N92-27796

MANIPULATION AND IDENTIFICATION OF OBJECTS BY MAGNETIC FORCES

Benjamin Joffe

Guidance and Control Section, Jet Propulsion Laboratory
California Institute of Technology, Pasadena, California

SUMMARY

This paper presents an overview of the results of research and engineering design activities over the past twenty years in the area of identification and manipulation of objects by magnetic forces. It discusses the relationship between the properties of objects and the parameters of magnetic fields, with the view toward being able to create forces for efficient manipulation and identification of different kinds of parts. Some of this information, particularly regarding nonferromagnetic materials, is relatively new and can be used to solve a variety of engineering problems by creating new types of automation systems. Topics covered include identification and orientation of bodies by magnetostatic and electrodynamic forces, electromagnetic recognition and orientation of nonsymmetric parts, and assembly and position control of parts by electrodynamic forces.

INTRODUCTION

At this symposium, broad exposition is given to the scientific and technical aspects of contactless manipulation of objects relative to a given coordinate system, via contactless application of forces induced by external magnetic fields. Presented here are a number of technical approaches applied to solve such problems as:

- contactless suspension and motion of objects relating to high-speed trains and other forms of transportation
- contactless containment and holding of parts of mechanisms and machines in given positions by use of magnetic bearings.

In previous publications several other problems connected with the manipulation and movement of objects have been examined. These include:

- contactless containment of molten metal used in metallurgy to obtain alloys of high purity
- contactless orientation and identification of machine parts.

Common to the solutions of the above-mentioned and other technical problems is the characteristic of a contactless application of force to the object. This force is generated as the result of the interaction of primary (external) and induced secondary magnetic/electromagnetic fields.

At this symposium, sufficient attention is already given to problems and technical approaches related to magnetic levitation and magnetic bearings. Therefore, these types of magnetic manipulation are not touched upon in this overview. We will consider the problems connected with

- manipulation, orientation, and assembly of a group of bodies based on their spacial relations
- recognition of objects by their external as well as hidden characteristics.

IDENTIFICATION AND ORIENTATION OF BODIES BY MAGNETOSTATIC FORCES

From electrostatic field theory it is known that with the appropriate choice of field characteristics and intensity it is possible to induce forces capable of contactless action on bodies made of various materials.

As known [1], a moment of force (moment of couple) **M** capable of orienting a body is created by the interaction of an induced magnetic moment $\mathbf{P_M}$ in the body with an external magnetic field having magnetic induction **B**.

For the body in the form of an ellipsoid, the moment of force is dependent on the following parameters of the field and the body:

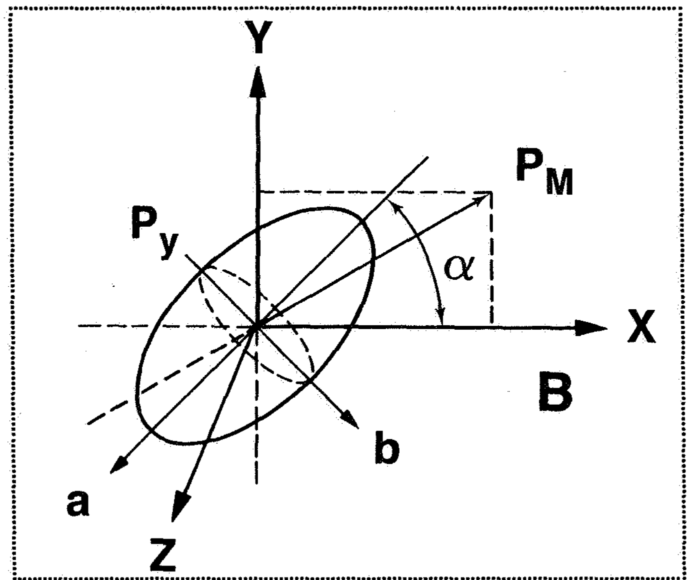
$$M = -\frac{1}{2} V k_M^2 B^2 \sin 2\alpha \frac{N_b - N_a}{(1+N_a k_M)(1+N_b k_M)} \quad (1)$$

where:

V	=	volume of the body
$\mathbf{k_M}$	=	magnetic permeability of the body
μ	=	magnetic permeability of the material
α	=	angle between major axis of the ellipsoid and induction vector of magnetic field
N	=	demagnetization factor

Figure 1

Ellipsoid in a magnetostatic field. Direction of magnetic field induction coincides with X axis.



For an ellipsoid, the demagnetization factor **N** relative to the axis of the body is $N_a + N_b + N_c = 1$, where **c** is an axis normal to the **a** and **b** axes of an ellipsoid (Figure 1).

On the basis of the above expression, when $N_a = N_b = N_c = 1/3$ (for a sphere), then $M = 0$. Therefore, for a body of spherical form the moment of force does not exist. For an ellipsoid ($N_a \neq N_b$), moment of force exists and is oriented collinear to the field. The maximum value of the moment of force, with all other variables being equal, corresponds to the position of the ellipsoid with $\alpha = 45°$. $M = 0$ when $\alpha = 0°$ or $\alpha = 90°$.

We will examine the relationship between this moment of force and the material properties of the body. Since the magnetic permeability of the body is $k_M = \mu - 1$, bodies made of material possessing magnetic permeability close to one have a moment of force of zero.

Therefore, in the magnetostatic field it is possible to orient bodies that have nonsymmetric form or structure, provided the magnetic permeability of the body differs from the magnetic permeability of the ambient surrounding. For those bodies made of conductive, nonmagnetic materials (aluminum, copper, brass, bronze, steel parts heated beyond the Curie point, etc.) whose magnetic permeability is close to one, it is not practically possible to orient them via a magnetostatic field. Naturally, a magnetic field is incapable of orienting bodies made of dielectric materials, since the magnetic permeability of a dielectric is close to the magnetic permeability of ambient air. Hence, manipulation by forces created in magnetostatic fields is effective only for bodies with ferromagnetic qualities [3-5].

Specific parts can be represented in the form of an oblate spheroid (washer, plate), as a cylinder with spherical ends (rod-shaped parts), and so on. Given data regarding the demagnetization factor with respect to geometrical configuration of the bodies, the moment of forces can be computed.

In a case in which it is desired to move a part in a particular direction, it is well known that the force can be established using a gradient of field. Here, the force acting on the body is directed along the gradient of the field and is equal in the first approximation to:

$$F = \frac{1}{2} k_M \, V \, \nabla B^2 \qquad \textbf{(2)}$$

where ∇ is the field gradient.

