MAGNETIC BALL BEARINGS

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ABSTRACT
An overview of the development and application of magnetic ball bearings to precision mechanisms is presented. The authors of this paper provide an overview of the development of magnetic ball and roller bearing designs. This overview uses technical information about magnetic ball or roller bearings from earlier published patents (beginning about 70 years ago) as well as from some of the latest inventions made by B. Joffe the co-author of this paper. However, new developments were made only recently [1]. No mention of them was made in the standard reference monograph on ball and roller bearings [2]. Also, magnetic ball or roller bearings are currently not discussed at Magnetic Bearings Symposiums and Conferences. What makes the magnetic ball bearings so special? The magnetic forces hold the bearings together and provide a controlled preload on the bearings with zero backlash. Design guidelines for the magnetic ball bearings are outlined and discussed. Several design concepts are introduced along with a discussion of the advantages gained with the magnetic ball bearing approach. Magnetic ball bearings permit extremely compact designs to be implemented with a minimum number of components. Many design mechanisms and machines which require a combination of precision motion, minimum mass and compact size are possible with these kind of bearings [12].

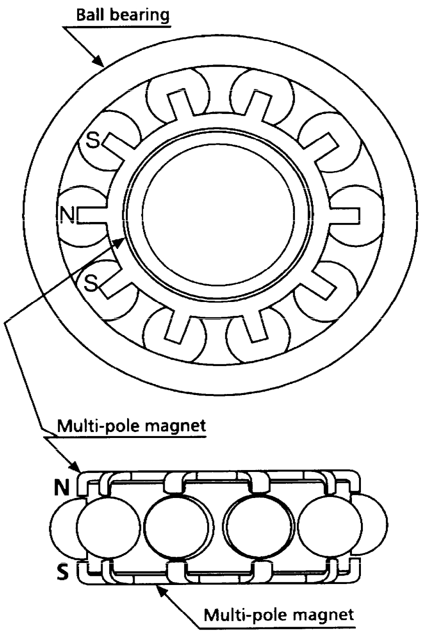

FIGURE 1. Ball Bearing with Magnetic Ball Separator [4]

I. AN OVERVIEW OF THE DEVELOPMENT OF MAGNETIC BALL BEARINGS

In 1926, H. C. Horrison proposed to hold all ball or roller bearing components together by using permanent magnets [3]. Initial efforts with magnetic ball bearings were concerned with maintaining the separation of the balls in the bearings. In 1944, R. P. Ellis [4] showed that the balls in a bearing race can be equally spaced without using a mechanical spacer. The separation of the ferromagnetic balls, based on his invention, was accomplished using two multi-pole magnets mounted to the sides of the bearing race rings. The number of poles on the magnets equals the quantity of balls in the bearing. The balls in this application are located between the concentrated magnetic fields as shown in Figure 1.

Later, in 1959, E. O. Norris [5] refined the magnetic configuration design of R. P. Ellis in order to separate the balls in a bearing race. He produced magnetic devices which separated the balls in a radial angular bearing. The inventor showed how to incorporate a magnetic device into such a mechanical bearing. In 1967, R. I. Markey [6] applied for a US Patent to protect his idea for a self-adjusting bearing preload force. In 1979, H. B. Irby [7] applied for a US Patent on magnetic ball thrust bearing which also did not require a ball separator as shown in Figure 2. He demonstrated how to reduce the thrust force by using magnetic force.

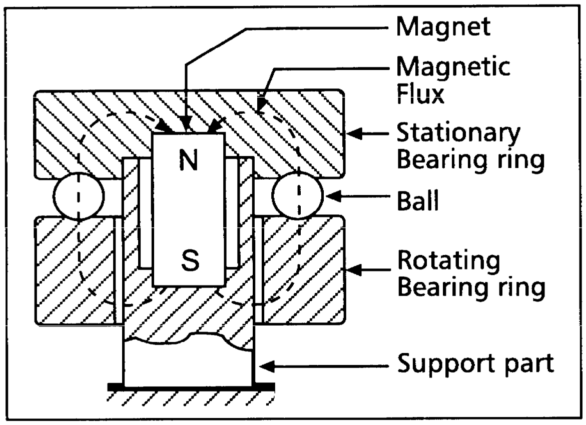

FIGURE 2. Magnetic Ball Thrust Bearing [7]

