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# 16. MAGNETICALLY SUSPENDED REACTION WHEELS

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## SUMMARY

Recent developments in the technology of magnetic suspensions point to an imminent application to spacecraft systems where long life is a requirement. Magnetic suspensions offer several advantages over conventional bearings, arising because of the contactless nature of the load support. In application to spacecraft reaction wheels, the advantages are: low drag torque, wear-free, unlubricated, vacuum-compatible operation and unlimited life. In addition, by the provision of redundancy in the control electronics, single-point failures may be eliminated. The rationale for selection of a passive radial, active axial, dc magnetic suspension is presented, and the relative merits of 3-loop and single-loop magnetic suspensions are discussed. The design of a .678 N-m-sec (.5 ft-lb-sec) reaction wheel using the single-loop magnetic suspension is developed; the design compares favorably with current ball bearing wheels in terms of weight and power.

## INTRODUCTION

In application to reaction wheels for spacecraft, the primary advantages of magnetic suspensions are: low drag torque, wear-free, unlubricated, vacuum-compatible operation and unlimited life. Operation in the neighborhood of zero speed poses no problems since the suspension capacity is independent of rotational speed, there are no lubrication anomalies, and drag is virtually zero ($70.7 \times 10^{-6}$ N-m/1000 rpm) (.01 oz-in./1000 rpm). In addition, by the provision of redundancy in the control electronics, single-point failures may be eliminated. Pioneering work in the development of magnetic suspensions was done at the University of Virginia, under the direction of Beams (reference 1). The earliest suspensions date back to 1937. Since then, magnetic suspensions of various configurations have been constructed. Recent developments in the technology of magnetic suspensions have been spurred by advancements in magnetic materials and microelectronics, and point to applications in spacecraft systems where long life is a requirement. Some recent designs with the viewpoint of an ultimate spacecraft application were reviewed by Henrikson et al (reference 2) and the design of a 1085 N-m-sec (800 ft-lb-sec) momentum wheel assembly was described in (reference 3).

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# MAGNETIC SUSPENSION CHARACTERISTICS

Magnetic suspension offers many advantages for rotational equipment, but as may be expected, some limitations are also incurred. A summary of these characteristics is presented in Table 1.

TABLE 1

MAGNETIC SUSPENSION CHARACTERISTICS

ADVANTAGES

- High reliability (no wear, lubrication, or fatigue)
- Low torque (starting, drag and ripple)
- High speed capability
- Low noise and vibration
- No single-point failures (with redundant electronics)
- Compatible with vacuum environment (no lubricant)
- Insensitive to thermal conditions (large gaps)

DISADVANTAGES

- Lower capacity per unit weight
- Control electronics required

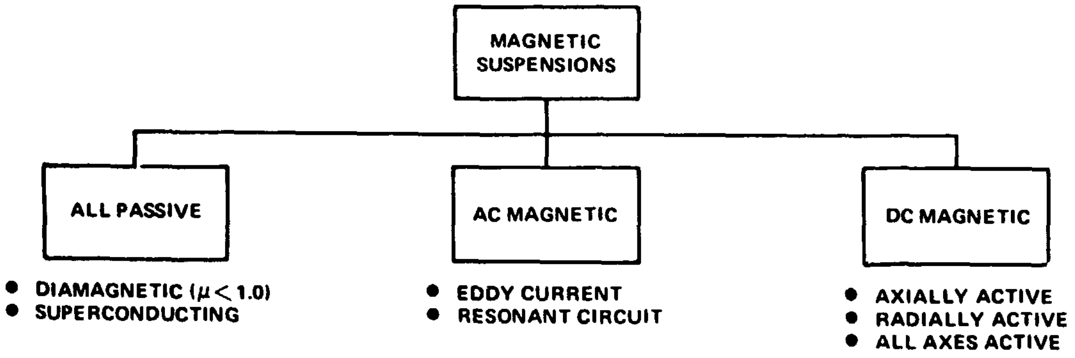
The advantages arise from the basic nature of contactless suspension (non-bearing). High reliability is possible because of the elimination of the lubrication, wear and fatigue characteristics normally associated with ball or fluid bearings; however, a control system must be provided, and its failure rate must be accounted for in the reliability calculation. In connection with this point, it is of interest to note that redundancy can easily be incorporated in the control system electronics; thus, single point failures can be eliminated in the entire system without duplication of the mechanical and structural elements (rotor, housing, etc).

The limitation of capacity is a result of the physics of magnetic force generation: a pair of magnetized surfaces can develop a load capability of $1.6 \text{ x } 10^{-6}$ N/$m^2$ (232 psi) at a flux level of 2 Wb/$m^2$ (near saturation level for iron). When compared with the 2065 x $10^6$ N/$m^2$ (300,000 psi) design limit for ball bearing steels, it can be appreciated that substantially more material must be provided to obtain the same total load capacity. In order to minimize total system weight, it is therefore very important to design the suspensions for the minimum required capacity and/or stiffness.

## SELECTION OF MAGNETIC SUSPENSION TYPE

The achievement of entirely contactless suspension is subject to the fundamental restriction of Earnshaw's theorem (reference 4), which specifies sufficient conditions for instability in inverse-square force fields. The practical consequence of the theorem is that stability under magnetostatic fields is impossible unless diamagnetic or superconducting materials are employed. In the presence of ferromagnetic materials, there is at least one statically unstable coordinate direction, and suitable time-varying fields must be generated to assure stable suspension.

Magnetic suspensions can, in general, be placed in three categories:



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The all-passive systems are magnetostatically stable and therefore do not require an active control system. However, diamagnetic suspensions have very low specific load capacity because their permeability is very close to unity. Superconducting suspensions require the added weight and complexity of a cryogenic cooling system. Of the active systems, ac systems (both eddy-current repulsion and ac resonant) are characterized by high power loss and poor damping characteristics. For application to reaction wheels, the choice therefore narrows to one of the dc magnetic systems.

