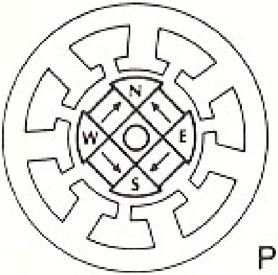


PROCEEDINGS OF THE

EIGHTH INTERNATIONAL WORKSHOP ON
rare-earth magnets
AND THEIR APPLICATIONS

and the

FOURTH INTERNATIONAL SYMPOSIUM ON MAGNETIC ANISOTROPY AND COERCIVITY IN RARE EARTH-TRANSITION METAL ALLOYS.

DAYTON, OHIO, USA — MAY 1985

Edited by KARL J. STRNAT
UNIVERSITY OF DAYTON

MEASUREMENT OF FORCES BETWEEN MAGNETS IN PASSIVE BEARING SYSTEMS EMPLOYING RARE-EARTH MAGNETS

T. C. Morcos, K. J. Strnat and J. L. Calvert
University of Dayton, Dayton, Ohio, USA

I. ABSTRACT

The availability of rare-earth magnets has made magnetic bearings and load suspension systems truly feasible. Their technological significance is expected to grow, considering the present development of very high-speed rotating machines such as motors, ultra-centrifuges and turbomolecular pumps, and of magnet-cushion railroads.

As part of an effort to develop mathematical design tools for such devices and a testing capability, we built a test stand capable of measuring two orthogonal components of the forces between magnets of any shape in pairs, or between a magnet and a soft magnetic part. This was used to determine such forces on several cylindrical and ring configurations typical of passive rotary bearings. Demagnetization curves were measured on each of the magnets used, so that quantitative comparisons with computerized model calculations could be made.

This paper describes the instrument and method, and it reports results of axial and radial force measurements as a function of the magnet separation, axial offset and tilt between the magnets of a bearing. These are compared with computer-aided analytical force calculations.

Discrepancies were found between predictions and measurement, and between measured forces in attraction and in repulsion. These are small for good, square-loop REPM or ferrites, but significant for magnets of low H_k and for mixed material pairs. The influence of material properties on the different force functions and the limitations of simple mathematical models are explored. Our results are put in perspective to theoretical and experimental force data published by other workers.

****

Paper No. II-7 at the 8th International Workshop on Rare-Earth Magnets and Their Application, Dayton, Ohio, 6-8 May, 1985. (Proceedings Book: University of Dayton, Magnetics, KL-365, Dayton, Ohio 45469, USA)

Address inquiries to: K. J. Strnat, University of Dayton, Magnetics Laboratory, KL-365, Dayton, Ohio 45469.

II. INTRODUCTION

The idea that permanent magnets could be used in bearings and other weight support systems is relatively old. For example, two papers published in 1960 and 1961[1,2] describe the basic approach to the design of passive magnetic bearings and point out many theoretical advantages of such bearing systems over conventional mechanical (ball, roller, or sleeve) bearings. By allowing an object such as a rotating shaft, or even a motor vehicle, to "float" in a magnetic field, material contact is avoided, thus reducing friction and wear and eliminating the need for lubrication and cooling.[3]

There exist some applications in which magnetic bearings are the only reasonable choice. They can be employed in situations requiring very high rotational speeds, or in a vacuum with no fear of contamination from the lubricants or danger of seizing because of oil deterioration.[3] This type of magnetic bearing application is particularly useful in navigational systems of space satellites, as well as in other military and/or space applications.

The further development and increasing availability of REPM's will allow the design of better and larger magnetic bearings and load support systems. In order to most effectively utilize these expensive magnets, but also ferrites, in such systems, better design and analysis tools must be developed to enable the engineer to properly predict the forces generated. The work reported in this paper is part of a project at the University of Dayton to develop a capability for the design of various types of magnetic bearing and coupling systems.[4,5,6] We have built an instrument which enables us to test the accuracy of computer-aided force calculations through the actual measurement of such forces. Magnet geometries of interest to designers of rotating passive permanent-magnet bearings were tested. Radial and axial forces between two magnets of cylindrical symmetry were measured as a function of magnet separation, axial offset, and tilt between the magnets. Some of these measurements were compared to computer-aided force calculations, while others went beyond our present analytical capability. Generally, the agreement between analytical and measured data was good. Some discrepancies were found, and possible explanations for these are described.

