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DESCRIPTION OF THE LARGE GAP MAGNETIC SUSPENSION SYSTEM (LGMSS) GROUND-BASED EXPERIMENT

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SUMMARY

A description of the Large Gap Magnetic Suspension System (LGMSS) ground-based experiment is presented. The LGMSS provides five-degrees-of-freedom control of a cylindrical suspended element which is levitated above a floor-mounted array of air core electromagnets. The uncontrolled degree of freedom is rotation about the long axis of the cylinder (roll). Levitation and control forces are produced on a permanent magnet core which is embedded in the cylinder. The cylinder also contains light emitting diodes (LEDs) and associated electronics and power supply. The LEDs provide active targets for an optical position measurement system which is being developed in-house at Langley Research Center. The optical position measurement system will provide six-degrees-of-freedom position information for the LGMSS control system.

INTRODUCTION

This paper describes the Large Gap Magnetic Suspension System (LGMSS) ground-based experiment and presents a simplified analytical model which can be used in analyses and simulations in the development of control system approaches and in evaluations of overall systems performance. The objectives of the LGMSS ground-based experiment are to investigate the technology issues associated with magnetic suspension, accurate suspended element control, and accurate position sensing at large gaps. This technology has potential applications in a wide range of areas including microgravity and vibration isolation systems, magnetically suspended pointing mounts, large-angle magnetic suspension systems for advanced actuators, wind tunnel magnetic suspension systems, and remote manipulation/control/positioning of objects in space. The simplified analytical model is based on the model developed in reference 1. This model was used to investigate candidate control approaches for the LGMSS. The control approaches are described and numerical results presented in reference 2.

EXPERIMENT DESCRIPTION AND BACKGROUND

The LGMSS ground-based experiment, as originally defined, is shown schematically in figure 1. It consists of a cylindrical suspended element which has a core composed of permanent magnet material embedded in it. Levitation forces and control forces and torques are produced on the permanent magnet core by air core electromagnets which are required to fit within an eight foot by eight foot square by four foot high volume. The core is suspended a total distance of three feet above the top surface of the electromagnet volume. In addition to the permanent magnet core, the suspended element also contains an array of LEDs and associated electronics and power supply. The LEDs are embedded in the surface of the suspended element and provide active targets for a photogrammetric optical position measurement system which is being developed at Langley Research Center. Each LED target is imaged by a cylindrical lens on a linear Charge Coupled Device (CCD) sensor. Position and orientation of the model is determined from the position of the projected target images. There are two sensors per sensing unit and a total of eight sensing units which are positioned symmetrically about and approximately six feet above the suspended element. The optical position measurement system provides six-degrees-of-freedom position information for the control system. The original parameters of the experiment are given in table 1.

Feasibility Studies

After defining the LGMSS experiment, two studies were performed to verify the feasibility of building a system to meet the experiment requirements and to investigate approaches to implement it. One study was performed by Madison Magnetics, Inc. and resulted in a proposed configuration of five electromagnets mounted in a planar array (ref. 3). This approach was designated the five-coil system and the study results are summarized below. The other study was performed by SatCon Technology Corporation and resulted in a proposed configuration of six electromagnets mounted in a planar array. This approach was designated the six-coil system and the study results are also summarized below.

Five-coil system.- An important conclusion of the Madison Magnetics study was that the implementation of the LGMSS experiment was feasible. The proposed implementation is shown schematically in figure 2 and consists of a planar array of five electromagnets mounted in a circular configuration. Since the LGMSS requirement is for five-degrees-of-freedom control, this represents the minimum number of actuators. The electromagnets are conventional liquid-helium cooled superconductors and combine the functions of levitation and control. The magnetization vector is horizontal (parallel to the long axis of the core) and the system is capable of providing 360 degrees yaw (rotation about the vertical axis) control.

Six-coil system.- The SatCon study also concluded that it was feasible to implement the LGMSS experiment. Their proposed approach is shown in figure 3 and consists of a planar array of six electromagnets mounted in a circular configuration. The two approaches are similar with the major differences being in the control approach and the number of coils. The six-coil configuration also uses electromagnets which are conventional liquid-helium cooled superconductors and which combine the functions of levitation and control. The magnetization vector is horizontal (parallel to the long axis of the core) and the system is capable of providing 360 degrees yaw control. The main reasons for adding a sixth coil were control system related. The six coil system results in a symmetrical configuration and also results in an overspecified system from the standpoint of control inputs. The sixth coil could be fitted in the allowable volume without a significant increase in total Ampere-turns.

