INTERACTION FORCES BETWEEN MULTIPLE BODIES IN A MAGNETIC FIELD

Benjamin Joffe
Jet Propulsion Laboratory
Pasadena, California

SUMMARY

Some of the results from experiments to determine the interaction forces between multiple bodies in a magnetic field are presented in this paper. It is shown how the force values and the force directions depend on the configuration of the bodies, their relative positions to each other, and the vector of the primary magnetic field.

A number of efficient new automatic loading and assembly machines, as well as manipulators and robots, have been created based on the relationship between bodies and magnetic fields. A few of these patented magnetic devices are presented. The concepts involved open a new way to design universal grippers for robots and other kinds of mechanisms for the manipulation of objects. Some of these concepts can be used for space applications.

INTRODUCTION

In the paper presented by the author earlier at the First International Symposium on Magnetic Suspension [1] an overview was provided of the parameters of magnetic fields and single bodies positioned in the magnetic fields that apply force and torque to the bodies. It is much more complicated to evaluate the interacting force value applied to a single body when that body is one of a group of bodies within the magnetic field. This is so because both the force and torque on the single body are now dependent not only on the parameters of the magnetic field and the body itself but also on the magnetic flux contribution from the other bodies being positioned in the primary magnetic field. All of these contribute to the total value and direction of the force being applied to the single body within a group.

There are some publications on this subject [2–5]. Some experimental research results on forces acting on bodies in a group were published in [2], [4], and [5], and some theoretical work was presented by Sermons [3]. This paper provides an overview of some of the results of these previous publications, as well as some patented concept designs based on these research results. The force effects between bodies in a magnetic field are illustrated using a simple group of objects. The first section of the paper discusses the interaction force effects between ferromagnetic bodies, and the second section illustrates the force effects between nonferromagnetic current-conductive bodies.

INTERACTION FORCES BETWEEN FERROMAGNETIC BODIES IN A MAGNETIC FIELD

The force effects between the bodies in a magnetic field can be illustrated using a group of three balls being positioned in a homogeneous permanent field, as shown in Figure 1, cells 1 and 3. For simplicity, the field distortion due to the presence of these ferromagnetic bodies is not shown. The bodies drawn with solid lines show their initial positions, prior to the effects of the magnetic field. The bodies drawn with dotted lines show the direction of motion resulting from the interaction of forces.

Let us analyze a few extreme conditions. First, let us look at the condition in which the magnetic permeability of the bodies is equal to the magnetic permeability of the primary magnetic field area. In this condition the bodies will have no distortion effects upon the field, and there will be no magnetic interaction forces between the bodies. In the second condition, which is typical for ferromagnetic bodies, the magnetic permeability of the bodies is much greater than that of the field area. The result is that the primary magnetic field flux distribution will change to minimize energy losses, since the field uses the ferromagnetic bodies as a pathway, creating interaction forces. The character of the direction of the forces applied to the bodies in the group is illustrated in Figure 1.

In this condition, when the induction vector of the field is colinear with the group of bodies and the field is homogeneous, as shown in Figure 1, cell 1, the interaction force between the bodies will have a tendency to bring the bodies into contact. When the induction vector of a homogeneous field is normally directed toward the stream of the bodies (see Fig. 1-3), the interaction force between the bodies will tend to separate them. In a

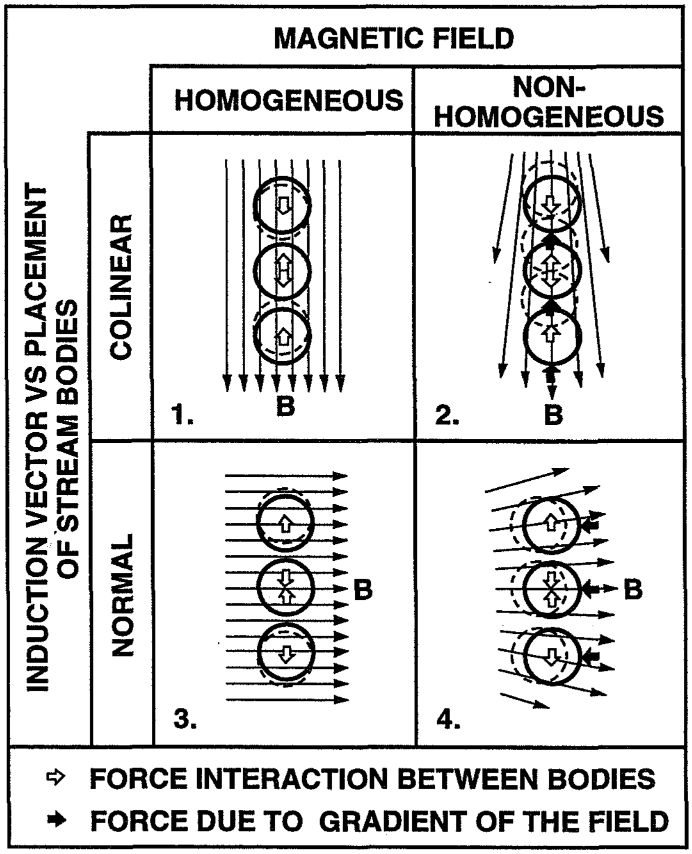


Figure 1. Four simplified sketches showing the interaction forces between ferromagnetic bodies, which are dependent on the angle between the magnetic field induction vector and the direction of the stream of bodies. For simplicity, the field distortion due to the presence of these ferromagnetic bodies is not shown. The bodies drawn with solid lines show their initial positions, prior to the effects of the magnetic field. The bodies drawn with dotted lines show the direction of motion resulting from the interaction forces.

condition of a colinear nonhomogeneous magnetic field (see Fig. 1-2), or a condition of a normally directed nonhomogeneous field (see Fig. 1-4), the interaction force between the bodies still tends to bring the bodies into contact or separate them, respectively. In addition, however, in both of these cases it tends to move the group of bodies toward the area of more concentrated magnetic flux, due to forces created by the gradient of the primary magnetic field.