III. EXPERIMENTAL SETUP

An apparatus was designed and built which allows the simultaneous measurement of two mutually perpendicular force components between pairs of permanent magnets or between a magnet and a softmagnetic part. This is not restricted to parts or pairs of cylindrical symmetry. It incorporates translation stages, load- cell force transducers, an appropriate electronics package, and voltmeters. A previous University of Dayton student had constructed a simpler device of this kind which measured axial forces only.[5] It served as a "backbone" for the new, improved system described here. A photograph of the force-measuring apparatus is shown in Figure 1.

Several criteria were established for the design of this instrument. It was essential that any part of the structure coming in close proximity (perhaps within 10-15 cm) to the magnets tested should be made of nonmagnetic materials. Spurious forces due to a permanent magnet's attraction to a steel or iron part would certainly falsify the force measurement. Aluminum and nonmagnetic stainless steel parts were used wherever possible. The use of some structural parts made of magnetic steel was unavoidable: care was taken to adequately separate these parts from the permanent magnets.

The horizontal and vertical translation stages necessary to accurately position the magnets are commercial items. They are constructed almost entirely of nonmagnetic materials. Both stages are equipped with scales and verniers which allow reading the position to within 0.1 mm.

Because both axial and radial forces (as referenced to cylindrical coordinates) are of importance in rotary bearing design, a method of accurately measuring both these force components simultaneously had to be devised. Strain-gage transducers are employed for both directions. There are two separate "load cells" which measure these forces on the lower, quasi-stationary magnet. The cell for measuring the axial (vertical) force is mounted on a rigid and heavy support structure sitting on a "sled" that can move only horizontally. The displacement (beam deformation) of either load cell when fully loaded is less than 0.05 mm. This was considered to be negligible compared to the magnet-to-magnet distances of interest. The translation stages could thus be employed as the primary positioning and position-reading devices, making the previously employed[5] complex optical position-measuring devices unnecessary.

