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CAMBION ®

DEVELOPMENT OF A DC MOTOR WITH

VIRTUALLY ZERO POWERED

MAGNETIC BEARING

TABLE OF CONTENTS

PREFACE

Previous magnetic bearing - DC motor system delivered to NASA by Cambridge Thermionic Corporation required 20-30 watts of continuous support power. Although this system performed will the continuous support power was a disadvantage for space applications.

The object of this contract was to develop a magnetic bearing - DC motor with a minimum of power required for the support system. It was felt that permanent magnets could be made to carry the steady state bearing loads while the electromagnets could be required only to counteract the transient base disturbance inputs.

The period of this contract was to be nine months in length. However, within three months the basic principal was reduced to practice. This principal was called "Virtually Zero Power" (VZP) and was demonstrated in a working device at NASA, Goddard Space Flight Center on 25 February 1971.

Following this demonstration, work proceeded to increase the radial support capability, design and fabricate a drive motor and design and fabricate the electronic drive circuitry.

Subsequent investigation showed that the radial stiffness could be increased by armoring the permanent magnet with steel. This also required the use of relatively narrow magnetic air gaps which put a greater burden on the mechanical alignment and electronic servo system. A magnetic bearing using steel armoring on the permanent magnets was designed and built. This device was to be a Magnetic Bearing Scanner Mount (MBSM).

NASA provided a motor to be integrated into the magnetic bearing system. This newly developed motor was considered to have qualities suitable for scanner pointing applications.

The motor was integrated into the magnetic bearing system and the complete device was delivered and demonstrated at NASA, Goddard Space Flight Center on 19 September 1972.

SECTION I - VZP DEMONSTRATION MODEL

1.0 MAGNETS

It became evident early in the development that there was need for a feasibility study to determine if it would be technically possible to carry all steady state bearing loads (axial, radial, and torsional) solely through the use of permanent magnets (requiring zero power).

The NASA Engineer stressed the importance of utilizing a high magnetic flux density (B) (through the use of permanent magnets), in the formula $F - kB^2$. It was felt that the required magnetic modulation, for stability in the presence of disturbances could be obtained more efficiently in this manner.

The selection of the most efficient geometrical configurations among the large number of possibilities became a basic problem. It was early concluded that there was insufficient information available to fix on a particular design. It was therefore decided to: (1) Examine a number of possible designs, (2) Make measurements, (3) Further investigate the use of the new Samarium-Cobalt magnets. (See Figures 1 and 2)

In Figures 3 through 9 in the Appendix are graphs taken from data on several configurations, including some with very small (1" x 1/4" discs 25 gram) Samarium-Cobalt magnets and more with very large (50 lb.) Alnico magnets. In connection with the use of the large magnets, two extremes in L/D ratios were examined. The large diameter tube (L/D = 1.337) is on the edge of torsional instability while the smaller diameter tube (L/D = 2.675) exhibits excellent torsional stability.

There is very obviously a discrete point on an L/D curve ratio where one passes from stability to instability - for any given ring geometry and gap. Although not a specified part of the project - since it would be sufficient to employ an arbitrarily high L/D ratio.

Engineering data on Samarium-Cobalt magnets, as well as samples, were provided by the Raytheon Company of Waltham, Massachusetts. Because of the newness of these magnets and the consquent lack of understanding of their behavior, some of the data concerning Force/Displacement attached to this report must necessarily be regarded as preliminary. It has become evident, however, that one is dealing with a very unusual material which must be handled by quite different methods than those normally employed with older "alnico" type magnets. Specifically, it is evident that if is desired to obtain the very high force levels possible with this light weight material, one must reduce the "armoring" (by ordinary steels) to the shortest possible path lengths. The Samarium-Cobalt magnet must be thought of as a large "air-gap" magnet.

A possible geometrical configuration began to evolve. It developed partly from the absolute necessity to keep the pole piece lengths – in the use of Samarium-Cobalt magnets – extremely short. Additionally, it is believed essential to have very high speed (low inductance) servo operation, an attempt has been made to utilize a linear ("ironless") motor in the high field provided by the supporting permanent magnets. Such an approach does appear to have merit, expecially due to its simplicity and apparent high order of theoretical efficiency.

A test of such a system was conducted on the "magnetic gate" fixture. It showed that a $\pm$ 3 lbs. of force change (electric modulation) is provided through the step-function application of 2.4 watts. (This is in a 24 lb. permanent magnet total available force level (at zero gap)). Results were obtained at a .050" air-gap. Due to flexural limitations of the test fixture, smaller air-gaps could not be examined. The mechanical assembly was not rigid enough to handle to higher force levels. It was apparent, however, that percentage modulation was tending to increase with gap reduction. Even so, such a 10% modulation might prove sufficient for servo control of a complete system. Because of the clearly demonstrated superior properties of the Samarium-Cobalt materials, it was then proposed to abandon any further activity with Alnico

type magnets so as to be able to concentrate on the efficient use of the new Samarium-Cobalt material. Subsequent emphasis was directed toward (1) linear generators, (2) linear motors suitable for use with Samarium Cobalt and "Virtual Zero Powered".

1.1 MAGNET TESTS

After selection of Samarium-Cobalt magnets, emphasis was next placed on construction of apparatus for evaluation and test. Two new cup cores were manufactured to contain the Samarium-Cobalt 1/4" x 1" magnets. Each magnet of the mating pair was fitted with a 1/2" diameter (.025" square cross-section) flux concentrating ring. On one of them there was built on, as an integral part, a shaft extension (1.5" x .150") so that additional devices might be installed on the end of the system. These new cup cores were not as thick as the set previously made because there is no armoring other than the rings. A miniature rate generator was constructed. A small linear motor coil was also built to fit into the leakage flux path of the "rotor" cup core, while being fixed to the "stator" core.

In addition to the above, a rigid stand was constructed to hold the stator coils approximately six inches apart and to clamp them securely in this position. (See Photographs 1 through 6.)

Quite clearly the elimination of the steel armoring to the Samarium-Cobalt magnets resulted in a higher effective force level both axially and, to some exent, radially as well. Axial measurements were reasonably straightforward. (See Figures 10-13)

Shims were employed (.003") to fix the air-gap and the breakaway force measured for each increment in displacement as shims were added from zero air-gap to the maximum of interest. The dial of the Chatillion force gauge recorded maximum force encountered and, since the breakaway point was precipitous, the method yielded high accuracy. All elements had to be made very rigid to preserve pole face alignment and prevent "cocking", in the face of high force levels.

Measurement of radial forces was not quite so easily accomplished. In fact, considerable effort was actually put into the design and construction of the apparatus before a satisfactory method was developed. The difficulty was in preserving accurate pole face alignment at small air gaps, in the presence of the high axial pulling force. This method finally worked out is illustrated in Figure 11. The data from this test is shown in Figures 12 and 13.

It was found very important to have the "stabilizing" rod long and stiff in order to preserve pole face alignment. However, when all had been put in order, it was readily possible to measure radial forces down to .003" air-gaps with excellent repeatability.

Some testing was also done with the idea of using one end of the magnetic bearing as the velocity (linear) motor. The constituted a negative feedback system and was attractive because of its simplicity. However, results were inconclusive, largely because sufficient force could not be obtained from the motor. In the space available within the cup core only 56 turns of #28 wire could be inserted and still allow for the necessary .025" radial "play". If the scheme was to receive further attention, larger cup cores would have to be employed. Tests did show that response time of the whole system was sufficiently short, and this was the point of most interest at the time.

Also the miniature rate generator was attached to the shaft and was tested. An unsatisfactory low output level was encountered, but again the time constant appeared reasonably short. (This small unit was built with the idea that it might later be placed within the shaft of the rotor).

1.2   VIRTUALLY ZERO POWER PRINCIPLE

Relatively early in the investigation, a rather far reaching decision was made: namely, "to fabricate a complete system as quickly as possible to prove out the overall theory of the Virtually Zero Power System". This was done and the principle was proved and there was no longer any doubt whatsoever concerning the validity of the theory of "VZP".

To construct a complete operable system in a short period of time required making numerous compromises. Previously built "cup cores" were known from tests to be quite efficient. Their effective use, however, entailed working at close air gaps (of the order of .005" - .010") where dimensional tolerances are critical. However, to achieve a time table of one month for completion of the apparatus made it impossible to consider their use.

It was found that a triplet configuration of 1" diameter "raw" Samarium-Cobalt magnets yielded 2 lbs. of radial force at air gaps of .100" to .200". To be sure, such a system could not be expected to give a steep radial force/displacement curve, but if fairly large radial clearances were employed, it appeared sufficiently high to allow construction of a workable demonstration - if rotor weight was kept low. Unfortunately, it was not possible to secure more than two Samarium-Cobalt magnets with large enough clearance holes from the Raytheon Company in time. This meant that only a pair of doublets were available.

The system was designed to separate the permanent magnet radial support magnets by approximately 5". Two axial force coils were built to act oppositely against a very light central disc of BFM steel. These force coils had to develop sufficient force to enable starting the system from zero air gap. It could be accomplished by application of 16 watts from the amplifier. Next, a very simple displacement system was built. This system consists of two photo-cells looking at two micro-miniature lamps. The rotor carries on one end a ring, mounted on transparent plastic, which divides the light equally to the two sensor cells when the central disc is halfway between the two force coil cup cores. Such a simple system proved adequate. See Figure 14.

A light shield was made to avoid effects of stray light and surrounded the whole sensor system. The rate generator employed makes use of one of the rotor carried support magnets - a temporary but effective measure.

When the rotor is precisely in the central position (unstable) the rotor "falls" to one side or the other to the stopped position (± .025") in 8-17 seconds, depending on the amplifier gain. This free fall situation is naturally dependent upon amplifier gain, P.M. air gap, etc., but in general is a measure of rate generator effectiveness.

Upon assembly of the apparatus, it was immediately found that the force coils vibrated as a tuning fork. This required that the free ends be rigidly clamped, which was done - the clamp being additionally used to support the force coil terminals.

By 2 February 1971, the system was operational. Some time was spent in observing the behavior of the unit. It was soon found that:

1. The bearing could be operated with virtually zero power to the force coils (Bearing Horizontal). Actually .05 watts.

2. That this situation also applied to Vertical Operation IF the amplifier was re-balanced in this position.

3. That the system would self-start in any position. Starting required approximately 16 watts peak and was completed in a measured 150 milliseconds.

It was found that initial balancing adjustments were critical, in that it was easily possible unwittingly to balance one unbalanced part of the system against another oppositely unbalanced part. When this was done, a totally unstable system resulted! A procedure, outlined below, was then worked out to avoid the problem:

1. Balance the amplifier with power stages shut off. This is done by adjusting the amplifiers recommended bias potentiometer while viewing the zero-center output meter.

2. Adjust the relative positions of the P.M.'s along the rotor shaft so that the equal force (unstable) position occurs with the central disc is precisely midway between the force coil cup cores.

3. Then physically move the fixed portion of the displacement sensor system (with the force coils ON) to make the central disc arrive in

the previously determined central position. (Note that the disc's axial motion follows the sensor motions, i.e. has the same sense).

4. Observe the zero-center meter. It should now read zero. If it does not precisely conform to zero, then minor amplifier balance adjustment may be made.

5. Note that the central axial position is that position at which the rotor is equally likely to move left (or right!). With the displacement sensor shut-off and this position is achieved, then the rotor will hold this position for a considerable time - staying away from the destination pole (whichever) for as much as a minute. (On rare occasions when all balance adjustments are nearly perfect.)

It was found that there was a small double zero position, but it indicated further detailed examination as its elimination would permit a closer approach to absolute zero power.

A very poor coast time was immediately noted. This was attributed to the open field resulting from the use of "raw" P.M.'s reacting on the axial shaft which penetrated two of them.

As experimental work continued, it was learned that with the displacement sensor shut-off ("rate alone") that center position could be manually maintained for extended periods. This was done by watching the zero-center meter while manually adjusting the amplifier balance control. Practice was required, after which it was possible to hold close to center positions for a long as was desired. Such controlling required no appreciable skill since ample time was available for introduction of correctional signals. This was due to the long time constant of the rate system as a whole. The next logical step was to introduce the 3rd servo or centering system. This was done on 3 February 1971 and proved highly effective. It should be remembered that this system senses the unbalanced conditions across the force coils (essentially the zero-center meter signal) and serves to remove this unbalance by biasing the amplifier in the proper direction by the proper amount.

Due to the low voltage level of the force coils (< 4V) it was not possible, at that time, to introduce the desired dv/dt signal. In spite of this, it was found possible to secure reasonably stiff servo response.

With the "3rd" servo in operation, it was immediately possible to secure reasonably stiff servo response. With the "3rd" servo in operation, it was immediately possible to see automatic compensation for applied axial loads. To be sure, nothing like optimum operation was achieved, but, in principle, the system was certainly a success. The rotor moved in opposition to axially applied loads with total motion of $\pm$ .020" before control was lost. Within these limits, and with the axial loads not exceeding several pounds, the system was stable and obviously kept the required power to low levels – usually less than 1/2 that required to counter the loads without the system in operation.

The concept of the Virtually Zero Power magnetic bearing system was thus proved out. Clearly, much remained to be done before a sophisticated motor-bearing could be fabricated. But it then became quite apparent that VZP magnetic bearing systems were practical.

At this time, an additional interesting experiment was conducted. The 2nd (displacement) servo was disconnected (after starting) and reliance was placed only on the 1st (rate) and 3rd (force balancing system).

In spite of the previously mentioned non-optimum characteristics of the 3rd servo system, operation was quite stable. The possibility of such a system had been predicted before testing so it was particularly gratifying to observe the actual validity of the idea.

In order to conserve overall power, it would be possible to disconnect the #2 servo system whenever the rotor is axially centered. This could be done (simply) by deriving power for the sensor lamps from un-differentiated output of the amplifier. This power is essentially zero when the rotor is in the center positions when starting is required, (thus the lamps are "On").

As a result of the work accomplished, during this early period it was concluded that the concept of a Virtually Zero Powered magnetically supported rotor was feasible. Further work was then pointed toward adding two additional magnets, and increasing the overall performance of the #3 servo system, and to add a motor. See schematic in Figure 15.

1.3 GENERAL DIFFERENCES BETWEEN ELECTROMAGNETIC & ELECTROMAGNETIC/PERMANENT MAGNET SYSTEMS

The following is a listing of the differences between electromagnetic and electromagnetic/permanent magnet systems:

1. No thermal problems. Control coils operate cold (very close to ambient.)

2. There is no mechanical strain accross the rotor and, therefore, a lighter supporting structure is possible. (In all fairness, this could also be done with the EM System).

3. Almost exactly 1/2 the number of electronic components are required. (The circuit is differential rather than push-pull).

4. There are no large steady state currents in electronic system – they operate in standby condition, except for transients. (About 2 watts + unresolved #3 servo differential power of approximately < 0.1 watts.)

5. It is readily possible to secure a satisfactory displacement signal with 1 (one) micro-miniature lamp only. Multiple redundancy is also possible.

6. Due to the "empty weight" being lower in the permanent magnet system, the payload to empty weight ratio can be higher.

7. The configuration is more attractive from a dynamic standpoint since outboard weights are very much smaller.

8. Cocking problems are reduced.

1.4.0 DEVELOPMENT OF BREADBOARD MODEL OF THE VZP MAGNETIC BEARING SYSTEM

There then followed the following series of events:

1. Preparing for demonstration of the breadboard model unit.

2. Demonstration of the unit at Goddard Space Flight Center on 25 February 1971.

3. Collection of data on the unit.

In Figure 16 is a plot of amplifier performance which shows that there is little, if any, "cross-over" distortion. It will be recalled that earlier mention has been made of a "double-zero" position. It became evident that in view of the linearity noted in the amplifier characteristics, it clearly could not be attributed to the amplifier. Therefore, the "double-zero" condition needed to be explained in some other way. It then was believed to be a fundamental characteristic of the system as a whole.

It was also noted that the rotor must accelerate (axially) either to the right or to the left from the neutral position as determined by the magnetic fields of the permanent magnets. The function of the force coils is to induce this acceleration to approach zero, as a limit.

Assume, for example, that the rotor is accelerated to the left but is very close to the zero acceleration position. We now move the bias control so as to start the acceleration through zero and beyond – to the right. One can see that to counteract the right hand acceleration (if we wish to approach zero again) the bias must now be moved through zero – to the left again. There is, therefore, an unstable "flip/flop" condition existing about the zero acceleration-zero power position. This is fundamental to the system as conceived at the time.

It became important to examine the magnitude of the unstable region. Measurements showed that the actual axial motion, in the unit, was of the order of plus or minus 0.0003" and that the power required to work against this instability was about .05 watts.