## Comparison of DC Magnetic Suspension Types

DC magnetic suspensions were first so termed because a steady-state current was used to provide passive magnetic restoring forces, with modulation of this current used to provide total (3-dimensional) stability and levitation. This category has since been extended to include systems in which the passive restoring forces are provided solely by permanent magnets. Rotational dc magnetic suspensions may be divided into three classes:

- Axial active, radial passive (1 degree-of-freedom is actively controlled)
- Radial active, axial passive (2 to 4 degrees-of-freedom are actively controlled)
- All-active (5 degrees-of-freedom are actively controlled)

The comparative characteristics of the three types of systems are summarized in Table 2.

TABLE 2

PROPERTIES OF DC MAGNETIC SUSPENSIONS

| Characteristics | Axial Active - Radial Passive | Radial Active - Axial Passive | All Axes Active |
|---|---|---|---|
| Stiffness | | | |
| Radial | Low | Adjustable | Adjustable |
| Axial | Adjustable | Low | Adjustable |
| Drag Torque | Lowest | Low | Low |
| Power Loss | Low | High | High |
| Control System | 1 degree-of-freedom | 2 to 4 degrees-of-freedom | 5 degrees-of-freedom |
| Reliability | High | Low | Lowest |

The principal advantage of using passive means to obtain restoring forces is inherent simplicity and reliability; neither sensors, electronics, nor control coils are required. When the quiescent field used to obtain the passive restoring forces is provided by permanent magnets, the power losses due to constant coil currents are eliminated. However, the suspension stiffness is entirely determined by the passive magnetics and, unless separate means are provided, cannot be altered from the original value. Additional damping forces (e.g., from eddy-currents) must be provided in order to ensure satisfactory dynamic response and well-bounded amplitudes at resonant conditions.

Active means of obtaining magnetic support forces have the advantage of adjustable stiffness and damping characteristics, which are obtainable by variation of control system parameters. The disadvantages are that sensors, electronics, and forcing coils are required, with a resultant lowering of reliability. Moreover, an active system requires suspension power not only during dynamic-load conditions, but also standby electronics power during static-load conditions.

Selection of a particular suspension type depends heavily on application requirements. In one important area, reliability, the axially active/radially passive suspension is superior to the other types. The reason for this is the smaller number of degrees of freedom required in the control system. Thus, it is primarily for the reliability consideration that the active axial-passive radial suspension was chosen for reaction wheels. It should be noted, however, that, for the same radial stiffness, the weight of this type of suspension is higher than for an active system, and that specific attention must be directed to designing for the minimum allowable radial spring rate for each application.

Consideration is now given to the nature of the passive-radial suspension and to the method of axial control force generation for it.

## Repulsion Versus Attraction

Schematic illustrations of passive repulsion and attraction suspension techniques are shown in Figures 1 and 2, along with a listing of advantages and disadvantages. In the repulsion system, the radial restoring force is generated by the reaction between like magnetic poles. In the attraction system, the radial restoring force is caused by the tendency of the rotor to be in a position of minimum reluctance of the magnetic circuit.

In comparing the relative merits of these techniques, two significant factors can be noted:

- The flux is contained within the magnetic circuit in the attraction suspension, but is forced to be external in the repulsive suspension. This flux containment results in reduced drag torques, and also minimizes unwanted vehicle disturbance torques that would otherwise be generated by interaction with the ambient magnetic field.

- In the repulsion suspension, a separate means (such as a dual-acting solenoid) must be provided to generate bidirectional axial control forces; in the attractive suspension, it is possible to modulate (increase or decrease) the existing magnetic field to generate axial control forces. In addition, non-uniformities in the permanent magnets cause periodic forces and large runouts, and large drag torques.

A comparison of the other features listed in Figures 1 and 2 also favors the attractive system.

To summarize, the preferred suspension for spacecraft reaction wheels:

- Is dc magnetic
- Is active-axial, passive-radial
- Uses an attractive magnetic circuit.

## CONTROL CONCEPTS FOR THE ACTIVE AXIS

As a consequence of Earnshaw's theorem, the radial restoring stiffness of the passive magnetics is accompanied by instability in the axial direction. Because this unbalance force is a function of the difference between the squares of two terms, the net force in the axial direction in a linear function of axial displacement near the equilibrium position. The axial equation of motion of the magnetic suspension is thereby given by

$$M \ddot{z} - K_u z = F$$

where

$z$ = axial displacement from the equilibrium position

$M$ = suspended mass

$K_u$ = unbalance stiffness

$F$ = applied force (total)

Axial stability can be obtained by controlling the current to the control coils to generate forces in the proper direction. Thus, if the control force includes rate-plus-displacement feedback given by

$$F_c = -B \dot{z} - K z,$$

then the axial equation of motion becomes

$$M \ddot{z} + B \dot{z} + (K - K_u) z = F_e$$

where $F_e$ is the external force. This equation indicates system stability can be obtained for $K > K_u$, a net static stiffness of $(K - K_u)$, and results in a power loss under external axial loads. In practice, the rate sensor may be avoided by using lead compensation of the position signal. A block diagram of the axial control system is shown in Figure 3, and the root locus in Figure 4.

In addition to the lead compensation, a minor loop integrator can be added (shown by dashed lines in Figure 3) in order that the unbalance stiffness of the passive magnetics can be used to advantage in overcoming constant external loads. The integrator also enables long-term, low-power operation by correcting for drift in any of the electronic components, including the position sensor. With integral feedback, the static axial stiffness is negative; the root locus of this system is shown in Figure 5.

## MAGNETIC SUSPENSION DEVELOPMENT

Three-loop magnetic suspensions and their application to a large momentum wheel were reported in reference 3, where the nomenclature "3-loop" was selected because of the 3-loop magnetic circuit.

A 1-loop suspension model (Figure A-1) based on the configuration evolved for the reaction wheel (Figure 7) was fabricated and tested in order to confirm the design approaches and obtain preliminary data. The model has been operated successfully through resonance speeds and has shown extremely low drag torques. Test results are discussed in the Appendix.