In Japan, Tatsuzo Ujo [8] proposed a duplex ball bearing in which preload is provided by two repulsive permanent magnets located between two radial bearings. Note that, in all of the inventions discussed above, the bearings are able to provide motion with only one degree of freedom. In recent years B. Joffe has developed magnetic ball bearing concept designs which allow two or more degrees of freedom for motion and zero backlash. This is accomplished by separating the balls in one or more layers in the device, choosing the geometry of the rolling surfaces and selecting the direction of the magnetic field. Such magnetic ball bearings have been presented in a few published US Patents [9-11], demonstrating the utility of magnetic ball bearings for different rotational and linear motion design applications.

II. BASIC PRINCIPLES OF MAGNETIC BALL BEARINGS

The operation of a magnetic ball bearing can be understood by considering the nature of the magnetic field between the poles of two oppositely polarized permanent magnets. An example of a magnetic ball bearing consists of two hardened flat bearing surface rings, a set of steel balls and two magnets to hold the rings together (refer to Figure 3a).

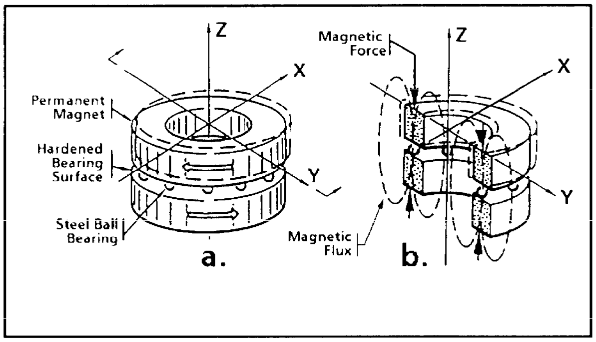

FIGURE 3. Magnetic Ball Bearing Concept Design. This geometry allows translation in both the X and Y directions and rotation about the Z axis [9].

The ferromagnetic balls are placed between the rings and the magnets hold the assembly together. The magnetic flux lines pass through the center of the ferromagnetic balls to complete the magnetic field (refer to Figure 3b). This causes the balls to self-center with respect to each other. The magnetic ball bearing unit, as described in Figure 3, allows 3 degrees of freedom (X, Y, θz). Magnetic ball bearings can be used in many configurations that require precision motion with zero backlash.

The magnetic field that is produced by a set of permanent magnets is utilized to align and retain ferromagnetic balls. To demonstrate this principal, we consider an example that utilizes a set of infinitely long permanent magnets separated by three non-ferromagnetic balls with the same permeability as the air gap. In this case, the magnetic flux lines from one magnetic pole to the other are all parallel, as shown in Figure 4a. The non-ferromagnetic balls do not influence the magnetic field.

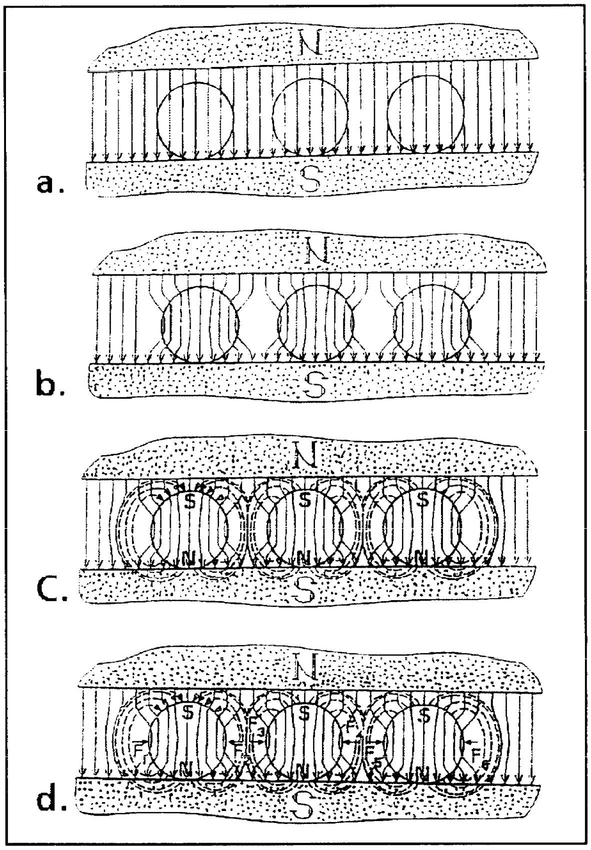

FIGURE 4. Magnetic Flux Distribution without and with Ferromagnetic Balls [1]