By experimenting with different configurations and sizes of bodies in magnetic fields [4] some interesting effects were discovered. One of them is illustrated in Figure 2, which shows how the magnitude and direction of the interaction force changes as two bodies—ferromagnetic cylinders—are shifted in relation to each other within the field. Figure 2 uses cylinders for illustration, but this effect is similar for other types of bodies, as well. For ferromagnetic bodies, the magnetic saturation effect is a very important factor, because it limits the possibilities of increasing the interaction force between bodies. If the saturation effect begins to occur, the next increase of the magnetic flux value will not create the same increase in interaction force as before, and if the full saturation effect takes place the next interaction force increase will not occur at all. From the design standpoint, this knowledge provides a positive benefit. What it indicates is that the appropriate magnet system need only be powerful enough to provide magnetic flux up to, but not exceeding, the onset of the saturation effect for the type of parts being manipulated. This permits designing systems that are efficient in terms of weight and size of the magnets and energy consumption.

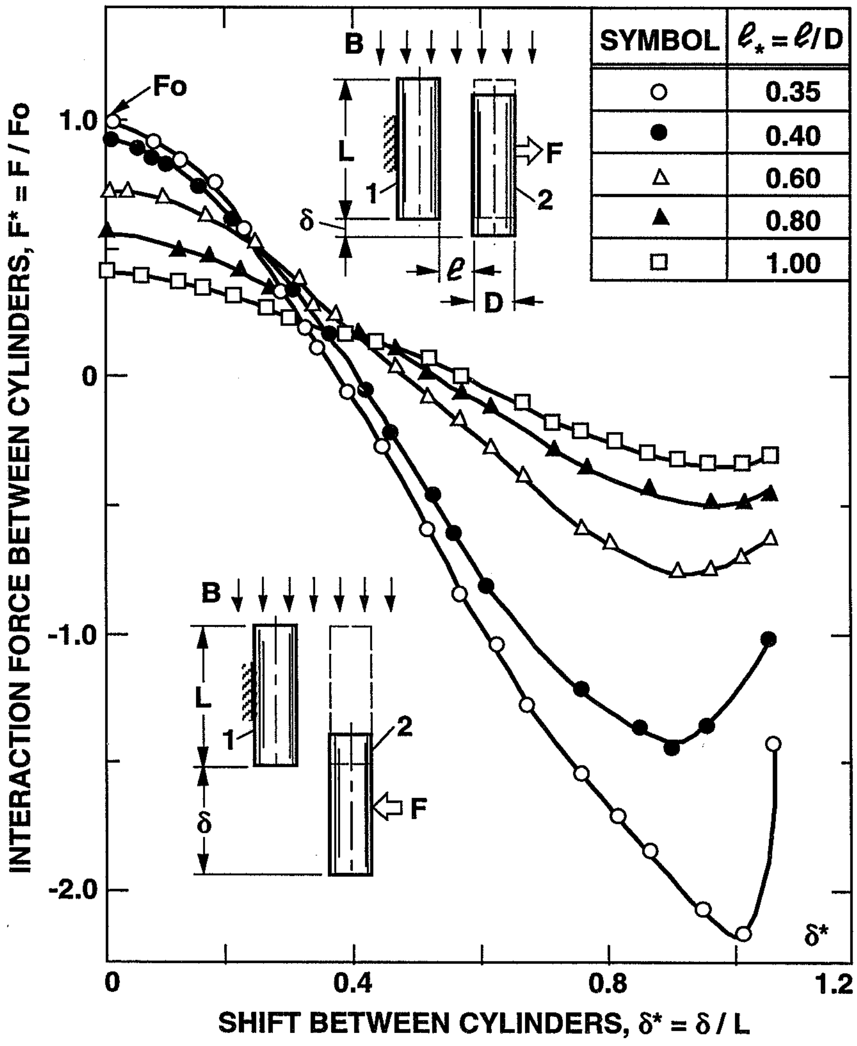


Figure 2. Magnitude of interaction forces between two ferromagnetic cylindrical bodies, based on the shift of the bodies relative to each other and the gap between them in a permanent magnetic field, with the magnetic induction (flux density) B = constant.

The saturation effect can also be observed in experiments where the gap of a permanent magnet is filled with ferromagnetic cylinders. The interaction force relation between the bodies, as shown in Figure 3, is dependent upon the quantity of bodies within the field, or the coefficient of fill. Prior to saturation, the interaction force increases in a relatively linear way as more bodies are added to the field. After saturation starts to occur, which is at a coefficient of fill close to 0.5 in Figure 3, the increase in the interaction force with the addition of more bodies begins to fall off. The interaction force can be calculated using the formula in the upper left corner of Figure 3, in which F_i is the interaction force on an individual body; P_i is the magnetic pressure, which is the result of the square of the induction field; and S_i is the area of the body in the field direction. These experimental results allowed the design of magnetic devices for various applications, two of which are described in patents [6] and [7].