It was then believed that the unstable region could be reduced in magnitude by a number of means such as (1) increased displacement system gain, (2) increased rate system gain, (3) reduced permanent magnet force level – this being the least desirable. But it was thought that the "backlash", as in mechanical devices, could not easily be eliminated entirely – but must be allowed for in bearing use. In some applications, for instance, the system may be deliberately biased to one side so that the rotor cannot accelerate through zero. This, however, would cost power. The Principal Investigator, Mr. Joseph Lyman, completed his portion of the task assignment at this point with the verification of the Virtually Zero Power principle by practical demonstrations and test.

1.4.1 NEW TECHNOLOGY

A fundamental technological development confirming previous work of the principal investigator was then reported. A stable Magnetic Suspension system was fabricated and a fundamental basic electromagnetic principle reduced to a practice, wherein a Magnetically Supported rotor utilizing permanent magnet primary support had been made stably operational utilizing Virtually Zero Power. The system is described as follows:

1.4.2 MECHANICAL CONFIGURATION

1. A triplet of 1" diameter "raw" Samarium-Cobalt magnets yielded >2 lbs. of radial force at air gaps of .100" to .200". Such a system could not be expected to give a steep radial force/displacement curve, but if fairly large radial clearances are employed, it appeared sufficiently high to allow construction of a workable demonstration – if rotor weight was kept low. Unfortunately, it was not possible to secure more than two Samarium-Cobalt magnets with large enough clearance holes from the Raytheon Company in time. This meant that only a pair of doublets were available. This proved to be sufficient, but provisions were made to complete the triplet pairs as soon as the additional magnets were received.

2. The system was designed to separate the P.M. radial support magnets by approximately 5". Two axial force coils were built to act oppositely against a very light central disc of BFM steel. These force coils had to develop sufficient force to enable starting the system from zero air gap. This could be accomplished by application of 16 watts from the amplifier.

1.4.3 DISPLACEMENT SENSING SYSTEM

1. A very simple displacement system was built. The system consisted of two photo-cells looking at two micro-miniature lamps. The rotor carried on one end a ring, mounted on transparent plastic, which divided the light equally to the two sensor cells when the central disc was halfway between the two force coil cup cores. This simple system proved adequate and is diagrammed in Figure 14. A light shield was made to avoid effects of stray light and surrounded the whole sensor system.

1.4.4 RATE SENSING SYSTEM

1. The rate generator employed made use of one of the rotor carried support magnets – a temporary but effective measure. When the rotor is precisely in the central position (unstable) the rotor "falls" to one side or the other to the stopped position ($\pm$ .025") in from 8-17 seconds. This free fall situation is naturally dependent upon amplifier gain, P.M. air gap, etc., but in general is a measure of rate generator effectiveness.

1.4.5 DESCRIPTION OF BEHAVIOR OF ASSEMBLED SYSTEM

1. When the system was operational, some time was spent in observing the behavior of the unit. It was soon found that:

    a. The bearing could be operated with zero detectable power to the force coils (Bearing Horizontal). Actually .05 watts.

    b. That this situation also applied to Vertical Operation IF the amplifier was re-balanced in this position.

    c. That the system would self-start in any position. Starting required approximately 16 watts peak and was completed in a measured 150 milliseconds.

2. It was found that initial balancing adjustments were critical, in that it was easily possible unwittingly to balance on unbalanced part of the system against another oppositely unbalanced part. When this was done, a totally unstable system resulted. A procedure, outlined below, was then worked out to avoid the problem:

   a. Balance the <u>amplifier</u> with power stages shut off. This is done by moving the amplifiers recommended bias potentiometer while viewing the zero-center output meter.

   b. Adjust the relative positions of the P.M.'s along the rotor shaft so that the equal force (unstable) position occurs with the central disc is precisely midway between the force coil cup cores.

   c. Then physically move the fixed portion of the displacement sensor system (with the force coils ON) to make the central disc arrive in the previously determined central position. (Note that the disc's axial motion follows the sensor motions, i.e. has the same sense.)

   d. Observe the zero-center meter. It should now read zero. If it does not precisely conform to zero, then minor amplifier balance adjustment may be made.

   e. Note that the central axial position is that position at which the rotor is equally likely to move left or right. With the displacement sensor <u>shut-off</u> and this position is achieved, then the rotor will hold this position for a considerable time – staying away from the destination pole (whichever) for as much as a minute. (On rare occasions when all balance adjustments are nearly perfect.)

3. Also, it was found that there was a small double zero position. No serious attempt had yet been made to uncover the cause of this situtation, but it deserved further detailed examination as its elimination would permit a closer approach to absolute zero power.

4. A very poor coast time was immediately noted. This was attribute to the open field resulting from the use of "raw" P.M.'s reacting on the axial shaft which penetrates two of them.

5. As experimental work continued, it was learned that with the displacement sensor shut-off ("rate alone") that center position could be manually maintained for extended periods. This was done by watching the zero-center meter while manually adjusting the amplifier balance control. A little practice was required after which it was possible to hold close to center positions for as long as was desired. Such controlling required no appreciable skill since ample time was available for introduction of correctional signals. This is due to the long time constant of the rate system as a whole.

1.4.6 3RD SERVO OR CENTERING SYSTEM

1. This system senses the unbalanced conditions across the force coils (essentially the zero-center meter signal) and serves to remove this unbalance by biasing the amplifier in the proper direction by the proper amount.

2. Due to the low voltage level of the force coils (<4V) it was not possible, within the developmental period, to introduce the desired dv/dt signal. In spite of this, it was found possible to secure reasonably stiff servo response.

3. With the "3rd" servo in operation, it was immediately possible to see automatic compensation for applied axial loads. To be sure, nothing like optimum operation was achieved, but, in principle, the system was certainly a success. The rotor moved in opposition to axially applied loads with a total motion of $\pm$ .020" before control was lost. Within these limits, and with the axial loads not exceeding several pounds, the system was stable and obviously kept the required power to low levels - usually less than 1/2 that required to counter the loads without the system in operation.

1.4.7 CONCLUSIONS

In effect, the concept of the Virtually Zero Power magnetic bearing system had been proved out. Clearly, much remained to be done before a sophisticated motor-bearing could be fabricated. But at this point it appeared that it could certainly be done.

It has now been shown that permanent magnets can be made to carry the steady state bearing loads while the electromagnets are only required to counteract the transient base disturbance inputs.

The servo system for this type of magnetic suspension is not unique in itself. However, the combined system provides some unusual characteristics. The first being the reduction of power consumption to a minimum. The second however, is that the rotor moves in opposition to axially applied loads so that the permanent magnets continue to carry the load and maintain the power consumption at a minimum.

SECTION II - VZP CONTROL TECHNIQUES

2.0   MAGNETIC BEARING MOTOR AND MOTOR DRIVE CIRCUITRY

Attention now turned to the drive motor for the magnetic bearing. The rotor consisted of a 1/2" diameter Samarium-Cobalt magnet magnetized across the diameter. The stationary motor coils were arranged around the diameter of the rotor magnet at 90° intervals. This was done to provide a two phase system. Hall Effect devices were installed (1 per phase) in the motor coils to provide non-contacting commutation.

In the motor drive circuitry current feedback was utilized to provide maximum torque and efficiency. (See Figure 17 in Appendix.) Speed control was obtained by use of a negative voltage feedback loop around the amplifier. Top speed was ultimately controlled by the back EMF generated in the coils. See Parts List- Figure 18.

Pertinent motor data can be found in Figure 19 in the Appendix.

Subsequent improvements in the motor drive circuit components may be seen in Figure 20 in the Appendix.

2.1   MAGNETIC BEARING SCANNER MOUNT

At this point in the performance of the contract, Cambion was requested to submit a proposal for a modification to the contract to include a magnetic bearing scanner mount, MBSM, using the techniques developed during the first part of the contract.

It was recognized that the use of the magnetic bearing device as a scanner made accurate speed regulation necessary. Such regulation is obtainable if the device is rotated by a synchronous motor. The average rotational speed is then as constant as the frequency of the supply, and if the waveform is sinusoidal the instantaneous torque is constant producing constant instantaneous speed. Figure 21 shows the schematic of a 2-phase, .8 Hz power supply. It is made of a classical phase shift oscillator built arount Z1, an operational amplifier. The frequency is set by C1 and resistance R1 and P1 in series and C2 and the resistance in parallel R2 and P2. P14, R14 and T14 are used to

adjust the gain to give a good sine wave at a reasonable amplitude. T14 is a thermistor which is traditionally used to stabilize the amplitude. R3, C3, R20 and C20 provide the 90° phase shift with Z2 making up for the resultant attenuation. P15 permits amplitude equalization of the two phases and P3 sets the phase difference of 90°.

The motor is driven by the transistors Q1 through Q4 which are all 3 ampere Darlington power transistors.

Use of larger (1" diameter) diametrically magnetized rare earth cobalt magnets permitted a more potent motor and the larger diameter made it easier to provide windings with less space unoccupied by copper.

All the motor drive circuitry, like the support, was powered from a $\pm$ 12 volt source.

The prime purpose of the Magnetic Bearing Scanner Mount, MBSM, device was to rotate a scanning mirror in a satellite.

It includes an integral motor which, like all the rotating elements, would be supported by magnetic rather than mechanical bearings. This avoids the problems that often affect mechanical bearings in the high vacuum of deep space. The mirror was not included, although the mounting provisions were provided.

Specifications:

Mechanical

(1)	Length (C.G. mirror to opposite end MBSM)	$9 \pm 1/2$"
(2)	Diameter	$5 \pm 1/2$"
(3)	Weight	7 ± 1 lb.
(4)	Potential speed	48 rpm
(5)	Support Capability I (with load applied symetrically to shaft not mirror case)	5 lbs.
(6)	Stiffness (as above under support capability)	350 lb/inch
(7)	Support Capability II (with plan or load at 45°angle with respect to shaft mirror case)	5 oz.
(8)	Mirror mounting provision	1/4-28 NF thread

Electrical

Input voltage: $\pm$ 12 volts

Input power: Less than 8 watts

2.2   CLOSE GAP BEARING

An attempt was made to provide a bearing with magnet gaps of less than
.010" therefore increasing the radial stiffness. This close gap bearing was
connected to electronics used to run VZP magnetic bearings previously but
it was not possible to levitate the rotor. See Figure 22.

A large number of experiments to determine the cause of this ensued.
The electromagnets were insulated from their aluminum plates, the plates
were slit, and the same experiment performed with one of the electromagnets
in the same coaxial position without any of the bearing structure. This
latter test showed that the single pole at 500 Hz. was due to the structure
and it was found that it could be caused by simply inserting the force ring
aluminum partition in front of the rate coil. Slitting this partition radially
improved matters slightly – zero phase shift moved up to 600 Hz.

Finally, the partition was shielded with a piece of .014" transformer
silicon steel on each side. The two silicon steel discs being joined by
ferromagnetic screws through the partition, which also held the shields on.
This eliminated the problem and pushed the zero phase shift up to 10 KHz.
It was decided to widen the .008" air gaps to .018" to reduce the stiffness
and thus the band width requirement.

Even then, levitation was not achieved. The rate coil did not fit the
one inch diameter rate magnet too closely – there is an eighth inch
clearance on the diameter – but the assembly and disassembly of the bearing
had made it somewhat eccentric, and it was thought that we were troubled
by acoustic feedback via rate coil bobbin/magnet contact. To prevent
this, the magnet was moved so that it came close to but did not enter the
bobbin. This sacrificed half the rate coil output. We also shifted to the
pulse mode of operation and achieved levitation. In this mode the output
of the rate coil is fed to a Schmitt trigger circuit whose trip points are

symetrical about zero voltage. When the preset velocity was reached in one direction the electromagnet that was pulling the rotor toward it was shut off and the other turned on. A circuit that accomplishes this is shown in Figure 23.

There are various advantages and disadvantages to this arrangement. One of the plus features is that the electromagnets are driven from the highest voltage available thus insuring the fastest response time. With the bearing levitated, it was possible to make some observations impossible without levitation. The pulse mode of operation meant that the rotor was constantly subject to reversals of the electromagnets and the frequency at which this took place was of interest. One would expect that as the Schmitt trigger trip points approach each other and also zero voltage the frequency would increase. This did happen, and it was possible to maintain levitation from 250 Hz. to 1,500 Hz. with less power being drawn at the higher frequency. A trip point of 100 or 200 millivolts was sufficient. The actual output of the rate coil did not look just as one would have expected from the theory of operation. Although it should not have mattered which way one sent the current through the nonpolorized electromagnets, operation was possible only with proper poling.

It appeared that there was a considerable direct transformer coupling from electromagnet to rate coil. Whether this inhibited linear mode operation more than pulse was not known.

With so many changes made to secure levitation, it would have been necessary to analyze each variable at a time to see which was critical. However, success with wider gap bearing led the development to return to previously proven approaches.

During this period of investigation two other areas were explored. A "Bang-Bang" type servo control was considered and "Clamshell" type magnetic circuits were also considered. The results of these two concurrent investigations are detailed in the following two sections.

2.3 "BANG-BANG" MAGNETIC BEARING AXIAL CENTERING SERVO

In Figure 23 is shown a circuit used to axially center the rotor without displacement measurement. The following explains the physics behind this circuit.

In a passive radial bearing (although the use of this method is not restricted to this case) there is a null force position somewhere. But this no force position is unstable because if the rotor approaches either magnetic pole it is accelerated toward same.

Now assume that in some unspecified manner one applies a servoed force field to the rotor such that the rotor motion is vectorially opposite to any other force applied. To make this statement more concrete let us assume that the radial support magnets providing the passive radial, and the unstable axial force are temporarily removed. If one now pushes the still servoed rotor with one's finger it pushes one's finger back. Imagine that the radial support magnets are again active. The servoed force field will cause the rotor to flee from the magnet poles rather than be drawn to same and come to rest where the nonservoed force field is zero i.e. at the formerly unstable equilibrium point.

One method of producing such a servoed force field is as follows:

Let the servoed force field be of the simple "bang-bang" type i.e. two valued either $+F_s$ or $-Fs$. When the rotor achieves a $+V_0$ axial velocity let the $-F$ force be applied and maintained until it causes the rotor to reach $-V_0$, when the $+F_s$ force is applied. This simple servo will produce the desired result as demonstrated below.

Triggering the servo force from $+F_s$ to $-F_s$ when $+V_0$ is achieved and vice versa is equivalent to triggering whenever the kinetic energy of the rotor reaches $1/2\, mV_0^2$. The successive triggers will occur when the various forces acting on the rotor have made a change in its kinetic energy of mV_0^2.

Sometimes the net force on the rotor is $F_e + F_s$ and sometimes $F_e - F_s$, where F_e is the external (perhaps finger) force. But the work done is $(F_e + F_s) x_1$ in the first case and $(F_e - F_s)(-x_2)$ in the second. Where x_1 and x_2 are the displacements. But both the increments of work are equal being equal to mV_0^2. Thus:

$$mV_0^2 = (F_e + F_s)x_1 = (F_e - F_s)(-x_2) = (F_s - F_e)x_2$$

If $F_s > F_e$, which is essential for proper operation, it is seen that $x_2 > x_1$. But x_1 is the direction in which F_e would move the rotor in the absence of F_s, thus the net actual movement per cycle, $x_1 - x_2$, is against F_e. Q.E.D.

The circuit shown in Figure 23 carries out this motif quite simply. It happens to be the exact one in use when the NASA representative visited us and the values etc. are by no means sacred but are put in to be concrete. The blocking capacitor C is used to prevent strain on power supplies and Q_1, Q_2 during experiments. It may be replaced by a direct connection. The voltage follower Z_1 is not essential, we have used similar circuits with the rate coil going directly to Z_2. Z_2, a Schmitt trigger, is the essential element, doing the triggering discussed above.

The diodes D_1 and D_2 are worthy of mention. They determine which force coil gets the current, but they also permit the energy from one force coil to enter the other when the switch is made and prevent inductive kicks from sending currents into Q_1 and Q_2 then.

2.4   CLAMSHELLS

During the Magnetic Suspension work it was found to be of interest to increase the magnetic forces by armoring Samarium-Cobalt magnets. When it was found that NASA was interested in having such done, Cambion utilized some of the work previously done to produce what was called the "Clamshell" structure.

The largest Samarium-Cobalt magnets available at the time of this work were hollow cylinders 1" O.D., 1/2" I.D. and 1/4" long available from three suppliers. Subsequently, larger magnets were made available.

In addition, extensive work was done on a previous NASA Contract Number NAS5-11585 showing that when utilizing fringing to make a radially passive device, the ring width to air gap length could not profitably be decreased below 5, which restricts one practically to high gap permeances, excluding leakage.

The clamshell structure did not maximize the air gap energy. It employed the Samarium-Cobalt magnet to provide a fairly high remnant, B_r, and was also advantageous because it would stay magnetized with an adversely low L/D ratio.

Ideally, the polarized material would be as close to the air gap as possible with a small surface area (to prevent leakage) flux concentrator used to bring the pole tips close to saturation. There are two things to mention about the output area of the concentrator. One mentioned previously is that the ring width should not be less that 5 times the air gap, and conversely it should not be too large, say above 10 times. If the magnet had sufficient volume to saturate an unduly large ring, say 20 times the air gap distance, one should make two concentric rings etc.