With a set of ferromagnetic balls, the permeability of the balls is greater than the air gap. For this condition the magnetic flux lines are deflected to pass through the balls since they represent a lower resistance magnetic path. This configuration minimizes the energy loss across the air gap; this increases the resulting force acting on the balls. The resulting magnetic flux lines are shown in Figure 4b. The magnetic field interacts with the balls and they become magnetized as shown in Figure 4c. The individual balls behave as a permanent magnet with poles that align with the primary field. The magnetized balls now repel one another to maintain a constant spacing between the balls. These interaction forces are shown in Figure 4d. Once this condition is obtained and the two magnetic poles are allowed to come in contact with the balls, then a zero backlash bearing is created. This is the process by which magnetic bearings are assembled.

Figure 5 illustrates the behavior of the attractive force between two magnetic poles as a function of the presence or absence of balls. The magnetic ball bearing force value F, in the Z axis, depends upon several parameters, one of which is the air gap size.

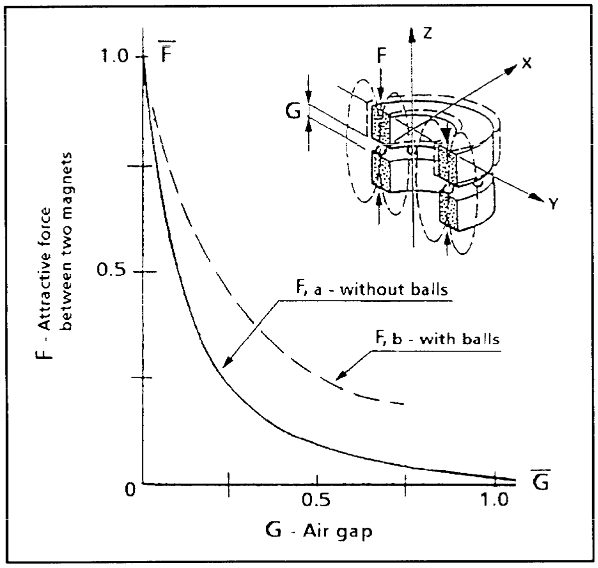

FIGURE 5. Attractive Force Between Two Magnets as a Function of Air Gap Both with and without the Presence of Ferromagnetic balls

The figure illustrates the force value F for air gap alone and for the presence of some unspecified number of balls between the magnets. The F-force depends also upon the magnetic permeability of the balls (i.e., the so-called "Ferromagnetic fill up" value). The relationship for the interaction forces between the balls is dependent on several parameters such as:

1. Magnetic permeability of ball material
2. Volume of ball
3. Magnetic field strength
4. Ball spacing

Note that the bearing preload can be controlled by changing the size or quantity of balls used in the assembly. Also, because of the nature of its construction, the preload of a magnetic bearing is essentially constant over its operational life.

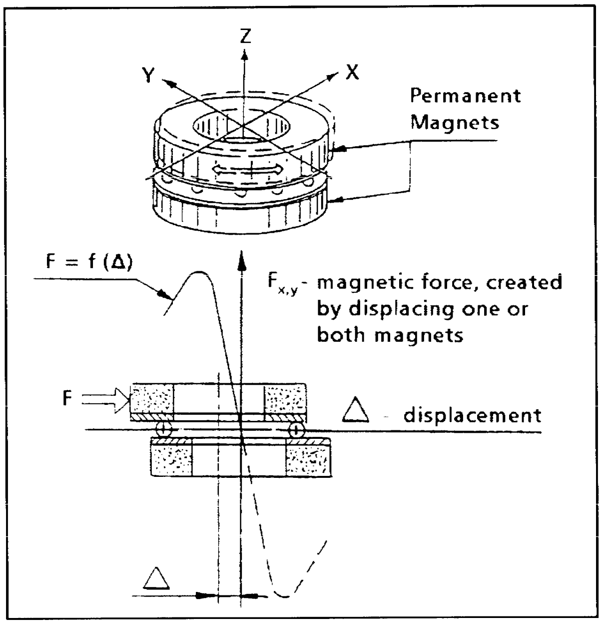

FIGURE 6. The Force Resulting from the Displacement of Two Magnets Relative to Each Other in the X or Y Axis Direction

Figure 6 illustrates the force experienced by a magnetic ball bearing race along the X or Y axis for a bearing with a two magnets design.