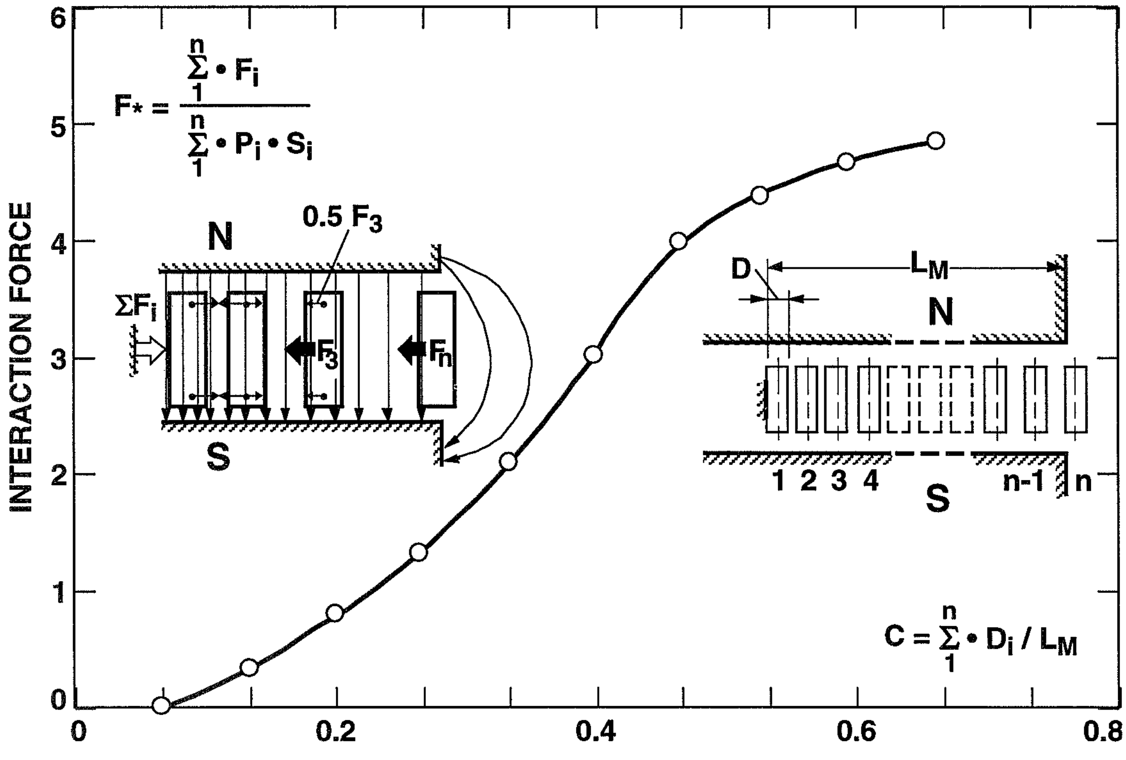


Figure 3. The dependency of the magnitude of forces acting on a single cylinder placed in the polar gap of a permanent magnet (B = constant) on the coefficient of fill (i.e., the number of cylinders that fits in the magnetic gap).

To provide the maximum possible force on ferromagnetic bodies, the magnetic field can be concentrated in the area where it is desired that the bodies be positioned. This can be done using different techniques. One of them, which is very well known, involves choosing a particular configuration of the magnetic poles that concentrates the flux in the desired area [8], [9]. Another way to achieve this is illustrated in Figure 4, which shows how the magnetic field can be concentrated in the gap between the poles (1) and (2) in order to position ferromagnetic bodies (3). In this polegap area, a system of electric wires (4 thru 7) is positioned. The powered wire system adds magnetic flux to the primary magnetic field in some areas and dislocates the flux of the primary field in other desired areas. Figure 4b shows how concentrations of the magnetic flux occur using this technique, allowing parts to be positioned in such concentrated flux areas by the magnetic forces.

If the wire system is configured with more than one layer, powering those layers one at a time can create a gradient of magnetic field that generates a force greater than the force of gravity, allowing the parts to be moved, for instance, in a vertical direction. This is a new way that multiple ferromagnetic parts can be assembled with nonferromagnetic components [10].

Another technique for achieving the same kind of effect is shown in patents [11] and [12], which describe how the concentrations of magnetic flux can be localized in desired areas. This is based on using an alternating electromagnetic field, with a system of conductive plates located between the magnetic poles. The primary

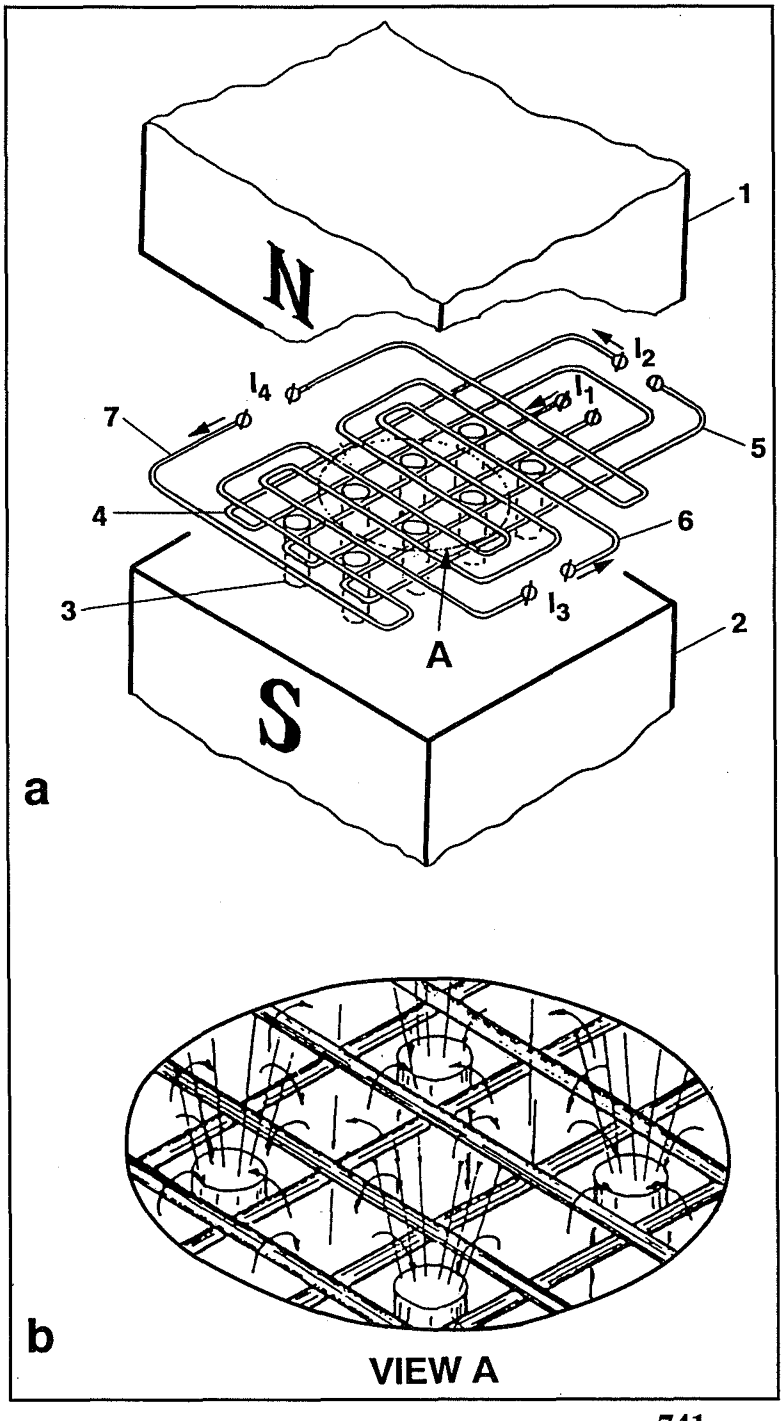


Figure 4. An example of the generation of localized zones with concentrated magnetic flux created by a system of conductors (wires) carrying current. Such a method of generating localized gradients of flux density can be utilized for moving ferromagnetic bodies along complex paths to the desired locations.

