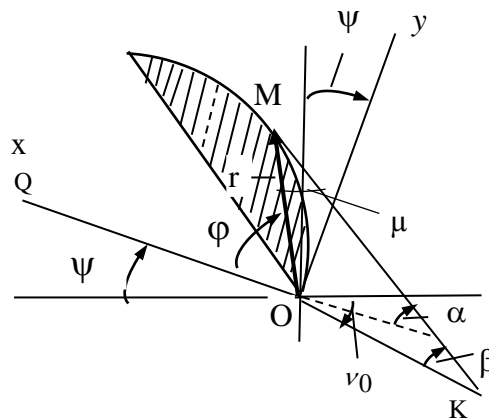


Figure 5. The calculation diagram of the cam profile

Calculate the differential from (11)

$$d\varphi = d\beta - \frac{\lambda}{R_0} \cdot \frac{L}{d_0} \cdot \cos \beta \cdot d\beta + \frac{r}{\sqrt{r^2 - L^2 \cdot \sin^2 \beta}} \cdot \left(\frac{L}{r} \cdot \cos \beta \cdot d\beta - \frac{L \cdot \sin \beta}{r^2} \cdot dr \right). \quad (12)$$

Taking into account that $\frac{dr}{d\varphi} = \frac{r}{\operatorname{tg}(\alpha - \varphi)}$

we have

$$r = L \cdot \sqrt{\sin^2 \beta + \frac{\cos^2 \beta}{\left(\frac{\lambda}{R_0} \cdot \frac{L}{d_0} \cdot \cos \beta - 1\right)^2}}. \quad (13)$$

Then the coordinates of point M of the thread exit from the cam are as follows:

$$x = r \cdot \cos \varphi, \quad y = r \cdot \sin \varphi.$$

Using x, y we have a cam profile.

To design a cam for force $Q = Q_0$, formulas (13) and (10) are written in a dimensionless form

$$\tilde{r} = \sqrt{\sin^2 \beta + \frac{\cos^2 \beta}{(W_1 \cos \beta - 1)^2}}, \quad \tilde{d} = \sin \beta = \frac{l}{W_1} \left(\frac{\lambda}{R_0} + \psi \right)$$

$$\text{Here } \tilde{r} = \frac{r}{L}, \quad \tilde{d} = \frac{d}{L}, \quad W_1 = \frac{L \cdot Q_0}{c \cdot R_0^2}.$$

The limit value for the cam angle is

$$\psi_s = W_1 - \frac{\lambda}{R_0}. \quad (14)$$

When contact head 5 with the contact wire moves down, cam 4 rotates clockwise (spring 6 is stretched). However, the force in cable 7 coming off cam 4 and attached to rod drum 3 is constant and equal to Q . Connect force Q with force P between the contact head and the wire. From the equilibrium condition of bar 3, it follows:

$$M = (G \cdot BC + P \cdot l) \cdot \cos \gamma, \quad (15)$$

where G - bar 3 weight, l - bar 3 length, BC - distance from the center of gravity of bar 3 to its axis of rotation. $M = Q \cdot r_0$ - constant moment of force Q . Let the weight of rod 3 be 200 N, the length be 6 m, the distance from the hinge to the center of gravity be 2 m, the angle of inclination of head 3 to the horizon be equal to 45° . The required force P between the contact head and the wire is assumed equal to 144 N. Then the value of the constant moment that must be applied to rod 3 will be equal to Nm according to formula (15). Suppose that head 5 with the wire has lowered vertically by 0.3 m. The angle decreases, and the cosine of the angle increases and is equal to 0.75. From formula (15), we find that the force between head 5 and the wire is 132 N. That is, the value of the force is within the tolerance.

Using the constant moment, we can determine the force $Q = M / r_0$ that the cam-spring mechanism must create. For this force, according to the above method, we determine the cam profile.

4. The cam-spring device for pantographs of metro cars

Let us consider the possibility of using a cam-spring device for pantographs of metro cars [5]. The required force between the shoe of the current collector and the contact rail is about 200 N. The structural diagram of pantographs of the lower current collection is shown in Fig. 6.

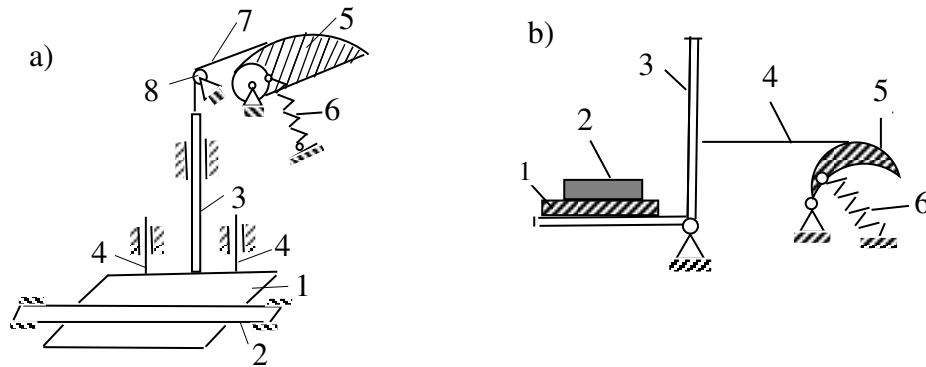


Figure 6. Pantographs of the lower current collection:

- a) - with a translational movement of the bracket with a shoe;
- b) - with a rotating movement of the bracket with a shoe.

