Analysis of the possibility of levitation of ferromagnetic bodies in a static magnetic field

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Abstract. The hypothesis of the existence of three-dimensional regions near the sources of the magnetic field, in which it is possible to obtain a stable position of the magnetic object in a stationary field. The hypothesis is based on the existence of two types of points: points with zero field level and points with local extremum of this field. The obtained distributions of magnetic forces act stabilizing on the object under study, in particular, create the effect of levitation of ferromagnetic bodies in the gravitational field of the Earth. Examples of configurations of the field sources that generate many such points. Systems of current windings providing creation of one-and two-dimensional configurations of areas near sources within which magnetic levitation is possible are analyzed.

1. Introduction

The idea of magnetic levitation – the balancing of body weight by magnetic forces-is currently being vigorously debated in connection with advances in high-temperature superconductivity. The experimental data obtained, however, indicate that the practical implementation of this idea is limited by the distances between the levitating body and the field sources and the critical values of the magnetic field induction for the superconducting systems used.

The known methods of magnetic levitation are based either on the diamagnetic properties of superconducting materials or on the dynamic effect of field pulses on the ferromagnetic body[1]. The creation of stationary magnetic levitation by such methods is difficult for two reasons. The first reason is related to the purely technical difficulties of creating powerful fields, maintaining the superconducting state of materials, ensuring compliance with the level of the field and the mass of levitated objects. The theoretical injunction (Earnshaw’s theorem [2]) to create steady state magnetic object through the field of stationary sources.

The studies given by the authors indicate the possibility of obtaining a spatial zone outside the field sources, within which it is possible to create a stable state of a magnetic object, in particular, a ferromagnetic body in the gravitational field of the Earth [3]. The idea of such magnetic levitation is associated with the presence in the distribution of the magnetic field of sources of special points, the field level in which is zero. In work [4] these points are called points with zero level of modulus of...
tension, in [1]- "magnetic wells", in [5] – magnetic" bulge", in works of the author [6-11] – points of magnetic anomalies.

This article discusses the results of research on obtaining spatial zones outside the field source in order to create magnetic levitation in a static magnetic field.

2. One-dimensional levitation of a ferromagnetic body in the field of a permanent magnet

The paper [4] presents the results of experimental studies of the magnetic field (MP) of a ring permanent magnet magnetized axially. A feature of the distribution of its MP is the presence of two points with a local minimum magnetic field along the axis of the magnet. The presence of these points is explained by the properties of the permanent magnet material. For Figure 1 shows the layout of the permanent magnet and the induction curves \( B_e \), given in [4], as well as the curves of the axial component \( B_z \) and induction module \( B \), calculated by the authors of this paper.

This figure shows that in addition to the points with zero magnetic field \( P_{a1}, P_{a2} \) points of local extremums are located in the direction of the same axis \( P_{m1}, P_{m2} \). For fig. 1, b shows the location of these points on the induction curve.

In this paper we used the author's methods for calculating the MP distributions of a permanent magnet, which is due to the possibility of their implementation in the mathematical systems Pascal and Maple [14, 15]. Differences of calculation formulas are connected only with coordinate system during calculations.

![Figure 1. The arrangement of the permanent magnet (a) and the distribution of the magnetic field induction \( B_e \) along axis (b)](image-url)
The authors' calculations of the components of the magnetic force acting in the axial plane of a permanent magnet on a ferromagnetic body reveal two areas between pairs of neighboring points: the zero field and the local extremum, where magnetic levitation of a ferromagnetic body is possible. The distribution of force (ponderomotive) and on one of these sites is shown in the curve in Figure 2.

\[ F = -\frac{dW}{dz}, \quad (1) \]

where
- F – ponderomotive force;
- W – magnetic energy;
- z – axis of the permanent magnet.

As seen in Fig. 2, plot \( P_{a1}, P_m, P_l \) the radial force distribution function is characterized by a negative slope, and the point \( P_m \) is the point of stable equilibrium (along the z axis). The same area with a negative slope is present for the left branch of the function with a point \( P_{a2} \).

Power stationary MP permanent magnet on the ferromagnetic test body was tested experimentally. The experimental setup is the following (Figure 3). In a horizontally located permanent magnet 1, a test tube 2 was placed, inside of which was a ferromagnetic ball 3. When moving the tube with the ball in the vertical direction and reaching the areas between the special points, the ball hung in positions 3 and 4. The walls of the tube kept the ball from lateral movements. Thus, experimental confirmation of one-dimensional (along the axis of the annular permanent magnet) levitation of a ferromagnetic body was obtained.
3. Local minimum point theory

Aside from the material properties of the permanent magnet, its geometry and the nature of the magnetization, by the first question, the problem can be formulated as follows: for the minimum number of MP sources it is necessary to determine the position of points of zero field and a local extremum of the field.

It is obvious that one point source of the magnetic field-dipole does not have such points in the distribution of its own MP in outer space.

In [6] considered a system of two shifted dipoles, which generates these points. The scheme of mutual arrangement of dipoles and their orientation is shown in Figure 4.

![Figure 4. The scheme of an arrangement of two coaxial flat symmetrical dipoles](image)

The peculiarity of these sources is their orientation and location: they are equally oriented and have a plane of symmetry.

In magnetic field theory, the intensity of a dipole source is described by a simple expression associated with the vector of its magnetic moment and the displacement vector relative to the origin of the coordinate system. For the considered system of two dipoles for the points of the plane in which the vectors of magnetic moments lie, simple mathematical relations are obtained:

\[
H_r = \frac{m}{2\pi(r^2 + a^2)^{3/2}}(2r^2 - a^2)e_r, \quad (2)
\]

\[
H_r = \frac{m}{2\pi(r^2 + a^2)^{3/2}}\left|2r^2 - a^2\right|, \quad (3)
\]

where \(H_r\), \(H\) – is the radial component and the module of the vector field strength in any observation point \(P_a\); \(m\) – module of the vector of the magnetic moment of the dipole source; \(r\) – is the radius of
the observation point on-axis sources; and – the distance (offset) of the source from the axis \(r\); \(e_r\),\nORT-vector axis sources.

