The Interaction Forces in Magnetic Support Systems of Vertical Type

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Abstract **─** In this article, the vertical and horizontal forces of the interaction of permanent magnets in a Magnetic Suspension (support) System of Vertical Type (MSVT) are considered. The magnetic support system contains multi-row magnetic bands (strips), which have alternating polarity. The magnetization vector, $\vec{M}$, is directed horizontally, as opposed to classical support systems where $\vec{M}$ is directed vertically. The results of the comparison of the vertical and lateral forces for the classic Magnetic System of Horizontal Type (MSHT) and the MSVT are presented too. An effectiveness factor, $\mu_{eff} = f_z / mg$, is adopted (where f_z is the vertical force per unit length of magnetic band and *mg* is its weight) and is used as the principle criterion for comparison. In this paper it is shown that when the vertical displacement of the moving part of the support system of MSVT causes the vertical force, f_z, to reach its maximum, the lateral force f_y is at its minimum.

Index Terms **─** Horizontal and vertical types of magnetic suspension, permanent magnets, stability, suspension effectiveness factor, vertical and horizontal forces.

I. INTRODUCTION

Well known systems of magnetic support (magnetic suspension) on permanent magnets of horizontal type (MSHT), are illustrated in Fig. 1 (a). Magnetic strips and their polar faces are located in the horizontal plane. The magnets of the mobile and fixed parts are mounted on a ferromagnetic base. The magnetic substrate (magnetically soft material) reduces scattering fluxes. This simplifies the installation of magnetic strips and also causes a significant increase in the vertical force, i.e., bearing capacity of the magnetic support. This is a very desirable effect that even takes into account the mass of the ferromagnetic base for magnets.

The effectiveness of the support (suspension) can be determined by the index $\mu_{eff} = f_z / mg$, where $f_V = f_z$ is the vertical force of interaction (repulsive force) of the magnets located on the fixed and on the movable parts of the support system. The vertical force is defined as the interaction force and is calculated per unit length of one pair of magnetic strips of the system; *mg*- is the weight of the magnets per unit length, [1]. The support system can contain many strips arranged in a certain way and at a certain distance from each other. For example, in Fig. 1 (a) there are two magnetic bands on the mobile and fixed parts of the support.

The bands are located in the same plane (MSHT) and have alternating polarity.

In Fig. 1 (b), the support has a step-like character (and is said to be a Magnetic Support of Step Type – MSST) with relative vertical shifts of neighboring strips [2].

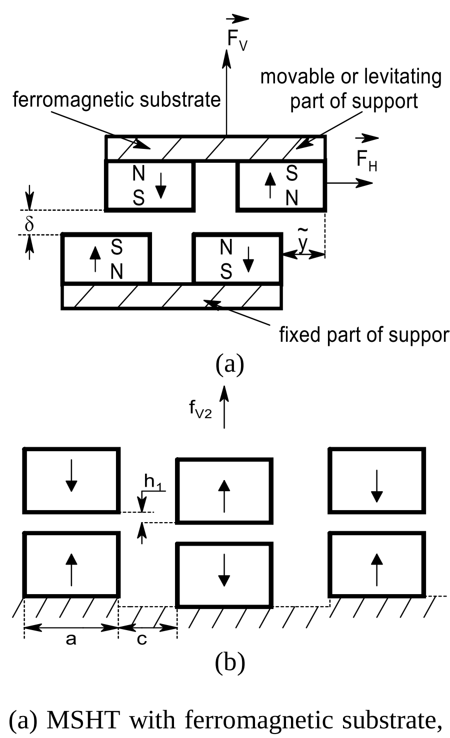

Fig. 1. (a) MSHT with ferromagnetic substrate, and (b) the scheme with the vertical displacement (MSSS).

The paper [2] also introduced a stability factor index $\gamma = f_V / f_H$, which is the ratio of vertical and lateral forces. This index is calculated for different values of lateral displacement.

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The value μ_{eff} can be chosen as the objective function for determining the optimum sizes of the cross section of the magnetic strip and the distance between them.

Different Permanent Magnet (PM) configurations have been proposed in the scientific literature with the objective to improve figures of merit similar to γ and μ_{eff} for magnetic bearings and force magnetic gears [3]-[5].