Figure 7 shows the force for a magnetic ball bearing designed around one magnet and one ferromagnetic plate. The approach to be used depends upon the need for the "Magnetic Spring" force in the X, Y axes. The concept in Figure 6 provides a more responsive force than the bearing shown in Figure 7.

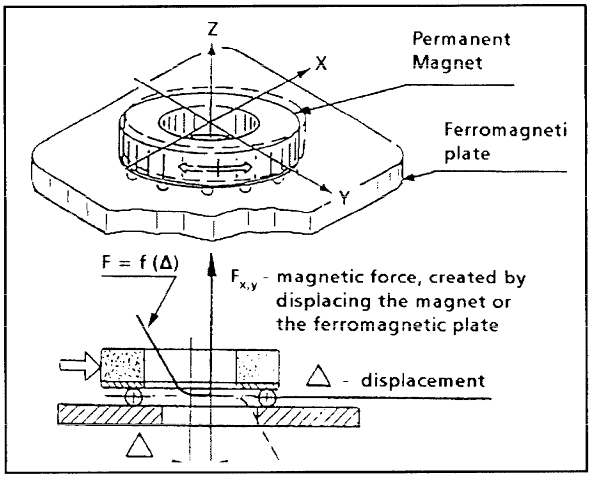

FIGURE 7. The Force Resulting from the Displacement of a Magnet Parallel to the Surface of a Ferromagnetic Plate