The clamshell structure was selected as bringing the polarized material as close to the air gap with as little leakage as possible considering that the magnet was axially magnetized.

Figure 24 shows the first clamshell configuration tried. The high permeance of the load meant the B_D would approach B_r, or about 8,000 gauss for Samarium-Cobalt. Neglecting leakage, the area of the ring structure would be 1/3 that of the magnet to aim for 24,000 gauss. The area of the magnet is $\pi/4(1^2-1/2^2)$ = 3/16 or 0.6 sq. inch. The first trial was made without thinning the ring from .050 inches radially to .035 as shown — it being easier to remachine after trial than making a new piece. Thus the ring area was $1.3\pi \times .05 = 0.2$ sq. inch. The single force ring partition shown mechanically grounded in Figure 24 was clamped in a 3 jaw lathe check. A half inch diameter aluminum rod, 18" long, had all the other parts slid on and affixed to one end of same. The other end

had a short piece of flexible wire joining it and the lathe tailstock. It was then possible to axially pull the clamshell via the tailstock to nearly center the ring, thus simulating the magnetic bearing situation.

The parts of Figure 24 were all designed so that the air gap should come out zero. Then a piece of .014 inch transformer lamination was used to make a washer and increase the air gap. This produced an air gap of about .008" each side.

Force measurements were made by pushing on the clamshell with a Chatillon force gauge in 4 directions and averaging the results.

As described, the clamshell took 2 pounds to push it beyond its maximum travel. The latter occurred at about .050" in radial displacement.

The clamshell was then cut down to conform to Figure 24 as drawn i.e. with a .035 inch radial ring. This produced 3.5 pounds.

A single magnet in "opposition" as shown in Figure 25 was permitted to stick itself to the outside of the clamshell. This did more good than had been expected. The force rose to 5 pounds.

A second outboard magnet brought it up to 7.5 pounds. The configuration conformed exactly to Figure 25.

Two 2 inch diameter washers on the outside of the outboard magnets brought the support capability up to 10 pounds. This is shown in Figure 26. This seemed like a useful force and we turned to making a complete bearing using this structure. We did, however, try three other experiments which may be of interest.

First, since it was easy, we put in an additional washer making the air gaps .014 instead of .007 inches. This always cut the force in half. This statement applies to Figures 24 through 26.

Second, clamshells were made using Vanadium-Cobalt steel available at the time. Although it is doubtful that saturation was reached in the cold rolled steel used in the preceeding, it was felt that any increase in force using the high B_s material would indicate that we had saturated the cold rolled. Actually,

there was no improvement. However, while it is certain that the high field alloy can go higher than cold rolled when both are correctly annealed we annealed neither, and there doesn't seem to be any data available on the performance of unannealed and fairly heavily machined high field material versus similarly treated (or untreated) cold rolled.

The ring was then cut down from .035 to .025 inches on the radius. This reduced the radial support to 8 pounds. (See Figure 26) It should be noted that this brought the ring/width/air gap ratio below 5.

2.5   VELOCITY ONLY AXIAL CONTROL

An important investigation was the attempt to correlate the theories regarding velocity only axial control with emperical observations. In particular, operation of the suspension in the linear mode was repeatedly attempted. This was done because it was felt that this mode may require less bandwidth and thus permit one to operate stiffer bearings without increasing the frequency response of the circuit elements - particularly the force electromagnets. Increasing the bandwidth of the electromagnets means subdividing the solid silicon steel (laminating) currently composing same, to reduce eddy currents. However, such an approach is difficult and makes the structure less rugged. The results are summarized in deltail in Section 8.1.

The non-linear or bang-bang mode was discussed previously. As mentioned, suspension can definitely work while the whole system is oscillating by pure electromagnetic feedback. In the simple non-self-oscillating theory one can easily visualize the waveform that will be at the rate coil terminals. With some simplifying assumptions (immediate appearance of the force in one electromagnet and disappearance in the other and assuming that the electromagnet force is constant over the range of displacement permitted) the velocity will be a symetrical triangular function of time as shown in Figure 27.

Figure 28 shows the observed wave shape. It is simply the triangular function riding on the electromagnetically induced square wave as shown.

It is apparent that the device cannot function according to the simple theory if the Schmitt trigger point is set below the electromagnetically induced voltage – in this case about 100 millivolts.

But the suspension actually worked well below this voltage. The whole system goes into oscillation at a high frequency e.g. 5KHz. The current switches from one coil to another at this rate. Whether the mechanically generated voltage phase modulates the 5 KHz carrier mentioned previously to maintain axial control or whether the device works a la the simpler theory is now known. This latter is possible because it may be that under these conditions the mechanically generated voltage is large enough to swamp out the electromagnetic induced EMF. It may also be a combination of these two effects.

While the circuitry is similar to that earlier shown in a National Semi-conductor, LM311H comparator, used in the Schmitt trigger in lieu of the 1/2 747 operational amplifier previously shown.

This was done because the 747 had a very low corner frequency (approximately 10 Hz) so that it would be stable as a voltage follower, without any external capacitance for compensation. The schmitt trigger circuit used did need an amplifier – a comparator is even more appropriate. The comparator needs no internal roll off and the LM311 as used had a rise time of only 1.5 microseconds.

With the 747 the highest self-oscillating frequency was about two KHz. Apparently its response and the natural parallel resonant frequency of the rate coils (5 KHz) worked together to limit the self-oscillating frequency thus.

With the LM311, the oscillations take place at 5 KHz– the band-width of the compartor being infinite in comparison.

The above discussion of the use of the 747 versus the LM311 is merely reporting. No significant improvements in practical levitation were noted using one versus the other. The use of the high speed comparator merely made the experimental apparatus correspond more closely to the idealized theory.

Using the simple theory, not contemplating electromagnetically coupled oscillation, one would expect that if the field direction of rate magnet, poling of rate coil, choice of force coil connections were once made properly that any of four different combinations of the above would be equivalent (the original configuration plus two reversals of three polings). In addition, since the force electromagnets were used in the soft iron attractive mode the direction of current flow in same were immaterial.

Actually one particular combination of the variables gave optimum results. In fact, it was not certain that we had a device which would work at all with two combinations. We had not made a special effort to ascertain whether this was possible. There was a minor exception to the above. One could reverse the rate magnet and rate coil connections with impunity.

From the above it appeared certain that the direct mutual rate coil – force coil inductance played an important role in practical suspension operation.

While, as mentioned heretofore, it was not known that the coupling and sometimes oscillation of the circuit degrading the suspension performance, it was suspected that this inhibited the linear mode of operation (described later on) and it certainly did no good. This last statement was based on the following reasoning:

If oscillation was helpful the necessary feedback could always be provided by circuitry rather than by stray coupling. Furthermore, with large electromagnetic feedback the percentage of electro-mechanical voltage went way down.

Having decided that it would be beneficial to reduce the electromagnetic feedback, some thought and simple experimentation was devoted to this end. Actually what one wants to reduce is the ratio of stray electromagnetic coupling to electromechanical. The actual values of voltage was immaterial until one reduced the electromechanical voltage below the point where amplifier noise (including long term drift) became important.

The resulting rate coil structure was not very efficient. The magnetic field intensity, H, vector had components parallel to the rotational axis and perpendicular (radial). If the magnet had a permeability more than three we are assured by the textbooks' thumb rule that we may consider H to be perpendicular to the magnet surface. (Apparently three is a good approximation to infinity). The material has a permeability of about 1.05 so this simplification was not good. By using a test similar to the familiar iron filing set up it has been concluded that the lines hug the cylindrical surface of the magnet very closely. Thus a coil that would change its flux linkages considerably with a small movement of the magnet would want to hug the corner of the Samarium-Cobalt cylinder closely. Increasing the O.D. of the coil would always further increase the voltage output of the coil, but the increase would be small because of the weak field a little way from the edge of the cylinder. The stray field pickup would however rise more than linearly with the coil radius thus degrading the signal to noise ratio.

Assuming that one continues to use a structure similar to the present, ther rules are: (1) hug the corner as closely as possible – considering the fact that the magnet moves (2) make the O.D. as small as possible and (3) use as fine wire as possible. (2) and (3) are interdependent. Fine wire permits more turns with lower O.D.

It should be noted that the circuitry need not be d-c coupled. This is one of the is one of the advantages of the VZP principal. Previously this fact was used to prevent the Schmitt trigger from causing an annoying large steady current from flowing in the force electromagnet when during experiments the Schmitt stayed locked one way.

One may capacitively couple the rate coil to the input circuitry, thus eliminating the effect of offset drift. Similarly one may transformer couple the rate coil to the input. These variations would enable one to get

along with less rate coil output voltage. A typical rate coil is 1.2"
I.D., 1.50" O.D. and axial length about 0.25". This does not hug
the magnet corner very well. As a positive by-product of this construc-
tion it is not useful to bring the magnet extremely close to the coil.
Little difference in output was noted between having the rate coil near
plane coincide with the magnet edge or 0.1" away. The 0.1" spacing
was convenient to prevent bumping.

It was best if the inevitable radial motion of the rate coil caused
no change in flux linkage and thus no spurious signal. Actually
lateral motion did generate a signal and the ratio of the axially genera-
ted signal to radially generated for equivalent sinusoidal excursions of
the same frequency provided a rejection figure of merit. Minimizing
this might invalidate the three rules set down previously. At the rota-
tional speeds we had employed the spurious signal never caused problems.

The axial component of the rate magnet flux was not useful in genera-
ting a rate output. Thus the magnet was used inefficiently. The rate
coil is to a dynamic loudspeaker as a generator is to a motor. Thus one
might be led to use a loudspeaker like structure. The dimensions of the
magnets practically available did not encourage one to attempt this.
The reasoning being that the addition of soft iron to the 1" O.D., 1/2"
I.D. and 1/4" long Samarium-Cobalt magnet would cause it to work into
too high a permeance to fully utilize the energy product. However
working into a permeance of 2 instead of 1, only costs about 10% of the
energy product. Merely putting a large (2" diameter) soft iron washer
on the magnet surface away from the rate coil nearly eliminates the
reluctance of half of free space and approximates this. The increase of
flux density in the wire was thus roughly 2 x .9 = 1.8. Experiments
showed that the simple addition of such a washer almost doubled the rate
coil output with no complications.

Axial stability will be achieved if the levitated object is subject to a servo system such that the object moves in the algebraically opposite direction to any non-servo force. This omits the desirability of damping, but with the velocity signal available damping is produced in the usual way although, as will be seen, there is a switch of algebraic sign.

Take Newton's Law with the mass constant.

$$F = ma \qquad (I)$$

Let the servo force be, (Ka), proportional to the acceleration, (a), and (K) be a positive quantity. Equation (I) becomes:

$$F + Ka = ma \qquad (2)$$

or----

$$F = (m - K)a \qquad (2^I)$$

If (K>m) the coefficient of (a) is negative and the object will accelerate in a direction opposite to (F). It will achieve a velocity and displacement that moves it against (F). The real mass, (m), has been given the attributes of the negative mass, (K-m).

In the case at hand, if the levitated object approaches pole I, and leaves pole 2, it is subject to a net force that without the servo would cause it to soon collide with pole I. According to Equation 2 this would be prevented by adding a force proportional to the acceleration to (F) with (K) being positive. If the actual acceleration, (a), is directed away from pole I, the (Ka) would appose (F) and the situation seems sensible. This argument is circular in that it assumes what it is to prove, but it does show that no inconsistency existed in this case. Conversely, the equation (F + Ka = ma) with (K>m) cannot be satisfied for a positive (F) and positive (a) since (Ka) alone exceed (ma). Thus (F) and (a) cannot both have the same sign.

In a sense we have changed the real mass, (m), into the artificial mass, (m-K), a negative quantity. As will be seen later, this connects up with the non-linear or bang-bang case. It is easy to show that either

the bang-bang or linear all electronic system essentially turns positive circuit elements into negative e.g. positive inductances into negative.

The practical servo system used must provide damping as well as the function discussed above. This may be done by adding to (Ka) the quantity (Dv) where (D) is a positive constant and (v) is the velocity.

$$F + Ka + Dv = ma \qquad (3)$$

In order to apply linear theory to this equation one must assume, traditionally but somewhat inaccurately, that (F) is a linear function of (X). Taking (x = 0) to be halfway between the magnetic poles, assume that (F = +AX), with (A) a positive quantity. The positive coefficient (A) corresponds to reality in that this will cause the pole collision we are seeking to avoid. Writing (3) over, with this modification, using Newtonian notation, and putting all the terms on the left side yields

$$(K - m)x + Dx + AX = 0 \qquad (4)$$

or in transform notation

$$(K - m)s^2 x + Dsx + A = 0 \qquad (4^!)$$

To avoid positive exponentials in the solution, and thus bound (x), this must be a Hurwitz polynomial. This requires that (K-m) and (D) be of the same sign. (K-m) is positive and thus the choice of (D) as positive is correct. This is convenient as it allows the acceleration and velocity signals to come from the same operational amplifier.

Figure 29 shows one of the circuits tried. Z_3 and Z_4 were used to reduce the crossover distortion which would be produced if the output of Z_2 went directly to the bases of Q_1 and Q_2. The negative feedback divided the three diode drops that would trouble one without Z_3 by a factor equal to the open loop gain of Z_3.

Z_1 is a voltage follower buffer that prevents the rate coil inductance from affecting the wave shaping elements connected to Z_2. Z_2 and its

associated network did the real work. Its transfer function is:

$$\frac{e_o}{e_i} = - \frac{1}{R_o C_o s + 1} \left(R_o C_1 s + \frac{R_o}{R_1} \right) \tag{5}$$

The $(R_o C_1 s)$ term is the acceleration and the $\frac{R_o}{R_1}$ term the velocity. The signs are proper. Selecting (R_o), (C_1) and (R_2) permits one to adjust the magnitudes of acceleration component and velocity component appearing at the output of Z_2.

It is often desirable to test using straight velocity feedback only. Feeling a strong viscous drag as the rotor is moved from pole to pole is reassuring and it also permits one to phase things properly. With wrong phasing, the rotor clicks from pole to pole more snappily with the electronics than without because of the positive feedback. However when $(K>m)$ the poling should be reversed. This was rather annoying since when the poling was reversed with $(K<m)$ one really clicks rapidly from pole to pole. The existence of a small (K) has reduced the effective mass but not made it negative and the permanent magnet force knocks the rotor around like a feather.

One way of looking at this whole matter is to note that the addition of an acceleration term turns the free fall differential equation under an attractive force proportional to (x), into the equation of damped simple harmonic motion.

Presumably one can then take over all the mathematical paraphenalia used with this classical stable second order system. However, the whole notion of negative effective mass etc. is not very satisfying intuitively.

In trying to fully understand the operation of the VZP a few all electronic models of the electromechanical system have been drawn. Newton's Law with the mass constant is modeled by the primitive circuit shown in Figure 30.

$$E = Lq = L\frac{di}{dt} \qquad\qquad (6)$$

with
$E = $ force

$L = $ mass

$q = $ displacement

$q = i$ - velocity

$q = \frac{di}{dt}$ - acceleration

Figure 3I shows an all electronic analog that makes the real positive inductance look like a negative inductance, (L-AM), (AM L). Here and in what follows (A) is not the large number tending to infinity associated with operational amplifiers. It is a finite number like 5 etc.

Figure 3I brings one into the currently popular area of active circuits, where negative impedance convertors, gyrators etc. abound. Tying the VZP to the powerful theorems of active circuit theory seemed to be the best way to proceed, but this had just been started.

Figure 32 shows the analog of an electromechanical bang-bang. It is a bang-bang negative impedance convertor. Note that, as with the bang-bang VZP, no obvious differention of the current (velocity) was done. The drop across R_I was analogous to velocity or current not its derivative, unlike Figure 3I, where the mutual inductance performed the differentiation.

Figure 33 shows a circuit which was an imperfect, but interesting analog of a suspension without any servo control. It was imperfect since it lacked an inductive element, the mass analog, and only lead to a first order equation not a second. But like the un-servoed bearing it had an equilibrium point, which was unstable viz: $(e_i = e_o = 0)$. The slightest departure from these conditions caused run away in one or the other direction.

Figure 34 shows a bang-bang mode of preventing this, and keeps the charge (analog of displacement) on C in the vicinity of zero. A_2 and its associated resistors form a Schmitt trigger symetrical around zero volts input.

2.6 CONCLUSION OF CONTROL EXPERIMENTATION

The following conclusions were drawn from the work done on Velocity only Axial Control:

1. It was still not clear whether operation in the linear mode was possible. The equations show that it was, but the analogous all electronic equivalent systems "looked" stange as will be seen.

2. While the axial control system <u>can</u> be made to operate just as described previously, one more often obtains operation in a mode that is a modification of same.