## APPLICATION TO REACTION WHEELS

The use of reaction wheels is a proven and accepted technique for control of spacecraft attitude. In a typical system, three orthogonally mounted wheels are employed, each developing bidirectional control torques in response to commands from the attitude control sensors.

The total momentum exchange system can be configured as having a nominal zero bias, or else can have a finite momentum along a particular spacecraft axis. In the case of a zero bias system, which is of particular interest here, the wheels must be capable of operation in both directions of rotation, including the region about zero speed. Although ball bearing supported wheels have achieved lifetimes in the neighborhood of 4 to 5 years, their use for longer missions is highly questionable. The main reason for this is the necessity of assuring the presence of a lubricant in the ball contact area over this period of time, and of providing a load-carrying film (or boundary lubrication) in the near-zero speed region. Also, while statistical proof of long life can be accomplished on a design basis for a ball bearing system, it is virtually impossible to guarantee its existence on each individual wheel.

The obvious solution to the ball bearing problem is to avoid contact of the bearing elements, and to eliminate the need for a lubricant supply. Magnetic suspension constitutes such a contactless support system, and forms the basis for the reaction wheel design described in this paper.

## Design Requirements

Each application of reaction wheels to a spacecraft attitude control system has its own particular set of requirements. For the purpose of this development, the requirements were based on an interplanetary spacecraft. These requirements and the values achieved are listed in Table 3.

The motor torque is the net (accelerating/decelerating) torque applied to the wheel, and its reaction is usable for vehicle control purposes. This torque must be delivered upon command in either direction over the total angular momentum range of the wheel. The maximum motor power of 8 watts includes that required for suspension and windage drag, in addition to the net torque delivered to the vehicle.

The suspension system peak power is consumed only momentarily, during initial levitation ($<$ .01 sec).

The cross axis rate input causes a deflection at each bearing due to gyroscopic effects. The interpretation of this requirement is that there be no physical contact of the touchdown bearing elements during this condition. The weight and volume requirements include the reaction wheel plus one channel of suspension control electronics.

Meeting the performance requirements at low ambient pressure and over the stated temperature range should not be a problem as it can be with ball bearing wheels. Because magnetic suspensions are low power devices and are directly compatible with hard vacuum, the housing can be vented directly to space with no adverse effects on the wheel. Performance over the temperature range should also be readily achieved because of the absence of lubricants and the use of sizable clearances. In fact, there should be no significant variation in performance from the standard test conditions.

TABLE 3

.678 N-M-SEC REACTION WHEEL CHARACTERISTICS

| Parameter | Design Requirements | Design Value Attained |
|---|---|---|
| Angular Momentum | ±.678 N-m-sec | ±.678 N-m-sec |
| Motor Torque (min) | ±.0136 N-m | ±.0149 N-m |
| Motor Power (max) | 8 watts | 7 watts |
| Suspension Power | | |
| Peak | 8 watts | 8 watts |
| Average | 1 watt | .5 watt |
| Max Cross Axis Rate Input | .0175 rad/sec | .83 rad/sec |
| Weight | 3.62 Kg | 2.54 Kg |
| Volume | .004095 $m^3$ | .001965 $m^3$ |
| Environment | | |
| Temperature | +20°C to +75°C | +20°C to +75°C |
| Pressure | $10^{-14}$ torr | $10^{-14}$ torr |
| Life | 10 years, operating | unlimited |
| Vibration | .1 $G^2$/Hz | > .1 $G^2$/Hz |

The 10-year life requirement does not apply in the normal mechanical sense because no wearout mechanisms are present. Thus, the definition of life is reduced to determining the reliability of the suspension control system based on constant failure rates.

## Magnetic Suspension

Three-loop and 1-loop suspensions were considered for this application. The 1-loop configuration is shown in Figure 6. It is the simplest of the designs in which a permanent magnet field is modulated to provide control forces; the permanent magnet and the control coil establish magnetic flux in the same magnetic circuit loop. Passive radial stiffness is attained through the action (minimum reluctance) of opposed concentric rings. Bidirectional control forces are provided by controlling the current in the coil.

The primary disadvantage of the 1-loop configuration compared to the 3-loop configuration is that the control current must counter the reluctance of the permanent magnet in the 1-loop design. This means that larger control currents are necessary to produce the same axial force, entailing larger power loss under dynamic loads. In addition, high-coercivity permanent magnet materials such as the rare earth cobalts are essential to prevent the possibility of demagnetization. Analysis shows that the reduction of the force-to-current gain is only 50 percent for the case when the magnet is designed for minimum volume, and can be even lower with an increase in magnet volume.

Since the passive radial stiffness is proportional to the square of the flux density, it is desirable to provide as high a bias flux density as possible, allowing sufficient modulation margin before saturation occurs. Considering that the flux density at saturation for soft material such as electomagnet iron is in the range 1.6 to 2.0 $Wb/m^2$, a bias density level of 1.4 $Wb/m^2$ is a suitable value for design; this leaves adequate margin for modulation to develop axial control forces.

The minimum radial stiffness required for the .5 ft-lb-sec reaction wheel was determined to be in the range 12,270 N/m (70 lb/in.) to 29,250 N/m (167 lb/in.), corresponding to a rotor weight in the range of .453 (1 lb) to 1.36 Kg (3 lbs). The following constraints on radial stiffness were considered in determining these values:

- Suspension without touchdown in any attitude, in both 0-g and 1-g environments.
- Radial and angular rigid-body resonance frequencies to be above 20 Hz.
- No touchdown under cross-axis rates up to .0175 rad/sec.

Previous testing on a 3-loop suspension model had demonstrated that the resonance speeds could be dwelt on for extended periods without significant effect on motor or suspension power. For this reason, the possible location of resonance speeds in the operating speed range was deemed acceptable, and no additional constraints were imposed.

Sizing 1-loop and 3-loop suspensions for the expected stiffness range revealed that the former were lighter by a factor of nearly 3:1. The weight comparison, the design simplicity, the fewer number of machined parts and ease of manufacture and assembly were the basis for selecting the 1-loop design for the reaction wheel. Iterations in the design process determined the rotor weight to be .816 Kg (1.8 lbs) and the corresponding value of radial stiffness, 19,280 N/m (110 lb/in.). The suspension was sized accordingly and is shown in the wheel layout of Figure 7.

