# Peculiarities of calculation the running resistances of the wire across the guides wire-tying machines

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**Abstract.** Wire rod manufacturers are interested in using their own materials for strapping coils. Therefore, the competitive advantage of manufacturers of wire-tying machines may be the possibility of using wire rod as a strapping material. At the same time, the rigidity of the rod causes great efforts to feed it along the guides around the strapped section. The presented technique for calculating can be used for the scientifically based design of wire feeders of prospective wire-tying machines.

## 1 Introduction

Rolled products of round cross-section of small diameters – wire rod – during production is stacked in coil and tied by hand or by special machines. The material for strapping is usually a special metal strapping tape. However, wire rod manufacturers are interested in using their own materials. Therefore, the competitive advantage of manufacturers of wire-tying machines may be the possibility of using wire rod as a strapping material.

At the same time, the rigidity of the rod (in comparison with the tape) causes great efforts to feed it along the guides around the strapped section. This is especially true for heavy coils. Their section is elongated in the axial direction. The rod, when circling around such a section, moves alternately along rectilinear and circular guides and several times plastically deformed. For scientifically based design of the elements of wire-tying machines, the method of calculation the running resistances of the wire across such guides is necessary.

## 2 The state of studies in the area under consideration

A review of the calculation methods was carried out. To determine the resistance to the movement of a deformable object, the method proposed by A. I. Tselikov is usually used. The essence of this method in determining the dependence of the bending moment on the curvature and the joint solution of the equations of the work of external and internal forces. According to A. I. Tselikov, work aimed at overcoming the resistance $P_d$ associated with the deformation of the fed object (rod) is the work of plastic bending of a workpiece of length $L$:

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$$A_{Pl} = P_d L = L \int_0^\chi M d\chi, \tag{1}$$

where $M$ is the current value of the bending moment required to bend the beam to the curvature $\chi$.

This method is used in the calculation of feeding devices in wire-tying machines by A. I. Merenkov [2], and in spring-coiling automata by E. G. Belkov [3], and with rotational bending and straightening by E. N. Moshnin [4] and M. Paech [5].

Experimental studies [6] show that the method gives a high convergence with experimental data for constant curvature guides (2.4% error). However, in the case of motion along the guides of variable curvature, the method gives a significant discrepancy (the error reaches 34%).

To take into account the resistance associated with friction, in all the considered techniques, frictional forces, defined as products of normal reactions to friction coefficients, are summed up. It is obvious that to take into account the friction forces arising in the curvilinear guides, more complex dependencies will be required taking into account the increase in resistance when moving on circular surfaces. This increase can be described by Euler's formula:

$$P = Q e^{f_0 \alpha}, \tag{2}$$

where $Q$ is the resistance to the movement of the rod at the exit of the rounded section; $P$ is the input force required to overcome this resistance; $f_0$ is the coefficient of friction; $\alpha$ is the angular value of the contact of the rod with the guide.

## 3 The method of force analysis of the motion of a wire along the guides of variable curvature

To calculate resistance to movement of the wire through the duct of the machine for strapping of heavy coils guide is divided into characteristic sections (Fig. 1). By sequentially analyzing the wire loading schemes on individual sections of the guide in the order opposite to the wire motion, we come to the determination of the required feed force.

The driving force acting on the wire at point $F$ can be determined from the equation of motion of the wire in the area $FG$ (Fig. 2):

$$F_{dF} \cdot \rho - N f_1 \cdot \rho - N k (\rho - a) - N_G \cdot l_1 = 0, \tag{3}$$

where $F_{dF}$ is the driving force acting on wire at point $F$; $N_G$ is a normal reaction of the guide at the point $G$ of the wire contact; $f_1$ – coefficient of friction; $k$ – coefficient of resistance, taking into account friction and chip removal (if the hardness of the guide is much higher than the wire hardness $k=f_1$), $\rho$ – radius of curvature of the wire.

From (3) for the driving force in this section:

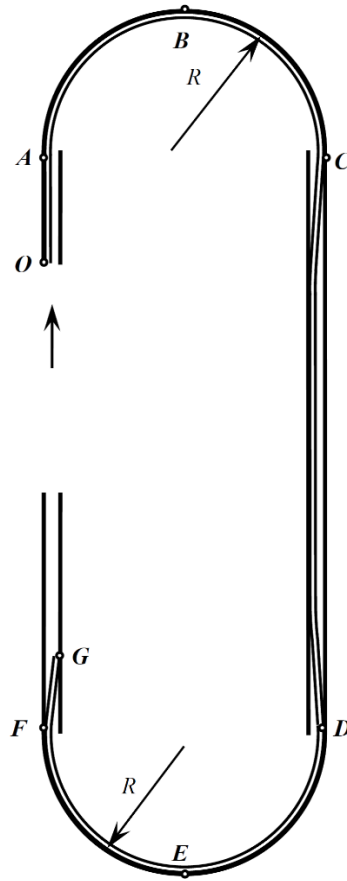$$F_{dF} = N \frac{f_1 \rho + k(\rho - a) + l_1}{\rho} = N C_1, \tag{4}$$