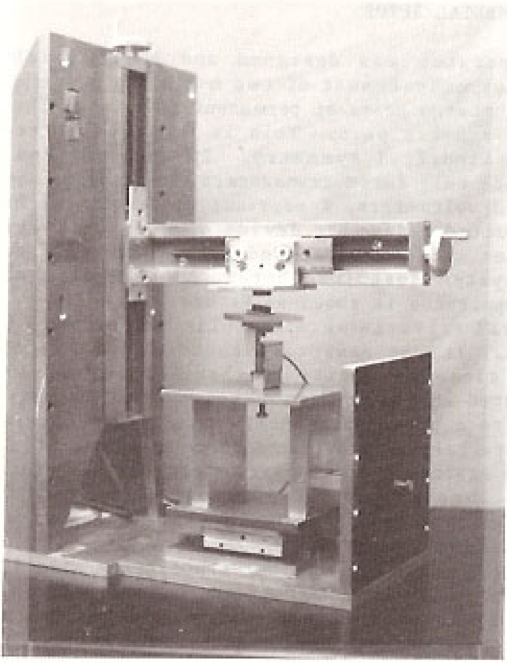


Figure 1. Force Measuring Apparatus

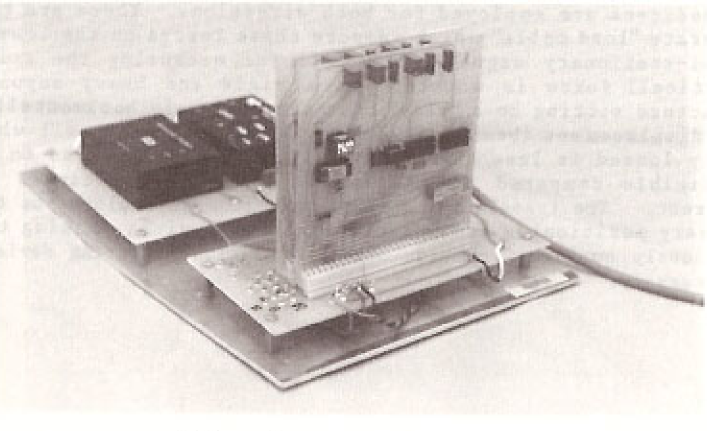


Figure 2. Electronics System

More complicated was the design of the radial-force-measuring portion of the system. Since two separate load cells are used for the axial and radial force measurements, it is important that each load cell "see" only a force which is essentially perpendicular to its load arm. Significant transverse force components can severely distort a load-cell's reading. Therefore, it was essential in the design of this instrument that the axial and radial force components be separated and channeled to the appropriate load cell.

The measurement of the radial (horizontal) force component is affected by the inescapable friction forces. In order to retain the integrity of the force measurement, the friction force must be reduced as much as possible. For this reason, the support stage "sled" was placed on a pair of ball bushings sliding upon parallel shaft rails mounted on a heavy, stationary aluminum-alloy base plate. In this structure, the shafts and the balls are made of magnetic steel. We experimentally determined the minimum distance needed between these and the lower magnet to make the spurious attraction force negligibly small (<0.1 gram). The actual distance was chosen larger still. The vertical-force load cell and the lower test magnet rest upon a heavy aluminum support block which can slide virtually frictionless on the ball bushings. The radial-force load cell is then mounted between this sliding support block and a stationary support, with one end firmly attached to either. The horizontal force on the magnet is now fully transferred to the load cell, and can also be measured with only a minimal displacement of the sliding block. The sample displacements under full load in the axial or the transverse directions can thus be ignored.

IV. EXPERIMENTAL PROCEDURE

Before any forces could be measured, several preparatory steps were necessary. All test magnets were first axially magnetized in a pulse charger with a peak field of 100 kOe. One magnet was then glued (with Duco cement) to an aluminum plate mounted on top of the axial-force load cell, and the other was glued to the movable aluminum magnet mount located directly below the scale of the horizontal translation stage (see Figure 1). For tests involving tilt, the lower magnet was mounted on an aluminum wedge which was then glued to the plate on the axial-force load cell.

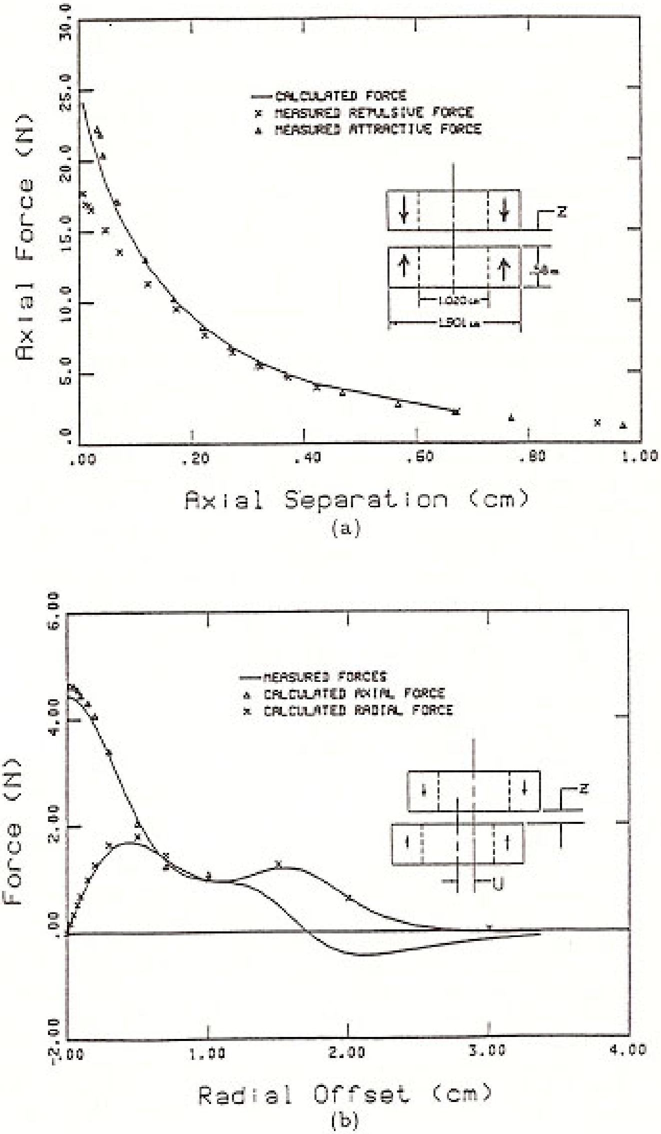
Before each measurement, the load cells' electronics system had to be properly calibrated. The op-amps were zeroed (i.e. the offsets were removed), the bridge circuit was balanced, and the gain was adjusted against a standard calibration resistor.