In the study of manipulation of ferromagnetic parts by interaction with magnetic fields, considerable contributions were made by a number of organizations and individuals throughout the world. These include General Motors Corp., Western Electric, and Eriez Magnetics Co. in the United States; Siemens-Schuckert A.G. and Telefunken in Germany; Phillipe Francois van Eeck and Vallourec in France; and the Institute of Physics of the Latvian Academy of Science [2-9].

The concept of using the gradient of the magnetic field for the manipulation of ferromagnetic parts will be illustrated by various methods and devices. However, due to the limited length of this article, only a short description of the main design ideas for one such device is presented here.

An example of the application of a force induced by a magnetic field acting on a ferromagnetic body is a device for arranging ferromagnetic components at a set distance from one another, described in a patent [10]. Such a device permits noncontact arrangement and transportation of components with a fixed interval between them. It is suitable for manipulating both rods and flat components of complex shape.

The device in Figure 2 is composed of a permanent electromagnet **1** with a magnetizing winding **2**. Stationary pole pieces **3** of the electromagnet profile and define a narrowing pole gap with a profile made so as to form a desired field gradient. Near the exit port of the guide **4**, made from nonmagnetic material, the pole pieces are provided with movable magnetic poles **6**. These poles are arranged so that the planes in which they lie are normal to the axis of symmetry of the pole gap, and they are adapted to move in these planes relative to the exit port of the guide **4** in a direction along their length. The "teeth" of the poles **6** are spaced apart by intervals **h** selected according to the desired specifications.

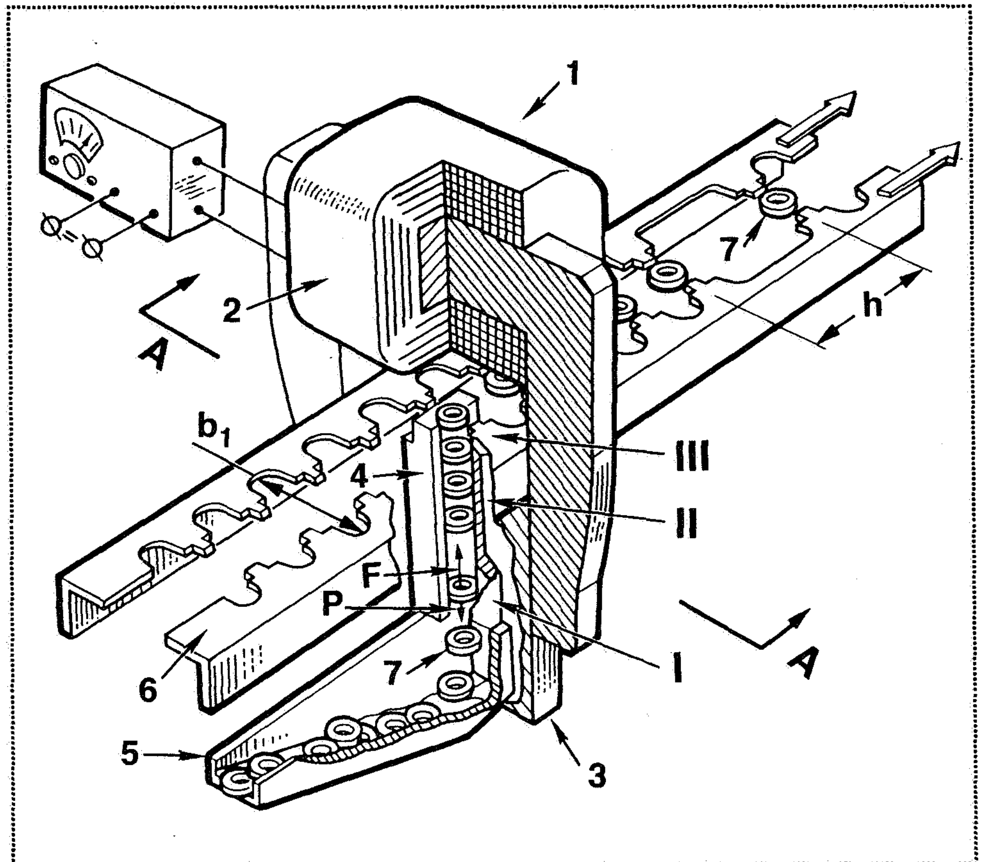


Figure 2. View of a magnetic device for arranging ferromagnetic components at a preset distance from one another.

Figure 3 is a section view taken along line A-A of Figure 2. The distribution of intensity **B** of the magnetic field of the electromagnet in the pole gap along axis OX of symmetry is shown in Figure 4.

To move parts **7** from their lower position **I** to the next position **II**, it is necessary to generate a force **F** exceeding the force of gravity **P** acting on the part, which can be done by generating a field with a specific gradient. To achieve this, the pole gap of the magnetic system in Figure 2 is made according to Figure 3, which assures an increase in the magnitude of the induction of the magnetic field along axis OX in correspondence with curve **8-9** (Figure 4).

The magnitude of the magnetic induction in the pole gap of the movable magnetic poles **6** is shown by curve **11-12**. Between its "teeth", the magnitude of magnetic induction must be greater, as shown by curve **13-14**.

As parts are introduced into the pole gap, they acquire unidirectional magnetization, which provides for their mutual

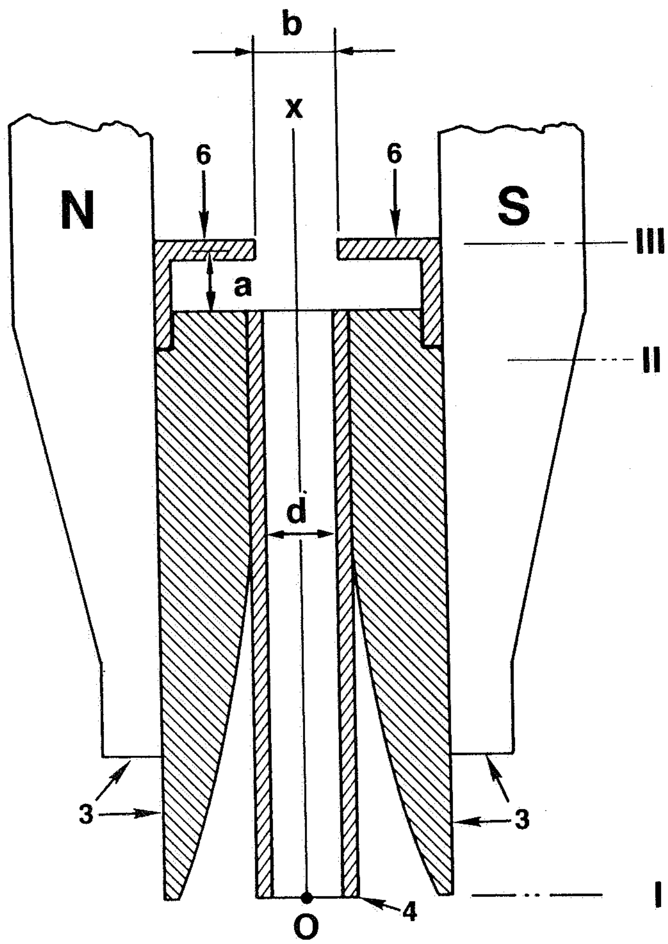


Figure 3. Section view A-A of the magnetic device in Figure 2.