Figure 4a shows an overview of the system (1,2 – magnet poles; 3 – ferromagnetic body; 4,5,6,7 – wire system).

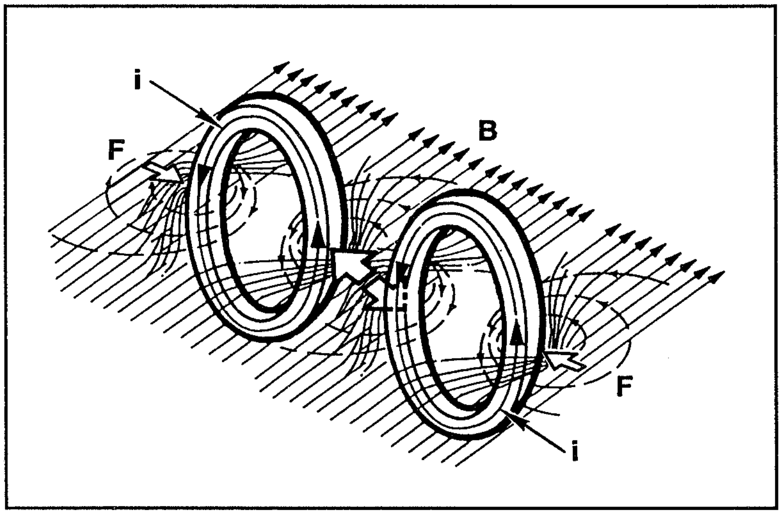
Figure 4b represents a close-up view of the electric wire system with concentrated flux lines.

magnetic field induces a current in the conductive plates, and the secondary magnetic field created by this current interacts with the primary magnetic field, creating extra flux in the same manner as was described above for the wire system configuration. This concentrates magnetic flux in areas where ferromagnetic parts are to be positioned. Such a system can be used for the efficient assembly of parts.

INTERACTION FORCES BETWEEN NONFERROMAGNETIC CONDUCTIVE BODIES IN A MAGNETIC FIELD

As is known, the mechanism for the creation of forces acting on current-conducting bodies in alternating magnetic fields is based on the interaction of secondary fields with the primary field, as was described in [1] and [2]. The interaction force effect between two bodies is illustrated in Figure 5. The induced current (i) in the conductive rings generates a secondary magnetic field that creates resistance to the primary field, with the result that the primary field is bowed out from the ring areas. As a result, on the ring periphery, zones of increased concentration of magnetic flux are created and form electrodynamic forces (F). Because the concentration of flux is greatest between the rings, the interaction forces are strongest in this area. The tendency, then, will be for the rings to move away from each other until the forces between the rings and on the outboard sides are equal.

Figure 5. Shown are the interaction force effects between two nonferromagnetic conductive rings, in coplanar positions, in an alternating magnetic field. For clarity, the primary magnetic field, with induction B, and the secondary magnetic fields created by induced currents (i) are shown in only one plane. F represents the electrodynamic force.



The experimental measurement of such electrodynamic forces between two conductive bodies was done in a homogeneous alternating magnetic field to avoid any influence on the measurement from a gradient of the primary field. The electrodynamic forces between two identical cylinders in a homogeneous field are shown in Figure 6, which includes plots for cylinders of copper, aluminum, and brass. This illustrates the direct dependence of the electrodynamic forces on the conductivity of the bodies.

Figure 7a gives the relative coefficients (K_1) characterizing the effects of form on the magnitude of the electrodynamic forces between two identical bodies. For a baseline, the forces between two balls are established as $K_1 = 1.00$. From the coefficients in this table, it is possible to determine the electrodynamic interaction forces for other configurations of bodies. Figure 7b shows the coefficients characterizing the effects of relative positioning on the magnitude of electrodynamic forces. It should be noted that the coefficients for solid cylinders (not shown) and hollow cylinders are the same. Using the information from Figure 6 and coefficients such

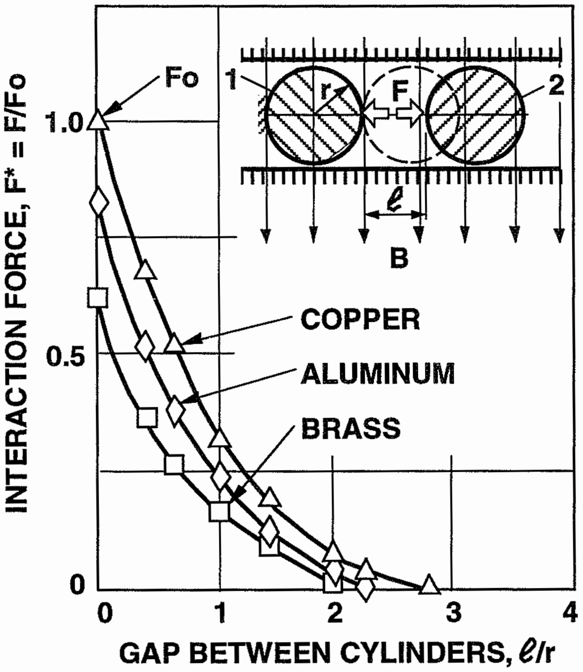
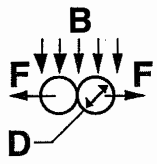
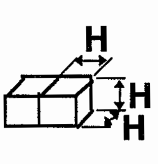
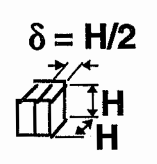
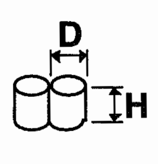
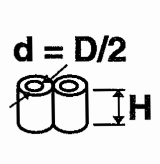


Figure 6. The magnitude of the interaction forces between two nonferromagnetic conductive cylinders in a homogeneous alternating magnetic field depends upon the gap between the cylinders.

TABLES OF COEFFICIENTS CHARACTERISING THE EFFECTS OF FORM AND RELATIVE POSITIONING ON INTERACTION FORCES BETWEEN TWO BODIES

a

BODIES / COEFF.					
K$_1$	1.00	1.21	1.90	0.67	0.57

b

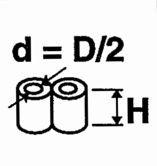
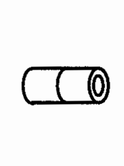
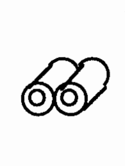
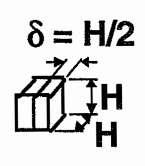
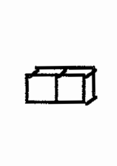
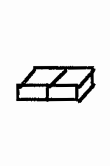
BODIES / COEFF.						
K$_2$	1.00	1.90	2.20	1.00	0.25	1.30

Figure 7a. Coefficients characterizing the effects of form on the magnitude of electrodynamic forces between two identical bodies.