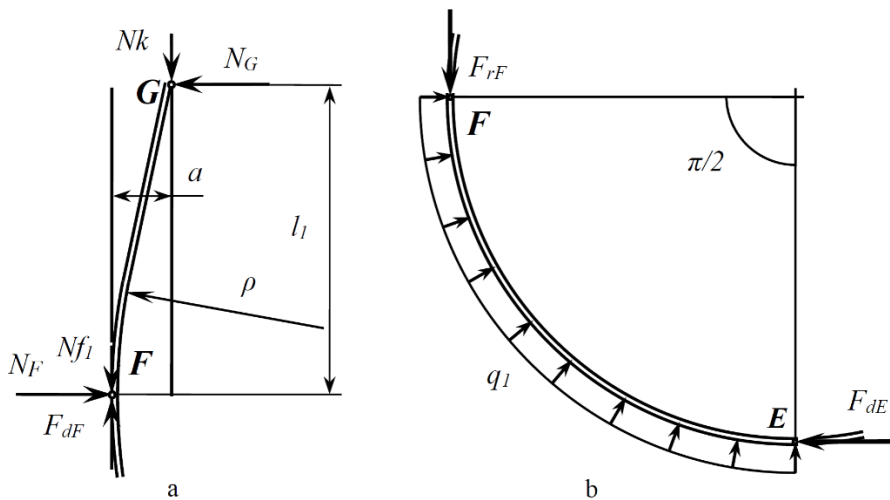**Fig. 1.** Scheme of arrangement of characteristic sections of the guide



**Fig. 2.** The wire loading scheme: a – in the section *GF*; b – in the section *EF*

In order to straighten a wire having a curvature $\chi=1/\rho$, it is necessary to apply to it a driving force of such magnitude that the resulting forces $N$ and $Nk$ cause the corresponding plastic deformation in section F.

The equilibrium condition between the external moment and internal forces can be expressed by the equation proposed by E. N. Moshnin to determine the bending moment for rigid-plastic bending with linear hardening:

$$M = \left(\frac{S}{W} + \frac{E_T}{\sigma_T}\frac{h}{2\rho}\right) W\sigma_T, \tag{5}$$

where $S$ and $W$ are the static moment of the cross section and the Z modulus; $E_T$ and $\sigma_T$ are the hardening modulus and yield point of the material; $h$ is the section height.

From where the value $N$, necessary for the plastic deformation of a wire (straightening of curvature $\chi=1/\rho$) is defined as

$$N = \frac{\sigma_T}{C_2}, \text{ where } C_2 = \frac{\sigma_T(l_1-ka)}{M}. \tag{6}$$

Whence from (4) taking into account (6) we obtain:

$$F_{dF} = \frac{C_1}{C_2}\sigma_T. \tag{7}$$

The force $F_{rF}$ of the resistance to the movement of the wire in the section $EF$ (Fig. 2, b) is of the same magnitude as the driving force $F_{dF}$ and is directed in the opposite direction. $F_{dE}$ is the driving force acting on the wire at the point $E$. Both forces are directed along the axis of the wire. They press it to the circular guide, on which there is a normal distributed load and friction forces. The wire makes a circular motion without deforming. These conditions are typical for the derivation of the Euler formula.

Therefore, using the Euler formula and taking into account that $F_{rF}=F_{dF}$, we write the following expression:

$$F_{dE} = \frac{C_1}{C_2}\sigma_T \cdot e^{f_1\frac{\pi}{2}}. \tag{8}$$

The force of resistance to movement on the section $DE$ (Fig. 3, a):

$$F_{rE}=F_{dE}. \tag{9}$$

The driving force $F_{dD}$ acting on the wire at the point $D$ is composed of the force necessary to plastic deformation of the wire and the force necessary to overcome the frictional forces.