Photographs of the mechanical setup and of the electronics system are shown in Figures 1 and 2. Because the lower magnet remained in a fixed location in every measurement, the position of its top pole face was employed as the vertical reference position. This was done by placing a piece of rigid phenolic of precisely known thickness snugly between the two magnets. The position of the upper magnet's lower pole face was read from the scale on the vertical stage, and the thickness of the phenolic was subtracted from this reading to obtain the position of the lower magnet (Z = 0.0 cm). The magnets were axially aligned by bringing them very close and then adjusting the upper magnet's horizontal position until zero radial force was obtained. This corresponds to maximum axial force. Such "magnetic centering" will, of course imply geometric centering only if the magnets have uniform properties and true cylindrical symmetry.

For tests in which the magnets were axially aligned, the position of minimum possible separation was the starting point. The axial force between the magnets was then measured for increasing separation between them. For tests in which the radial offset U was the independent variable, the desired axial separation Z was set and then the magnets were axially aligned. Measurements were then made for increasing radial offset. For tests involving tilt, U = 0.0 cm was taken to be the relative position yielding the maximum axial force while maintaining the minimum possible separation. This is clearly not the position where the the geometric centers are exactly above each other. The same method was used to provide an initial position for the radial sweep tests.

V. EXPERIMENTAL RESULTS

Force measurements were made on a wide variety of magnet geometries employing several different permanent magnet materials. Here we shall only discuss those results we considered to be most interesting. The original goal was to test the accuracy of a computer program, written by Mr. Steven Dellinger, a University of Dayton student[6], which calculates the axial and radial forces generated between permanent magnet pairs. Figures 3(a) and (b) describe the results of two such tests, both employing the same set of identical $SmCo_5$ rings. Their dimensions and relative positions are shown in the insert sketches. Figure 3(a) shows both attractive and repulsive axial forces measured as a function of axial separation (Z) with the magnets axially



(a)

(b)

Figure 3. Comparison of Measured and Analytically Determined Force Values. Identical $SmCo_5$ Rings. (Positive Force Repulsive.)

aligned. Figure 3(b) shows axial and radial forces for the repulsive mode measured as a function of radial offset (U) with Z held constant.

The computer-generated force predictions, in each case, follow the general curve shape of the measured data. However, in some cases the force magnitudes were off by several percent. This is especially true for small separation in the repulsive mode. These errors can be attributed to several sources and can be classified into two categories: errors inherent in the computer program and errors inherent in the measurement techniques.