II. MAGNETIC SUSPENSION (SUPPORT) SCHEMES OF THE VERTICAL TYPE

A fundamentally different structure has a magnetic support system of vertical type on permanent magnets, Fig. 2 (a) and Fig. 2 (b). The first scheme proposed by Iskanderov [6] and the second by the author of this paper. The main advantages of these supports are: a small gap δ, and the elimination of the impact of the magnets of the stationary and moving parts under dynamic loads, which leads to displacements in the vertical plane. The placement of the magnetic strips can be carried out with high accuracy due to the use of rolling channels, T-bars, etc., serving simultaneously as structural components and magnetic flux concentrators. The increased accuracy of the placement of magnetic strips and the independence of the gap from vertical movements make**s** it possible to achieve significantly lower values of the working gap and, consequently, an increase in the bearing (vertical) support capacity and efficiency index μ_{eff}. In addition, in this paper it is shown that when the maximum vertical load on the moving part is reached, the lateral force tends to its minimum, and, consequently, the forces acting on the stabilizing mechanical (or electrodynamic) system reduce to a minimum. As a consequence of the reduction of the instability forces, the external stabilization system is simpler and cheaper to design. In contrast, levitation configurations, characterized by high destabilizing forces, require high-performance, complex and expensive stabilization systems [7]-[11].

The results of a theoretical analysis of the vertical and lateral forces acting in the MSVT, Fig. 2 (a) and Fig. 2 (b) are presented in this paper. The considered suspension system does not work on repulsion, as in does the classical system (Fig. 1), but on attraction. System 2, shown in Fig. 2 (b) differs from system 1; Fig. 2 (a) in that the magnets in the middle of the support "work" with both pole faces. The lateral (or horizontal) force destabilizing the suspended part depends on the accuracy of the placement of magnetic strips and ideally (if the system is symmetrical) is zero. In the initial position, when the magnetic strips are exactly opposite one another ($\tilde{y} = z = 0$, see Fig. 2 (a) and Fig. 2 (b)), the vertical force acting on the moving part of the system is zero.

It is clear that the mobile and fixed parts of the support system can be swapped (depending on the technical requirements imposed on the MP system). As the load increases, the moving part moves down, the vertical force, balancing the weight of the moving part, increases to a certain maximum, and the lateral force (if the system is not exactly symmetrical) decreases. Such a picture of interaction takes place within certain limits of vertical displacement: $z_{\max} > z > 0$. For the MSVT systems, shown in Fig. 2 (a) and Fig. 2 (b), the use of a ferromagnetic substrate leads to the same effect as for the MSHT, but in the case of Fig. 2 (b) a fixed part of the magnetic flux is used on both sides (without placing the magnets on a ferromagnetic base). In order to increase the bearing capacity, the systems shown in Figs. 2 (a) and 2 (b) can be transformed into multi-row systems.

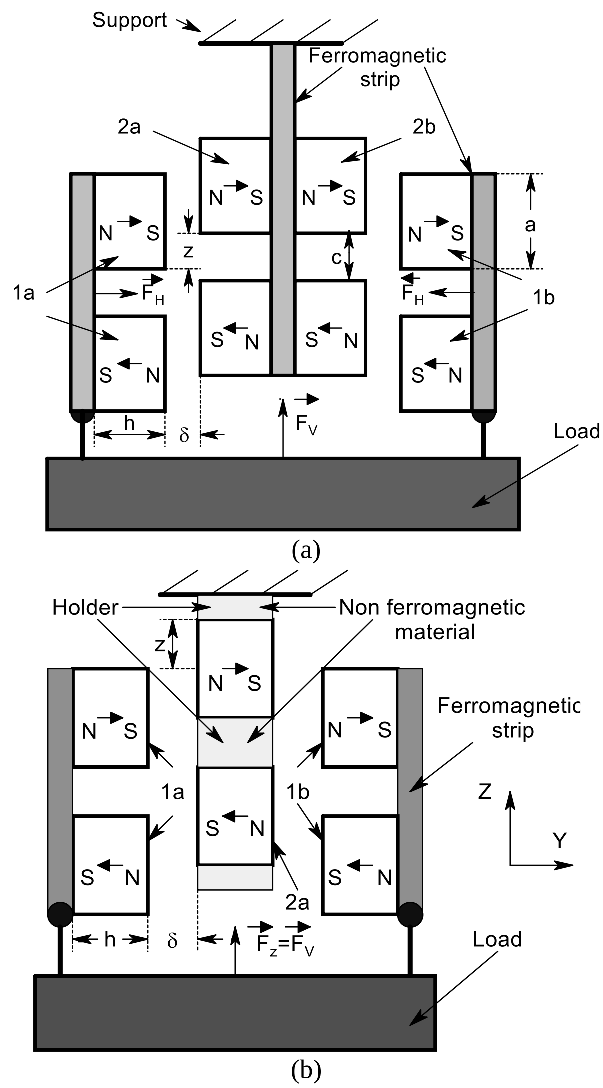

Fig. 2. (a) Scheme 1 MSVT, and (b) scheme 2 MSVT.