Selected Configuration

As a result of the feasibility studies and further in-house studies, the requirements for the LGMSS experiment were refined and a decision was made to procure the design, fabrication, installation, and test of an LGMSS. The revised LGMSS requirements are presented in table 2. An open, competitive, procurement effort resulted in the selection of a configuration proposed by Intermagnetics General Corporation. This configuration is shown schematically in figure 4. As shown in the figure, there are two large concentric levitation coils and a separate set of control coils. The levitation coils are superconducting coils which are operated in the persistent mode. In the persistent mode, a superconducting coil is charged up to a certain current value and the terminals are shorted through a persistent mode switch. Since the superconductor has zero resistance, the current continues to flow or persist in the coil. In the configuration shown, the coils have currents flowing in opposite directions. The control coils are shown in a generic configuration since the contract is in the design phase and a final configuration has not been selected. The control coils are conventional room temperature coils. Figure 5 shows the levitation coils and permanent magnet core in more detail. As shown in the figure, the magnetization vector of the core is vertical (perpendicular to the long axis). By adjusting the persistent-mode currents to the correct values, a vertical field and gradient can be produced at the location of the core which will produce a stable levitation force and also a stable torque about the roll and pitch axes. Required control forces and torques are provided by the separate control coils. Yaw torque in this configuration is provided by producing a second-order gradient (gradient of a gradient) along the long axis of the core in the x-y plane. It should be noted that this configuration has the potential for providing active roll control.

LGMSS ANALYTICAL MODEL

This section presents an analytical model of the LGMSS which is based on the model developed in reference 1. This model assumes a magnetization vector which is parallel to the long axis of the core. An analytical model for a core with a vertical magnetization vector, which includes yaw torque generation with second-order gradients, is being developed. Figure 1 shows the coordinate systems and initial alignment. A set of orthogonal $\bar{x}, \bar{y}, \bar{z}$ body fixed axes defines the motion of the core with respect to inertial space. The core coordinate system is initially aligned with an orthogonal x, y, z system fixed in inertial space. A set of orthogonal x_b, y_b, z_b axes, also fixed in inertial space, define the location of the electromagnet array with respect to the x, y, z system. The x_b and y_b axes are parallel to the x and y axes respectively and the z_b and z axes are aligned. The centers of the two axis systems are separated by the distance h. The angular acceleration of the core, in core coordinates, can be written as (see ref. 1)

$$\{\dot{\bar{\Omega}}\} = (1/I_c)(\mathrm{Vol}(\{\bar{M}\} \times [T_m]\{B\}) + \{\bar{T}_d\}) \tag{1}$$

where I_c is the core moment of inertia about the axes of symmetry (y and z), Vol is the volume of the core, $\{\bar{M}\}$ is the magnetization of the core, $[T_m]$ is the vector transformation matrix from inertial to core coordinates, $\{B\}$ is the flux density produced by the electromagnets, and $\{\bar{T}_d\}$ represents external disturbance torques. A bar over a variable indicates that it is referenced to core coordinates. The translational acceleration of the core, in core coordinates, can be written as

$$\{\dot{\bar{V}}\} = (1/m_c)(\mathrm{Vol}([T_m][\partial B][T_m]^{-1}\{\bar{M}\}) + \{\bar{F}_d\}) \tag{2}$$

where m_c is the mass of the core, $[\partial B]$ is a matrix of the gradients of $\{B\}$, and $\{F_d\}$ represents external disturbance forces in core coordinates. The simplified field model of reference 1 has been extended to include expansion of the field around the operating point to first order terms. This means that each element of $\{B\}$, for example B_x, can be written in the form

$$B_x = \tilde{B}_x + (\tilde{B}_{xx})x + (\tilde{B}_{xy})y + (\tilde{B}_{xz})z \tag{3}$$