3. As far as simple user tests of the quality of suspension are concerned, the modified mode was superior. By simple user tests one means ease of hand starting of the bearing by pushing it off a pole and resistance to the stopping of suspension by introducing outside forces axially and/or radially.

4. The modified mode was simply a mode in which the whole circuit was normally oscillating by reason of the direct electromagnetic coupling (transformer) between the force electromagnets and the rate coil. The additional mechanical/electrical coupling via force electromagnets acting to change the velocity of the axial motion was superimposed on the above.

5. While it was possible to operate the suspension in accordance with the theory set forth in previous sections this could only be done over a small range of critical velocities (critical velocity is where the force magnets are switched). Attempting to reduce this velocity by lowering the Schmitt trigger voltage caused the Schmitt to be triggered "immediately" by the square wave voltage induced in the rate coil when the current started its approximately linear rise in the newly "on" electromagnet. This did <u>not</u> prevent levitation. Setting this velocity too high did prevent levitation, presumably by allowing the armature too close to a pole.

6. The above was, as mentioned, caused by the fact that there was considerable magnetic coupling between force coils and rate coil. It was <u>felt</u> that this coupling may prevent operation in the linear mode. This was because amplitude stable oscillations were only possible in non-linear systems.

SECTION III - TORQUE MOTOR

3.0 INSTABILITY

Two basic problems remained in the magnetic bearing system. One was the lack of mechanical rigidity and second was the inadequate frequency response in the system.

The lack of mechanical rigidity caused vibrations to occur during high axial force levels which destabilized the servo system.

The frequency response of the system was inadequate for the fast response required by the narrow ($\pm$ .007") magnetic gaps. This was because of the high non-linear force levels in the axial direction.

At axial gaps of $\pm$ .017" it was possible to operate the magnetic suspension system with an additional one pound weight attached to the rotor. However, stability was poor and power consumption was relatively high. The system was very sensitive to outside disturbances which would disrupt its operation and it was found that a soft mounting surface was necessary.

With the magnetic suspension system operating the following measurements were made:

Radial Stiffness (each bearing)	125 lb./in.
Axial Support Capability	10 lbs.
Power Requirement	$\pm$ 13 VDC at 50 ma $\pm$ 11 VDC at 50 ma (2.4 watts total)
Time Constant (time for rotor to fall from center to one pole - .017")	0.16 seconds
Rotor Weight	1.5 lbs.

A two phase DC motor as described earlier in this report was connected to the magnetic bearing. The bearing was rotated up to 2600 RPM where rotor vibration was encountered. Below 2600 RPM operation was very smooth.

To reduce the instability a change was made to the force coil configuration. One of the two force coils was removed and a Samarium-Cobalt permanent magnet armature was added to the rotor. What resulted was a force coil that could push and pull. The flux path of the permanent magnet armature passed through the force coil thus providing a bias level for the force coil to work on. This method reduced the inherent time lag in the force coil thus increasing the response of the magnetic suspension system. The system then operated in a more stable manner. However, one drawback was that the additional permanent magnets added a radial and axial destabilizing force thus adversly effecting the axial and radial stiffness.

3.1 TORQUE MOTOR

The NASA representative recommended at this time that Cambion consider incorporating into the magnetic bearing system a motor built for NASA by Sperry Marine Systems Division. The motor was a three-phase ironless armature type and was developed with specific characteristics in mind appropriate for magnetically supported systems.

A study was made of the possible integration and it was found that the motor could be added to one end of the bearing with a minimum of changes.

Cambion designed and made the mounting fixtures for the motor and installed the motor on the magnetic bearing. Bearing operation did not change except for some increased sag (003") at the motor end when in a horizontal position. A complete wiring diagram may be seen in Figure 35.

SECTION IV - WORKING MODEL

4.0 ELECTRONIC CONTROLLER

The electronic controller had evolved somewhat from the circuitry that had been used on the first VZP model.

A schematic diagram of the final controller may be seen in Figure 35. The position signal is generated by the six lamps and the six photocells. The velocity signal is generated by a permanent magnet mounted on the rotor which induces a voltage in the rate coil proportional to the axial velocity. The rate coil consists of 50,000 turns of #50 AWG wire wound on a 1.2" diameter bobbin.

The velocity and/or position signals are amplified by an operation amplifier (Burr-Brown 1506/15). The operational amplifier is operated open-loop and has a gain of 104 dB. A balance control is included so that the output of the operational amplifier may be set to zero with zero input. The amplified signal then goes to a complementary-symetry power amplifier. The power amplifier consists of a bias network and two Motorola darlington silicon power transistors MJ4032 (PNP) and MJ 4035 (NPN). The signal from the power amplifier then goes to the force coil which controls the position of the rotor. The force coil is made up of 250 turns of #23 AWG wire with an inside diameter of 1.15", and outside diamter of 1.5" and is .725" long.

A portion of the signal from the operational amplifier is fed to a RC integrator and then back to the non-inverting input of the operation amplifier. This signal is required for virtually zero power operation or, in other words, is necessary for the force coil to position the rotor at the neutral force position.

4.1 AUTOMATIC STARTING

Attention now turned to automatic starting of the bearing upon application of power. Because of the high axial forces present in the "clamshell" type magnetic bearing, automatic starting would not take place. At an axial magnetic gap of .017" the radial stiffness was 250 lbs./in. (both bearings). However, for this

value of radial stiffness 4000 lbs./in. of axial stiffness would be required to lift the rotor off the magnetic pole faces. The servo system could only provide 500 lbs./in. which was enough to control the rotor when near its center position but not enough to lift if off the pole face.

Temporary mechanical stops were installed in the air gaps and it was found that with a mechanical air gap of $\pm$ .005" the bearing would start automatically. However, this method was not completely dependable and was not pursued further because of work needed to be done on the motor.

4.2 MAGNETIC BEARING STIFFNESS

The three-phase D.C. motor, supplied by NASA, was integrated into the magnetic bearing assembly. The added weight of the motor did not permit operation in the horizontal position because the bearing sag exceeded the radial clearance of the motor.

Efforts were made to increase the stiffness of the magnetic bearing and, there-fore, decrease the sag. These efforts were ineffective because of a bent shaft. The 1/2" diameter aluminum shaft was replaced and much better results were obtained. However, rotor-stator contact still occurred in the horizontal position.

The magnetic gaps were decreased to increase the radial stiffness. On the motor end the gap was reduced to $\pm$ .007" and the opposite end was reduced to $\pm$ .014". However, because of the destabilizing force of the permanent magnet force coil the radial stiffness was not as high as expected. The $\pm$ .014" gap should have been 300 lbs./in. radial stiffness but because of the P.M. force coil being reduced to 75 lbs./in., the opposite gap ($\pm$ .014") was 150 lbs./in. as it sould have been. This resulted in a total radial stiffness of 225 lbs./in.

After conferring with the NASA representative, it was decided that the motor air gap would have to be widened. The maximum radial clearance for the motor as designed was $\pm$ .0075". This occurred between the outside diameter of the stator and the inside diameter of the rotor. Since this was the limiting clearance, we decided to take .010" off the inside diameter of the rotor outer ring. Removing this amount of material would increase the radial gap to $\pm$ .0125".

Because of the construction of the rotor and the close proximity of the magnets, the outer steel ring had to be removed by machining.

The new steel ring was constructed from carpenter BFM Iron to the new dimensions. The new ring was installed on the rotor and the motor was assembled on the magnetic bearing.

Although the motor gap was now $\pm$ .0125", adjustment for the motor centering was still difficult. Adjustment was completed and the magnetic bearing-motor was hand carried to NASA-Goddard and demonstrated in operation on 19 September 1972.

On the following page is a list of the specifications for the magnetic bearing-motor as delivered. (Performance specifications for the motor itself are not included.) For a layout diagram of magnetic bearing and motor see Figure 36.

4.2 NASA MAGNETIC BEARING AND MOTOR SPECIFICATIONS

Description	Contract	Actual
Length	9 ± 1/2 inches	10 inches
Diameter	5 ± 1/2 inches	4.5 inches
Weight (with motor)	7 ± 1 lbs.	6.25 lbs.
Weight (less motor)		4.15 lbs.
Potential Speed	48 RPM	2200 RPM
Radial Support Capability I (symetrical load)	5 lbs.	6.5 lbs.
Stiffness (radial)	350 lbs./in.	225 lbs./in.
Maximum Force (radial)		6.75 lbs.
Horizontal Support Capability II (with mirror)	5 oz.	9 oz.
Input Voltage	± 12 VDC	± 12 VDC
Input Power	Less than 8 watts	0.5 watts (2.4 watts in position mode)

4.2.1 SUPPLEMENTARY DATA

Description	Actual
Magnetic Gap (motor end)	± .007 inches
Magnetic Gap (opposite end)	± .014 inches
Axial Stiffness	3570 lbs./in.
Axial Support Capability	10 lbs./amp
Servo Time Constant	4.8 seconds
Sag (rotor horizontal in 1G environment)	.002 inches at motor end
System Resonant Frequency (Operating)	4384 Hz
Electromagnet Gap	.032 inches nominal
Radial Stiffness (motor end)	150 lbs./in.
Radial Stiffness (opposite end)	75 lbs./in.

5.0 RECOMMENDATIONS AND CONCLUSIONS

Previous to this contract magnetic bearings, in general, had three main faults: 1. They required relatively large amount of power to operate, 2. They contained considerable dead weight and 3. They were large in size as compared to ball bearings.

The device developed under this contract plainly shows that continuous power consumption can be reduced to extremely low levels - milliwatts. Further investigation showed that the size and weight of a magnetic bearing can be reduced by a ratio of better than 2 to 1.

By the addition of steel armoring to rare earth - cobalt permanent magnets, high levels of radial and axial stiffness are achieved with very little expended in weight and volumn. This then produces a magnetic bearing that can perform jobs that were previously done by mechanical bearings but without the problems of lubrication and friction.

The use of rare earth - cobalt permanent magent material in the force driver also reduces the size and weight because of a reduction in steel and copper required to do the same job. An added benefit is the increase in the response time of the force driver because of the biasing effect of the permanent magnet material.

Although the device developed under this contract shows a great improvement in magnetic bearings it is only the beginning. Further research and development can produce a new generation of magnetic bearing that will be useful in both space and commercial applications.

APPENDIX

Figure 1

B-H Curve Showing Characteristics of Rare Earth·Cobalt, Platinum Cobalt, Indox VI and Alnico V

1. RARE EARTH COBALT
2. PLATINUM COBALT
3. INDOX VI
4. ALNICO V
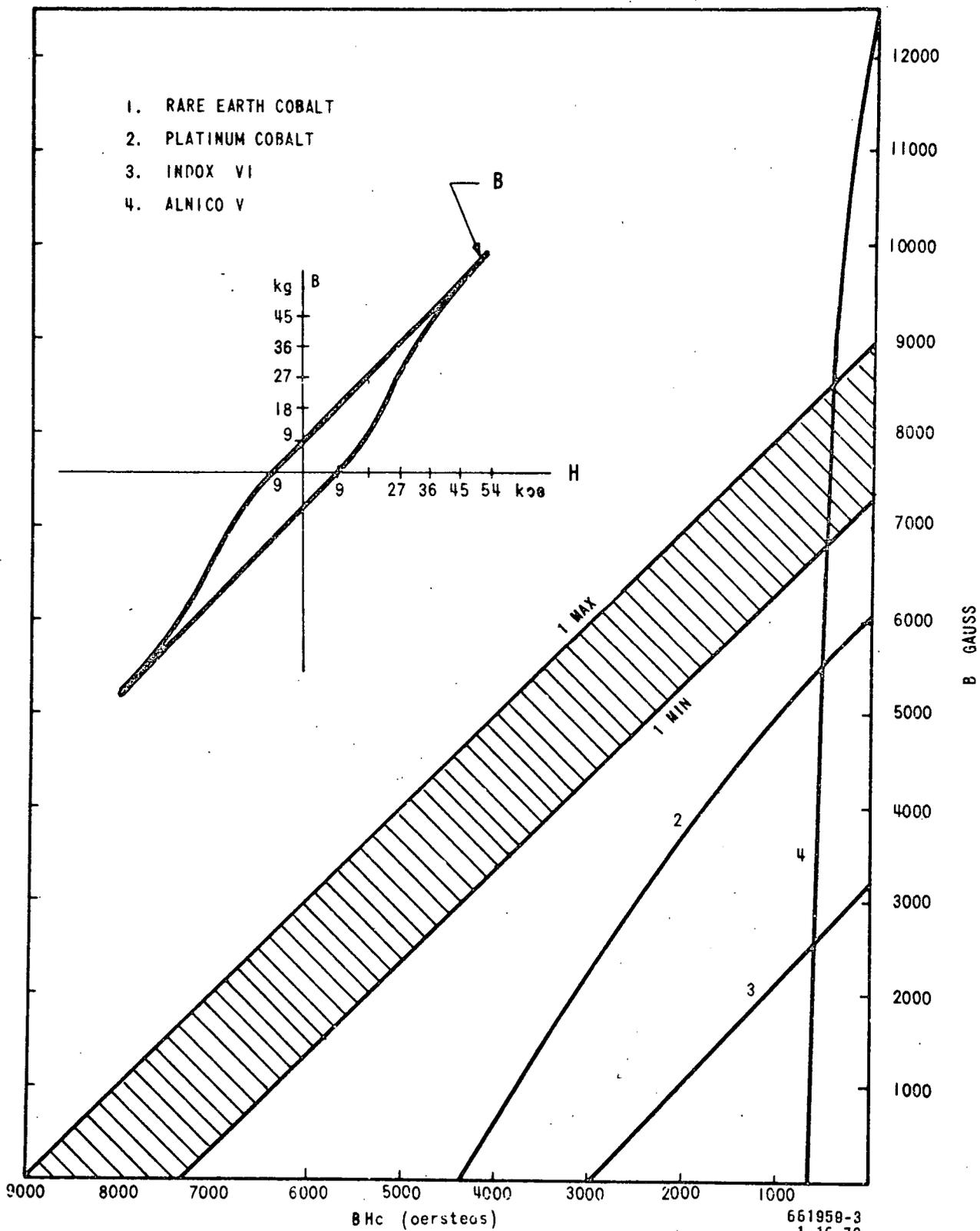
Figure 2

RAYTHEON COMPANY
Microwave and Power Tube Division
Waltham, Massachusetts

SAMARIUM COBALT MAGNETS

MAGNETIC PROPERTIES

Coercive force	7,500 - 9,000	Oersted
Intrinsic coercive force	25,000	Oersted
Residual induction	7,500 - 9,000	Gauss
Energy product, max	20	MG Oe
Curie temperature	850	°C
Temperature coefficient	0.02	% per °C

PHYSICAL PROPERTIES

Specific gravity	8	g/cc
Electrical resistivity	5×10^{-4}	ohm-cm

MECHANICAL PROPERTIES

Tensile strength	8,000	psi
Compressive strength	>> 10,000	psi
Flexural strength	12,000	psi

44

Figure 3

RAYTHEON
SAMARIUM
COBALT
MAGNET

RING POLES
.025" WIDE
.025" DEEP

C = .012"

A = .030"
B = .012"

SCALE 1-1 APPROX

FORCE (GRAMS)

600

500

400

300

200

100

A   B   C

.070 .060 .050 .040 .030 .020 .010 0

DISPLACEMENT (INCHES)