III. INTERACTION ANALYSIS FOR MSVT SYSTEMS

The forces of vertical and horizontal interaction in the magnetic systems can be determined using the expression for the potential energy of a permanent magnet that is located in an external magnetic field [2]:

$$E_p = \mu_0 \iiint_V \vec{M} \cdot \vec{H} \cdot dV . \quad (1)$$

In (1) $\vec{M}$ is the magnetization vector (e.g., the magnet *1a* or *1b*) and $\vec{H}(y,z)$ is the vector of magnetic field intensity (of the external magnetic field), created, for example, by the magnet *2a* or *2b*; V is the volume of the magnet, $\mu_0 = 4\pi \cdot 10^{-7}\ H/m$. Expressions for the interaction forces of permanent magnets can be obtained using the equation $\vec{F} = -\vec{\nabla} E_p$. For the vertical and horizontal components of the force, this formula gives:

$$\vec{F}_z = -\hat{z}\frac{\partial E_p}{\partial z}, \qquad \vec{F}_y = -\hat{y}\frac{\partial E_p}{\partial y}. \quad (2)$$

The efficiency μ_{eff} of support schemes shown in Fig. 2 (a) and Fig. 2 (b) can be estimated using the following expression [2]:

$$\mu_{eff} = f_z / mg , \quad (3)$$

in which $f_z(N/m) = f_V$ is the vertical interaction force per the unit length of the system that includes magnets *1* and *2*, and *mg* is the weight per unit length of the same magnets.

To find the interaction force of magnetic systems, we must first determine the magnetic field intensity $H(z,y)$ in those systems. Each magnet has a rectangular cross-section and can be represented by two faces (strips), each with a uniformly distributed fictitious magnetic charge with a surface density [1]: $\sigma = \pm\mu_0 \cdot M$. In [2] the two-dimensional potential of the magnetic field produced by the "face-charge" at any point $P(y,z)$, Fig. 3 (a) was obtained and can be represented as:

$$\phi(y,z) = -\frac{\sigma}{4\pi \cdot \mu_0}\int_0^a \ln\left[z^2 + (y-u)^2\right] \cdot du , \quad (4)$$

u is the variable of integration.

The components of the intensity of the magnetic field are determined by the following expression:

$$H_y(y,z) = -\frac{\partial\phi(y,z)}{\partial y}; H_z(y,z) = -\frac{\partial\phi(y,z)}{\partial z}. \quad (5)$$

By substituting (4) into (5), we obtain the expressions for the intensity of the magnetic field at the point $P(y,z)$:

$$H_y(y,z) = \frac{\sigma}{4\pi\mu_0}\left[\ln(y^2+z^2) - \ln((a-y)^2+z^2)\right], \quad (6)$$

$$H_z(y,z) = \frac{\sigma}{2\pi\mu_0}(arctg\frac{y}{z} - arctg\frac{y-a}{z}). \quad (7)$$

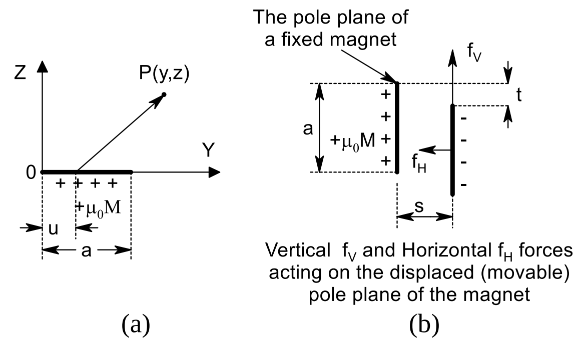

Fig. 3. (a) Charged strip, and (b) calculated scheme.

In contrast to the scheme in Fig. 1 (a) (or Fig. 1 (b)), in the proposed new schemes (Fig. 2 (a) and Fig. 2 (b)), the pole faces are arranged vertically. The calculation scheme for the interaction of two pole faces in this case is shown in Fig. 3 (b). Now:

$$H_y(y,z) = H_{Vertical} = H_V$$
$$H_z(y,z) = H_{Horizontal} = H_H .$$

In other words, the coordinates y and z change places (including in (4)).