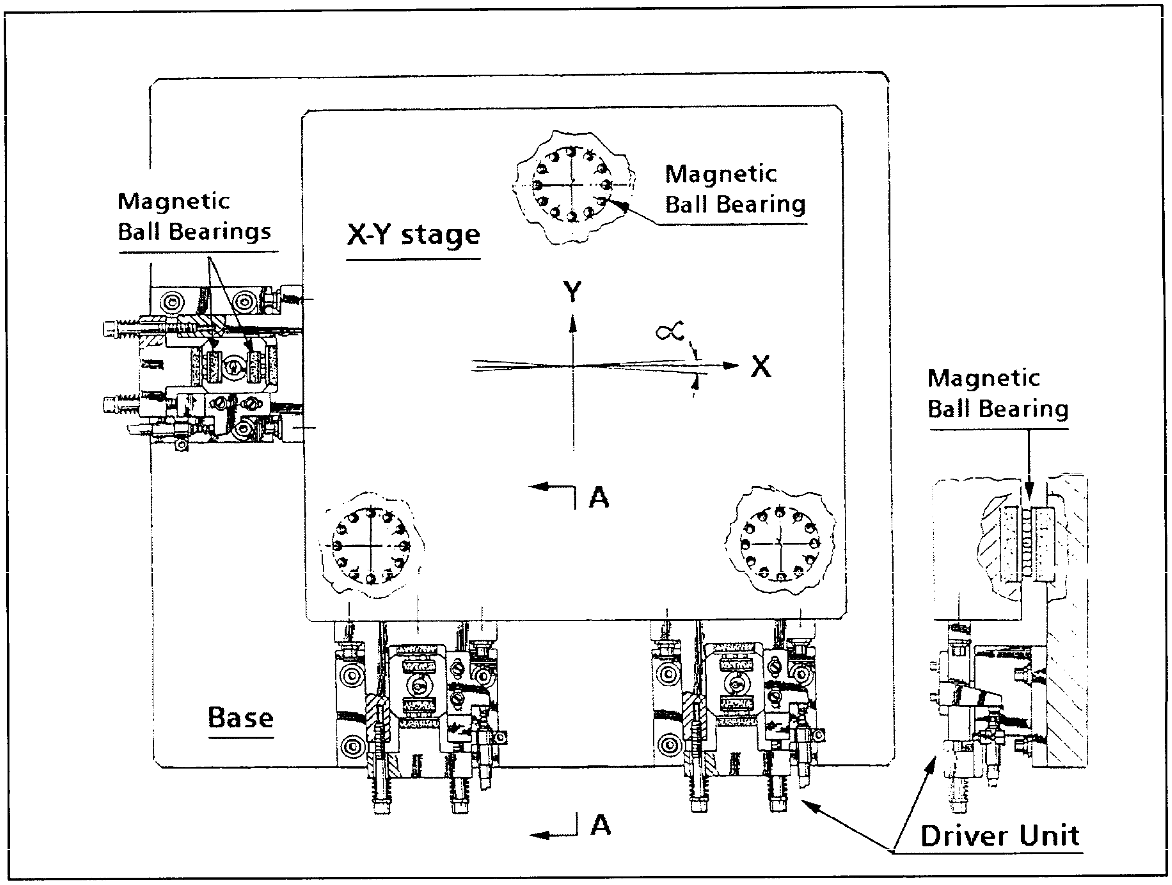

FIGURE 8. Sketch of an Ultra-high X-Y Stage and Position Driver Units, both of which incorporate magnetic ball bearings [12]

III. EXAMPLES OF APPLICATIONS USING MAGNETIC BALL BEARINGS

The above magnetic bearing principals apply to both linear and radial configurations. Many designs and applications can utilize these magnetic bearing principles to produce advanced mechanisms. The designs combine minimal size and minimum part count to make this concept ideal for many mechanism designs.

The effectiveness of the new kind of magnetic ball bearings allows greatly simplified high and ultra-high precision mechanisms and machine designs, as is well illustrated in another US Patent [12]. Figure 8 shows a sketch of a high precision X-Y stage resting on three magnetic ball bearings. Three of the cam driver units move the stage to the target position. The magnetic bearings allow the driver units to have three degrees of freedom of movement.

A magnetic coupling that eliminates the lateral wobble present in a ball screw axial drive device is shown in Figure 9. This application utilizes the magnetic bearing configuration shown in Figure 3. One of the magnets mounts into a steel flange that is then attached to a moveable object. The other magnet ring mounts into a sleeve connected to the flange of a ball nut. The magnets are sized to ensure that the bearings do not unseat during operation. In this application the magnetic bearing concept eliminates the lateral motion, or wobble, that may be present in the ball screw device. Higher levels of precision translation are achieved when standard ball screw components are used with magnetic ball bearing couplings. Reference [11] presents additional concepts utilizing a variety of magnetic ball bearings.

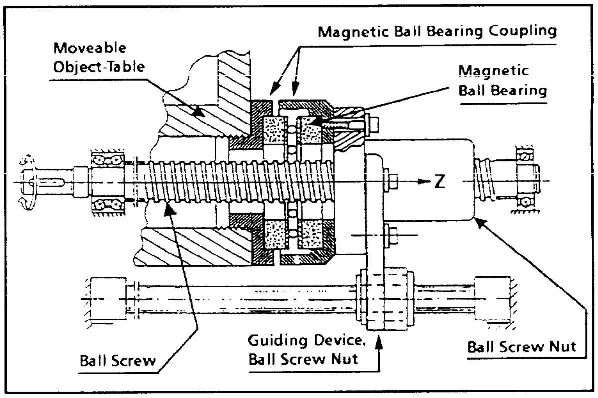

FIGURE 9. Ball Screw Translator with Magnetic Ball Bearing Coupling [9, 10]

IV. MULTI-LAYER MAGNETIC BALL BEARING CONCEPTS

Several examples of magnetic ball bearing concept designs with two layers of balls are presented in Figures 10 and 11. Such types of bearing devices can provide more degrees of freedom. The concept designs shown illustrate different configurations and materials of their components. In Figure 10 the inner bearing ring is a permanent magnet, with the induction of the magnetic field in the Z axis. The outer component can be made from ferromagnetic material or can also be permanent magnets.