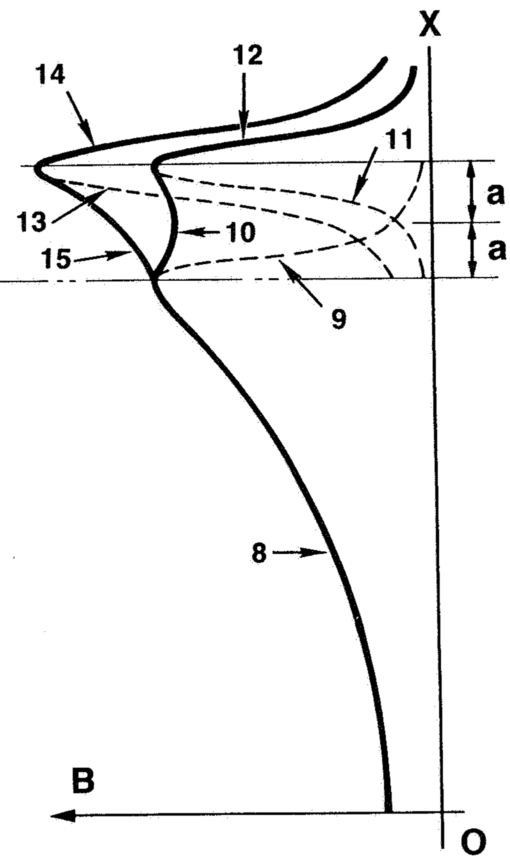


Figure 4. Distribution of the magnetic field intensity along the OX axis of symmetry of the pole gap in Figure 3.

force of repulsion. This, in turn, forms an ordered flow of parts (Figure 2).

The distance between the movable magnetic poles **6** and the parallel plane of stationary magnetic poles **3** is related to dimension **d** of the work-parts and the dimension of the pole gap **b**, specifically **a** = (0.5 to 0.8)**d** and **b** = 1.1**d**. Distance $\mathbf{b}_1$ between the movable magnetic poles **6** is chosen with the constraint that the magnitude of induction at level **III** in the pole gap must be approximately equal to the maximal magnitude of induction of the stationary pole pieces. Therefore, the resultant profile of the magnitude of induction is represented by curve **8-10-12**; moreover, due to the dip in the portion of the curve **10**, the possibility of movement of the parts is excluded between positions **II** and **III**. As the movable magnetic pole **6** brings its "teeth" over the guide **4** containing work-pieces **7**, an increase in the magnitude of magnetic induction is observed, as shown in the curve **8-14-15**. Under the action of the field with such a gradient, a force is induced capable of translating the part from position **II** to position **III**, and due to the unidirectional magnetization only one part can occupy this position in the pole gap. Only when the next set of "teeth" of the movable pole gap **6** is brought over the channel **4** will the next part in the channel move from position **II** to position **III**, and so on.

From the above example, it can be seen that with the appropriate choice of field distribution it is possible to sharply define the effects on the arrangement of ferromagnetic parts.

The effect of magnetic field gradient manipulation can also be achieved by shunting sections of the pole gap, therefore providing for an effective control of the positioning of ferromagnetic objects [11].

IDENTIFICATION AND ORIENTATION OF BODIES BY ELECTRODYNAMIC FORCES

The mechanism for the creation of forces acting on nonmagnetic and ferromagnetic conducting bodies in alternating magnetic fields is based on the interaction of external and induced (by the body itself) secondary fields.

With the goal of determining parameters influencing the magnitude and direction of the moment of force, we will examine a nonmagnetic conducting body, such as an ellipsoid. An ellipsoid at first approximation can be replaced by some electrodynamic equivalents: one, two, or several ring-coils closed on some impedance

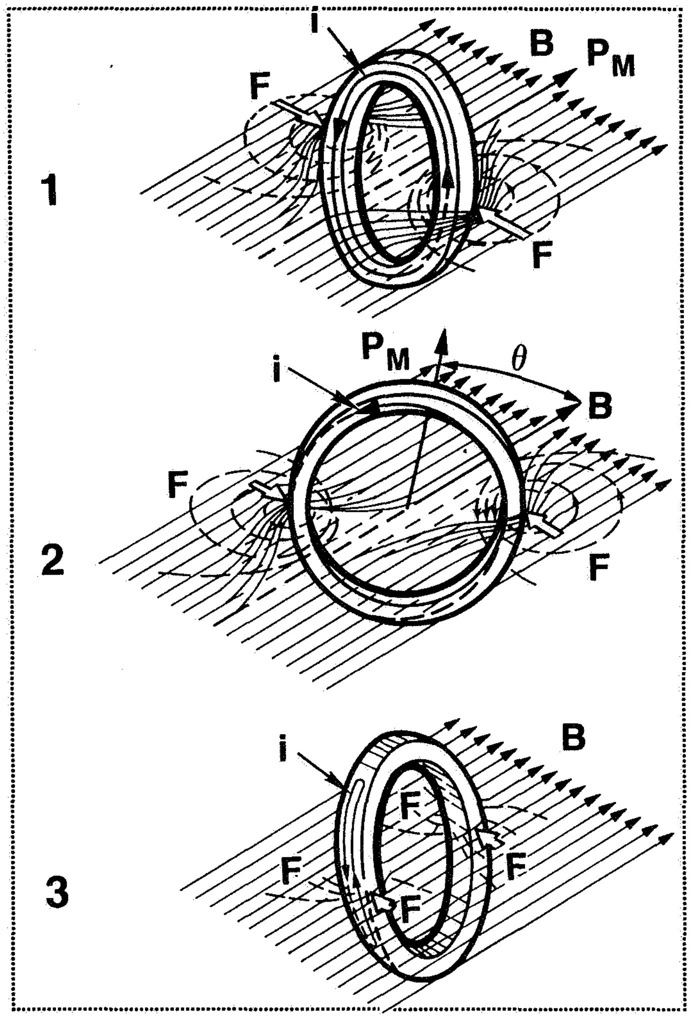
$$Z = R+j(\omega L-\frac{1}{\omega C}) \tag{3}$$

In the case of a nonmagnetic conducting ring, radius $\mathbf{r} = \mathbf{a}$ with impedance $\mathbf{Z}$, we will consider total impedance of the ring. Due to the small capacitive effect we may omit the $\mathbf{j/\omega c}$ term in (3) and write

$$Z = R+j\omega L = R(1+j\tan\varphi_o) \tag{4}$$

Figure 5.