The vertical force of interaction of two charged faces (repulsive force) obtained for horizontally located "charged" pole surfaces (for the scheme in Fig. 1 (b)) is now a lateral destabilizing force (for MSVT). Conversely, the lateral destabilizing force in the MSHT schemes is now a "holding" or supporting force in schemes with vertically arranged pole faces. Taking (1) and (2) into account, the forces of interaction of the faces, can be represented as:

$$f_H = \sigma\int_t^{t+a} H_H \cdot dy ; \quad f_V = \sigma\int_t^{t+a} H_V \cdot dy . \quad (8)$$

After substituting (6) and (7) into (8) and integrating, we obtain expressions for the vertical f_V and horizontal f_H interaction forces of a unit length of two charged faces:

$$f_V(t,s) = \frac{\mu_0 \cdot M^2}{4\pi}\Big\{2s(arctg\frac{t+a}{s} + arctg\frac{t-a}{s} - 2arctg\frac{t}{s} - 2t\ln(t^2+s^2) + (t+a)\ln\left[(t+a)^2+s^2\right] + (t-a)\ln\left[(t-a)^2+s^2\right]\Big\}, \quad (9)$$

$$f_H\left(t,s\right)=\frac{\mu_0\cdot M^2}{2\pi}\left\{(t+a)(arctg\frac{t+a}{s}-\right.$$

$$-2t\,arctg\frac{t}{s}+\left(t-a\right)arctg\frac{t-a}{s}+$$

$$\left.+\frac{s}{2}\ln\frac{(s^2+t^2)^2}{\left[s^2+\left(t-a\right)^2\right]\left[s^2+(t+a)^2\right]}\right\}, \qquad (10)$$

where t and s are given in Fig. 3 (b). To obtain expressions for the interaction forces of the magnetic systems of the moving and bearing parts of the suspension system (support), it is necessary to sum (taking into account the signs) the interaction forces of the corresponding pole faces. For example, the vertical force for the scheme in Fig. 2 (a) (or in Fig. 4) is composed of the interaction of the faces: (1 and 2) minus the faces (1 and 3); the result is multiplied by 4. Of course, for a more accurate calculation of the vertical force, it is necessary to take into account the interaction of face 1 with faces 4 and 5. Similar calculations must be made with faces 6 and 2,3,4,5. In accordance with the calculated data, it suffices to take into account the first image. The error does not exceed 4-5%.

As for the lateral force of interaction, it can be neglected if the magnetic strips along the fixed (bearing) and suspended parts of the system are fairly accurately placed (i.e., when the gaps δ in the left and right parts of the support system are approximately equal). When calculating the vertical and horizontal interaction forces of the MSTV system shown in Fig. 2 (a), only the first images of the faces of the magnets with respect to the central ferromagnetic strip (the axis of symmetry) were taken into account.

Calculations of the vertical and horizontal forces of interaction of the MSTV system shown in Fig. 2 (a) were performed considering only the first images of the faces of the magnets relative to the central ferromagnetic strip (the axis of symmetry). The effect of subsequent images is negligible.

As an example, the expression for the vertical force f_V , calculated for the case of interaction of two-row systems (Fig. 2 (a) or Fig. 4) is given below:

$$\begin{aligned}f_V &= 2f(z,\delta)-4f\left(z,\delta+2h\right)+2f\left(z,\delta+4h\right)-\\ &-2f(z,3\delta+4h)-f(a+c+z,\delta)+\\ &+2f(a+c+z,\delta+2h)-f(a+c+z,\delta+4h)-\\ &-f(a+c-z,3\delta+4h)+f(a+c-z,\delta)-\\ &-2f(a+c-z,\delta+2h)+f(a+c-z,\delta+4h)+\\ &+f(a+c+z,3\delta+4h).\end{aligned} \qquad (11)$$

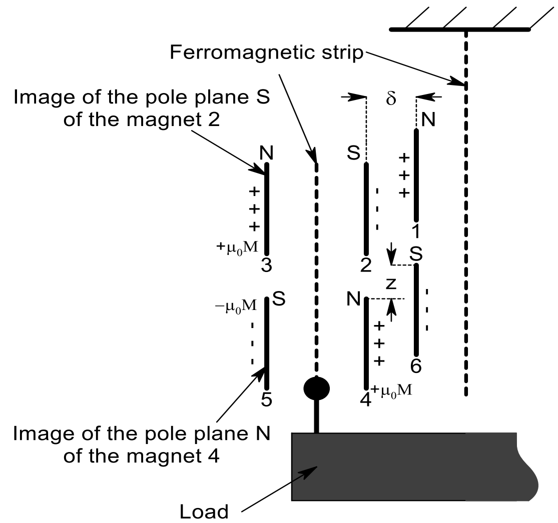

Fig. 4. Calculation scheme (corresponding to left side of Fig. 2 (a).