10 Squares to the Inch

45
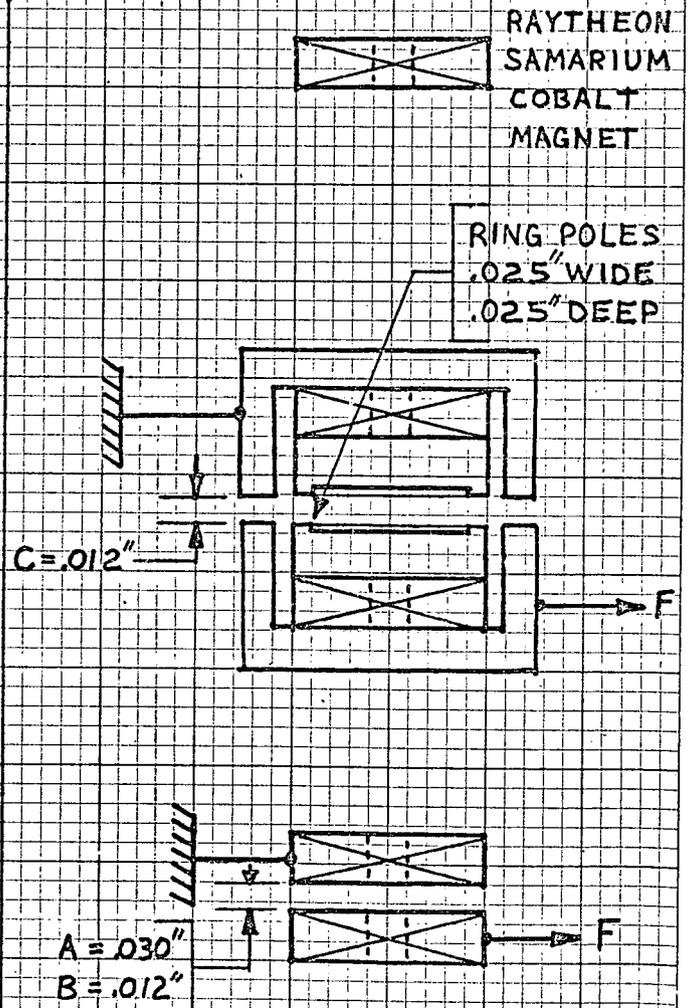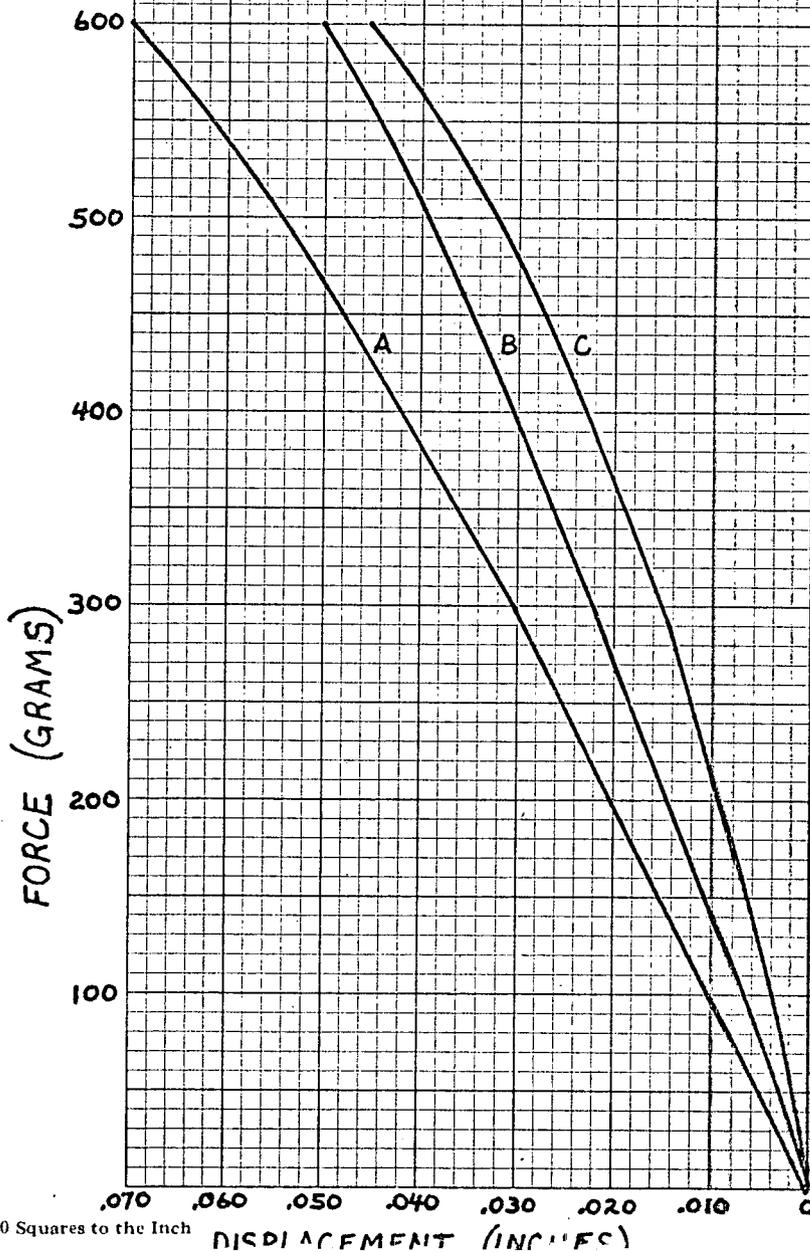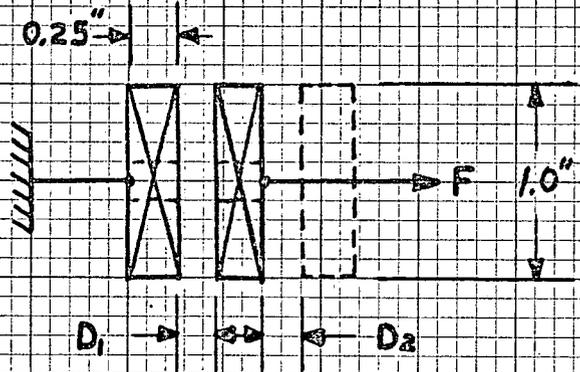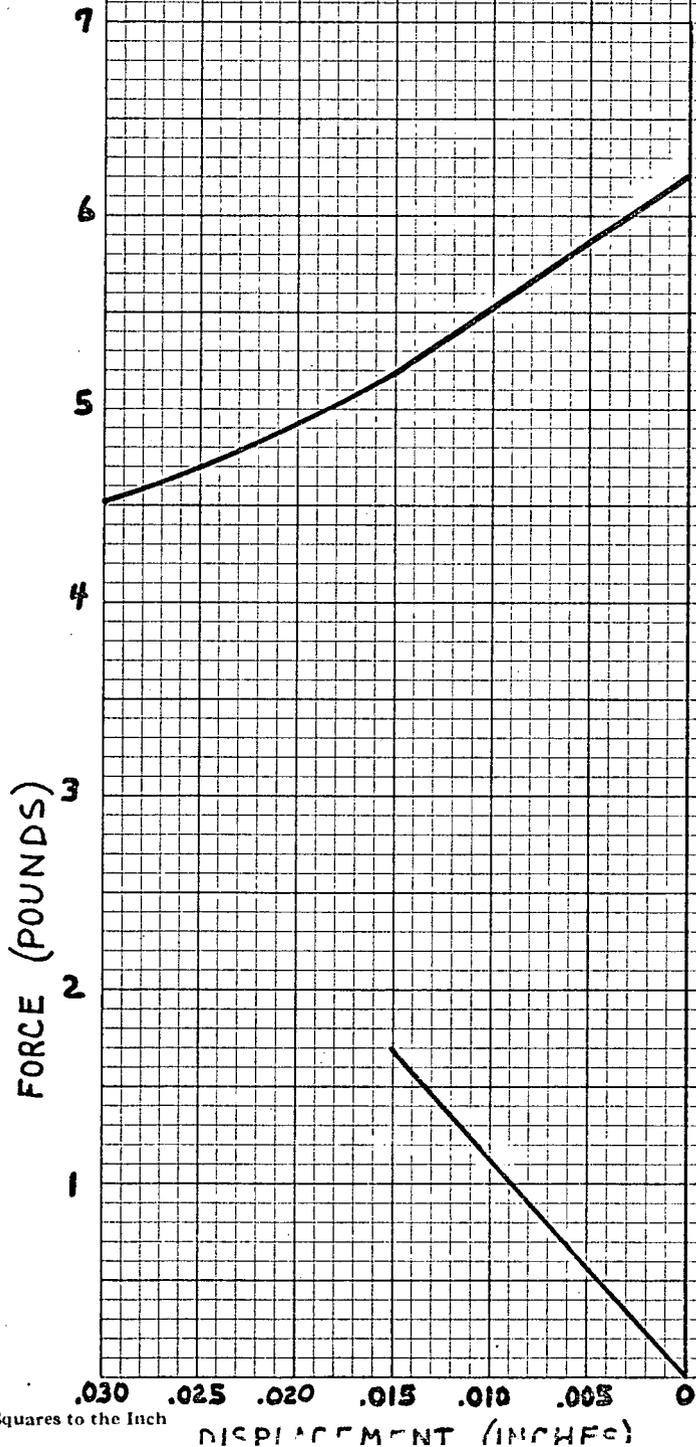
Figure 4

Figure 5

AXIAL DISPLACEMENT VERSUS FORCE
DATA TAKEN BY MR. JOSEPH LYMAN
11 DEC 1970
DRAWN BY PAUL SIMPSON
5 JAN 1971

CAMBRIDGE THERMIONIC CORPORATION
445 Concord Avenue
Cambridge, Massachusetts   02138

RAYTHEON
SAMARIUM-COBALT
MAGNETS

F
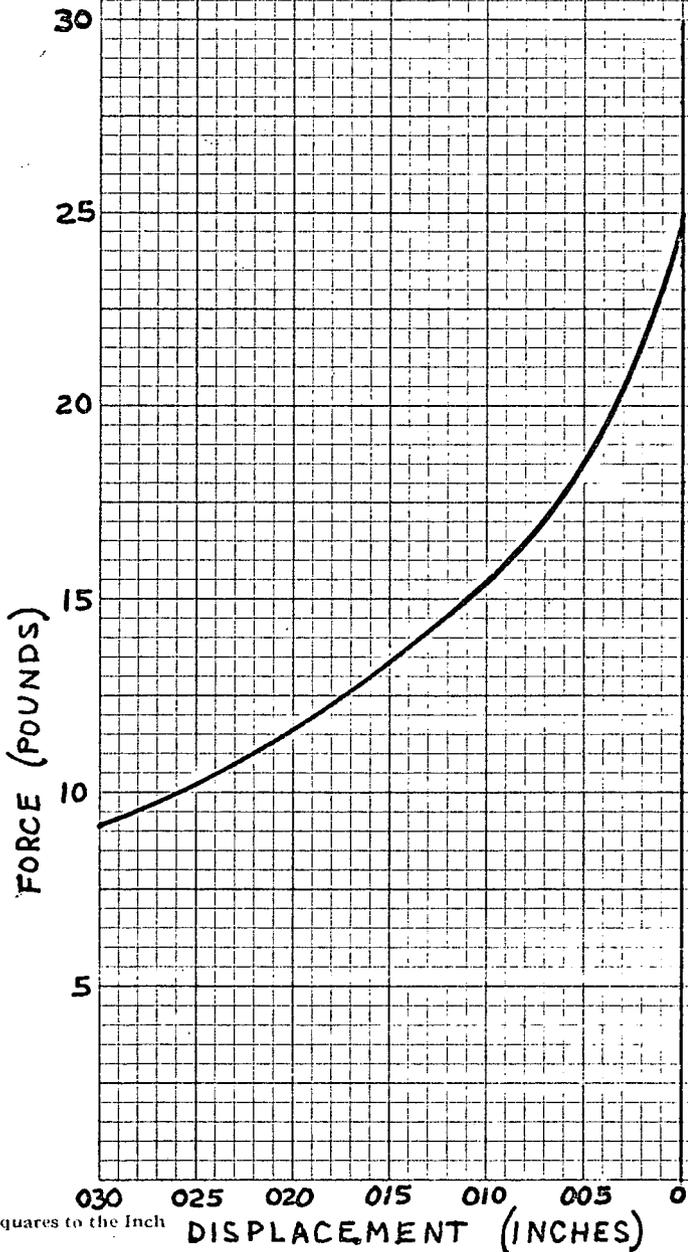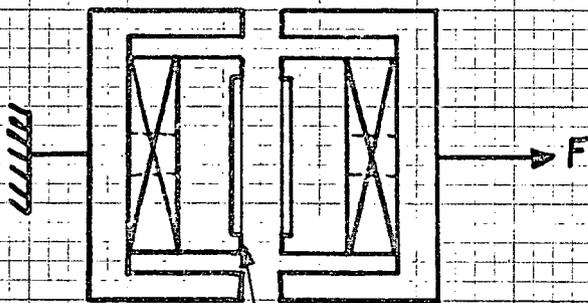
RING POLES
.025" WIDE
.025" DEEP

SCALE 1-1 APPROX

FORCE (POUNDS)

DISPLACEMENT (INCHES)

10 Squares to the Inch

47

Figure 6

Figure 7

Figure 8

RADIAL DISPLACEMENT VERSUS
FORCE   (2" DIA. TUBE)
DATA TAKEN BY MR. JOSEPH LYMAN
5 DEC 1970
DRAWN BY PAUL SIMPSON
5 JAN 1971
1~8

CAMBRIDGE THERMIONIC CORPORATION
445 Concord Avenue
Cambridge, Massachusetts — 02138

F

2.00"

ALNICO MAGNET

10

5

FORCE (POUNDS)

.030   .020   .010   0   .010   .020   .030
DISPLACEMENT (INCHES)

50.

10 Squares to the Inch

Figure 9

PHOTOGRAPH 1

SAMARIUM COBALT MAGNETS IN CUP CORES AND
LINEAR MOTOR COIL (1" GRID)