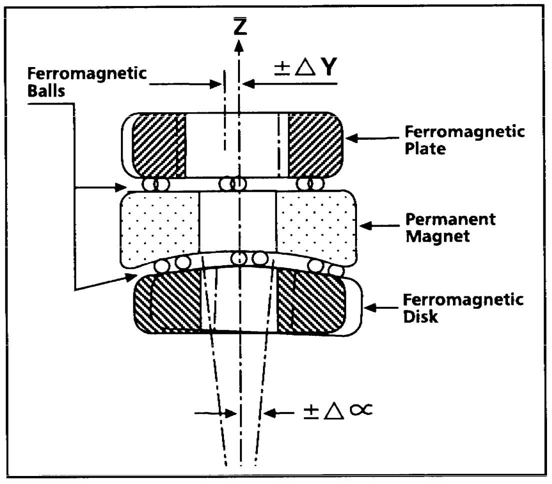

FIGURE 10. Multi-layer Magnetic Ball Bearing Concept Providing Four Degrees of Freedom [9, 10]

Figure 11 shows a multi-layer magnetic ball bearing composed of rectangular components. The vector of magnetic field induction is directed along the Y axis. The same bearing material combination is shown as was discussed for the design in Figure 10, with the differences that this design can be recommended for linear motions. This bearing has four degrees of freedom of motion. If fewer degrees of freedom are required, then one of the layers of balls can be guided. One such application is shown in Figure 12. Magnetic ball bearings allow a simpler design for guiding an object along a prescribed path. There is zero backlash and no risk of binding between two guiding surfaces.

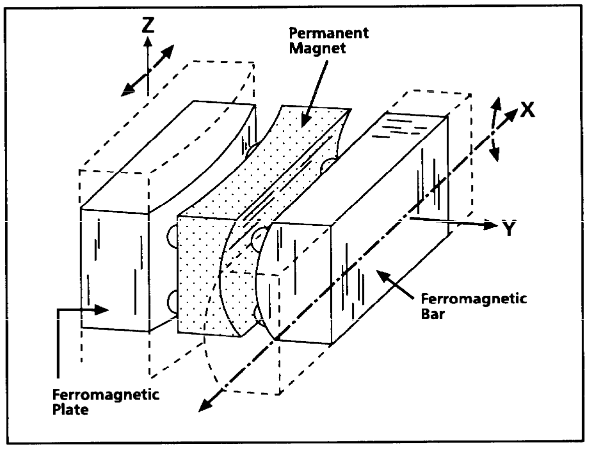

FIGURE 11. Magnetic Ball Bearing Concept Allowing Translation, Roll, Pitch and Yaw Motions {9, 10]