The errors attributable to the program are discussed in detail in Dellinger's paper.[6] As seen in Figures 3(a) and (b), the measured attractive-mode forces were considerably larger than the repulsive-mode forces for very small axial separations. This is due primarily to the shifting of the magnets' operating points along the M vs. H curve. If the computer program assumes a single, constant value for M, it cannot take into account this variation of the magnetization which occurs when the top of the M vs. H curve is not perfectly flat. In using the program to calculate the forces of Figures 3(a) and (b), we estimated the open circuit demagnetizing factor of the rings and used this to obtain an overall "average" magnetization value from the M vs. H curve. We chose $M = 560$ emu/cm^3, corresponding to approximately 90% of the remanent magnetization M_r. Through a more refined use of the magnet's measured M vs. H curves, it is possible to obtain a better fit between the calculated force curves and the measured values for attractive and repulsive forces. This is done by using different M values read from the demagnetization curves at an estimated value of the appropriate (average) external field to which the magnet is exposed.[6]

Any inhomogeneity of a real magnet's salient properties throughout its volume cannot be taken into account in our present computer program, and this can also lead to errors. When brought close together in the repulsive mode, the magnets could experience significant local demagnetization on the side facing either magnet. Some of this induced nonuniformity of M is reversible, and some is irreversible, when the magnets are separated again. When axially misaligned and close together, the magnets can also impose upon each other large transverse fields which might alter the magnet's usual direction of magnetization. For these reasons, the computer-generated force predictions are consistently larger than the actually measured repulsive-mode forces. These discrepancies are small for magnets having high coercive force, a flat demagnetization curve and very high anisotropy (stiff magnetization vector). Most REPM and certain ferrite grades fulfill these conditions, and thus the calculations yield good results, while Alnico magnets certainly do not.

The incongruity of measured and predicted forces between the magnets is not wholly attributable to the insufficient description of the magnetization state and to errors within the computer program. A degree of uncertainty in the magnets' relative positions is caused by the small displacement of the load cells' load arms (assumed to be less than 0.1 mm). The translation stages are also slightly deformed when the magnets exert large forces. These errors are magnified at small axial and radial displacements, when the uncertainty in the magnet position is comparable to Z or U. The electronic force measurement technique, though far more accurate than our previous mechanical measurements [5], could be further improved through the use of cathetometers, or some other optical sensing device, to more accurately determine the magnet positions.

Horizontal friction forces, though minimized in the design of the instrument, were unavoidable. They affect the transverse (or radial) force component. As seen in Figure 3(b), the computer program predicted values slightly higher than the measured radial forces. This could be due to a small friction force component opposing the true radial force between the magnets. This error is dependent upon the total weight of the sliding support block, as well as the magnitude of the axial force between the magnets, so it is not constant. Friction forces and errors could have been reduced by lowering the mass of the sliding support block. However, the block weight must be larger than the greatest axial attraction force to be measured.

Improper pre-measurement calibration of the load cells is another possible source of experimental error. Electronic drift present in the instrumentation system's circuit components is unavoidable (though we minimize such drift by allowing the electronics to warm up overnight). It, too, contributes to inaccuracies.

Many other interesting measurements were performed which are not compared to analytical results. One such test, the results of which are shown in Figure 4, measured the axial force, as a function of Z, between identical $SmCo_5$ rings, non-identical $SmCo_5$ rings, and a ring and a disk (both $SmCo_5$). In each case, the magnetic moment vectors were in the same direction, suggesting an attractive force (positive in Figure 4). While the force profiles in the first two cases (identical and non-identical rings) were of the same general shape and magnitude and the force was always positive, the ring and disk actually repelled each other at small axial separations. The force then became attractive as Z was increased and remained fairly constant over a large range of Z. Though the force profile in this case was very interesting, the magnitudes of the forces generated between the ring and the disk were quite small -- limiting the practical use of such a bearing configuration.

Several measurements were made with the lower magnet tilted at various angles. Figure 5 compares the axial forces between two identical $SmCo_5$ rings, in the attractive mode, for three cases: with the lower magnet untilted, at a 10° tilt, and at a 23° tilt. The force magnitudes for a given axial separation decrease as the degree of tilt is increased. Note that the three curves are for the same distance, Z, of <u>closest</u> axial approach.