$$F_{dD}=F_{dD}'+F_{dD}'' \tag{10}$$

where $F_{dD}''$ is the force, required to overcome the frictional forces the motion of the wire in a circular segment of the guide, which can be defined as
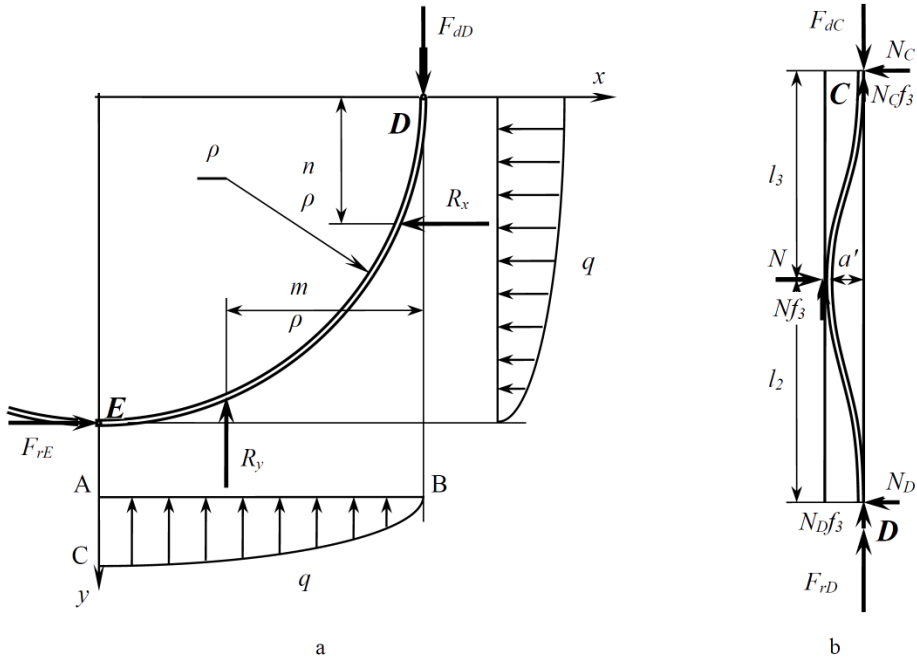
$$F_{dD}'' = F_{dE} \cdot e^{f_1\frac{\pi}{2}}. \tag{11}$$

**Fig. 3.** The wire loading scheme: a – in the section *DE*; b – in the section *CD*

Force $F_{rD}{'}$ were determined from the equations of motion of the wire:

$$F_{rE} = R_x;\qquad(12)$$

$$F_{dD}{'} \cdot \rho - F_{rE} \cdot \rho + R_x \cdot n\rho - R_y(\rho - m\rho) = 0.\qquad(13)$$

The value of $R_y$ can be determined from the condition for the transition to the plastic state of the wire material in the cross section. Neglecting the influence of longitudinal forces, taking into account (5) and (9), we obtain

$$R_y = \frac{\sigma_T}{C_3} + \frac{F_{dE}}{m}(1-n), \text{ where } C_3 = \frac{\sigma_T m\rho}{M}.\qquad(14)$$

From (10) and (13), taking into account (8), (11) and (12), we finally obtain

$$F_{dD} = \frac{\sigma_T \cdot n}{C_3} + \frac{C_1}{C_2}\sigma_T \cdot e^{f_1\frac{\pi}{2}}\left(1 + e^{f_2\frac{\pi}{2}}\right).\qquad(15)$$

On the *CD* section there is a buckling of the wire (with a sufficient section length), resulting in normal reactions $N_C$, $N$, $N_D$ (Fig. 3, b). Total value of these reactions

$$N_D + N + N_C = 2a'\left(\frac{F_{dC}}{l_3} + \frac{F_{rD}}{l_2}\right),\qquad(16)$$

The drag force on this section is $F_{rD}=F_{dD}$

As an assumption, let's assume that $_3=l_2=L_{CD}/2$, where $L_{CD}$ - the length of the *CD*. Then taking into account (16):

$$F_{dC} = F_{dD}\frac{L_{CD}+4f_3 a'}{L_{CD}-4f_3 a'}.\qquad(17)$$

Section *BC* is similar to section *EF*. Section *AB* is similar to section *DE*. Section *OA* is similar to section *CD*. Formulas for determining the forces at points *B*, *A*, *O* are identical to formulas (8), (15), (17).

Then the force Q required to feed the wire through the guides is definitively determined by the following expression:

$$Q = \left[\frac{\sigma_T \cdot n}{C_3} + C_4 \cdot e^{f_4 \frac{\pi}{2}} \left(1 + e^{f_5 \frac{\pi}{2}}\right)\right] \frac{L_{OA} + 4f_6 a\prime}{L_{OA} - 4f_6 a\prime}, \tag{18}$$

where $C_4 = \left[\frac{\sigma_T \cdot n}{C_3} + \frac{C_1}{C_2}\sigma_T \cdot e^{f_1 \frac{\pi}{2}}\left(1 + e^{f_2 \frac{\pi}{2}}\right)\right]\frac{L_{CD} + 4f_3 a\prime}{L_{CD} - 4f_3 a\prime}$.

## 4 Conclusions

1. The presented technique for calculating the resistance to the movement of the rod along the variable-curvature guides can be used for the scientifically based design of wire feeders of prospective wire-tying machines.
2. The obtained dependences of the feed force on the parameters of the guide can be the basis for optimization calculations.
3. The conducted experimental researches [6] allowed to estimate reliability of the presented method of calculation (relative error in comparison with experimental data in the considered area of factor space does not exceed 2,7%).

## References

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