The coordinate of the zero field point is determined from the condition
\[
H = |H_r| = 0.
\]

\[
(4)
\]

\[
r_{m1} = a\sqrt{6} / 2 \approx 1.2247 a; r_{m2} = -a\sqrt{6} / 2 \approx -1.2247 a; H = 0.202m / 2\pi a^3.
\]

More subtle studies show a fundamental difference in curves \(B_e, B_z, B\) and their behavior near the zero-field point. The zero-field point is a saddle point, not a minimum (extreme) point. In comparison with the model [6], the proposed model of MP permanent magnet allows to calculate the position of the zero field point (7) and takes into account the sign of induction or tension in (8).

Since the zero field point is equal to the saddle point for a pair of dipoles, at points near it the forces acting on the ferromagnetic body do not provide a state of stable equilibrium for lateral deviations from the axis.

The property of a pair of displaced dipoles to generate these singular points is preserved in a permanent magnet due to symmetry transformations [17], which is illustrated in Figure 5.

![Figure 5. Scheme of experiment on one-dimensional levitation of a ferromagnetic body in the magnetic field of a ring magnet](image)

Elementary magnetized volumes of a permanent magnet located symmetrically to the axis \((z)\) are represented by a pair of vectors with a magnetic moment \(dm\). Integral methods are widely used to calculate the external magnetic field generated by a uniformly magnetized permanent magnet in the axial direction [6, 7]. In this case, the volume of the permanent magnet is divided into elementary sources in the form of selected volumes, within which the magnetization vector is considered to be constant, and the resulting field is determined by the overlap of the fields of elementary sources. The intensity of the external magnetic field at any point can be represented by the following expression [18, 19]:

\[
H = \frac{B}{\mu_0} = \frac{1}{4\pi} \sum_{j=1}^{N} \sum_{v=1}^{l_j} \left( \frac{n_{vj} \times M_j}{\Delta S_{vj}} \right) \times \frac{r}{\sqrt{r^2 dS}},
\]

where \(B\) – the induction vector, \(\mu_0\) – magnetic constant, \(N\) – number of allocated volumes ferromagnetic element; \(j, l_j, M_j\) – number, number of faces and magnetization vector selected volume;
\( v - j \)-th face number selected volume; \( \mathbf{n}_{vj} \) – external normal vector, drawn to the plane of the \( v \)-th face of \( j \)-th selected volume; \( \Delta S_{vj} \) – the surface area of the \( v \)-th face of the \( j \)-th selected volume; \( \mathbf{r} \) is the vector, drawn from observation point to midpoint (geometric center) of each selected volume's.

In the case of the considered ring permanent magnet, uniformly magnetized along the axis \( (M_j = M) \) and placed in the center One hundred seventeen coordinate systems from the ratio (9) are obtained the following expressions are axial and radial component of the field strength in arbitrary observation point \( P(z, \varphi) \):

\[
H = \frac{M}{2\pi} \left\{ \int_{0}^{1/2} \int_{-\pi/2}^{\pi/2} \frac{(\xi_1 - \lambda_1 \eta) \sin \phi}{\left[ 1 + (\xi - \lambda_1 \eta)^2 + \rho_1^2 - 2\rho_1 \sin \phi \right]^{3/2}} d\varphi d\eta \right\}^{1/2} \left\{ \int_{0}^{1/2} \int_{-\pi/2}^{\pi/2} \frac{(\xi_2 - \lambda_2 \eta) \sin \phi}{\left[ 1 + (\xi - \lambda_2 \eta)^2 + \rho_2^2 - 2\rho_2 \sin \phi \right]^{3/2}} d\varphi d\eta \right\}^{1/2}.
\]

For figure 6, a-b shows the distribution of magnetic induction \( B = \mu_0 H \) in the central section permanent magnets having the same outer radius and different size internal radius and height.

**Figure 6.** Field distribution in the Central plane permanent magnet

Calculations are carried out in accordance with ratios (10). The results are shown in Fig. 6. When calculating the volume of a permanent magnet it was divided into elementary volumes with a diameter of 0.1 the field level is used to construct distributions were averaged within the flat square cells the size of the side is 2 mm, and the number of gradations of the field for all the permanent magnets of the selected constant, 10. Central rectangular area the permanent magnet is not painted over. As seen for fig. 6, a-b, zero field points are y ring permanent magnet regardless of its geometries. The latter determines only the position zero field points: points can be placed on its axes are both outside the scope of the permanent magnet and in the inner free space.
4. Conclusion
The field distributions of the ring axial magnetized permanent magnet are simulated and compared with known experimental and computational data. It is established that such magnets have special points in the distribution of the magnetic field outside the volume and analytical relations for the points of the zero field and the local extremum of the field along the axis of the magnet are obtained. It is proved that the presence of these points creates conditions for one-dimensional magnetic levitation of a ferromagnetic object.

Based on the simulation of the field distribution of a pair of coaxial dipoles arranged symmetrically to the plane, it is shown that such a system is a carrier of the properties of one-dimensional magnetic levitation. Sets of such pairs of dipoles constructed using symmetry properties inherit this property. As supporting examples schema modeling using these sources of a permanent magnet. The use of current circuits expands the possibilities of modeling source systems to obtain sets of zero-field points and local extrema forming magnetic levitation regions. The configuration of current circuits with a flat magnetic levitation region is obtained.

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