Let us analyze the first option a). The pantograph of the lower current collector contains current collector shoe 1, which is in constant contact with contact rail 2, shoe holder 3, rigidly and perpendicularly fixed to the shoe, sliding inside the sleeve, mounted on the bar. Rods 4 are the guides for the movement of shoe 3. Spring 6 is attached to the cam at one end and to the bar at the other one. Cable 7, coming off the cam, is thrown over fixed block 8 and connected to the shoe holder.

The initial position of cam 5 corresponds to its rotation angle ψ_s . In this position, spring 6 is stretched and the pressing of shoe 1 on the rail is equal to Q_0 . As the thickness of the shoe or rail decreases, the spring will be compressed and the cam will rotate clockwise, but the set point for pressing the shoe against the rail remains constant. The constancy of the tension force of cable 7 is ensured by the variable curvature radius of cam profile 5. The end position of the cam corresponds to $\psi = 0$. In this position, the spring is extended by λ .

It is supposed to use two parallel cam-spring mechanisms in one pantograph. Each such device must provide a constant force of 100 N.

Let the stiffness of the linear spring be N / m, the initial deformation of the spring under the force $Q = 100$ N be equal to $\lambda = 1 \cdot 10^{-2}$ m, $R_0 = 1 \cdot 10^{-2}$ m, $L = 5 \cdot 10^{-2}$ m. Using formulas (11 - 13), let us determine the shape of the cam which creates a constant force $Q = 100$ N when the cam rotates

within the range from $\psi = 0$ to the limit $\psi_s = \frac{\lambda}{R_0} \cdot \left(\frac{L}{d_0} - 1 \right)$. In this case, $\psi_s = 2.3$ rad (133°)

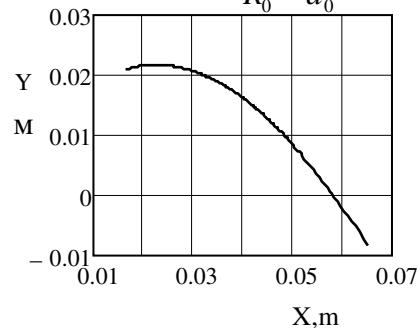


Figure 7. The cam profile with a linear spring

Taking into account that the maximum movement of the shoe is $S_m = 0.02$ m, from the formula expressing the equality of the elastic force and force Q

$$S_m = \frac{c}{2Q} [(\lambda + R_0 \psi_I)^2 - \lambda^2],$$

let us determine the required maximum cam angle. In this case, it is $\psi_I = 0.92$, i.e. $\psi_I = 52.7^\circ$. It can be seen that the maximum required cam angle ψ_I is less than maximum ψ_s .

5. Calculation of strength of the spring and cable

The spring index c_1 is equal to the ratio of the average diameter of the spring coil to the diameter of the wire rod from which the spring is wound $c_1 = D_0 / d = 4.6$. The number of required spring turns is determined by formula $n = (G \cdot d^4) / (8 \cdot D_0^3 \cdot c) \approx 18$ turns. $G = 8 \cdot 10^{10}$ MPa – shear modulus [6]. At spring index $c_1 \geq 4$ the correction factor k , taking into account the influence of the curvature of turns and lateral forces is calculated by formula $k = (4c_1 - 1) / (4c_1 - 4) + 0.65 / c_1 = 1.35$.

We check the fulfillment of the strength condition for a spring made of round wires under the action of static or slowly varying variable loads $\tau_{\max} = k \cdot 8 \cdot F \cdot c_1 / (\pi \cdot d^2) = 709 \cdot 10^6 \text{ N/m}^2$. $\tau_{\max} < [\tau]$ is equal to $[\tau] = 750 \cdot 10^6 \text{ N/m}^2$ [6] for springs made of steel 60C2, 60C2A and 50HFA. It means that the spring strength condition has been met.

It is necessary to check the strength condition for a cable with a diameter $d = 1 \cdot 10^{-3} \text{ m}$ at $Q = 100H$. Let us calculate the voltage value in the cable $\sigma = Q / S = 127.4 \cdot 10^6 \text{ N/m}^2$. As $\sigma < \sigma_m = 160 \cdot 10^6 \text{ N/m}^2$, the cable strength condition has been met.

6. Conclusion

The possibility of using cam-spring devices in pantographs is shown. They are used to create a constant contact pressure during the current collection. The methodology for calculating the cam-spring mechanism is suitable for existing and developed pantographs of electric vehicles.

The results of this work can be used in the development of new pantographs for trolley buses and metro cars.

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