PHOTOGRAPH 2

MAGNET IN CUP CORE WITH FLUX CONCENTRATING RING

PHOTOGRAPH 3
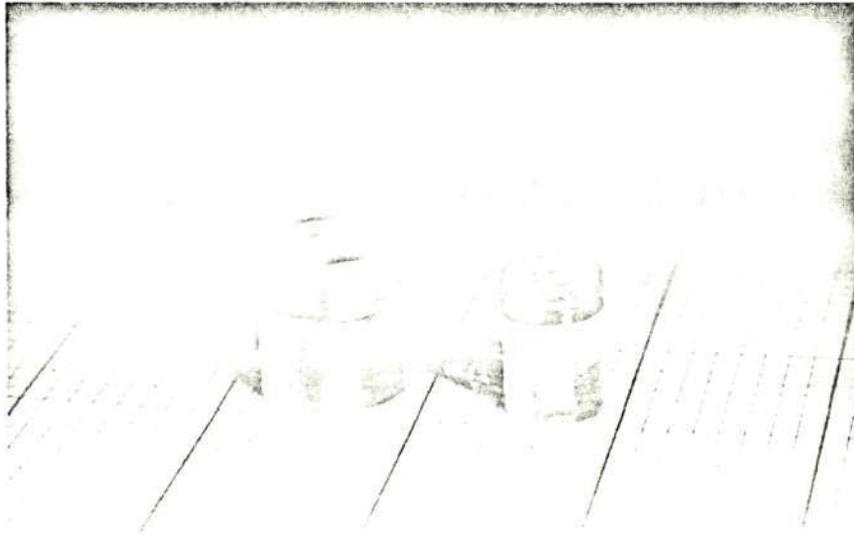
SMALL RATE GENERATOR

PHOTOGRAPH 4
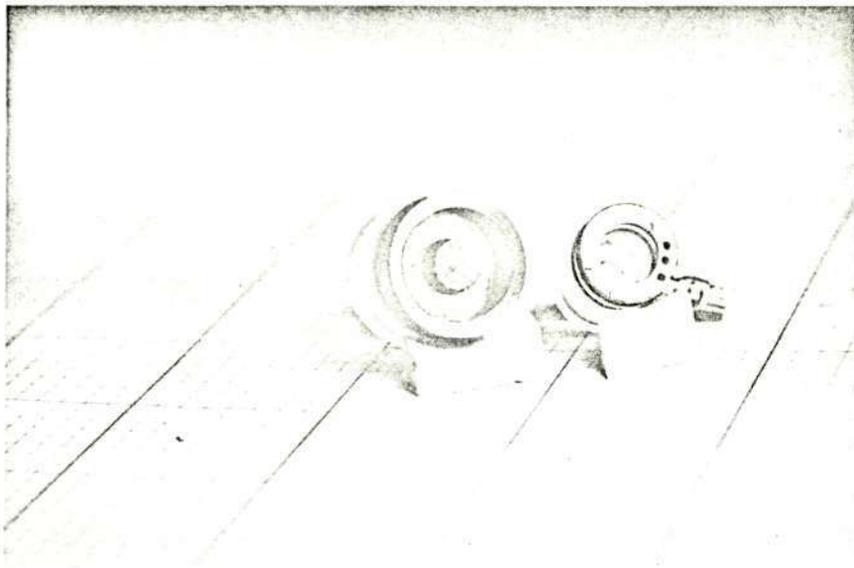
SMALL RATE GENERATOR WITH SAMARIUM COBALT MAGNET

53

E
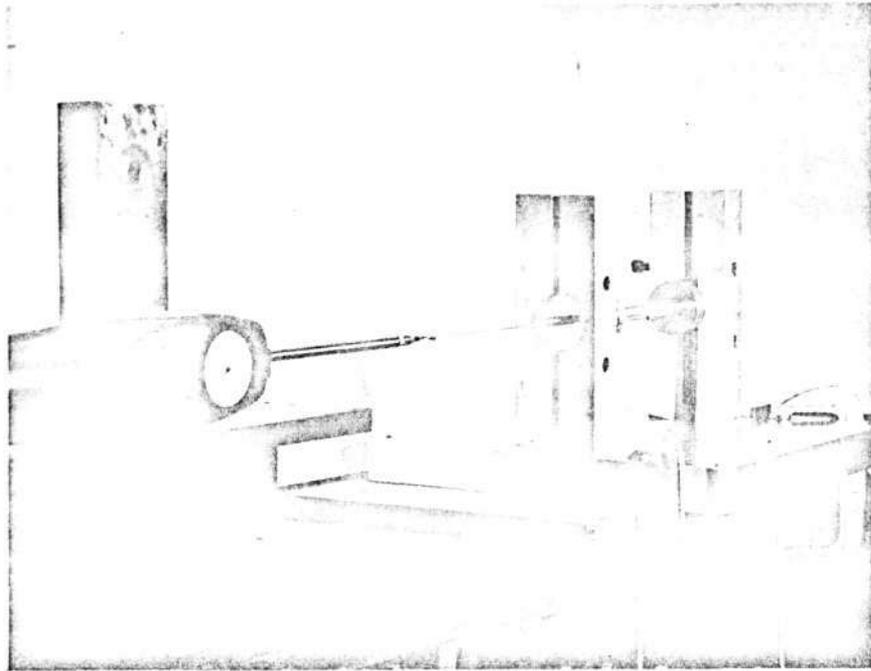
PHOTOGRAPH 5

AXIAL TEST SET-UP

PHOTOGRAPH 6
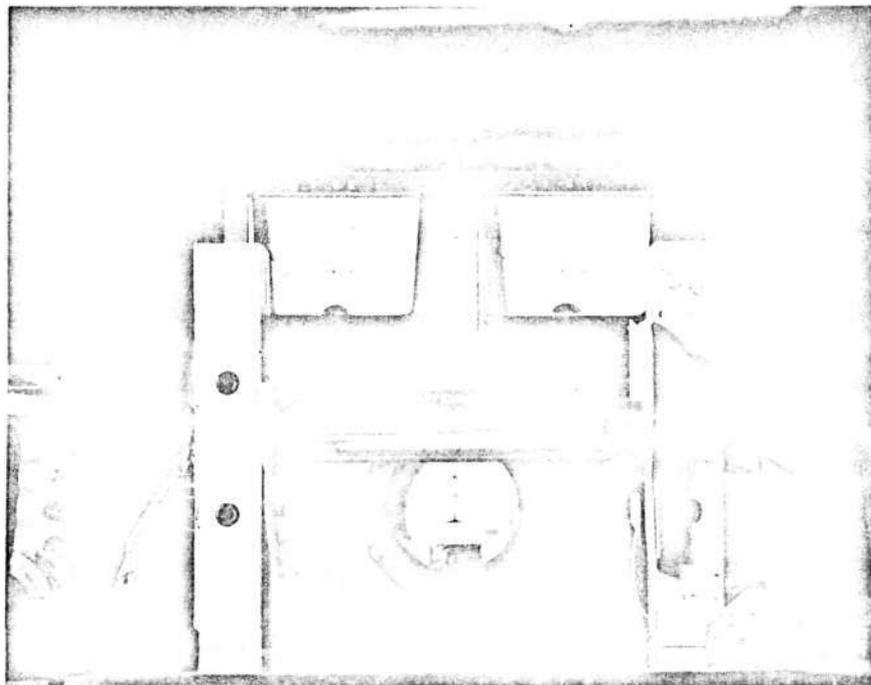
TEST FIXTURE

54

Figure 10

2-3
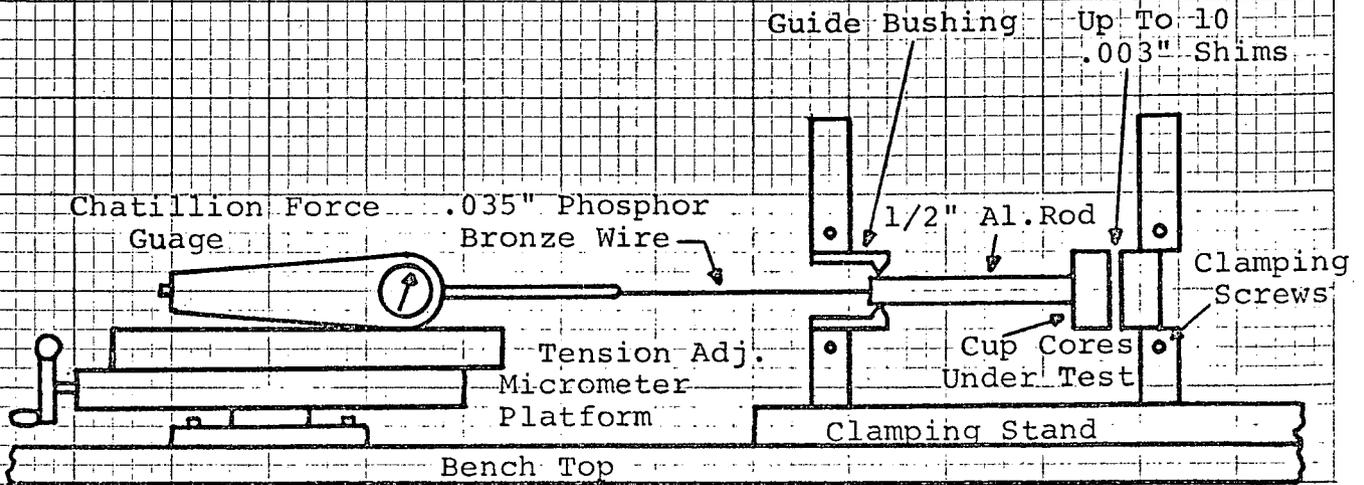
AXIAL TEST FIXTURE

Figure 11
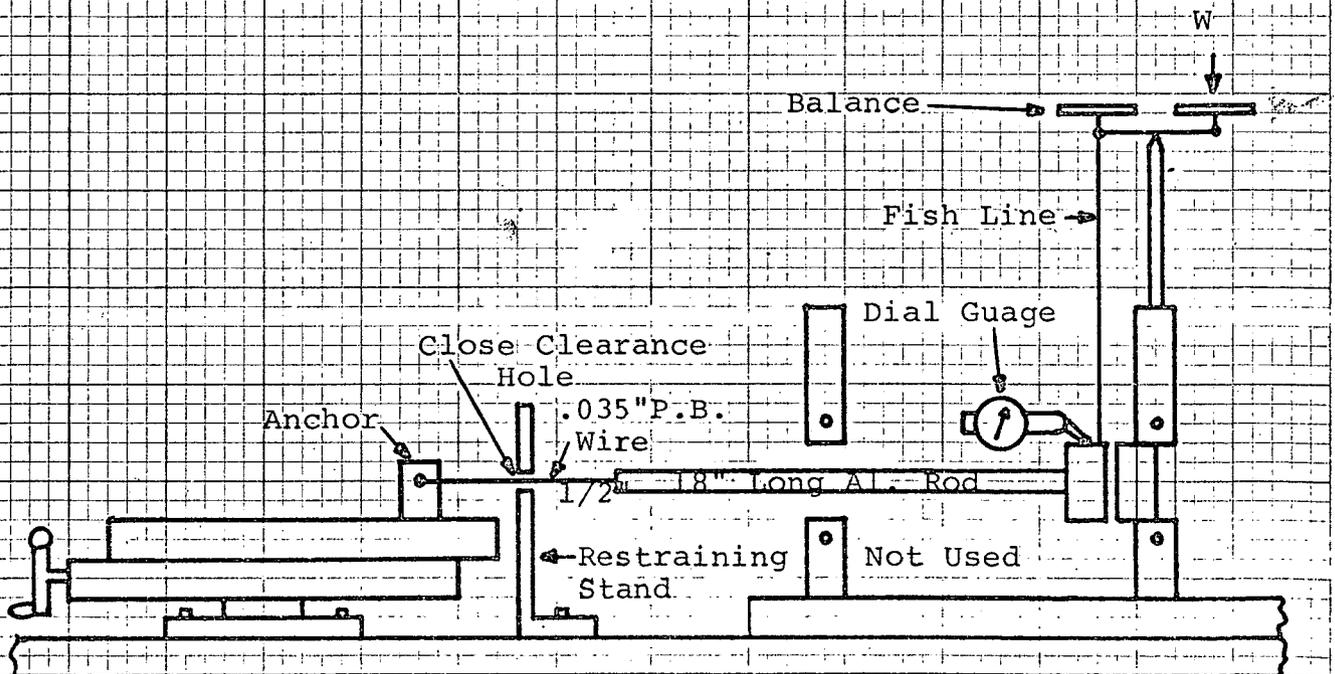
RADIAL TEST FIXTURE

DRAWN BY PAUL SIMPSON
4 FEB 1971

PRECEDING PAGE BLANK NOT FILMED

10 Squares to the Inch

55

Figure 12

Figure 12

AXIAL DISPLACEMENT VERSUS FORCE
DATA TAKEN BY MR JOSEPH LYMAN
14 JAN 1971
DRAWN BY PAUL SIMPSON
4 FEB 1971

2-1

CAMBRIDGE THERMIONIC CORPORATION
445 Concord Avenue
Cambridge, Massachusetts 02138

RINGS .50" O.D.
BFM IRON
.025" X .025"

.525"

F

1.50"

1.25"

.275"

BFM IRON

1.000"

.250"

RAYTHEON
SAMARIUM COBALT
MAGNET

PRECEDING PAGE BLANK NOT FILMED

FORCE (POUNDS)

50

40

30

20

10

.018 .015 .012 .009 .006 .003 0

DISPLACEMENT (INCHES)

10 Squares to the Inch

56

Figure 13

12-280
Made in U S A
NATIONAL

PRECEDING PAGE BLANK NOT FILMED
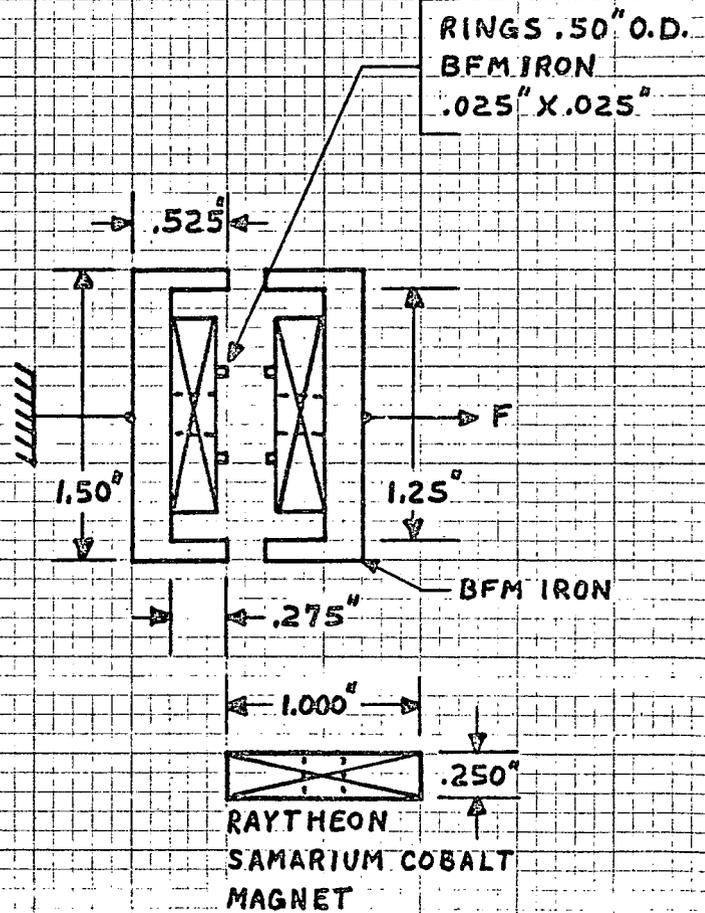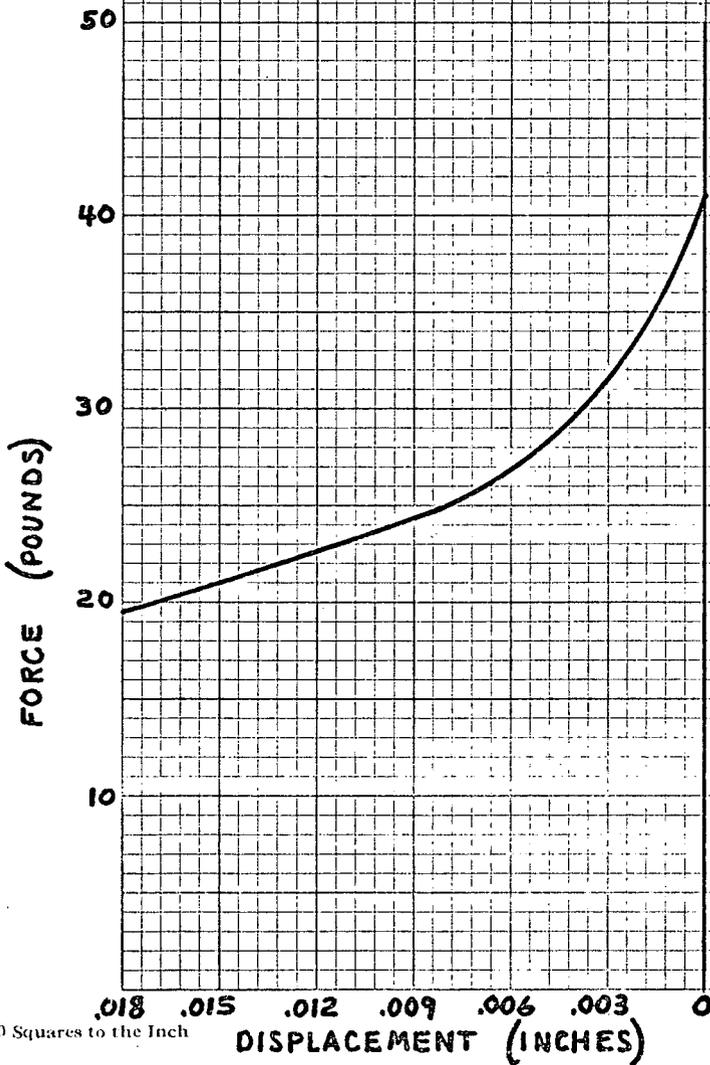
RADIAL DISPLACEMENT VERSUS FORCE
DATA TAKEN BY MR. JOSEPH LYMAN
18 JAN 1971
DRAWN BY PAUL SIMPSON
3 FEB 1971

2-2

1.500"
1.250"
.275"
.525"
.012"
F
BFM IRON
RINGS .50" O.D.
BFM IRON
.025" X .025"
1.000"
.250"
RAYTHEON SAMARIUM COBALT MAGNET

FORCE (GRAMS)