where $\tilde{B}_x$, $\tilde{B}_{xx}$, $\tilde{B}_{xy}$, and $\tilde{B}_{xz}$ are values calculated at the operating point and the notation $\partial B_i/\partial j \equiv B_{ij}$ has been used. Since the fields and gradients are linear functions of coil currents, the components of $\tilde{B}_x$ produced by coil n of an n-coil system can be written as

$$\tilde{B}_{xn} = K_{xn}(I_n/I_{max}) \tag{4}$$

where I_{max} is the maximum coil current, K_{xn} is a constant which represents the magnitude of $\tilde{B}_{xn}$ produced by I_{max}, and I_n is the coil current. For the total system, $\tilde{B}_x$ can be written as (see ref. 1)

$$\tilde{B}_x = (1/I_{max})\lfloor K_x \rfloor \{I\} \tag{5}$$

where

$$\lfloor K_x \rfloor = \lfloor K_{x1} \; K_{x2} \bullet\bullet\bullet \; K_{xn} \rfloor \tag{6}$$

and

$$\{I\}^T = \lfloor I_1 \; I_2 \bullet\bullet\bullet \; I_n \rfloor \tag{7}$$

The other fields and gradients can be written in the same way. A block diagram of the system is shown in figure 6. This model is nonlinear and is of the form

$$\dot{x} = f(x,u) \tag{8}$$

where x is given by

$$x^T = \lfloor \overline{\Omega}_y \;\; \overline{\Omega}_z \;\; \Theta_y \;\; \Theta_z \;\; \bar{v}_x \;\; \bar{v}_y \;\; \bar{v}_z \;\; x \;\; y \;\; z \rfloor \tag{9}$$

and the input u is given by

$$u^T = \lfloor I_1 \; I_2 \bullet\bullet\bullet \; I_n \rfloor \tag{10}$$

The states Θ_y and Θ_z in (9) are the pitch and yaw angles of the core respectively.

CONCLUDING REMARKS

The Large Gap Magnetic Suspension System (LGMSS) ground-based experiment has been described and a simplified analytical model presented. The analytical model is for a suspended element core with a horizontal magnetization vector. An analytical model for a suspended element core with a vertical magnetization vector, which includes yaw torque generation with second-order gradients, is being developed. The objectives of the experiment are to investigate the technology issues associated with magnetic suspension, accurate suspended element control, and accurate position sensing at large gaps. This technology has potential applications in a wide range of areas including microgravity and vibration isolation systems, magnetically suspended pointing mounts, large-angle magnetic suspension systems for advanced actuators, wind tunnel magnetic suspension systems, and remote manipulation/control/positioning of objects in space.

REFERENCES

1. Groom, Nelson J.: Analytical Model Of A Five Degree Of Freedom Magnetic Suspension And Positioning System. NASA TM-100671, March 1989.

2. Groom, Nelson J.; and Schaffner, Philip R.: An LQR Controller Design Approach for a Large Gap Magnetic Suspension System (LGMSS). NASA TM-101606, July 1990.

3. Boom, R.W.; Abdelsalam, M.K.; Eyssa, Y.M.; and McIntosh, G.E.: Repulsive Force Support System Feasibility Study. NASA CR-178400, October, 1987.

TABLE 1. - LGMSS FEASIBILITY STUDY PARAMETERS

- Core dimensions
  (two sizes)
  - Diameter = 4 in.
    Length = 9 in.
  - Diameter = 2 in.
    Length = 12 in.
- Suspension support capability
  - Core weight plus 15 lb.
- Electromagnet volume
  (floor mounted)
  - 8 ft. X 8 ft. square X 4 ft. high
- Suspension height
  (above electromagnet volume)
  - 3 ft.
- Position range
  (yaw)
  - 40 deg.
- Accuracy
  - Translation (x, y, z) = ± 0.001 in.
  - Rotation (Θ_x, Θ_y, Θ_z) = ± 0.002 deg.