To quantify the quality of the scheme, we consider only the left-hand side of the support, i.e., asymmetrical support Fig. 5.

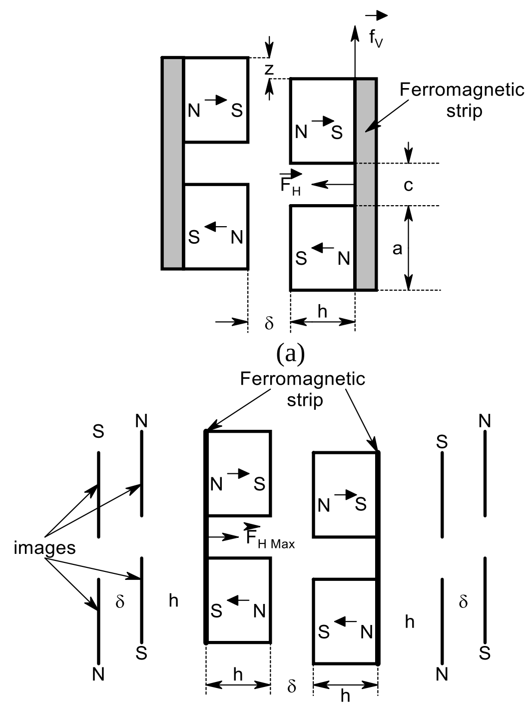

Fig. 5. (a) The support (or suspension) scheme, and (b) the calculation scheme.

The results of calculations f_V , f_H and μ_{eff} for

$a = 0.021m$, $h = 0.014m$, $M = 230A/m$ are given in the following Table 1. Figure 6 shows the dependencies $f_V(z)$ H $f_H(z)$.

Table 1: Calculation results

δ, mm	z, mm	$f_V, N/m$	$f_H, N/m$	μ_{eff}
	0	0	237	0
	5.0	138	200	9.1
6	10.0	208	113	15.3
	15.0	239	0	17.6
	20.0	213	-107	15.7
	0	0	167	0
	5.0	82	145	6.04
10	10.0	141	88	10.4
	15.0	165	14	12.2
	20.0	153	-59	11.3

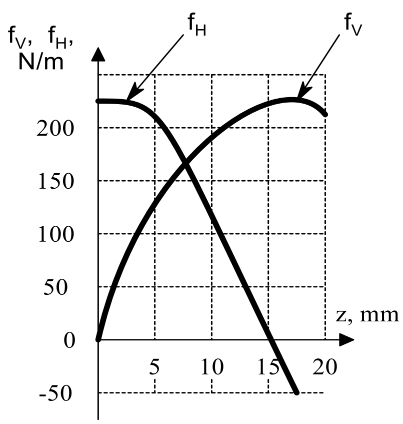

Fig. 6. Dependencies of the vertical and horizontal forces from vertical displacement at $\delta = 6mm$.

IV. CONCLUSION

The vertical and horizontal forces of interaction between permanent magnets in a magnetic support system of vertical type (MSVT) have been investigated. The main results of the investigations are briefly summarized below.

1. The systems of magnetic support (magnetic suspension) of vertical type with permanent magnets MSVT-1 (Fig. 2 (a) and MSVT-2 (Fig. 2 (b)) considered here, seem to be a very promising direction for their creating. They can be realized with relatively small gaps ($\delta = 5 \div 7mm$ or less) and therefore allow to achieve high values of effectiveness factor μ_{eff}.
2. The analysis of the obtained data for the MSVT-1 and MSVT-2 indicates that the investigated magnetic suspension systems outperform the classic horizontal system MSHT, (Fig. 1 (a)).
3. The ratio $\gamma = f_V / f_H$ increases with increasing z (vertical displacement of the movable part of the support) indicating a reduction of the instability of the support system in the horizontal plane.
4. When the lateral force is close to 0, the vertical force (for the size of the magnetic system shown in the table) increases to hundreds of units, reaching its maximum (Fig. 6); which is an undoubted advantage of MSVT, since the requirements for a stabilizing system (roller, electromagnetic or electrodynamic) are substantially less stringent. This is also true for other correctly chosen sizes of the magnetic system.

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