500
400
300
200
100

DISPLACEMENT (INCHES)
.030 .020 .010 0

10 Squares to the Inch

57
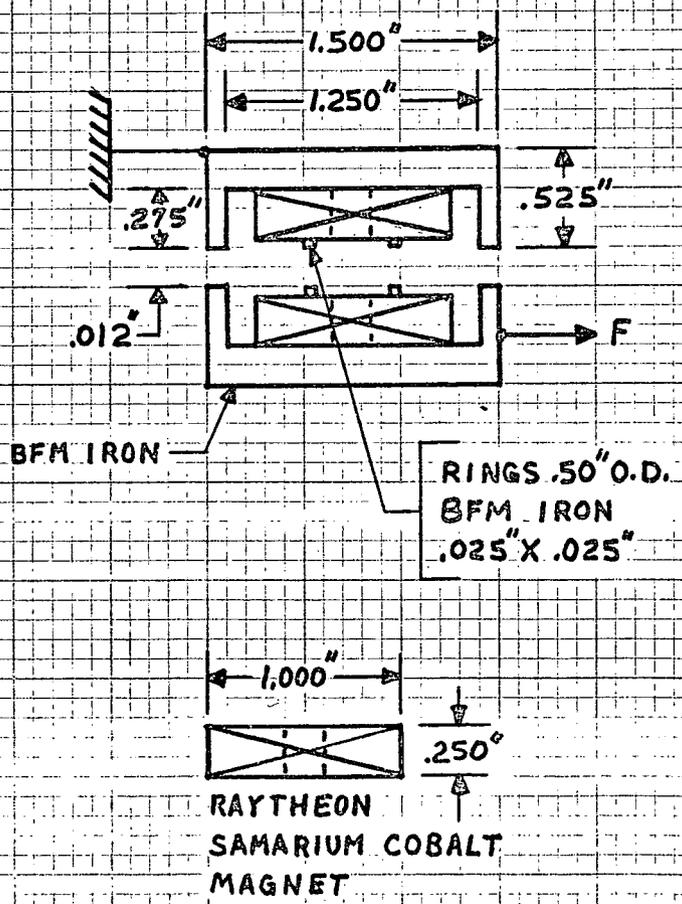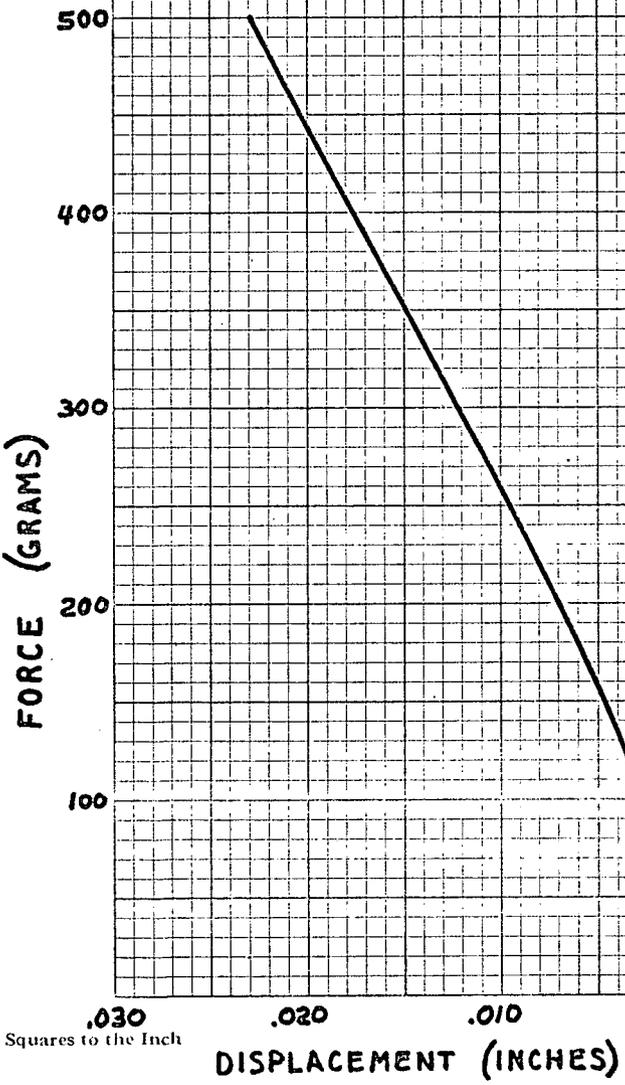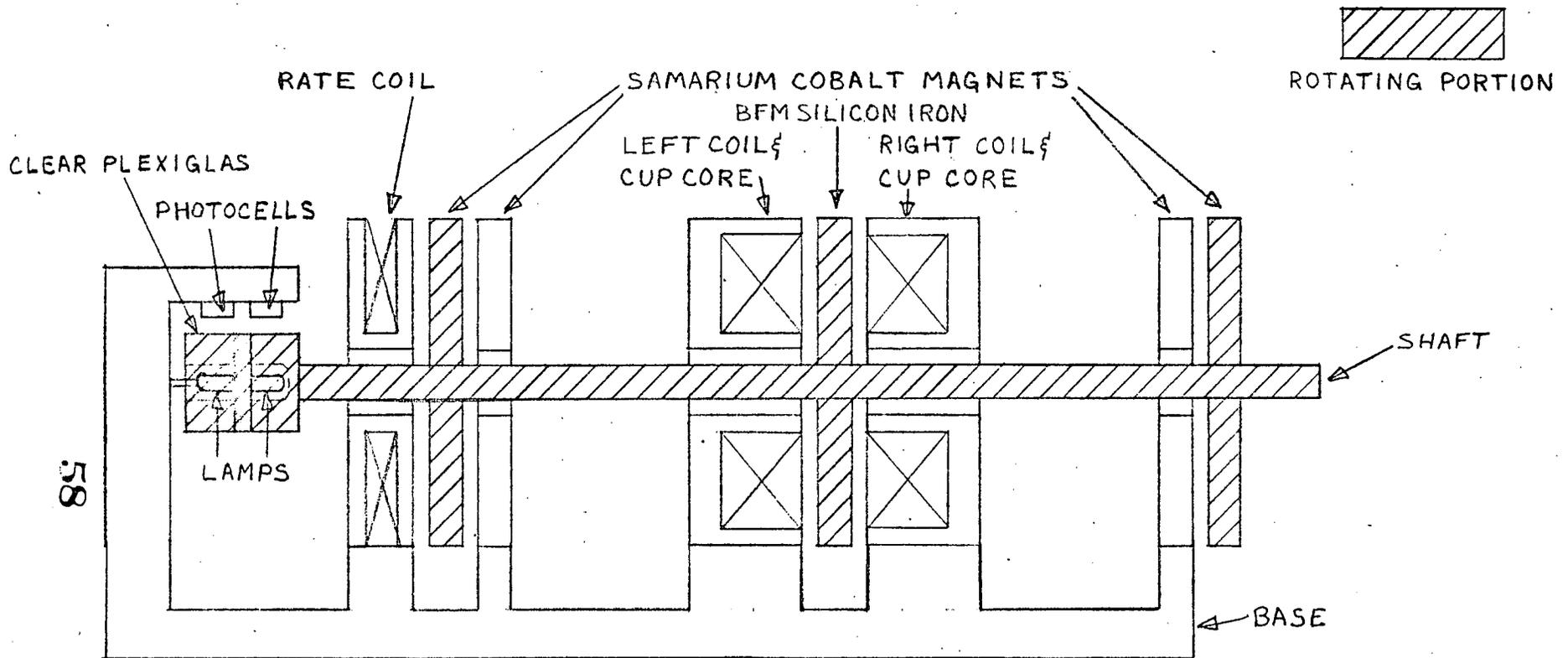
VIRTUALLY ZERO POWER MAGNETIC BEARING LAYOUT
(NOT TO SCALE)

Figure 14

58

PAUL A. SIMPSON
26 FEB 71

Figure 15

VIRTUALLY ZERO POWER MAGNETIC BEARING
SCHEMATIC DIAGRAM

PAUL A. SIMPSON
26 FEB. 71

REVISED
25 MAR 71
PAS
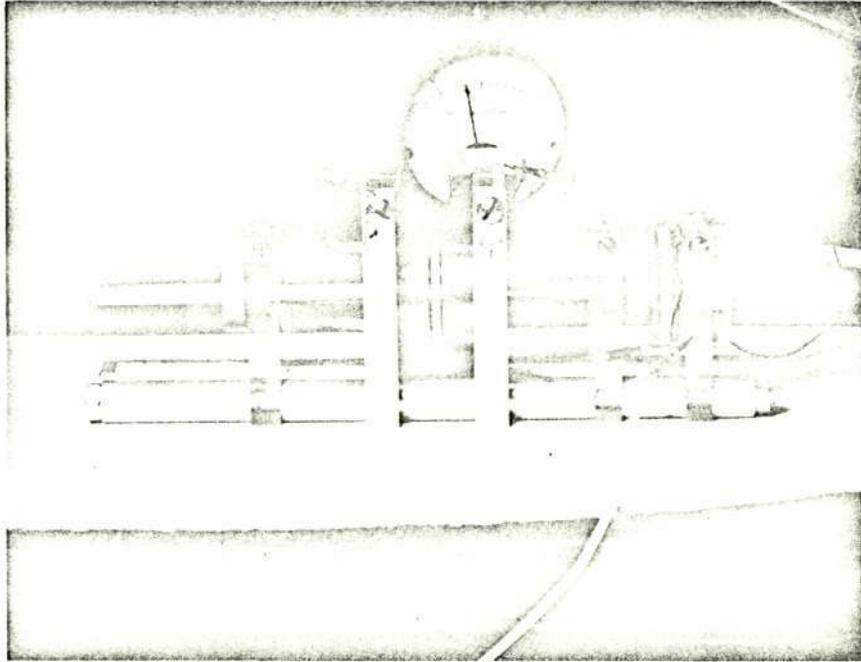
PHOTOGRAPH 7

VIRTUALLY ZERO POWER MAGNETIC BEARING IN OPERATION

PHOTOGRAPH 8
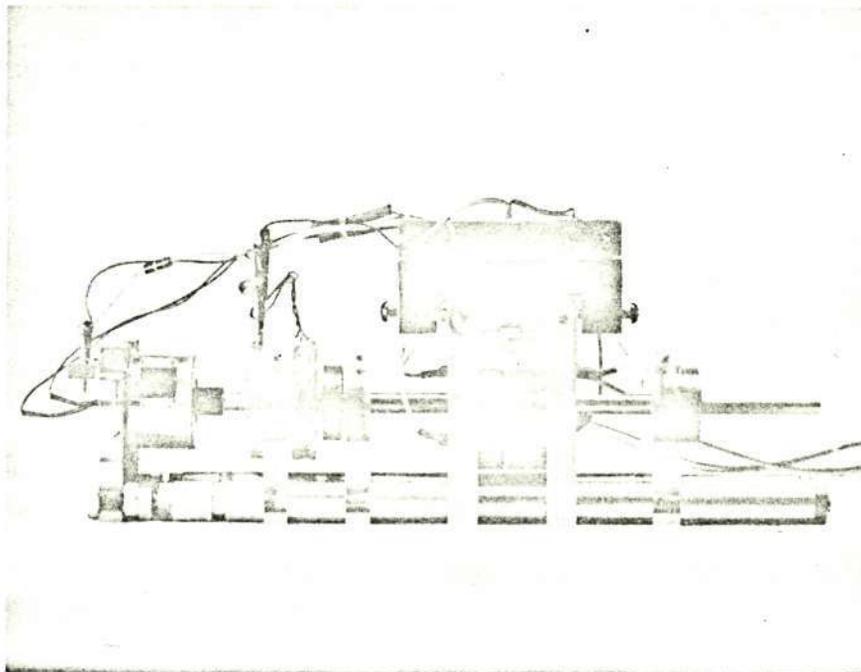
VIRTUALLY ZERO POWER MAGNETIC BEARING WITH FORCE
COIL CLAMP AND DISPLACEMENT SENSOR (LEFT END).

PHOTOGRAPH 9
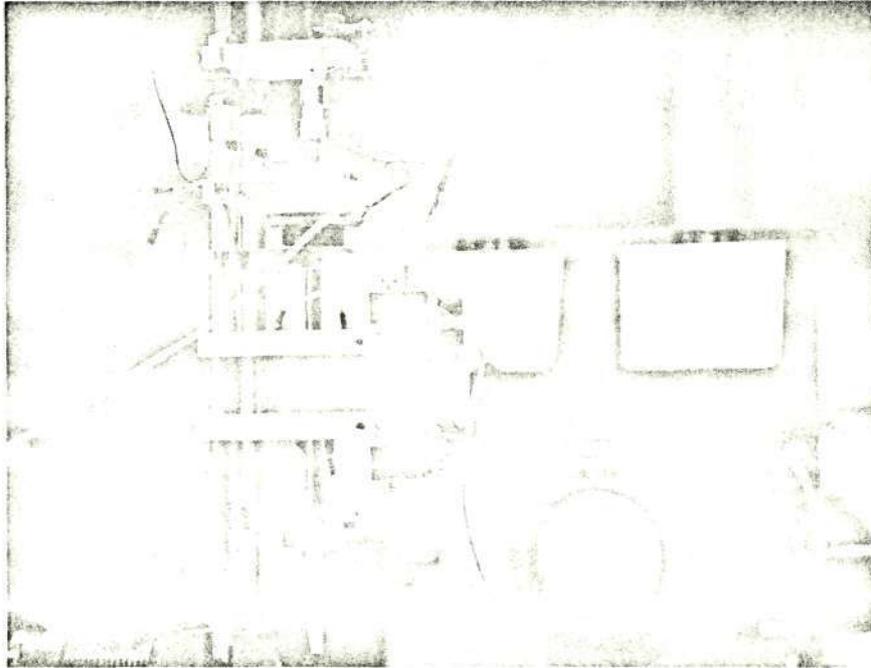
VIRTUALLY ZERO POWER MAGNETIC BEARING
IN OPERATION VERTICALLY

PHOTOGRAPH 10
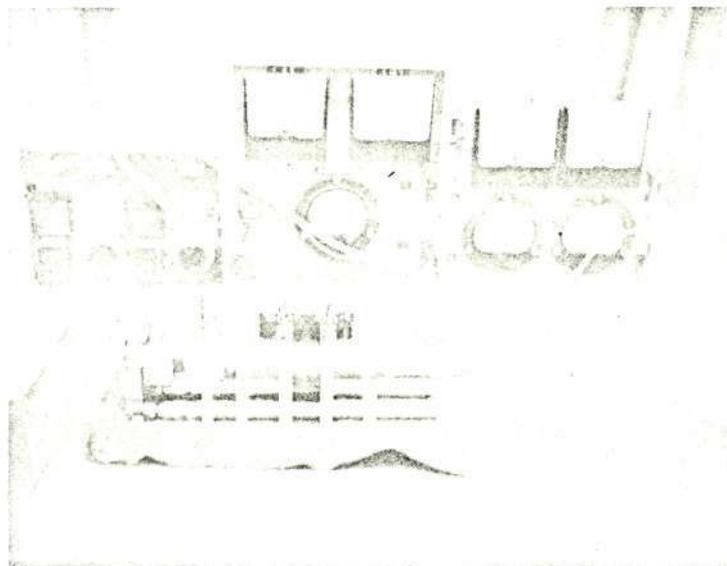
VIRTUALLY ZERO POWER MAGNETIC BEARING
IN OPERATION AT CAMBION

Figure 16

NOTE: OUTPUT VOLTS MEASURED BETWEEN POINTS "B" AND "C" ON SCHEMATIC DIAGRAM. INPUT MILLIVOLTS MEASURED BETWEEN POINT "A" AND COMMON ON SCHEMATIC DIAGRAM. INPUT MEASURED WITH KEITHLEY 150B MICROVOLT-AMMETER. OUTPUT MEASURED WITH KEITHLEY 610C ELECTROMETER.

OUTPUT VERSUS INPUT
VIRTUAL ZERO POWER BEARING AMPLIFIER
DATA TAKEN-MR. JOSEPH LYMAN
6 MARCH 1971
DRAWN BY PAUL SIMPSON
25 MARCH 1971   4-1

CAMBRIDGE THERMIONIC CORPORAT
445 Concord Avenue
Cambridge, Massachusetts 02138

VOLTS OUTPUT

6
5
4
3
2
1

2.0   1.0   0   1.0   62 2.0
MILLIVOLTS INPUT

A1

S1

R1

R2

H1

R3
R4

AR1

R5

R12

TORQUE
LIMIT

R6

R7

R8

MAX. SPEED

TACHOMETER

R13

A2 SAME AS A1

L1

Ø1

R9

Ø2

+14V

COM.

−14V

Q1

R10

Q2

R11

28VDC

| -4 | -3 | -2 | -1 | ITEM | | LIST | OF MATERIALS |
QTY	QTY	QTY	QTY	NO.	CODE IDENT	PART OR IDENT. NO.	NOMENCLATURE OR DESCRIPTION
			1	AR1			OPERATIONAL AMPLIFIER, HIGH POWER. ANALOG DEVICES #402
			1	H1			HALL DEVICE, SIEMENS #SV566
			1	L1			MOTOR ARMATURE COIL
				R1			10KΩ 1/2 WATT 10% POTENTIOMETER
				R2			5KΩ 1/2WATT 10% POTENTIOMETER
				R3			470Ω 1/2 WATT 10% CARBON
				R4			470Ω 1/2 WATT 10% CARBON
				R5			470Ω 1/2 WATT 10% CARBON
				R6			470Ω 1/2 WATT 10% CARBON
				R7			2.5KΩ 1/2 WATT 10% POTENTIOMETER
				R8			25KΩ 1/2 WATT 10% POTENTIOMETER
				R9			1Ω 2 WATT 10% CARBON
				R10			470Ω 2 WATT 10% CARBON
				R11			470Ω 2 WATT 10% CARBON
				R12			10KΩ 1/2 WATT 10% CARBON
				R13			10KΩ 1/2 WATT 10% CARBON
				Q1			TRANSISTOR, POWER MJ1000
				Q2			TRANSISTOR POWER MJ900