Conducting ring in an alternating magnetic field, shown for clarity in only one plane. **1** - ring placed perpendicular to the field with an arbitrary alignment; **2** - transient unstable alignment; **3** - oriented ring in a stable alignment.



If an external magnetic field is not significantly deformed by an induced current in the ring, the result is that the ring is penetrated by

$$\Phi = B_o e^{j\omega t} S\cos\theta \qquad (5)$$

Therefore we have an induced EMF of

$$\varepsilon = -\frac{\partial\Phi}{\partial t} = -i\,\omega\, B_o S\cos\theta\, e^{j\omega t} \qquad (6)$$

The current in the ring contour is

$$i = \frac{\varepsilon}{Z} = \frac{i\omega B_o \cos\theta\, e^{j\omega t}}{R(1 + j\tan\varphi_o)} \tag{7}$$

where:

$\omega=2\pi f$	=	circular frequency of an alternating magnetic field
φ_0	=	angle of phase difference between the induction of an external magnetic field and the induced loop current
S	=	ring contour area
$\tan\varphi=\omega L/R$	=	loop inductive impedance/active impedance.

Magnitudes **L** and **R** are computed in the first approximation, taking into account the skin effect on the circular contour carrying a current. Skin effect in a loop of circular section was studied even back in 1930 on the basis of solution for skin layer in case of infinite half plane [2,8].

Electric current in the ring can be represented as an alternating magnetic dipole with a moment

$$P_M = -iS = \frac{\omega B_o S^2 \cos\theta}{R} \bullet \frac{(-j)\, e^{j\omega t}}{1+j\tan\varphi_o} \tag{8}$$

after some simplification:

$$P_M = \frac{\omega B_o S^2 \cos\Phi_o \cos\theta}{R}\, e^{i(\omega t - \frac{\pi}{2} - \varphi)} \tag{9}$$

For the instantaneous value of the moment of force for the interaction of the ring with the magnetic field **M = B sin***θ*, and for the average value,

$$M_{eff} = \frac{P_M B^* + P_M^* B}{4} \sin\theta \tag{10}$$

or

$$P_M = |P_M| e^{j(\omega t - \frac{\pi}{2} - \varphi_o)} \tag{11}$$

where

$$|P_M| = \frac{\omega B_o S^2 \cos\varphi_o \cos\theta}{R} \tag{12}$$

The absolute moment of electrodynamic force according to (**10**) is

$$M_{eff} = \frac{|P_M| e^{j(\omega t - \frac{\pi}{2} - \varphi_o)} B_o e^{-j\omega t} + |P_M| e^{-(\omega t - \frac{\pi}{2} - \varphi_o)} B_o e^{j\omega t}}{4} \sin\theta \tag{13}$$

or

$$M_{eff} = \frac{|P_M| B_o \sin\varphi_o \sin\theta}{2} \tag{14}$$

Substituting the value of $|\mathbf{P}_M|$ yields

$$M_{eff} = \frac{\omega B_o S^2 \cos\varphi_o \cos\theta}{R} \bullet \frac{B_o \sin\varphi_o \sin\theta}{2} \tag{15}$$

The final result, after some simplification, is

$$M_{eff} = -\frac{\omega B_o^2 S^2 \sin 2\varphi_o}{8R} \sin 2\theta \tag{16}$$

The phase angle φ_o between the induction of the external (primary) field and the magnetic moment $\mathbf{P}_M$, formed by the induced ring current **i**, has a significant effect on the magnitude of forces and the moment of force.

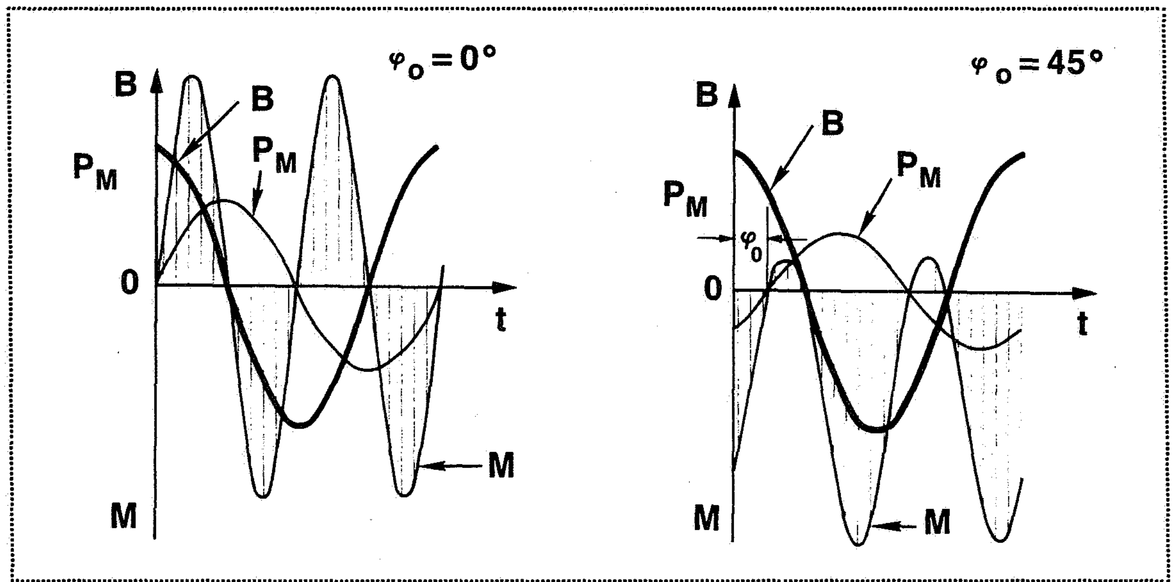


Figure 6. Relation between the magnitude of the moment of electrodynamic force **M** acting on a conductive ring and the angle of phase shift φ_0 of the magnetic moment $\mathbf{P_M}$ relative to induction **B** of the magnetic field.