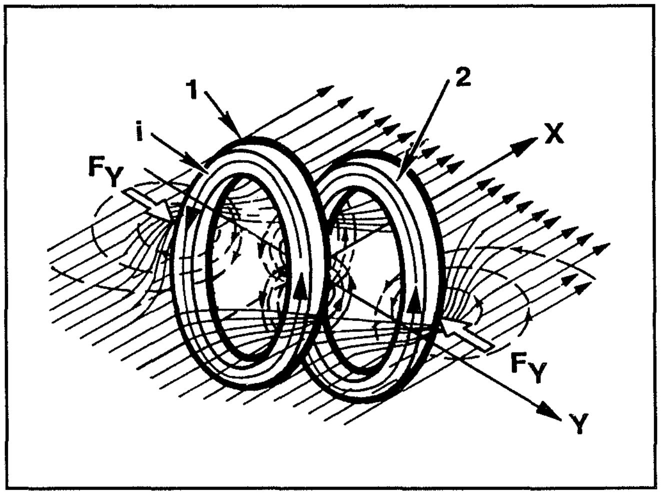
Figure 7b. Coefficients characterizing the effects of relative positioning of two identical bodies on the magnitude of electrodynamic forces.

as those shown in Figure 7, it is possible to predict the electrodynamic interaction forces for various types of bodies within magnetic fields. Based on this research, several new methods were developed for separating bodies for automation [13], [14], [15], [16].

It is well known that when the magnetic field is nonhomogeneous, the gradient of the field will have a direct influence on the force value between the bodies. The difference between nonferromagnetic conductive bodies and ferromagnetic bodies is that the force directions relative to the gradient of the field are opposite. In the case of ferromagnetic bodies, the force direction is toward the area of highest flux concentration, and with conductive bodies the force direction is toward areas of lower flux concentration.

Now, let us look at the case of two non-coplanar rings in a magnetic field. The interaction force effect between two such bodies is shown in Figure 8. As with the coplanar rings described above, the induced current (i) in the rings (1) and (2) generates a secondary magnetic field that creates 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 (F_y) that tend to move the rings toward contactless convergence and centering on the same axis (X).

Figure 8. Shown are the interaction force effects between two nonferromagnetic conductive rings, in non-coplanar positions, in an alternating magnetic field. For clarity, the primary magnetic field and the secondary magnetic fields created by induced currents (i) are shown in only one plane.



Based on this effect, different kinds of methods and devices for automation were created. One of them, which is illustrated in Figure 9, involved the alignment of multiple objects (1) positioned on a nonconductive plate (3) in which is mounted numerous conductive targets (2). The targets are mounted in the plate in the configuration in which the objects are to be positioned after alignment. Because of the interactive force effects, the objects and the conductive targets interact in the same manner as the two non-coplanar rings in Figure 8.

Using this technique, many applications can be developed. An increase in the alignment effect can be achieved by placing the objects between two nonconductive plates with conductive targets [17]. In fact, multiple layers of plates and objects to be aligned can be configured. Creating the target as a conductive coil with a switch that can open and close the loop provides still more opportunities for the manipulation of objects. Some of these design possibilities are illustrated in patent [18].

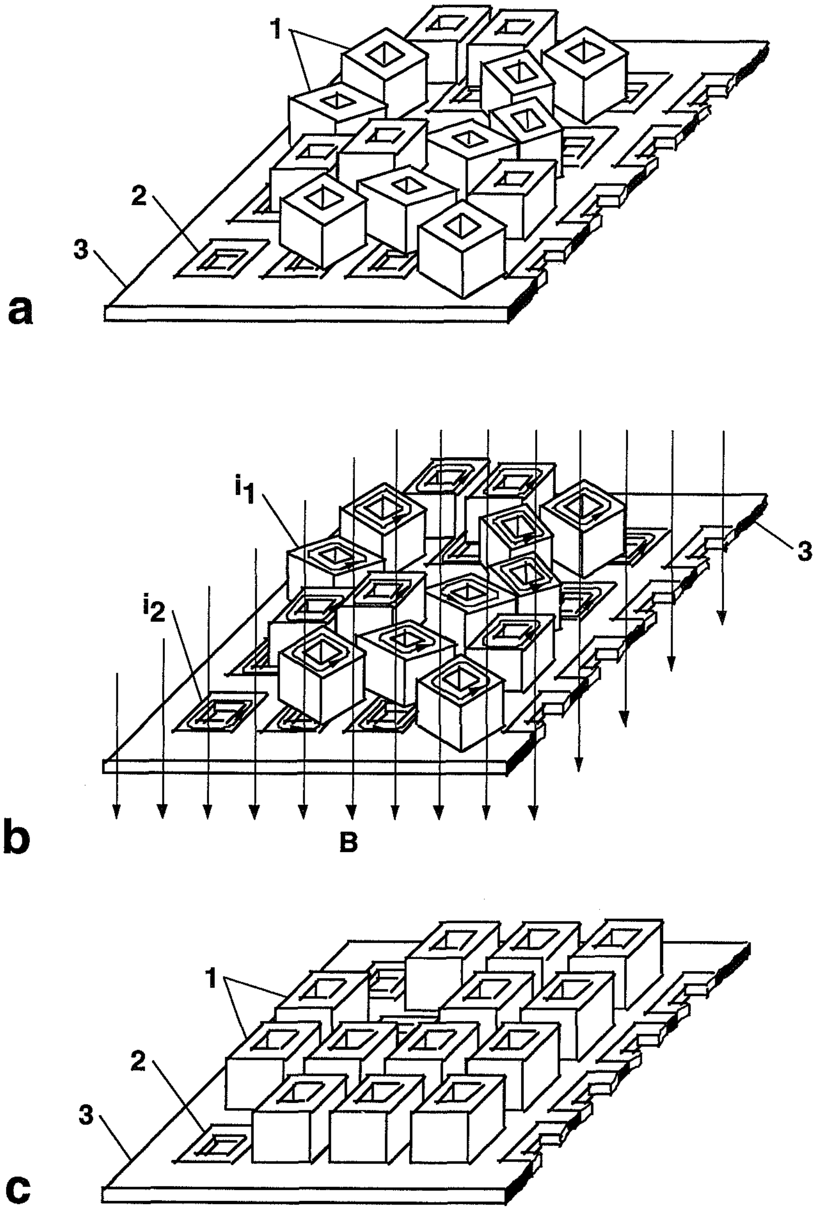


Figure 9. Illustration of alignment of a group of bodies, which can be achieved by interaction of electrodynamic forces between the bodies (1) in the group and between the bodies (1) and the conductive targets (2) mounted in a plate (3).