## RWA Design Description

A minimum weight design was achieved by optimization of the rotor radius and the maximum operating speed [88.9mm (3.5 in.) rotor radius at 1500 rpm)]. Several variations of the spin motor configuration, when combined with the rotor, housing, and suspension tradeoff data, showed that the minimum weight design utilized a segmented spin motor, with its cage serving as the major RWA inertia element.

The spin motor is made up of two 40-degree segments, thus leaving ample circumferential room for the provision of redundancy (common cage feature). The motor characteristics are shown in Figure 8. The magnetic suspension configuration completely contains the permanent magnets, thus eliminating the potential problem of flaking due to the existence of microcracks in the material. The spacer ring is sized to transmit all the mechanical loads rather than the magnets. The design permits the parts to be machined with relatively loose tolerances, the pole piece clearances and the touchdown bearing clearances being set at assembly.

The touchdown system must be capable of absorbing the impact at touchdown, and also capable of dissipating the energy in the wheel. The use of journal bearings was chosen for the reaction wheel design. A survey of potential materials was made and a Garlock product, DU, was chosen. DU is a prefinished, inert, high performance bearing material that requires no lubricant, and presents no outgassing problem. In this application the calculated life is 255 hours at the maximum RWA speed of 1500 rpm.

Normal contact of the touchdown bearings as a sequenced event occurs at zero wheel speed. However, in the case of unscheduled touchdown at maximum speed, the wheel energy must be dissipated thermally. If this energy is contained within the volume of a single bearing, the calculated temperature rise is 38°C; at the upper ambient of 75°, the resulting touchdown bearing temperature of 113°C is well within the allowable material limit of 280°C.

The magnetic suspension has a radial stiffness of 19,280 N/m (110 lb/in.) and an axial stiffness of 175,000 N/m (1000 lb/in.). The axial stiffness can be varied from 0 to 350,000 N/m (2000 lb/in.) electronically. The permanent magnets used for the suspension are made from samarium cobalt because of its reversible, straight-line demagnetization characteristic and high intrinsic coercive force. This is especially important in the 1-loop design, because the control flux, which goes through the magnet, opposes the permanent magnet flux when it is desired to decrease the flux density in the gap. The B-H characteristic also enables the magnet to be magnetized prior to assembly and eliminates the need for keepers. The weight breakdown of the system is given in Table 4.

TABLE 4

.5 FT-LB-SEC REACTION WHEEL WEIGHT BREAKDOWN

| Element | Weight Kg (lbs) |
|---|---|
| Housing | .860 (1.9) |
| Rotor (including cage)<br>Motor Cage | .815 (1.8) |
| Magnetic Suspension | .453 (1.0) |
| Motor Stator (2 segments) | .272 (.6) |
| Electronics | .090 (.2) |
| Vent Valve | .045 (.1) |
| Connector | .045 (.1) |
|  | 2.58 Kg (5.7 lbs) |

## SUSPENSION ELECTRONICS

The suspension electronics provides control forces to maintain levitation of the rotor in the axial direction. The main components, as shown in Figure 9, are the axial position sensor, compensation network, power amplifier, and an integrator. The primary design considerations are maximum reliability and minimum power consumption.

### Position Sensors

Various types of position sensors are capable of measuring distances on the order of .128 to 1.28 mm (.005 to .050 inch) as required in this application. Of these, the eddy-current sensor offers a number of advantages making it very attractive. It has a high sensitivity providing a good signal to noise ratio; the sensing probe is small, thus minimizing mounting problems; and the electronics is very simple.

In the eddy-current sensor an ac source excites the probe which is simply a coil of wire oriented so that the induced field intersects the sensed surface. The surface must be a conductor so that eddy currents can be induced in it. The closer the probe to the sensed surface, the greater are the eddy currents. An electronic circuit converts the eddy current variation to a dc signal. An ac oscilator excites the probe through a high source impedance. The voltage across the probe then varies as the probe impedance changes with the varying eddy currents. The voltage is converted to dc by rectification and filtering. The eddy-current sensor can provide a typical output scale factor of .3 volt per mil and has good linearity. It is somewhat sensitive to temperature and excitation frequency changes, but in the closed loop magnetic suspension application this is not a disadvantage.

## Compensation

Compensation consists of a lead/lag network which is required to stabilize the static unbalance in the axial direction. Enough phase lead must be added to lift the phase curve up above -180 degrees at the zero dB gain crossover frequency. Approximately 40 degrees of lead at 100 Hz is adequate. This will result in increased gain at high frequencies, tending to excite mechanical resonances. Thus, the lag is used to keep the high frequency gain as low as possible without introducing excessive phase lag at crossover.

An integrator is used, with positive feedback to minimize steady-state power consumption and to eliminate the effects of control electronics or position sensor drift. It operates very slowly so that it does not interfere with the dominant dynamics of the suspension system. Steady-state coil currents are integrated and added to the position signal, thus moving the position command to a point where the rotor is at a force equilibrium with the permanent magnet forces. At this point no coil current is required.

## Power Amplifier

The power amplifier consists of a linear power bridge which controls current in either direction through the coils in response to the compensated position error signal. A current feedback loop is incorporated because the magnetic force is provided by current rather than voltage. A high gain loop minimizes the effects of coil inductance.

The amplifier operates from a +28-volt dc power source. A small ±8-volt power supply is included in the suspension electronics for the I.C. operational amplifiers. The use of this supply is selected over the more conventional ±15 volts to conserve power. Each operational amplifier uses less than 5 mw of power. The power consumption of the suspension electronics with the wheel at operating speed is .4 watt. Some power, about .1 watt, is lost due to pickup of rotor frequency by the suspension electronics. Thus, the total standby power loss is .5 watt. The lift-off power consumption is 8 watts.