Comparing the magnitudes of the sum of the moments of electrodynamic forces dependent on the angle of phase shift, it becomes clear that **M** is zero at $\varphi_0 = 0°$ and that **M** is maximal at $\varphi_0 = 45°$.

This means that, with all the other parameters of the body and the primary magnetic field, selection of the frequency of the magnetic field has the deciding effect on the magnitude of induced forces and therefore on the possibilities of manipulation of an object by the interaction of forces.

Investigations carried out at the Institute of Physics of the Latvian Academy of Science allowed determination of a number of interesting effects [2,7,12]. For example, it was established that at the lower frequencies the greater the relative outer diameter of the ring $\mathbf{d}^* = \mathbf{d}/\mathbf{D}$, the smaller the moment of force (**d** = inner diameter, **D** = outer diameter). This was to be expected. However, as the frequencies are increased the value of the moment of force corresponds to that of a solid disk (Figure 7). With further increase in frequency of the field an increase in the moment of force was observed. For rings with $\mathbf{d}^*$ between 0.80 and 0.95 the increase in the moment of force was 50 percent greater than the moment of force in a solid disk. With a fixed value of the field frequency for each diameter of a disk there is a corresponding value of the moment of force. Therefore, the value of the moment of force determines the dimension of the opening in the part. This allows the use of this effect, for example, to sort parts based on geometric considerations.

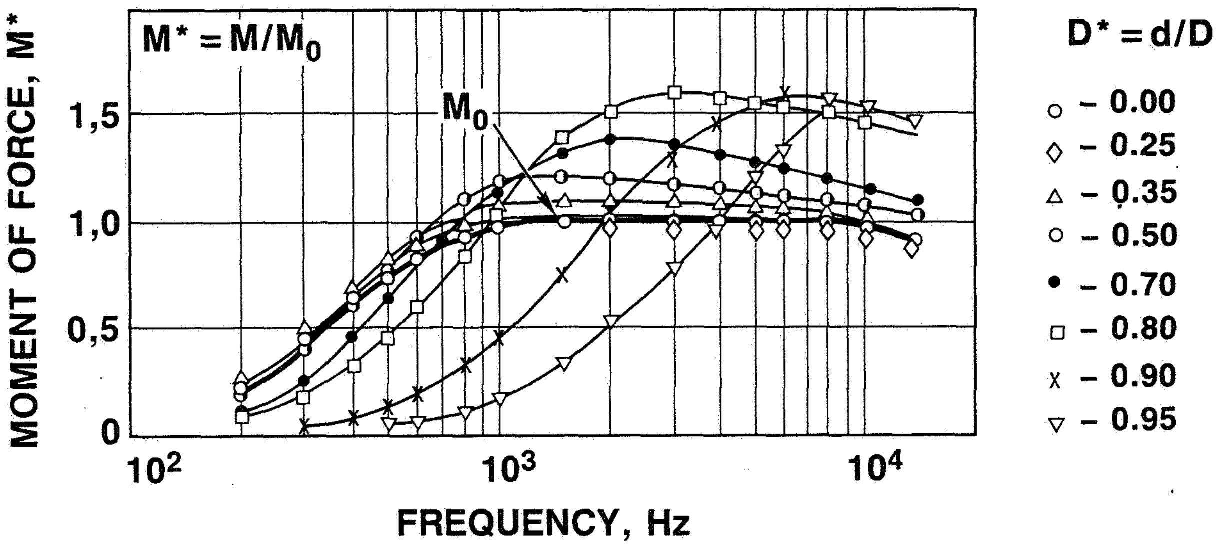


Figure 7. Dependency of the moment of electrodynamic force on the frequency of magnetic field for different values of the central hole in an aluminum washer, constrained to **B** = constant.

Cylindrical parts with a central opening show interesting relationships. Specifically, if the moment of force acting on a solid cylinder achieves a maximum at $\Theta = 45°$, then for the hollow cylinder the value of this angle may be different. This angle depends on the frequency of the field. It was established that the final orienting position of such tube-like bodies can be manipulated by varying the field frequency [7].

The question of how the moment of electromagnetic forces depends on hidden characteristics was investigated by placing a non-magnetic conducting cover on a bushing with a cut in its side. Based on the theory of skin effect, one could expect that in the presence of a nonmagnetic conducting cover acting as an electromagnetic screen, a decrease of the interaction force would be observed. To determine the effect of the cover on the moment of electrodynamic force acting on a bushing with a cut, both a bushing without a cover (thickness of cover $\delta = 0$) and bushings with covers of various thicknesses made of the same material were placed in fields of specific characteristics and frequency. As a result, it was discovered that if the induction in the zone of electromagnetic effect was constant, then with the frequency of the magnetic field sufficient for penetration of the field through the entire assembly the moment of force with the increase of thickness of cover δ does not decrease but actually increases (Figure 8). Only at frequencies of pronounced skin effect does the moment of force decrease with the increase of thickness of

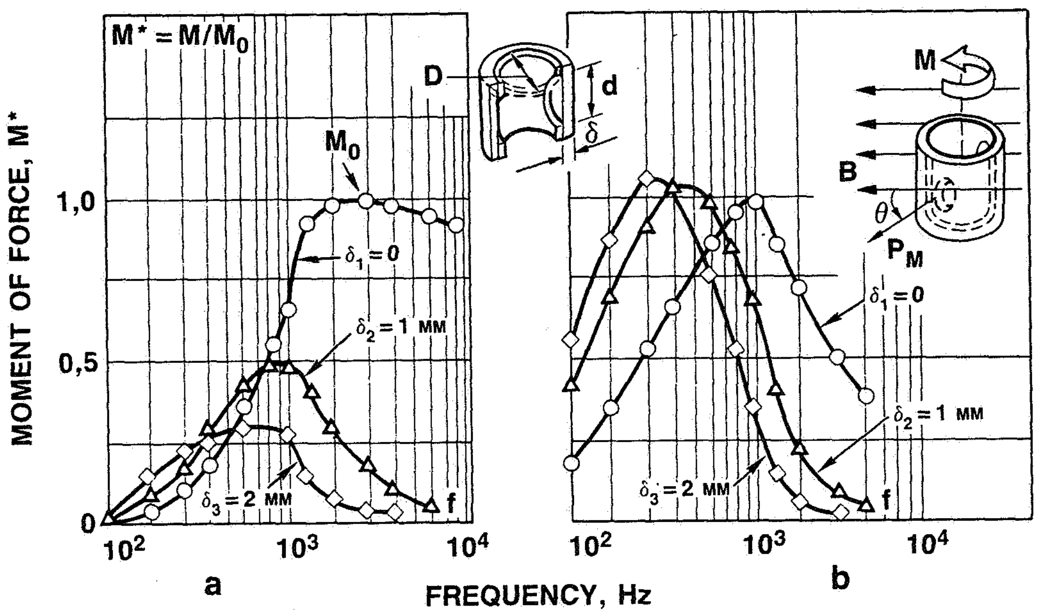


Figure 8. Dependence of **M** on **f** for a bushing with a cut in it, screened with a cylindrical cover of thickness δ. **(a)** - B=const; **(b)** - **f**B^2=const.