Figure 9a shows a disorganized group of bodies on a plate before the primary magnetic field is generated.

Figure 9b shows the induced currents in the bodies and the conductive targets as a result of the primary alternating magnetic field being applied.

Figure 9c shows the organized, aligned group of bodies as a result of the acting of the electrodynamic forces.

An example of such a concept design is presented in Figure 10. The object to be manipulated (1) is positioned between four coils (2,3,4,5). When a primary electromagnetic field (B) is applied, a current (i_1) is induced in the object. When the switches (6,7) for both sets of coils are open, as shown in Figure 10a, no interaction force occurs between the object and the coils. If, for example, the switch (6) for one pair of coils (2,3) is closed (Figure 10b), the primary field induces a current (i_2 and i_3) in that set of coils. As a result of the interaction between the currents in the object and the coils, an electrodynamic force is created that moves the object to the left. If the switch (7) for the other set of coils (4,5) is closed while the other switch is open, as is shown in Figure 10c, the opposite effect occurs, resulting in an electrodynamic force that moves the object toward the right. For simplicity, Figure 10 does not show the magnetic flux interactions among the primary alternating magnetic field (B), the magnetic field-induced currents in the movable object (1), and the coil system (2,3 and 4,5). Some of these interactions are shown in Figure 8 and in Figure 11 below.

By creating such designs with multiple coils, the manipulation effects on the object can be made more complex. A coil system could also be designed for remote operation of the switches, either manually or by computer programs, for contactless positioning of objects. These kinds of devices could be used for many automation applications, including nonmanned object manipulation on spacecraft.

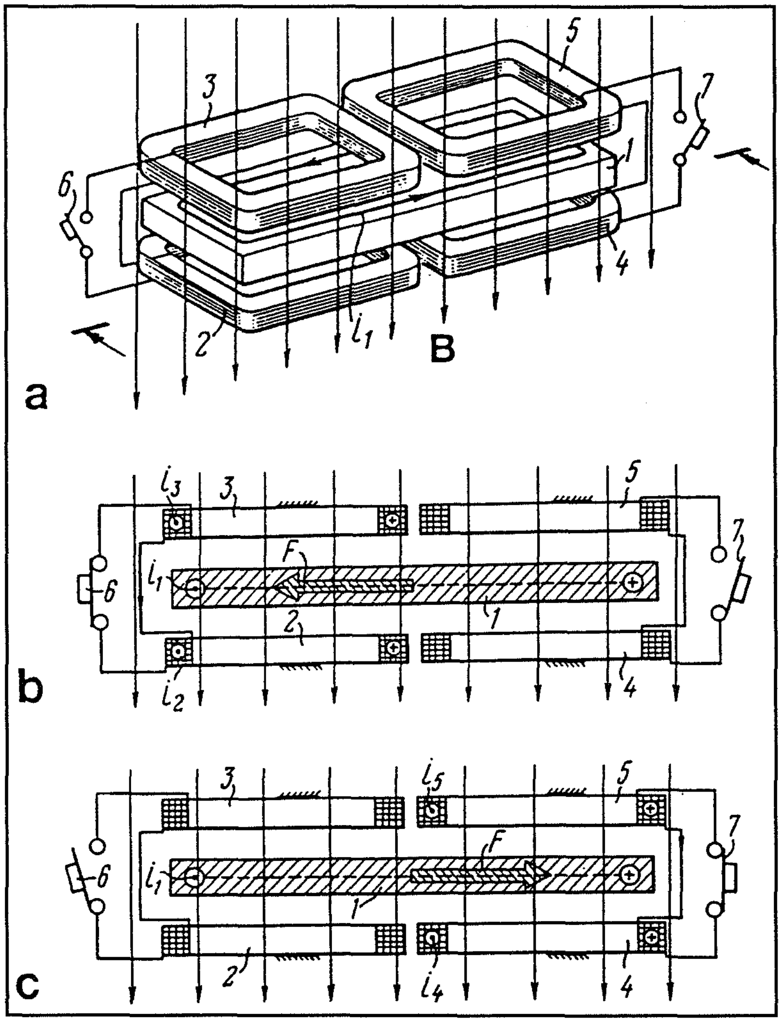


Figure 10. The concept design of an electromagnetic device for manipulation of an object (1) by electrodynamic force (F).

Figure 10a shows an overview of the concept design.

Figures 10b and 10c present a cross-section view of the object and the coil system (2,3,4,5), showing how the electrodynamic force applied to the movable object changes as a result of closing and opening the loop of the coil system by operating the switches (6,7).

The force relations between non-coplanar bodies within a magnetic field can also be used for more complicated manipulations of objects, including the contactless assembly of parts [19].

Another example of the use of interaction forces between non-coplanar conductive bodies in a magnetic field is shown in Figure 11. A conductive plate (1) can be used as a contactless screen for separating a subset of conductive bodies from a larger set of bodies (2). The magnetic flux at the edges of the plate in relation with the induced current in the bodies creates interaction forces that separate the bodies at the edges of the plate from those under the plate. This technique can be used, for example, for preparing groups of parts for packaging.

