

Investigation of the conditions of movement of magnetic transport devices on ferromagnetic surfaces of various orientations

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Abstract. Every year, more and more enterprises are automated, robotic facilities are produced in tens of thousands. A special niche is occupied by transport devices moving along curved surfaces. Sheathing of ships' hulls, tanks, towers, gas storage facilities, and similar metal structures is convenient to maintain during operation and repair with magnetic transport devices. The computational schemes and mathematical models of transport devices of magnetic type with wheel propulsors on ferromagnetic surfaces are presented in this paper. Geometric and force parameters affecting movements on horizontal, inclined, and vertical surfaces were investigated. The gravity of the transport device, the reaction of the processing equipment, the traction between the drive wheels of the bogie and the ferromagnetic surface, the normal reaction of the ferromagnetic surface to the drive wheels, the attraction developed by the electromagnet were taken into account. The results obtained will contribute to the introduction of mathematical modeling methods into the practice of designing magnetic transport devices moving on ferromagnetic surfaces.

1 Introduction

Currently, a variety of robotic devices are widely used in the repair and maintenance of various engineering structures made of ferromagnetic materials. A promising direction in this area is the use as a mobile base of such magnetic transport devices, which move directly on the ferromagnetic surface and are held on it by magnetic forces [1].

Work on the creation and introduction of magnetic transport devices for moving technological and diagnostic equipment in various industries is carried out quite widely in many countries [2–11].

The history of the development of land vehicles has imprinted on the structures of magnetic transport devices moving on surfaces, the location planes of which deviate significantly from the horizontal. In modern conditions, magnetic transport devices with caterpillar [12–13] and wheeled [14–15] propulsion are most often used.

The choice of the principle of movement of a magnetic transport device depends on a number of factors:

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1. The nature of the work performed, i.e. the purpose of the transport device (e.g. transport of equipment where vibration and shock may occur);
2. The nature of the goods carried (dimensions, mass, completeness, the nature of contact with the surface, the need for frequent stoppages and manoeuvres);
3. Conditions of the movement surface (its area, curvature, height of irregularities, thickness of the sheeting, thickness of the non-magnetic coating, moisture, oil content, presence of fouling, etc.);
4. The state of the environment (air, water, aggressiveness, temperature, etc.).
5. Thus, the carrying capacity of magnetic transport devices with a caterpillar propulsor is higher than that of devices with a wheel propulsor, since the magnetic elements installed on the caterpillars contact with the ferromagnetic surface directly or with a relatively small gap.

At the same time, magnetic transport devices with a wheeled propulsor are lighter and more manoeuvrable than devices with a caterpillar propulsor.

The introduction of magnetic transport devices is hampered by insufficient information about their design and application in the system of maintenance and repair of engineering systems. The studies carried out in this area [5, 16–24] do not fully consecrate all the features of the movement of magnetic transport devices on ferromagnetic surfaces of different orientation and configuration.

The paper [25] analyzed the possibilities of using a magnetic type transport device with a wheeled propulsor to move on ferromagnetic surfaces of various configurations. It has been proven that the most effective is the structural arrangement of the transport device, which is a platform on which two wheel propulsors are pivotally fixed – bogies with an integrated electromagnet and an electric motor driving a pair of wheels.

The purpose of the current study is to develop a computational scheme and mathematical models that allow to describe and analyze the effects of various geometric and power parameters on the conditions of movement of magnetic transport devices with a wheel propulsor on ferromagnetic surfaces with different orientations – horizontal, inclined, and vertical.

2 Materials and methods

Figure 1 shows a computational diagram of the interaction of a wheeled propulsor of a transport device with a ferromagnetic surface, the position of which relative to the horizon is determined by an angle of inclination that varies in the range from 0 to 180 degrees. Let us assume that the point of application of all forces coincides with the point O of hinging of the propulsor to the platform.

We introduce the following designations: F_G – is the gravity of the transport device (transmitted through the hinge attachment of the bogie to the platform); F_W – is the reaction from the processing equipment (also transmitted through the hinge attachment); F_T – is the force of traction between the driving wheels of the bogie and the ferromagnetic surface; F_N – is the normal reaction from the ferromagnetic surface to the driving wheels; F_E – is the force of attraction developed by the electromagnet.

Consider the sum of forces relative to the axes X and Y (Figure 1).

$$\sum X = 0; F_T - F_G \sin \alpha - F_W \sin \beta = 0; \quad (1)$$

$$\sum Y = 0; F_E - F_G \cos \alpha - F_W \cos \beta = 0, \quad (2)$$

where α – is the angle of inclination of the ferromagnetic surface; β – is the angle that determines the direction of the reaction from the processing equipment to the normal of the ferromagnetic surface.