The electronics is packaged in three cordwood modules within the wheel housing. Since there is no thermal dissipation or severe vibration, the modules are not embedded with epoxy. This minimizes the weight of the modules, to about .023 Kg (.05 lb) each.

## CONCLUSIONS

The application of magnetic suspension to spacecraft reaction wheels offers several advantages as compared to conventional bearings, arising from the contactless load support. These advantages are: lower drag torque 70.7 x $10^{-6}$ N-m/1000 rpm (.01 oz-in./1000 rpm), no lubricant required, the lack of any wear-out mechanism provides virtually unlimited life, no increase in power at low temperature, lower steady-state power, no single point failure mechanism in the unit (with redundant suspension electronics and spin motor), launch loads are not taken by the on-orbit bearing surfaces, and the unit is unaffected by vacuum operation.

The design is competitive with ball bearing reaction wheels in terms of weight and power. All the concepts used in the reaction wheel design have been either utilized in flight hardware, or, as in the case of the magnetic suspension, have been demonstrated in development hardware. The sensitivity of the design to peak motor power is .136 Kg/watt (.3 lb/watt) and to momentum, .803 Kg/N-m-sec (2.4 lb/ft-lb-sec).

The advantages of magnetic suspensions summarized here apply to other momentum devices, such as bias wheels and energy wheels.

## ACKNOWLEDGMENT

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## NOTE

Customary units were used in the preparation of this paper.

# APPENDIX

The design of a magnetic suspension model and its principal test results are described in this appendix. The model (photograph, Figure A-1) employs the radial-passive, axial-active, 1-loop suspension configuration shown in Figure 6. The model incorporated the suspension evolved in the reaction wheel design. The model was different from the configuration of Figure 7 in that an existing non-segmented ac induction motor was used rather than the segmented motor, no cover was fabricated, and the electronics were external, in breadboard form. However, the suspension system was the same as that developed for the reaction wheel design, and the results are therefore representative. The axial control system utilizes a single lead-lag network for compensation, with a current amplifier to drive the control coils. Provisions were made for tests with or without the positive integral feedback technique. An eddy-current proximitor was used for axial position sensing. Sliding-contact touchdown bearings made from a teflon-based material were provided.

## Test Results

The test model has been successfully levitated and operated at speeds up to 3200 rpm (design speed being 1500 rpm). Successful operation of the touchdown system has also been achieved over this speed range. Very stable suspension has been attained, with minimal power loss under both ambient conditions and steady external loads, achieved by the use of positive integral feedback of control current.

The measured model characteristics are summarized in Table A-1.

TABLE A-1

ONE-LOOP MODEL CHARACTERISTICS

| | |
|---|---|
| Momentum (1500 rpm) | .19 N-m-sec (.14 ft-lb-sec.) |
| Drag Torque Coefficient | 10.6 x $10^{-6}$ (N-m/1000 rpm (.0015 oz-in/1000 rpm) |
| Stiffness | |
| Radial (each end) | 17,500 N/m (100 lb/in.) |
| Axial Unbalance | -250,000 N/m (1430 lb/in.) |
| Suspension Power | |
| Lift Off | 12 watts |
| Operating | .5 watt |
| Rotor Weight | 0.68 kg (1.5 lb) |

The net axial stiffness and damping were continuously adjustable, depending on the feedback gain settings. It was possible to operate from both control coils simultaneously (series or parallel), or from only one coil at a time. The frequency response was in good agreement with analysis.

The tests have demonstrated the viability of the one-loop suspension concept and its application to reaction wheels.

- ADVANTAGES
  - LOWER UNBALANCE STIFFNESS RATIO ($K_U/K_R \approx -2$)
- DISADVANTAGES
  - STRAY FIELDS
    - HIGHER DRAG TORQUES
    - INTERACTION WITH ADJACENT COMPONENTS
  - SEPARATE AXIAL CONTROL TECHNIQUE REQUIRED
  - LOWER CAPACITY
  - MAGNETS ON SHAFT
    - SPEED LIMITATION

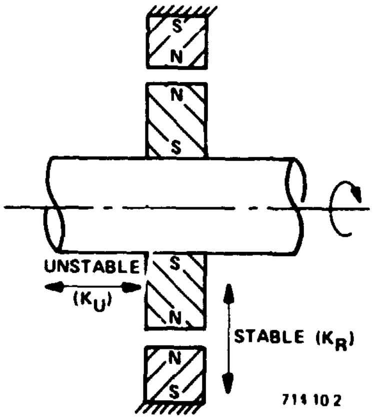

Figure 1
Passive Radial Suspension, Repulsion

- RESTORING FORCE DUE TO VARIATION OF RELUCTANCE
- ADVANTAGES
  - CONTAINED FIELDS
  - FIELD MODULATION FOR AXIAL CONTROL
  - HIGHER CAPACITY
  - MAGNETS STATIONARY
- DISADVANTAGES
  - HIGHER UNBALANCE STIFFNESS RATIO ($K_U/K_R \approx -8$)
  - COIL MUST OVERCOME MAGNET RELUCTANCE