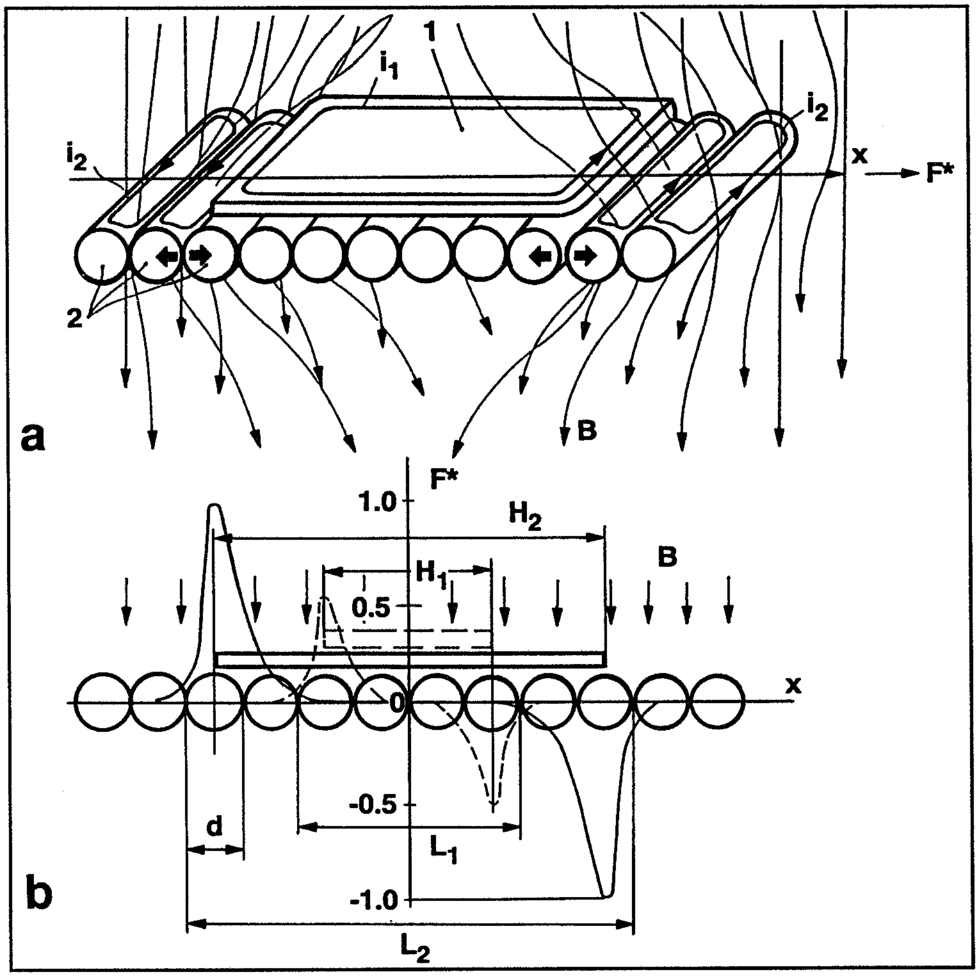


Figure 11a illustrates the use of a conductive plate (1) as a screen for separating a subset of conductive bodies (2) from a larger set of bodies in an alternating magnetic field.

Figure 11b shows the characteristics of magnitude and direction of electrodynamic forces (F) generated by the interaction of a primary magnetic field and secondary fields induced in the screen (1) and the bodies (2).

Force magnitude at the screen edges is shown for two different screen sizes, H1 and H2.

The forces created by the interaction between the primary field and induced fields in the bodies can be used not only for providing linear motion of bodies in relation to one another but also for achieving rotation. This effect is illustrated in Figure 12, which shows a cylindrical conductive body (1) located inside a conductive frame (2). Applying an alternating primary magnetic field (B) to this system induces currents, and consequently secondary magnetic fields, in both the cylinder and the frame. The induced current in the cylinder is generated ninety degrees from the direction of the primary field. The current position of the frame is dependent upon the angle position of the frame. The induced current in the cylinder has a tendency to align itself with the induced current in the frame. If the frame is oriented at some angle such as that shown in Figure 12a and 12b, counterclockwise rotation will result. If the frame location has the opposite angle position, as shown in Figure 12c, the cylinder rotation will be clockwise.

From this we can see that varying the position of the frame allows the manipulation of the torque, speed, and direction of rotation of the cylindrical body. To increase the interaction forces, a second conductive frame can be placed on the opposite side of the cylinder from the first one [20]. It is also understood that by organizing the primary field with a gradient, a levitation effect for the cylinder can be achieved, as well, thus reducing the friction force between the body and the frame. The torque value can also be increased by using a multi-winding coil instead of a solid frame loop. This concept can be used to develop electric motors and, for example, such things as devices for polishing surfaces [21].