71279	LM	FIGURE 18	
SCALE	SHEET	64	REV

Figure 19

MOTOR DATA

1.	O.D. Sam. Co. Magnet	1.5 Cm.
2.	I.D. Iron Collar (Return Path)	3.0 Cm.
3.	Mean Dia. Air Gap	2.25 Cm.
4.	Mean Field at Above	2,000 Gauss
5.	Magnet Length	1.5 Cm.
6.	Wire Size	#36(25 Circular Mils)
7.	Turns/Coil (There are 2 coils/ phase, 4 per motor)	600 Turns
8.	Active Wire Length/Phase	3600 Cm.
9.	Back EMF @1200 RPM	10 Volts
10.	Inactive Wire Length/Phase (Est.)	5000 Cm.
11.	Resistance/Phase	160 Ohms
12.	Peak Torque/Ampere (1 Phase)	26 Oz. In.
13.	Average Torque for 1 Ampere in Each Phase	26 Oz. Inc.
14.	Average Torque @0.05 Amp/Phase	1.3 Oz. In.
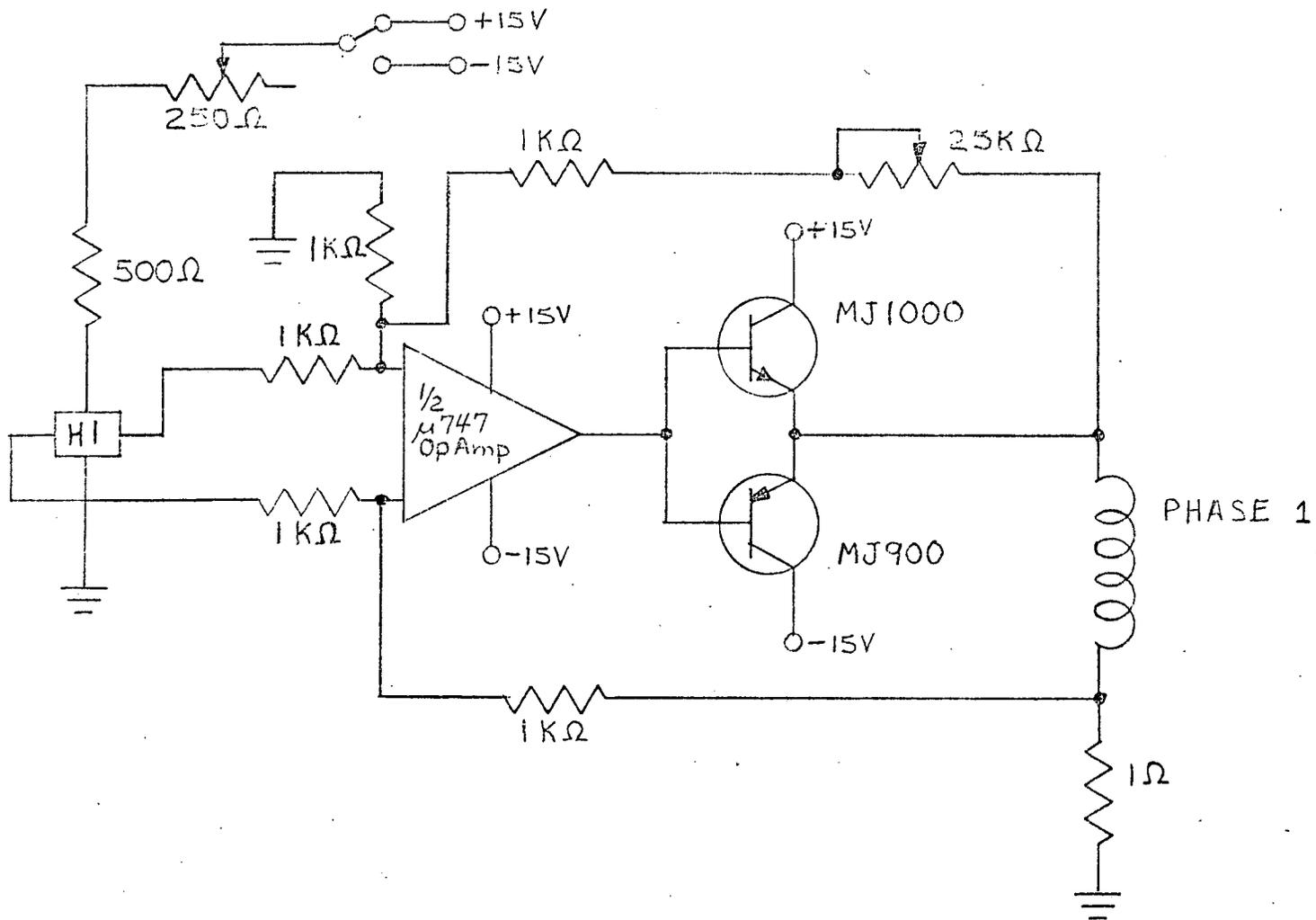
Figure 20

FIGURE 20

2 PHASE DC MOTOR

29 SEPT 71
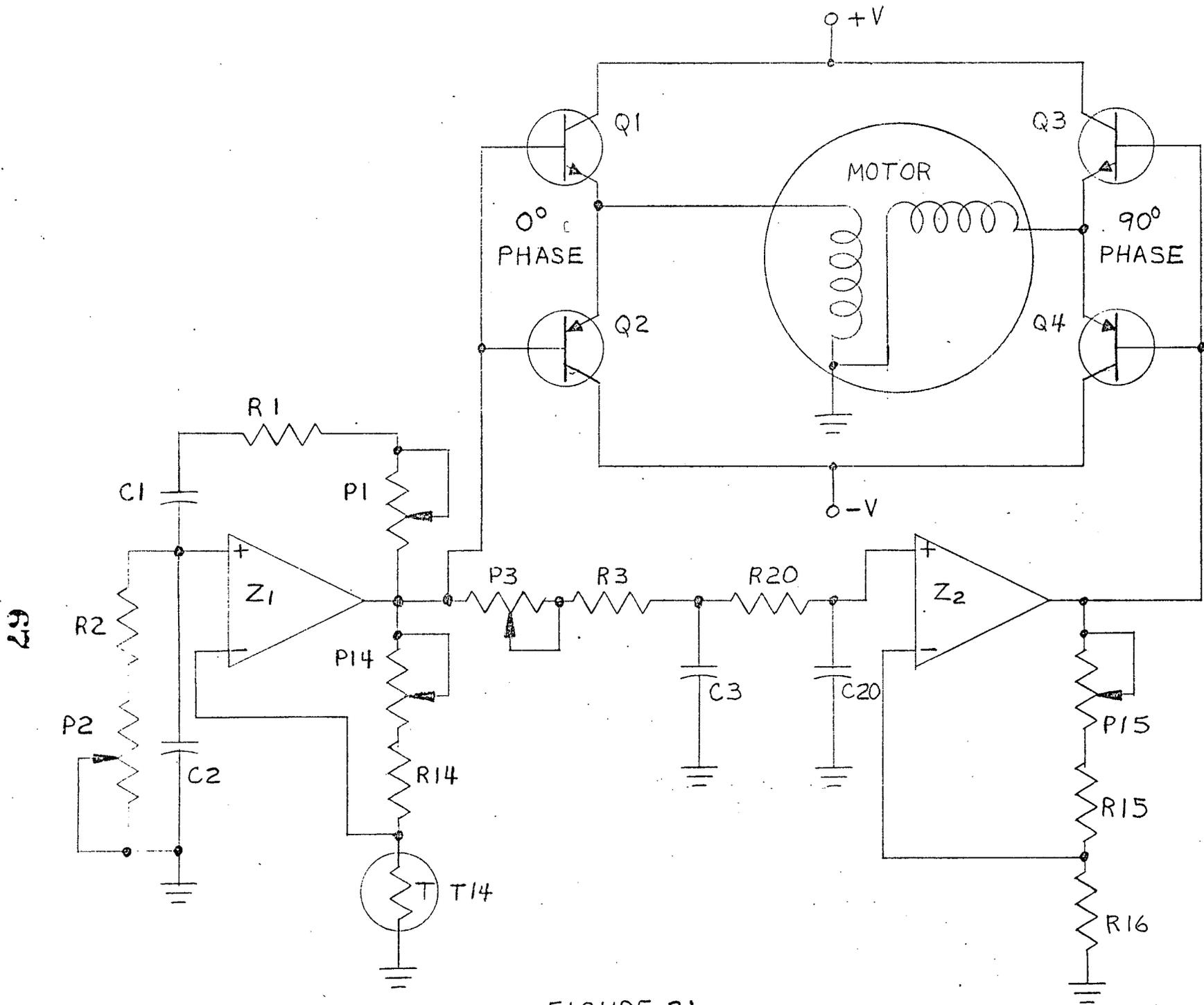
FIGURE 21

Figure 21

Page intentionally left blank

Figure 23
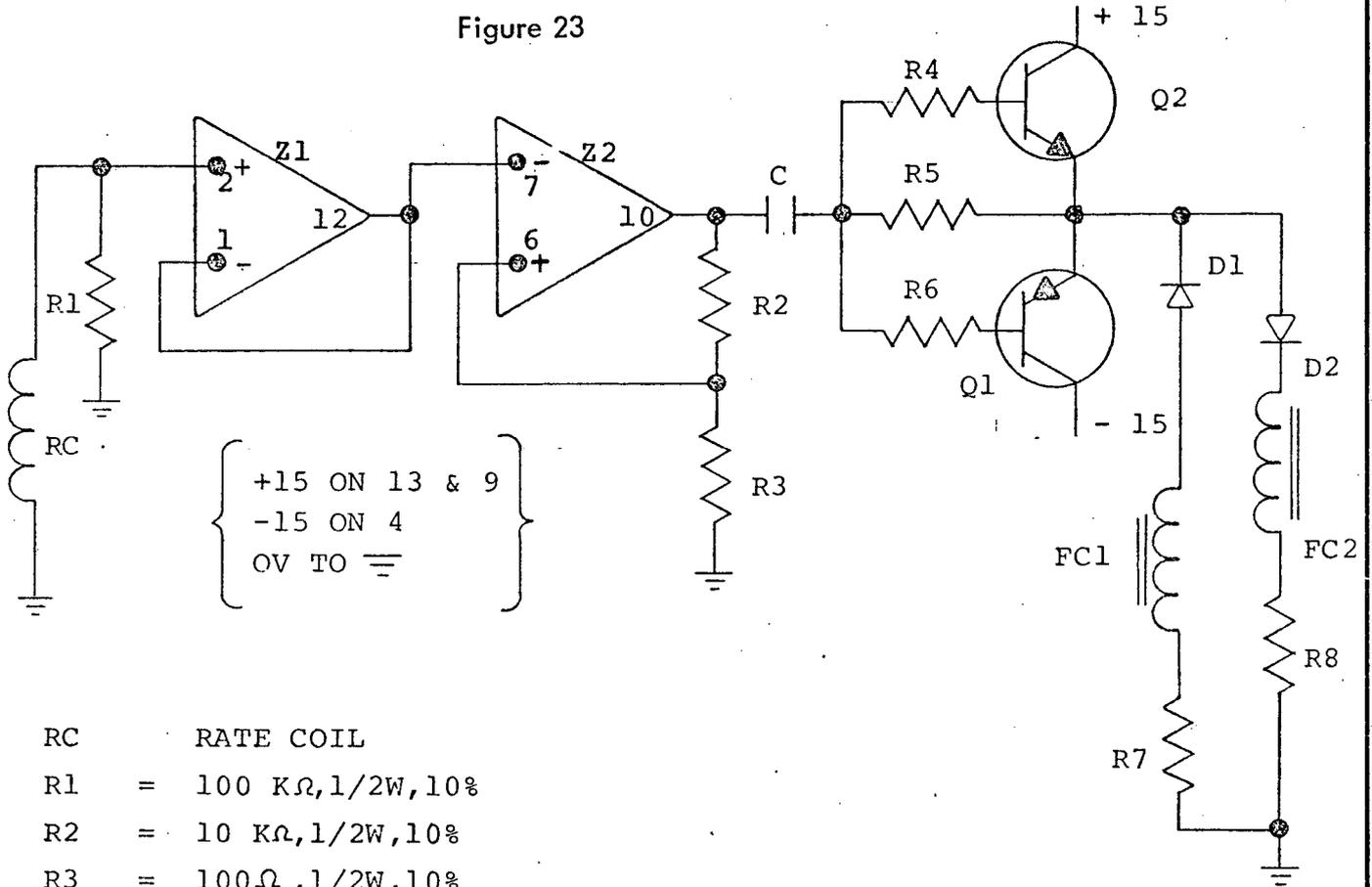
{ +15 ON 13 & 9
  -15 ON 4
  0V TO ⏚ }

RC		RATE COIL
R1	=	100 KΩ, 1/2W, 10%
R2	=	10 KΩ, 1/2W, 10%
R3	=	100Ω, 1/2W, 10%
R4=R6=		1000Ω, 1W, 10%
R5	=	2,200Ω, 1/2W, 10%
R7=R8=		0.1Ω, 5W, 10%
Z1=Z2=		1/2 747 OP. AMP.
D1=D2=		6A, 50V DIODE
Q1	=	16A, NPN DARLINGTON
Q2	=	16A, PNP DARLINGTON
C	=	25 MFD, 20V, NON POL ELECTROLYTIC

Figure 24

.008 TYP
AIR GAP

1.300 DIA   1.200 DIA   NS   .500 DIA   1.00 DIA

.100

MECH. GROUNDED FRAME

Figure 25

.035 FLAT

.075

RADIAL FORCE

N NS S

.250

Figure 26

N NS S

FERROMAGNETIC MATERIAL

AXIAL VELOCITY OR RATE COIL VOLTAGE

TIME

Figure 27

RATE COIL EMF (VOLTS)

0.2

0.1

TIME
MILLISECONDS

-0.1

-0.2

← 4 MILLISECONDS →

Figure 28

Figure 29

CHECKED | CHECKED
VERIFIED | APPROVED

CAMBRIDGE THERMIONIC CORPORATION

445 Concord Avenue   Cambridge 38, Massachusetts, U.S.A.

DRAWN | SCALE

DATE

72

Figure 30

Figure 3I

L

M

Figure 32

A

R4

R3

L

R1
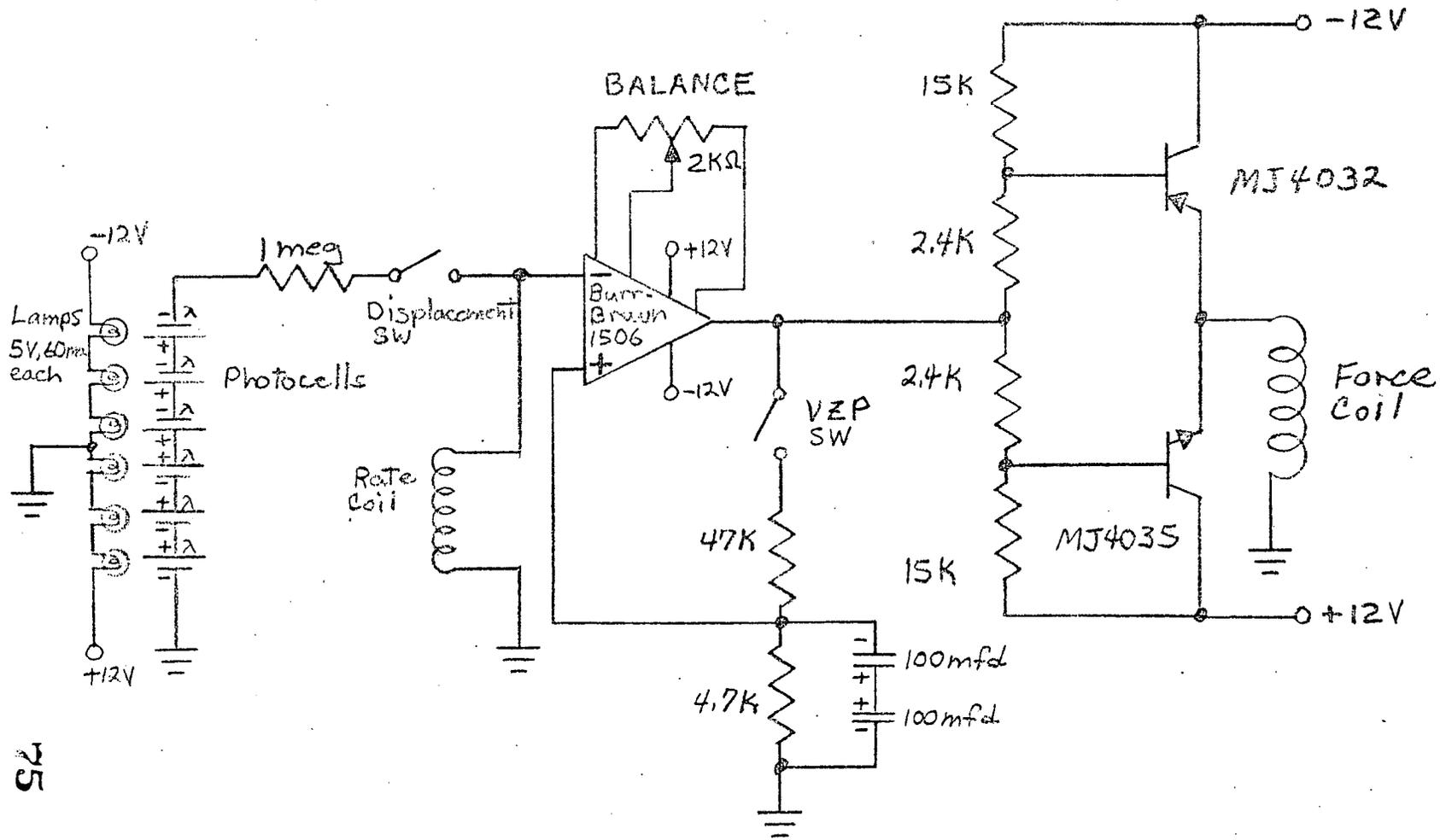
Figure 33

Figure 34

ELECTRONIC DRIVER SERVO FOR
NASA MBSM.

Figure 35

P.A.A. 2-23-23

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