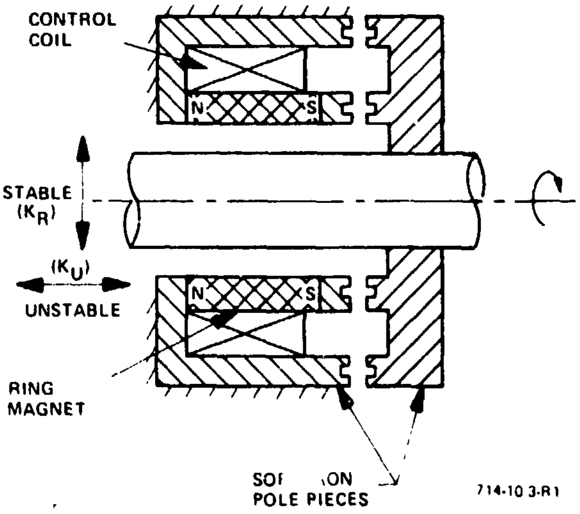

Figure 2
Passive Radial Suspension, Attraction

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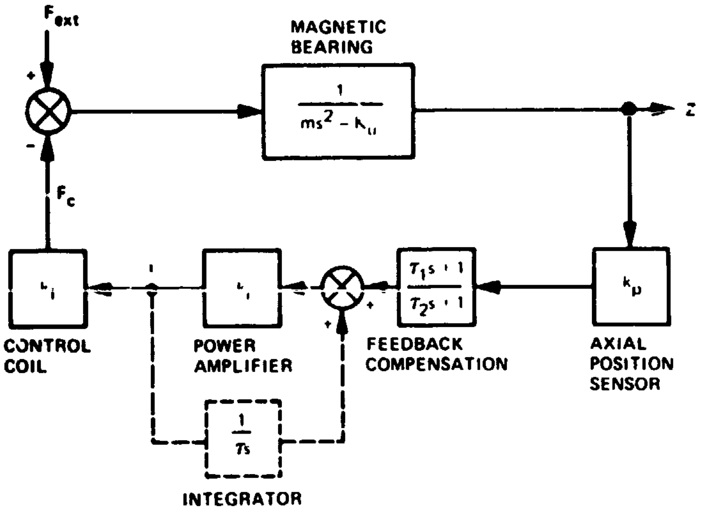

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Figure 3
Axial Control System Block Diagram

$F_c \quad k\frac{(T_1s+1)}{(T_2s+1)}Z$

- POSITION STIFFNESS - $(K - K_u)$
- POWER LOSS UNDER STEADY LOAD

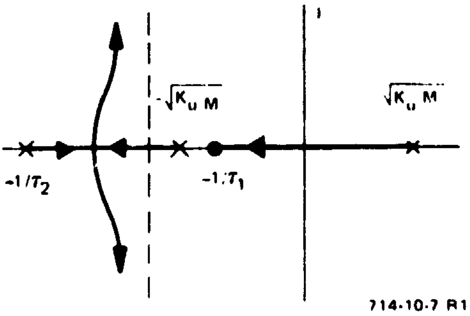

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Figure 4
Root Locus, Lead Compensation

- INTEGRAL REGENERATIVE FEEDBACK

$$F_c = k\frac{(T_1s+1)}{(T_2s+1)}\frac{(Ts)}{(Ts-1)}Z$$

- NEGATIVE STIFFNESS - $-K_u$
- ZERO POWER LOSS UNDER STEADY AXIAL LOADS
- COMPENSATES FOR ELECTRONICS AND SENSOR DRIFT

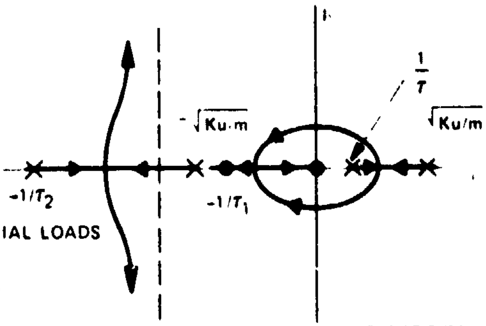

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Figure 5
Root Locus, Integral Feedback

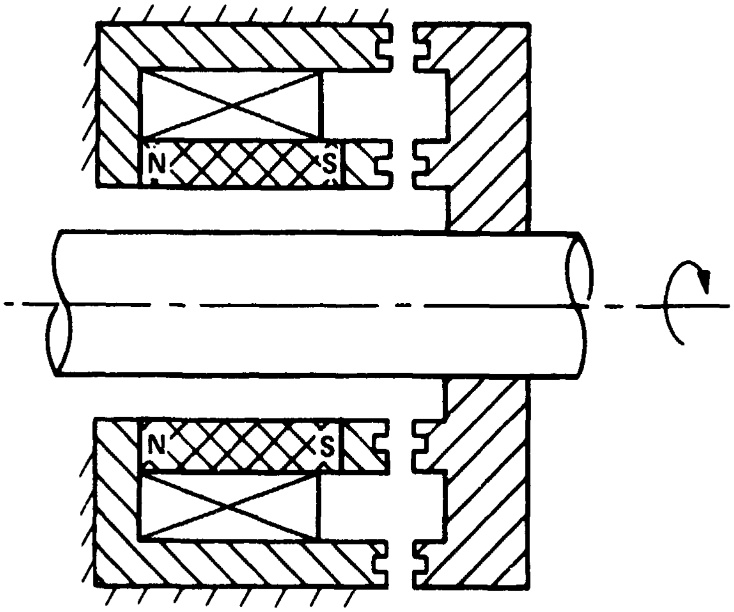

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Figure 6
One-Loop Suspension Configuration