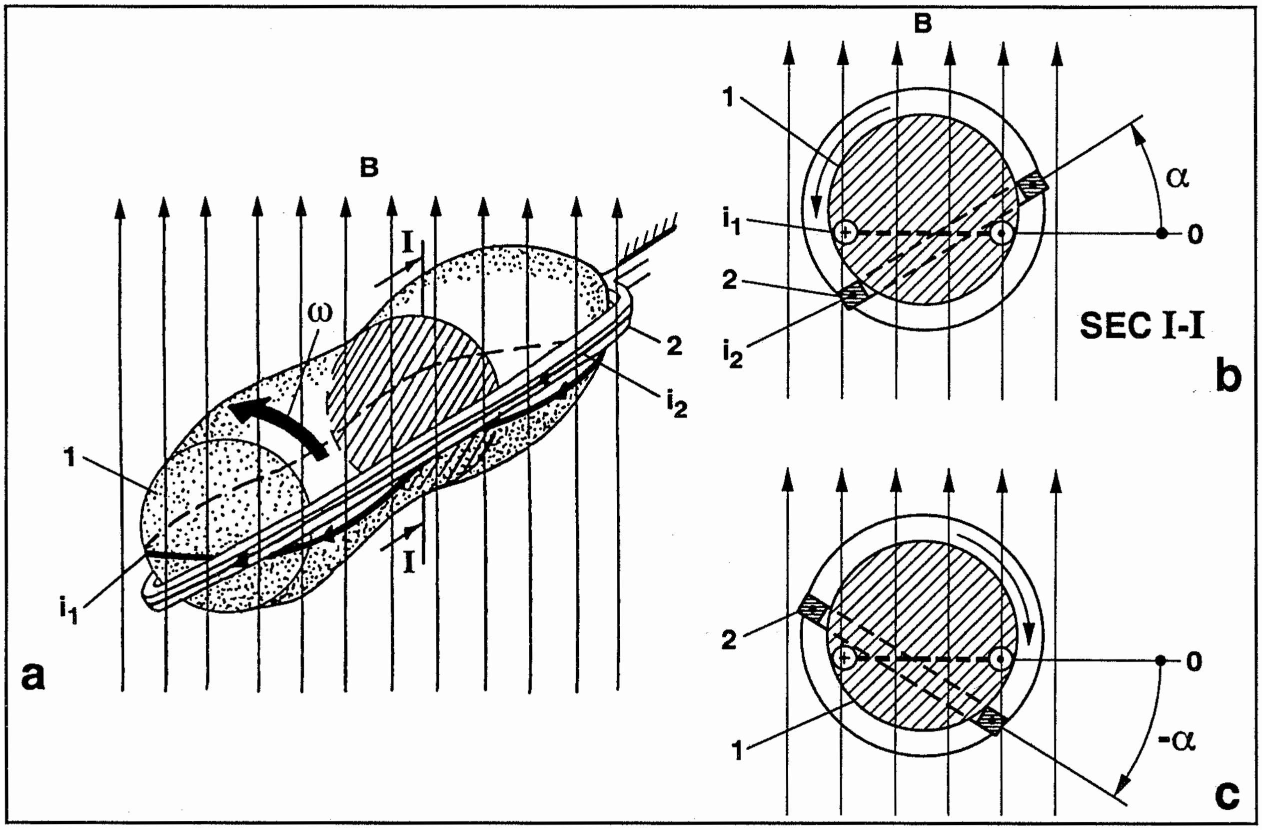


Figure 12a shows the effects of interaction between a cylindrical conductive body (1) and its encompassing conductive frame (2), both of which are in the alternating magnetic field. The interaction force relation between the induced currents in the two bodies creates torque that results in the rotation of the cylindrical body.

Figure 12b gives a cross section I–I from Figure 12a.

Figure 12c is the same as 12b, except that it shows a different frame angle (a) position relative to the induced current in the cylindrical body. This results in the opposite torque direction, creating a different direction of rotation for the cylinder.

CONCLUSION

This paper has presented only a brief overview of the interaction forces between ferromagnetic and current-conducting bodies positioned in simple groups. The results of the investigations of these groups were sufficient to provide an understanding of the dependence among the bodies and to allow the creation of new types of devices, some of which were described in this paper.

In the next presentation the author plans to provide some interaction force calculations as well as to analyze the force relations for more complex groups of bodies.

It is also of special interest to analyze the dependence of the interaction forces between magnetized bodies or permanent magnets. Some information about these forces, which depend upon the types of magnetic materials used, the sizes of the bodies, and their configuration, is already available. With regard to more complicated configurations of magnetized bodies, which have already been used in designs of new kinds of mechanisms and machines [21], specific information on the interaction forces still needs to be gathered. A related area of investigation would be to analyze the interaction forces when other movable components, made from different kinds of materials, are involved in the mechanism along with magnetized bodies. Examples of such mechanisms are contained in patent [22].

From the research presented here it is clear that designs based on these concepts could have applications in a wide variety of areas, including the space program. Specifically, the use of magnetic interaction forces would allow the production of lightweight, efficient, multi-functional mechanisms for remotely controlled, nonmanned spacecraft applications, where durability and versatility of the designs are extremely important.

REFERENCES

1. Joffe B. "Manipulation and Identification of Objects by Magnetic Forces." Presented to the International Symposium on Magnetic Suspension Technology, Hampton, Virginia, August 19-23, 1991. NASA Conference Publication 3152, Part 2, 1992, pp. 617-638.

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

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

4. Baltvilks A.T., Joffe B.A., Kalnin P.K. "Force Interaction of Ferromagnetic Cylinders and Disks 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 Force 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. Joffe B.A., et al. "Device for Contactless Separation of Individual Ferromagnetic Components from a Flow of Components," U.S. Patent No. 4,113,142, Class 271/171.

7. Joffe B. "Rotating Drive Magnetically Coupled for Producing Linear Motion," U.S. Patent No. 5,331,861, Class 74/89.15.

8. Kulberg A.Y., Joffe B.A., et al. "Device for Arranging Ferromagnetic Components at Preset Distance from One Another," U.S. Patent No. 4,153,151, Class 198/456.

9. Joffe B.A., et al. "Automatic Assembly Device," U.S.S.R. Patent No. 518,318, Class B23p.

10. Joffe B.A. "Assembly of Elongated Ferromagnetic Components," U.S.S.R. Patent No. 737,189, Class B23.

11. Kalnin R.K., Joffe B.A., et al. "Device for Assembly of Ferromagnetic and Nonmagnetic Components," U.S.S.R. Patent No. 707,189, Class B23p.

12. Joffe B.A., et al. "Device for Assembly of Ferromagnetic and Nonmagnetic Components," U.S.S.R. Patent No. 812,499, Class B23p.

13. Joffe B.A. "Method for Separation of Parts," U.S.S.R. Patent No. 442,979, Class B65h.

14. Joffe B.A., et al. "Apparatus for the Simultaneous Contactless Separation of Individual Nonmagnetic Electrically Conductive Bodies from a Continuous Flow," U.S. Patent No. 3,661,241, Class 198/33.

15. Joffe B.A., Kalnin R.K. "Method of Dismantling Units," U.S. Patent No. 4,109,366, Class 29/427.

16. Kern I.I., Joffe B.A., Graubin Y.J. "Method for Multiple Directional Distribution of Nonsymmetric Parts," U.S.S.R. Patent No. 441,763, Class 62-229.6Y.

17. Joffe B.A., et al. "Device for Making Sets of Nonmagnetic Current-Conducting Components," U.S. Patent No. 4,144,637, Class 29/739.

18. Joffe B.A., et al. "Method of Oriented Feeding of Nonmagnetic Current-Conducting Components and Devices for Effecting the Same," U.S. Patent No. 4,077,027, Class 335/219.

19. Kalnin R.K., Joffe B.A., et al. "Method of Assembly of Nonmagnetic Current-Conducting Components," U.S. Patent No. 4,238,658, Class 219/9.5.

20. Kern I.I., Joffe B.A., Summer V.A. "Device for Rotation of Parts," U.S.S.R. Patent No. 420,441, Class 62-837.

21. Joffe B.A., et al. "Machine for Lapping Flat Surfaces of Parts," U.S.S.R. Patent No. 804,402, Class 621.923.5.

22. Joffe B. "Rotating Drive Magnetically Coupled for Producing Linear Motion," U.S. Patent No. 5,331,861, Class 74/89.15.