TABLE 2. - LGMSS STATEMENT OF WORK PARAMETERS

- Core dimensions
  (two sizes)
  - Diameter = 1.25 in.
    Length = 5.85 in.
  - Diameter = 2.30 in.
    Length = 7.80 in.
- Suspension support capability
  - Core weight plus 50% of core weight
- Electromagnet volume
  (floor mounted)
  - 8 ft. X 8 ft. square X 4 ft. high
- Suspension height
  (above electromagnet volume)
  - 3 ft.
- Position range
  (yaw)
  - ±360 deg.
- Accuracy
  - Translation (x, y, z) = ± 0.01 in.
  - Rotation (Θ_x, Θ_y, Θ_z) = ± 0.02 deg.

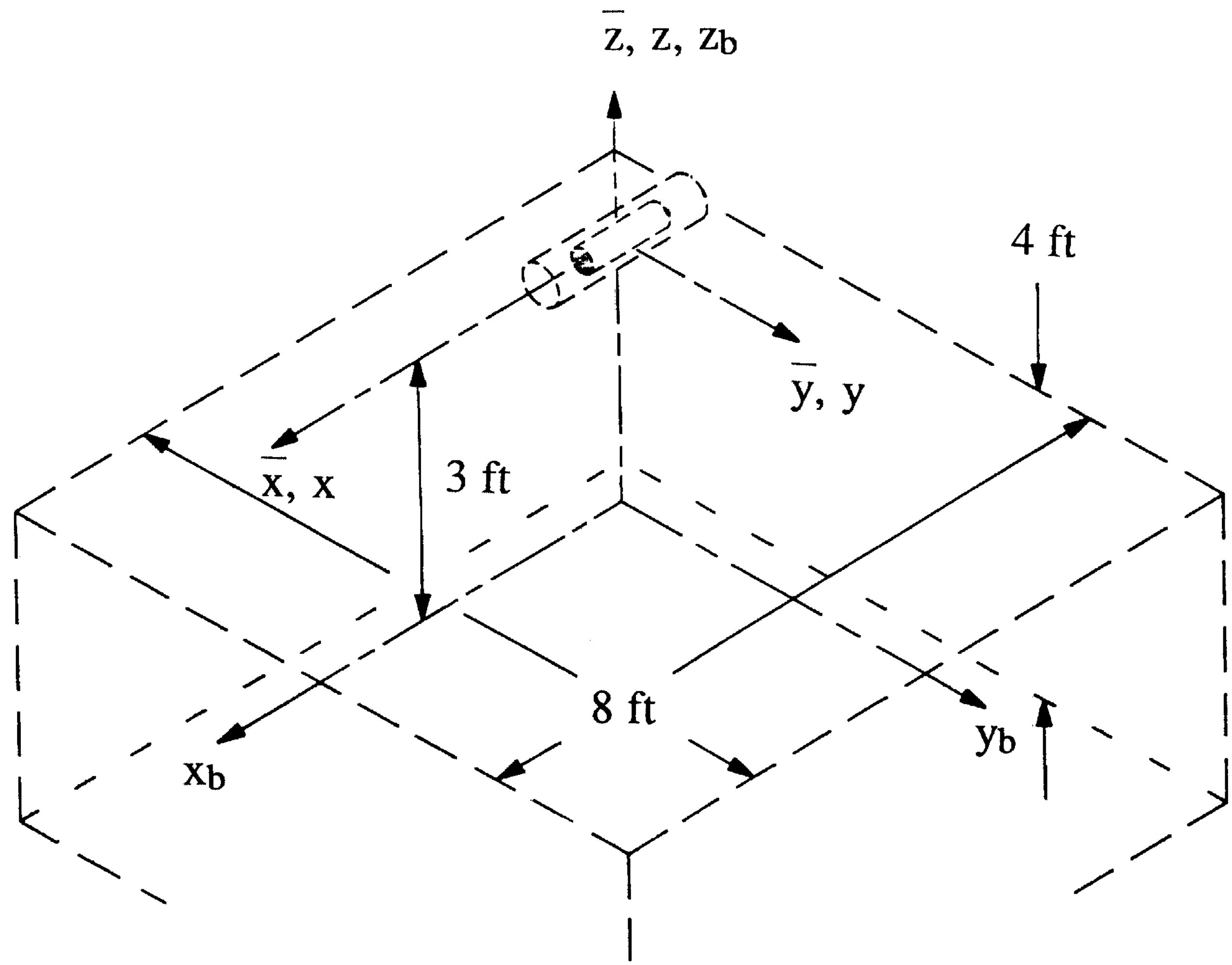

Figure 1.- LGMSS ground-based experiment definition.