Figures 6(a) and (b) show the axial and radial forces, as a function of radial offset U, between identical $SmCo_5$ rings in the attractive mode, again with the tilt of the lower magnet as the parameter. The solid curves (no tilt) were actually discrete measurements similar to the others, but the individual points were connected by a solid line for ease of comparison. The curve shapes are similar for the no-tilt, 10° tilt, and 23° tilt cases, with relative maxima and minima occurring at approximately the same locations. Again, the peak force values tend to decrease as the degree of lower magnet tilt increases. Yet, while the no-tilt force profiles are symmetric about the point of no radial offset (U=0.0), the tilted cases do not show such symmetry, reflecting the fact that offset in the plane of the tilt changes the local relative geometry differently for positive and negative values of U. It would be interesting to see analytical force predictions of these tilted bearing geometries.

<u>ACKNOWLEDGEMENT</u>

T. C. Morcos acknowledges partial financial support of this project under his DoD graduate fellowship grant. The grant is administered by the US Army Research Office under grant No. DAAG 29-83-G-0007.

REFERENCES

1. F. T. Backers, "A Magnetic Journal Bearing," Philips Technical Review; Vol.22, No.7; pp.232-238, 1960.

2. M. McCaig, "Permanent Magnets for Repulsion Systems," Elec. Rev.; p.425; Sept. 15, 1961.

3. Karl J. Strnat, "Review of Devices Using Rare Earth-Cobalt Magnets," Proc. 4th Intl. Workshop on Rare Earth-Cobalt Perm. Magnets, ed. H. Kaneko, Soc. Non-Trad. Technology, Tokyo, Japan, 1979, p.12.

4. James B. Y. Tsui, et.al., "The Effect of Intrinsic Properties on Permanent Magnet Repulsion," IEEE Transactions on Magnetics, Volume Mag-8, June 1972, p.188.

5. Andrew Y. Piatnicia, "A Study of Permanent Magnet Bearings," Undergraduate Thesis, U.D. Honors Program, April 14, 1983.

6. Steven J. Dellinger and Karl J. Strnat, "Field and Force Calculations for Passive Magnetic Bearing Systems" (this proceedings). See also: S. J. Dellinger, M.S.E.E. thesis, University of Dayton, March 1984.

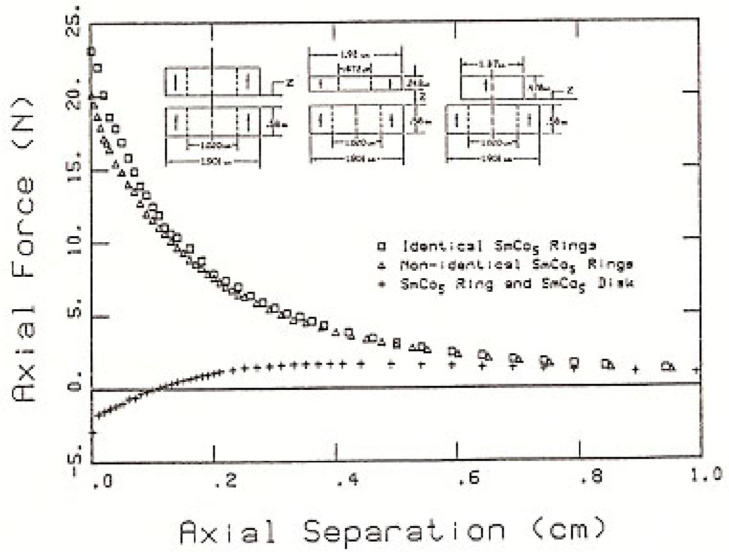


Figure 4. Axial Force as a Function of Axial Separation for Different Magnet Combinations. (Positive Force is Attractive.)