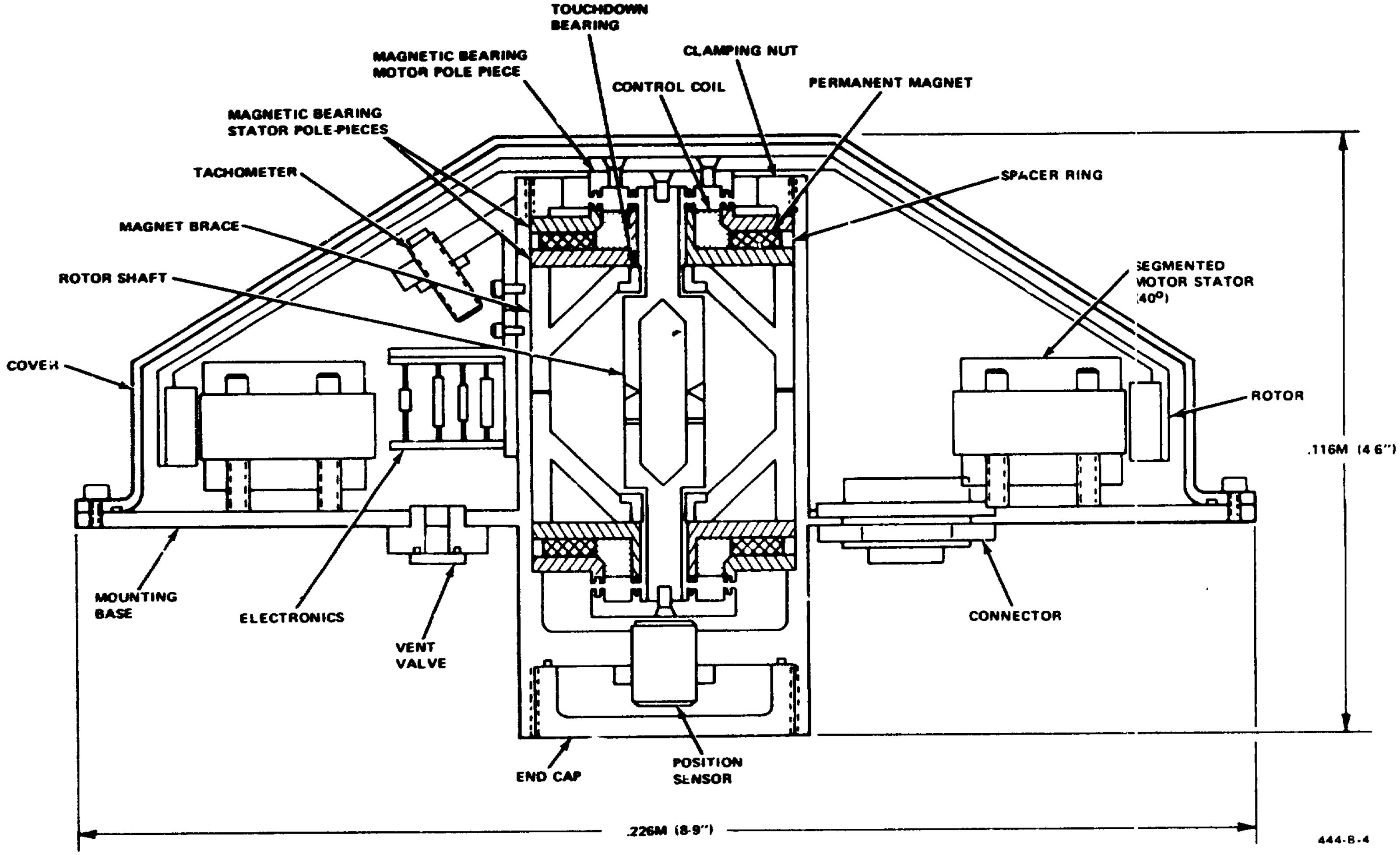

Figure 7
Preliminary RWA Design Layout

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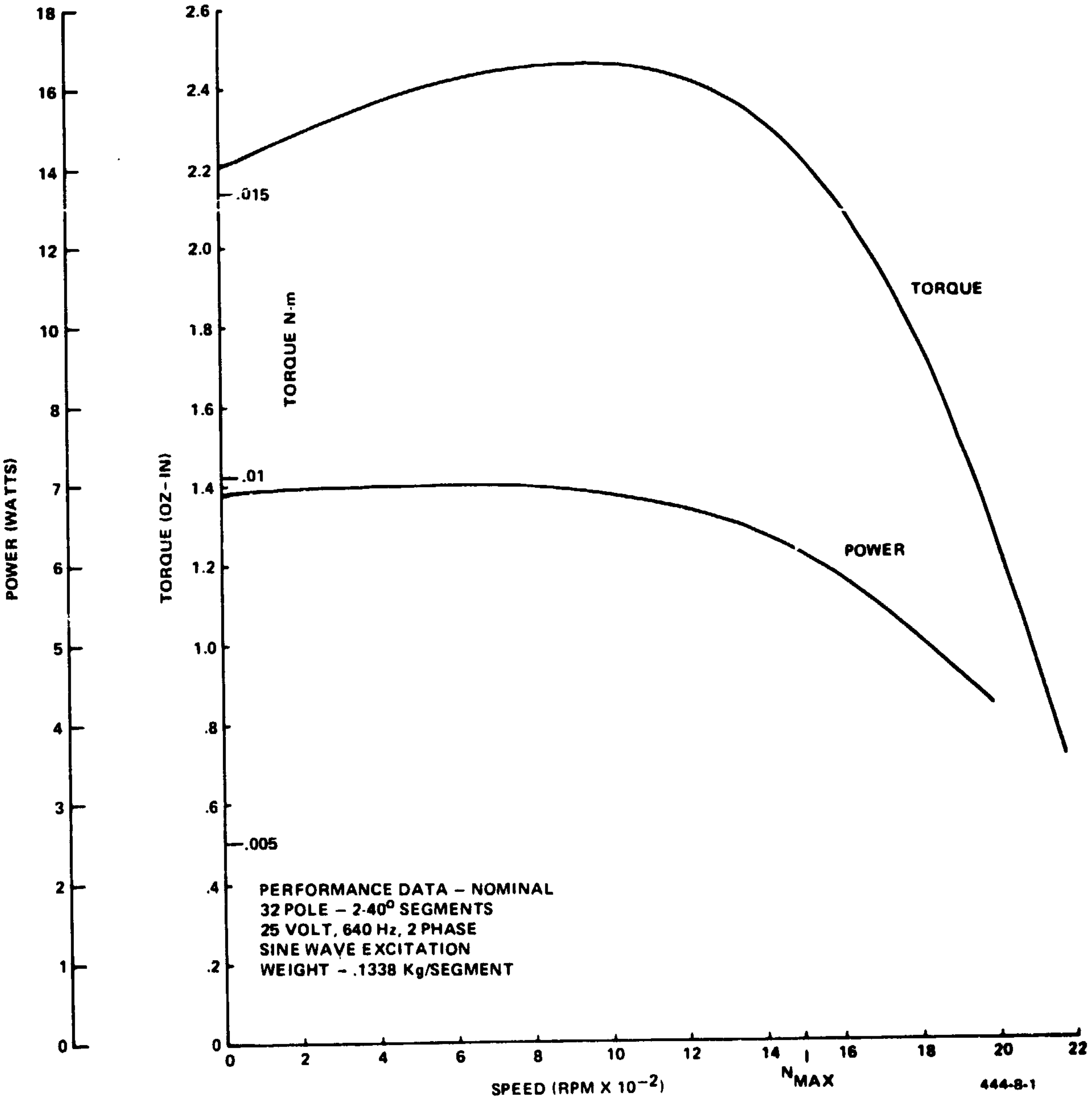