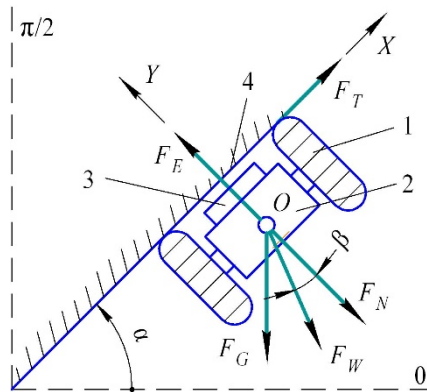


Fig. 1. Scheme of forces acting on the bogie of the transport device: 1 – driving wheels; 2 – bogie with an electric motor; 3 – electromagnet; 4 – ferromagnetic surface.

It should be noted that $\alpha = 0^\circ$ corresponds to the case of movement of the transport device on the ceiling surface; $\alpha = 90^\circ$ – vertical surface; $\alpha = 180^\circ$ – horizontal (floor) surface.

As is known, the maximum traction F_{Tmax} in the contact zone is determined by the traction coefficient ψ and the pressure F_p of the wheels on the ferromagnetic surface:

$$F_{Tmax} = \psi F_p, \quad (3)$$

Here $F_p = F_E - F_G \cos \alpha - F_W \cos \beta = F_N$.

To hold the bogie on the ferromagnetic surface, it is necessary to meet the condition

$$F_{Tmax} \geq F_G \sin \alpha + F_W \sin \beta. \quad (4)$$

If condition (4) is not met, the bogie will slip off the surface.

Given the expressions (1)–(3), inequality (4) can be represented as

$$\psi(F_E - F_G \cos \alpha - F_W \cos \beta) \geq F_G \sin \alpha + F_W \sin \beta \text{ or}$$

$$F_E = \frac{F_G(\sin \alpha + \psi \cos \alpha) + F_W(\sin \beta + \psi \cos \beta)}{\psi}. \quad (5)$$

3 Research results

Based on the obtained expression (5), an analysis of the influence of the geometric and force characteristics of the transport device on the fulfillment of the condition of its movement on the ferromagnetic surface is carried out.

Let us consider several particular cases of conditions of movement of the transport device for characteristic values of angles α and β :

$$1. \begin{cases} \alpha = 0^\circ, \beta = 0^\circ; \\ \psi(F_E - F_G - F_W) \geq 0, F_E \geq F_G + F_W. \end{cases} \quad (6)$$

$$2. \begin{cases} \alpha = 0^\circ, \beta = 90^\circ; \\ \psi(F_E - F_G) \geq F_W, F_E \geq F_G + F_W / \psi. \end{cases} \quad (7)$$

$$3. \begin{cases} \alpha = 90^\circ, \beta = 0^\circ; \\ \psi(F_E - F_W) \geq F_G, F_E \geq F_W + F_G / \psi. \end{cases} \quad (8)$$

$$4. \begin{cases} \alpha = 90^\circ, \beta = 90^\circ; \\ \psi F_E \geq F_W + F_G, F_E \geq (F_W + F_G) / \psi. \end{cases} \quad (9)$$

5.
$$\begin{cases} \alpha = 180^\circ, \beta = 90^\circ; \\ \psi(F_E + F_G - F_W) \geq 0, F_E \geq F_W - F_G. \end{cases}$$
(10)

6.
$$\begin{cases} \alpha = 180^\circ, \beta = 90^\circ; \\ \psi(F_E + F_G) \geq F_W, F_E \geq F_W / \psi - F_G. \end{cases}$$
(11)

Let us determine the intermediate values of the angles α and β corresponding to the maximum value of the right side of the inequality (5). For this, it is enough that two conditions are met:

$$\begin{cases} K_\alpha = \sin \alpha + \psi \cos \alpha = \max; \\ K_\beta = \sin \beta + \psi \cos \beta = \max. \end{cases}$$
(12)

This will be the case if these conditions depend on the value of the traction coefficient ψ . The maximum values of the coefficients K_α and K_β , and the values of the corresponding angles α and β for some values of the traction coefficients are given in Table 1.

Since the coefficients K_α and K_β are greater than one, the most unfavorable case of operation of the transport device is when the angle between the ferromagnetic surface on which the device moves and the horizon corresponds to the maximum of the coefficient K_α and the angle of application of the reaction from the processing equipment corresponds to the maximum of the coefficient K_β .

The right side of the inequality (5) decreases monotonously as the traction coefficient increases, so the force of attraction of the electromagnet F_E must be calculated for the minimum value of the traction coefficient ψ at which the transport device can operate on a ferromagnetic surface. The average value of the traction coefficient for the case under consideration can be taken $\psi = 0.4$. Then $K_\alpha = 1.077$; $K_\beta = 1.077$.

In this case, the inequality (5) can be represented as: $F_E \geq 2.7(F_W + F_G)$.

If the direction of the reaction from the processing equipment is known, then the force developed by the electromagnet must be found by the formula:

$$F_E \geq K_\alpha (F_G / \psi) + K_\beta (F_W / \psi).$$
(13)

Here $K_\alpha = 1.077$ at $\psi = 0.4$ and arbitrarily oriented surface; $K_\beta = \sin \beta + \psi \cos \beta$.