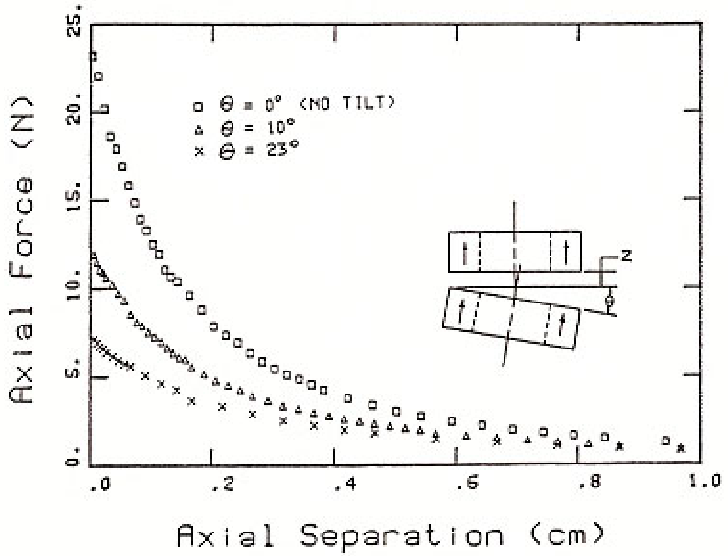


Figure 5. Axial Force as a Function of Axial Separation with Tilt as the Parameter. Attractive Mode. Identical $SmCo_5$ Rings — See Figure 3(a) for Magnet Geometries.

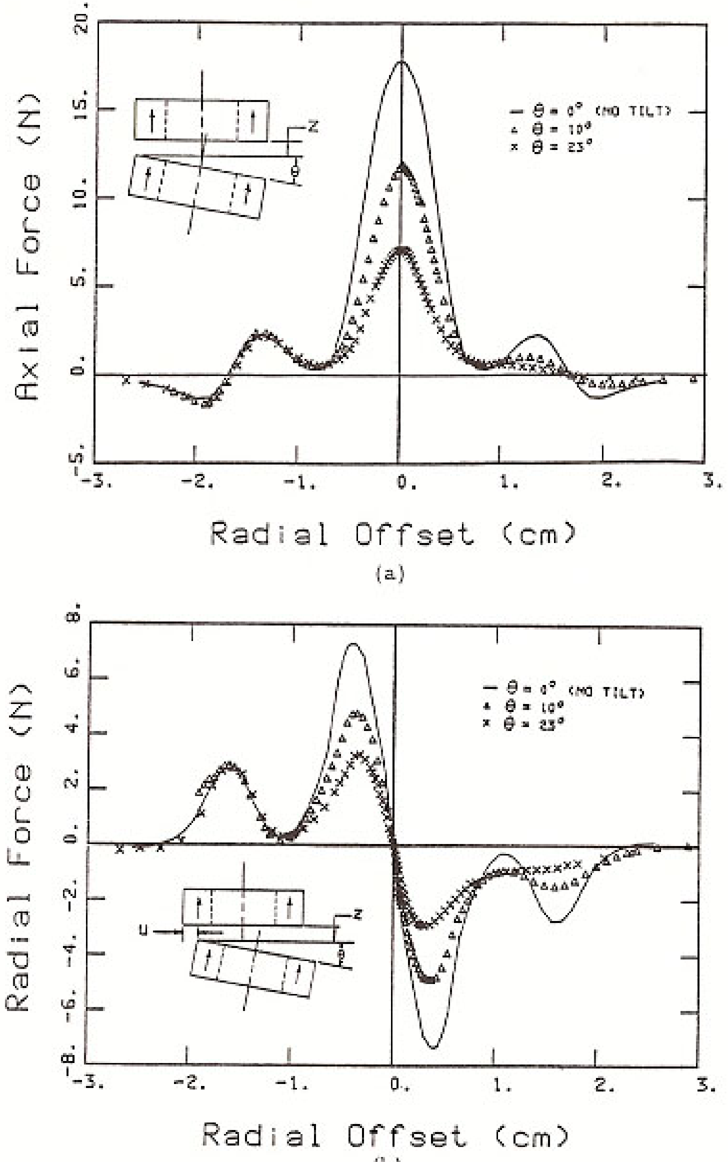


Figure 6. Axial and Radial Forces as a Function of Radial Offset with Tilt as the Parameter. Identical $SmCo_5$ Rings -- See Figure 3(a) for Magnet Geometries. (Positive Force Attractive.)