Figure 8
Performance Data, Segmented Spin Motor

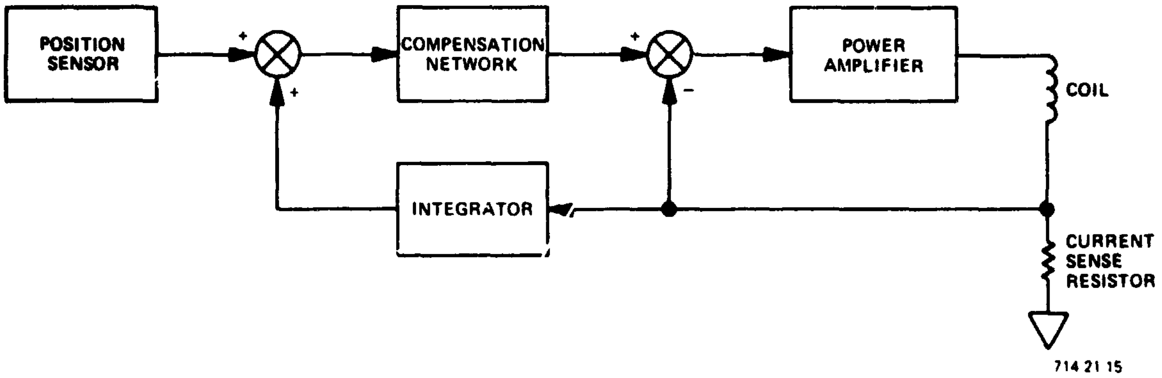

Figure 9
Suspension Electronics Block Diagram

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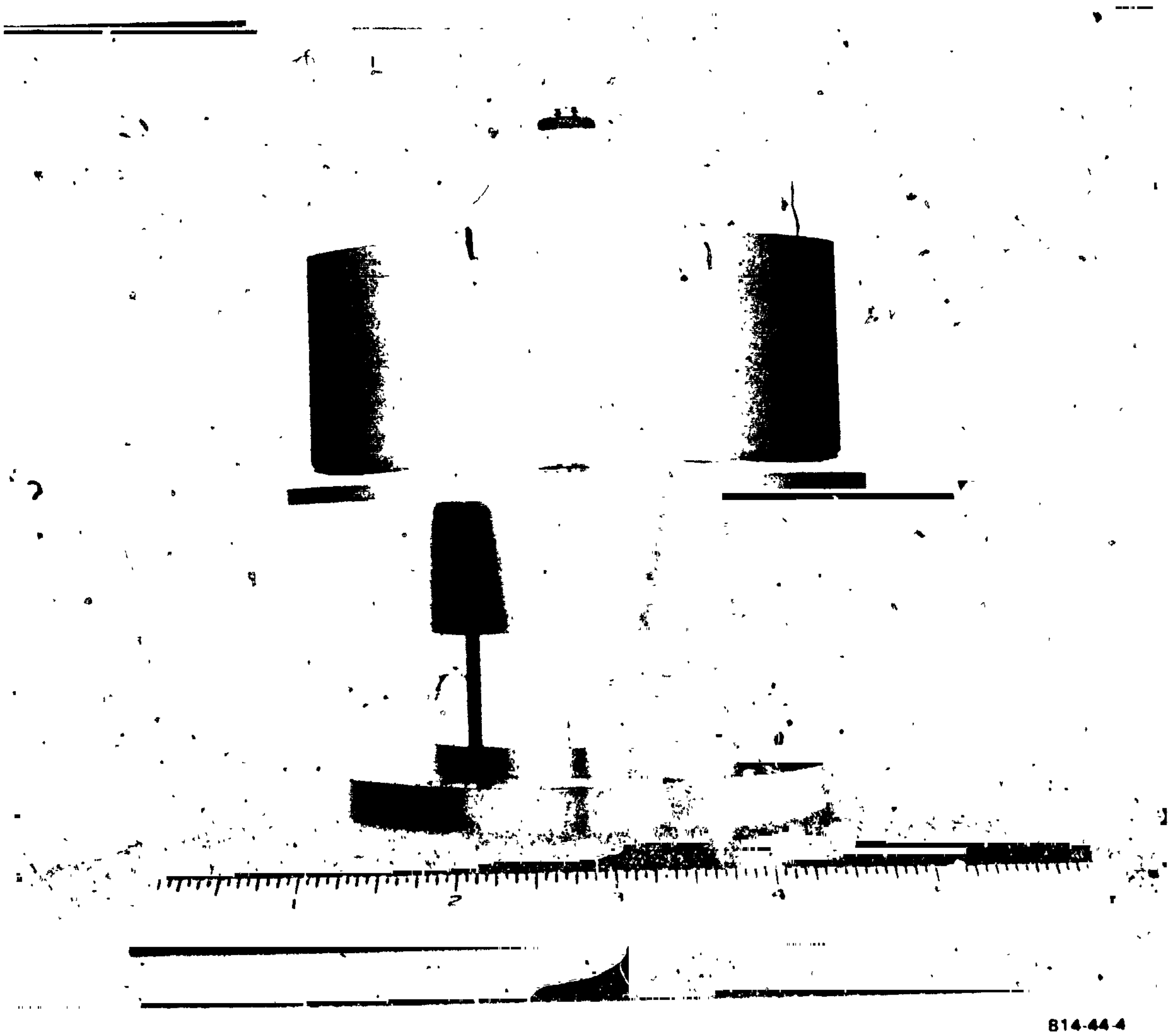

Figure A-1
One Loop Magnetic Suspension Model