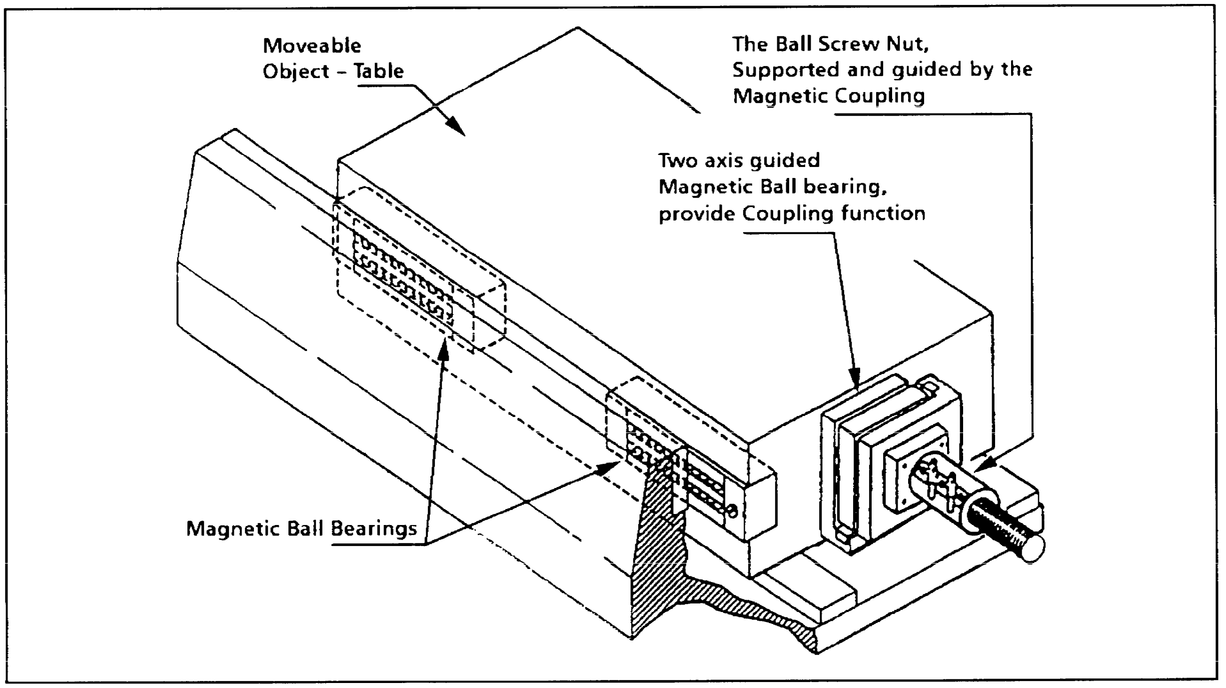

FIGURE 12. Application of Magnetic Ball Bearing Technology to the Design of a Stage which ...ist... e Driver and the Moveable ...

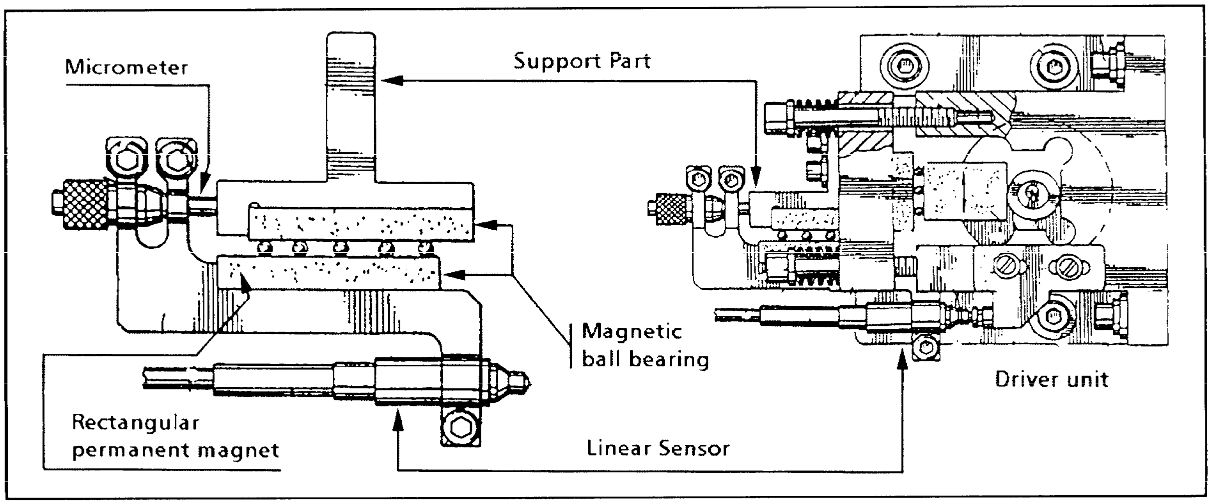

FIGURE 13. Linear Adjustment Measurement Device for a Driver Unit Design [12]
It is showing another example of how a magnetic ball bearing
can combine holding, guiding and spring loading functions.

V. CONCLUSION

A magnetic ball bearing device incorporates mechanical components such as balls or rollers and race parts in combination with a single or multi-magnet system. The magnetic field interacting with the bearing components is able to create forces which, when appropriately applied, can improve performance and reveal important characteristics. These features open new possibilities for many motion mechanisms, especially for precision mechanism designs. Some of the unique characteristics of magnetic ball bearings are:

- ability to maintain motion in one of the desire axes with zero backlash and low resistance bearing motions in the other axes;
- magnetic forces hold the bearing together and provide a controlled preload on the bearing;
- permits extremely compact designs to be implemented with a minimum number of components, and no need for a ball separator or separators should the bearing have multi-ball layers;
- permits the simple combination of several functions without introducing extra design complexity; an example is a magnet bearing used as a bearing and as a spring element. Such a spring effect can be provided to one or more bearing race elements, simultaneously or in different sequences;
- with a relatively small bearing size, magnetic ball bearings allow relatively large bearing motion displacements;
- permits holding together, without extra fasteners, some other application components;
- can be used occasionally as a completed application design, for example, as a translation stage or as a coupling.

VI. REFERENCES

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