If there is no reaction from the processing equipment, then condition (13) will be:

$$F_E \geq K_\alpha (F_G / \psi).$$
(14)

Table 1. Dependence of coefficients K_α and K_β on values of traction coefficients.

ψ	0.1	0.2	0.3	0.4	0.5	0.6
$\alpha ; \beta, \text{deg}$	84.3	78.7	73.3	68.2	63.4	59.0
$K_\alpha; K_\beta$	1.005	1.020	1.044	1.077	1.118	1.166

In Figure 2 and 3 we can see graphs showing the effect of the angle of inclination of the ferromagnetic surface α and the traction coefficient ψ on the required magnitude of the force developed by the electromagnet F_E . The data are obtained at: traction coefficient $\psi = 0.4$; gravity of the transport device $F_G = 300$ N, and reaction force of the processing equipment $F_W = 150$ N.

4 Discussion

Analysis of the obtained expressions (6)–(14) and the data of Table 1 allow us to assess how the spatial orientation of the ferromagnetic surface affects the conditions of movement of the transport device:

1. The first and second cases correspond to the location of the transport device on the ceiling surface. In the first case, it is necessary that the force developed by the electromagnet compensates for the gravity of the device and the reaction from the processing equipment. The worst case is the second case, as the reaction from the processing equipment is directed against the traction.
2. The third and fourth cases correspond to the operation of the transport device on a vertical surface. The worst case is the fourth case where the reaction of the processing equipment and the gravity of the transport device are directed against the traction.

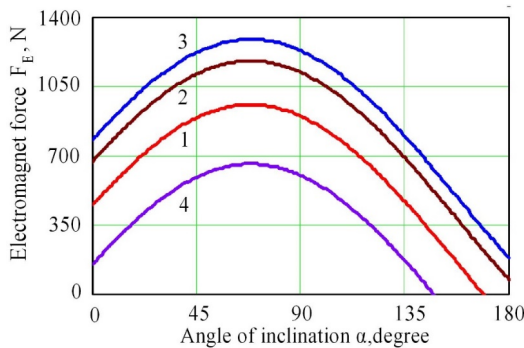


Fig. 2. Dependence of the required electromagnet force on the angle of inclination of the ferromagnetic surface: 1 – $\beta=0^\circ$; 2 – $\beta=45^\circ$; 3 – $\beta=90^\circ$; 4 – $\beta=180^\circ$.

3. The fifth and sixth cases correspond to the operation of the transport device on a horizontal surface. In these cases, the gravity of the transport device is directed in the same direction as the gravity of the device, i.e. towards the ferromagnetic surface, thus achieving a higher limit of traction than when the device is on the ceiling and vertical surfaces.

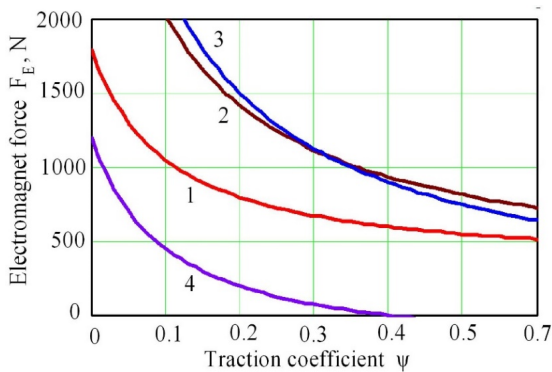


Fig. 3. Dependence of the required electromagnet force on the traction coefficient at the angle of inclination of the ferromagnetic surface: 1 – $\alpha=0^\circ$; 2 – $\alpha=45^\circ$; 3 – $\alpha=90^\circ$; 4 – $\alpha=180^\circ$.

4. The most unfavourable of the cases considered is the fourth, when the transport device is on a vertical surface and the reaction of the processing equipment is directed against the traction forces.

The nature of the changes in the graphs presented in Figures 2 and 3 makes it possible to assess the features of the transport device movement on the ferromagnetic surface:

1. The greatest force developed by the electromagnet is necessary when moving the mobile device on a vertical surface; when moving on a horizontal surface, the value of this force can be minimal.
2. When changing the angle β that determines the direction of action of the reaction from the processing equipment to the normal of the ferromagnetic surface, in the range from 0 to 90 degrees, the force developed by the electromagnet changes by 1.45...5.4 times for different types of surfaces.
3. As the traction coefficient ψ increases, the required value of the force developed by the electromagnet F_E decreases nonlinearly, and strive for a certain limit. When the mobile device moves on a horizontal surface ($\alpha = 180^\circ$) and the traction coefficient ($\psi \geq 0.5$) is high, it can move with the electromagnet off.

5 Conclusion

The dependences of the angle of inclination of the ferromagnetic surface and the traction coefficient on the value of the force developed by the electromagnet are obtained. It is established that the greatest force developed by the electromagnet is necessary when the mobile device moves on a vertical surface.

When moving on a horizontal surface, the value of this force can be minimal, with an increase in the traction coefficient, the required value of the force developed by the electromagnet nonlinearly decreases, and tends to a certain limit.

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