cover. Even more evident is the force interaction with a constant power used in the formation of the magnetic field. Variation of the value of induction with respect to the frequency of the magnetic field is possible under the restriction fB^2 = constant [2,7].

As shown in Figure 8, the moment of force acting on a screened part at a corresponding frequency can be more than twice the magnitude of the moment acting on the part without a cover at frequencies less than 1.0 kHz. This demonstrates the possibility of effective methods of manipulation by internal hidden characteristics of a wide variety of parts. The condition that for the frequencies above 1 kHz a marked decrease of the moment of force is observed in the case of the presence of a cover gives testimony that it is possible not only to manipulate an assembly by its internal hidden characteristics but also to carry out the identification of an assembly, for example, by the thickness of the cover.

The application of the above effects can also be used in the development of new types of mechanisms.

Research in this area has shown other equally interesting results [2], but because of space limitations I will have to restrict myself to these few examples.

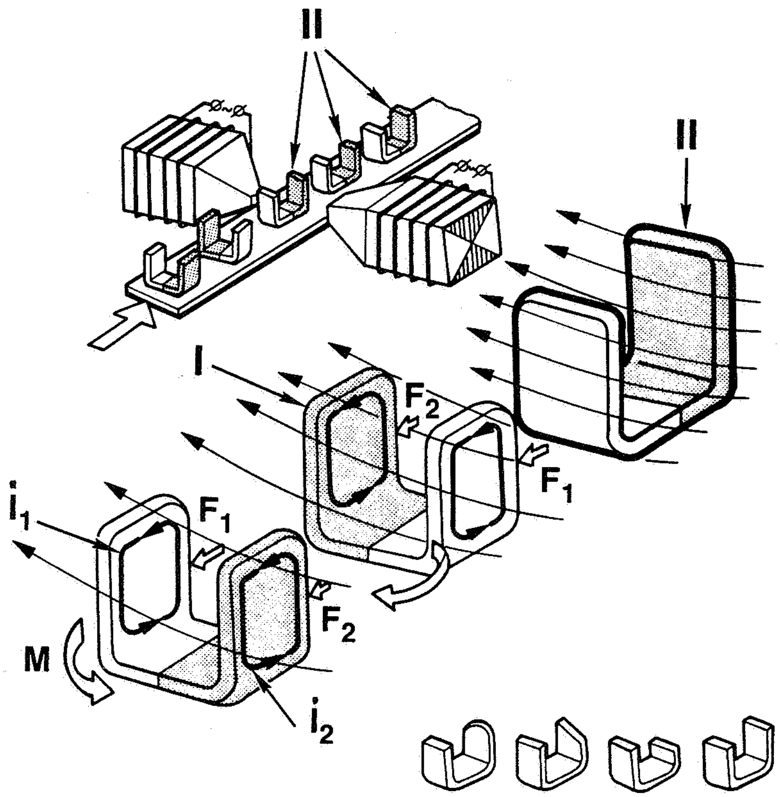
ELECTROMAGNETIC RECOGNITION AND ORIENTATION OF NONSYMMETRIC PARTS

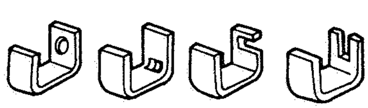
In engineering practice, difficulties most commonly arise in orientation of parts by one or more of the characteristics of nonsymmetry. An example of recognition and orientation of parts with a common type of nonsymmetry by means of electrodynamic forces is shown in Figure 9.

Various asymmetric U-shaped clamps with holes, slots, and notches may be assumed as a clamp-analog, symmetric in shape, but asymmetric with respect to the electric conductivity of its component parts (Figure 9). When such a part is transferred from position **I** in the direction of the axis of symmetry of the alternating magnetic field, currents $\mathbf{i_1}$ and $\mathbf{i_2}$ are induced in separate vertical sections of the clamp. The interaction of these currents with the non-uniform magnetic field gives rise to a resultant component of electrodynamic forces. Assume the center of gravity of the clamp-analog to be on the geometric axis (a more complicated case, with respect to orientation by standard methods), while the section of the part marked by dots has greater electric resistance. Therefore, $\mathbf{i_1} > \mathbf{i_2}$, and, because the parts are placed in the non-uniform alternating magnetic field, the separate vertical sections of the clamp are acted upon by forces $\mathbf{F_1}$ and $\mathbf{F_2}$, where $\mathbf{F_1} > \mathbf{F_2}$. These forces create a moment that rotates the clamp-analog to position **II**. Hence, given two indeterminate positions, the asymmetric clamp occupies a single, unique position corresponding to a stable orientation.

Figure 9.

Schematic of contactless electrodynamic orientation of nonmagnetic conducting U-shaped part based on its nonsymmetry characteristic. The effect of orientation is illustrated on bimetallic part — generalized analog of this part type.





According to results of investigations of the electrodynamic action upon bimetal U-shaped clamps differing in magnitudes of nonsymmetry, even a relatively small nonsymmetry in electric conductivity in different sections of the part gives rise to a sufficient moment of electrodynamic forces. This adequately solves the problem of active contactless orientation [13-20].

As the electromagnetic method is suitable for the analog, it also is applicable to all variations in a group defined by this analog. This indicates a great versatility of the methods and means for contactless identification and manipulation of components [2,7,12], even though only one example has been shown here.

A multifunctional capacity is characteristic to all the electromagnetic devices. Given an adequate choice of parameters of a magnetic field and the geometry of the electromagnet working zone, it is possible to perform the functions of identification, orientation, locking, and piece-by-piece feeding of parts.

The functionality of devices based on electromagnetic principles is applicable to parts falling into the following categories:

- size of part: 1 to 100 mm.
- mass of part: 0.01 to 2,000 gram
- conductivity of material: $1 \cdot 10^6$ to $60 \cdot 10^6$ 1/Ohm•m.

The effect of active identification and manipulation of the position of such parts is ensured by an electromagnetic field with the following parameters:

- induction: 0.1 to 1.0 T
- frequency: 50 to $50 \cdot 10^3$ Hz
- power: 0.1 to 1.5 W.

These parameters have predetermined magnitudes for specific parts. The time required to manipulate parts typical of the instrument manufacturing industry is on the order of 0.1 to 0.2 seconds, while that of the larger bodies is 0.6 to 1.2 seconds [7].

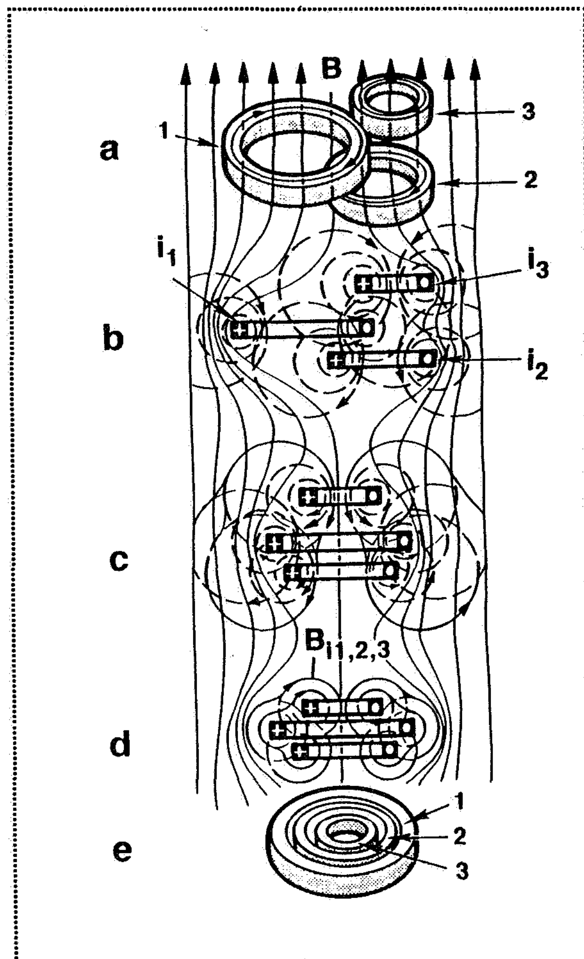
ASSEMBLY AND POSITION CONTROL OF PARTS BY ELECTRODYNAMIC FORCES

The underlying idea for assembly by electrodynamic forces is based on placing individual components in an alternating magnetic field with the vector of induction directed along the axis of assembly [20].

When parts **1**, **2**, and **3** (rings, for example) are placed in such a field (Figure 10), attractive forces are generated which collect rings on a single axis.

Figure 10.

Process of ring assembly under the influence of electrodynamic forces. **a**,**b** - initial placement of rings; **c**,**d** - placement of rings at intermediate positions; **e** - final assembly.



Assembly is accomplished not by the method of directed physical alignment as is the case in ordinary mechanical assembly, but by force interaction between secondary magnetic fields generated by induced currents i_1 through i_3 in the rings. Furthermore, the parts move into a final assembly position via the shortest trajectories.

Figure 10(b) shows the dynamics of interaction of the primary magnetic field with the magnetic fields of the induced currents in parts 1 through 3. The induced fields in the rings create resistance to the primary field, with the result that the primary field is bowed out from the ring area. On the ring periphery, zones of increased field induction are generated and form electrodynamic forces that move parts onto the axis of assembly (Figure 10(c)). As a result of the interaction of magnetic fields generated by currents i_1 through i_3, the effect of field coupling takes place and forms a magnetic loop (Figure 10(c,d)), encompassing all the rings. The resulting electrodynamic forces cause further contactless convergence and centering of the rings, as shown in Figure 10(e).

As the primary magnetic field **B** reverses direction, the induced currents i_1 through i_3 and subsequently their magnetic fields reverse direction as well, in a manner similar to that shown in Figure 6. However, the resulting force action formed in the process of primary and secondary field interaction remains the same for each case examined (Figure 10(b-e)).

The process of the assembly of such elements can be carried out even if the offset error of the initial positioning is 80 percent of the linear dimension between their respective axes. For this type of assembly it is necessary that the contours of currents in the initial positioning of the parts overlap at least partially.

Although only one new kind of magnetic assembly has been shown here, other methods are presented in [9,21,22].

Investigating the effect of force interaction of nonmagnetic conducting parts in a primary alternating magnetic field with the

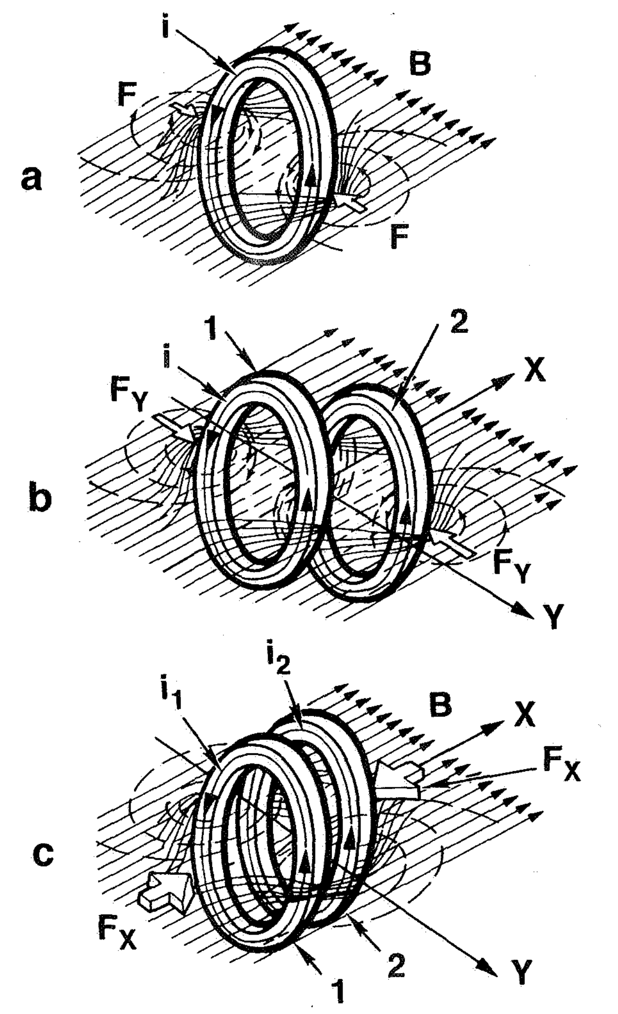


Figure 11.

Shown is an example of a closed conducting loop **1** used in generating a specific field gradient used to control the position of ring **2**. For clarity the magnetic field is shown in only one plane.

(a) - Distribution of the external magnetic field as the result of interaction with the secondary field induced by loop current **i**.

(b),(c) - Distribution of the external magnetic field and characteristics of resulting electrodynamic forces acting on ring **2** in proximity with loop **1**.

presence of nearby additional conductive contour shows the effect to be equivalent in some ways to the presence of a pronounced local field gradient. This condition is illustrated in Figure 11(a). When anonmagnetic conductive loop **1** is introduced into an alternating external magnetic field, the interaction between the primary and the induced (by loop current **i**) secondary magnetic fields forms zones of depleted and saturated field in the periphery of loop **1**. This generates a pronounced local field gradient. Clearly, as the position, dimension, or geometry of loop **1** are changed, the distribution of the resulting magnetic field will change. Figure 11(b) shows one such field redistribution, as a second body **2**, which for clarity of demonstration is in the form of a ring, is placed in the proximity of loop **1**. When the diameters of rings **1** and **2** are equal, the resulting stable configuration of the rings is shown in Figure 11(c). The resulting force acting on ring **2** also depends on the interaction of fields induced by loop currents in rings **1** and **2**. The dynamics of the movement of ring **2** relative to ring **1** correspond to the case illustrated in Figure 10.

By introducing a number of nonmagnetic conductive contours, each equipped by an externally controllable closing/opening switch, it is possible to create complex field gradients. These, in turn, allow new types of electromagnetic devices to be created [23,24].

A literature search to determine the level of scientific and technological advancements in this field showed that some of the information presented here, developed at the Institute of Physics, Latvian Academy of Science, is still innovative.

CONCLUDING REMARKS

By using force interactions of magnetic fields, recognition and manipulation effects can be achieved for parts that vary in both form and materials. Such methods continue to be useful for a wide variety of earth-bound automation applications. At the same time, because they can be applied remotely, involve contactless interactions, and are universal in the sense that one system can be used for parts of different configurations, they may also have potential applications for automated manipulation and identification of objects in space activities.

These processes are relatively simple, are extremely reliable, and can perform in a wide variety of environmental conditions. Because of this, the knowledge gained through the study of these techniques can open the way to the development of new types of mechanisms for spacecraft.

I wish to thank the members of the Actuators and Inertial Sensors Group, Guidance and Control Section, Jet Propulsion Laboratory, for their assistance and encouragement, and for their perceptive criticism of this paper.

REFERENCES

1. Kirko I.M.; Preis V.F.; Joffe B.A.: "Contactless Methods of Orientation of Discrete Bodies-Parts in Magnetic and Electric Fields," in Theory of Machines of Automatic Action. Moscow: "NAUKA" Science Publishing House, 1970, pp.129-142

2. Joffe B.A.; Kalnin R.K.: Orientation of Parts by Electromagnetic Field. Riga, "Zinatne," Latvian Academy of Sciences Publishing House, 1972.

3. Moskowitz L.R.: Permanent Magnet Design and Application Handbook. Boston, Massachusetts. Gahners Books International, Inc. 1976.

4. Baltvilks A.T.; Joffe B.A.; Kalnin P.K.: "Force Interaction of Ferromagnetic Cylinders and Disks in Completing by Magnetic Field," in Automation of Assembly Processes, Installment 6. Riga, Polytechnic Institute, 1977, pp. 7-22.

5. Baltvilks A.T.; Joffe B.A.; Kulberg A.Y.: "Investigation of Magnetostatic Interaction of Ferromagnetic Parts in the Zone of Magnetic Saturation Applicable to Solution of Problems of Assembly," in Automation of Assembly Processes, ISSN 0320-6963. Riga, Polytechnic Institute, 1978, pp. 47-59.

6. Edminster J.A.: Theory and Problems of Electromagnetics. New York. McGraw-Hill Book Co., 1979.

7. Davydenko E.P.; Kanaev A.S.: Mechanization of the Production by Means of EMAGO Devices. Riga, "Zinatne," Latvian Academy of Sciences Publishing House, 1984.

8. Burke H.E.: Handbook of Magnetic Phenomena. New York. Van Nostrand Reinhold Co., 1986.

9. Sandler B.Z.: Robotics. Designing the Mechanisms for Automated Machinery. Englewood Cliffs, N.J. Prentice-Hall International, Inc., 1991.

10. Kulberg A.Y.; Joffe B.A.; et. al.: "Device for arranging ferromagnetic components at preset distance from one another," US Patent No. 4,153,151 class 198/456.

11. Ryzhov V.D.; Joffe B.A.; et al.: "Device for Contactless Separation of Individual Ferromagnetic Components from a Flow of Components," US Patent No. 4,113,142 class 271/171.

12. Sommer U.A.: Orientation of Plane Asymmetric Parts by Means of EMAGO. Riga, LatInti, 1975.

13. Joffe B.A.; et al.: "Method for Orientation of Current-Conducting Nonmagnetic Bodies in a Magnetic Field and a Device for Carrying same into Effect."

US Patent No. 3,636,486 class 335/219.

14. US Patent No. 3,645,377 class 193/33.

15. US Patent No. 3,651,439 class 335/219.

16. US Patent No. 3,656,075 class 335/219.

17. US Patent No. 3,661,241 class 198/33.

18. US Patent No. 3,924,211 class 335/284.

19. US Patent No. 3,930,212 class 335/284.

20. Kalnin R.K.; Joffe B.A.; et al.: "Method of Assembly of Nonmagnetic Current-Conducting Components," US Patent No. 4,238,658.

21. Sermons G.Y.: Dynamics of Rigid Bodies in Electromagnetic Field. Riga, "Zinatne," Latvian Academy of Sciences Publishing House, 1974.

22. Zhuk V.V.: Electrodynamic Method for Clustered Assembly of Parts. Riga, LatInti, 1979.

23. Joffe B.A.; et al.: "Method of Oriented Feeding of Nonmagnetic Current-Conducting Components and Devices for Effecting the Same," US Patent No. 4,077,027 class 335/219.

24. Joffe B.A.; et al.: "Device for Making Sets of Nonmagnetic Current-Conducting Components," US Patent No. 4,144,637 class 29/739.