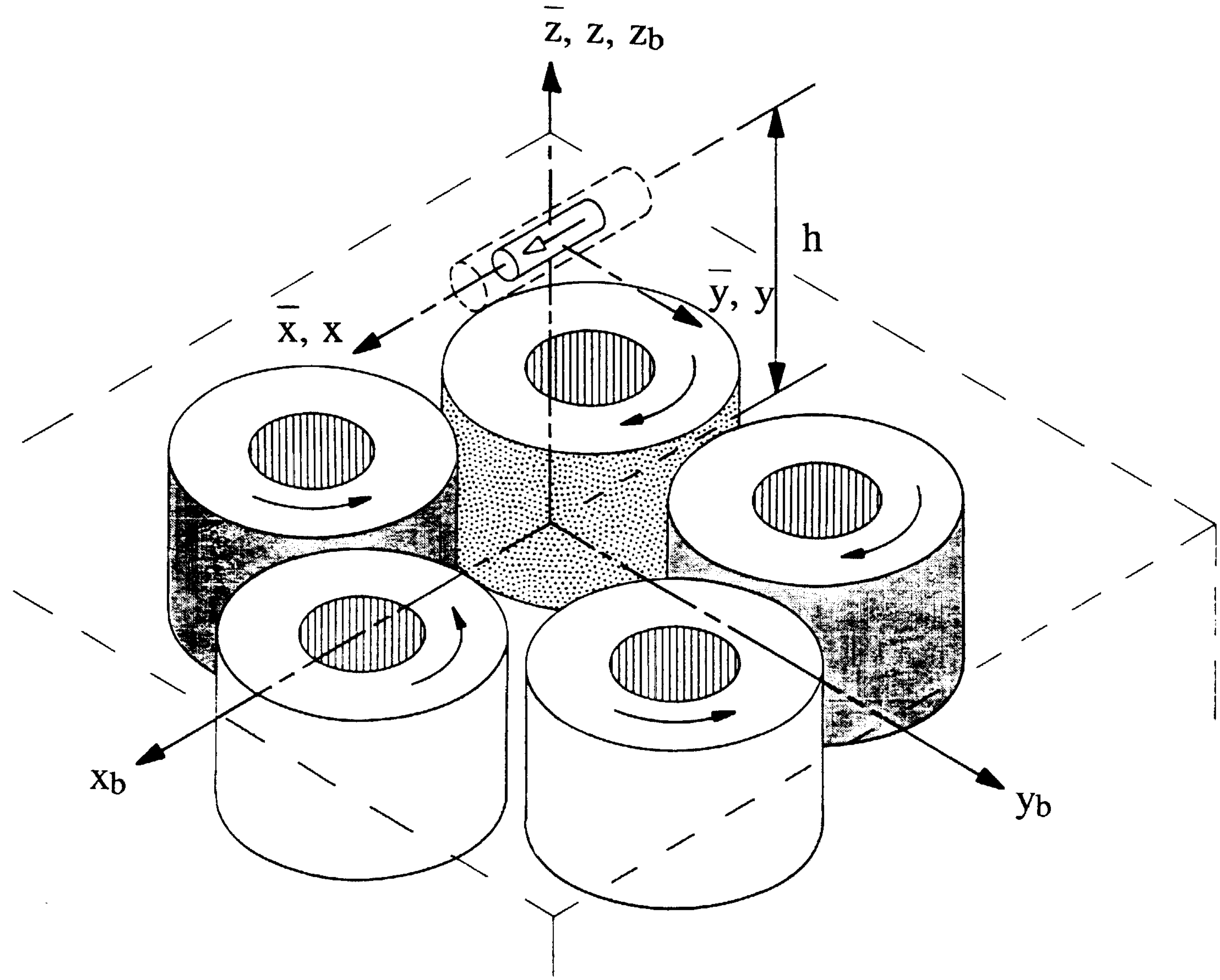

Figure 2.- LGMSS Five-Coil configuration.

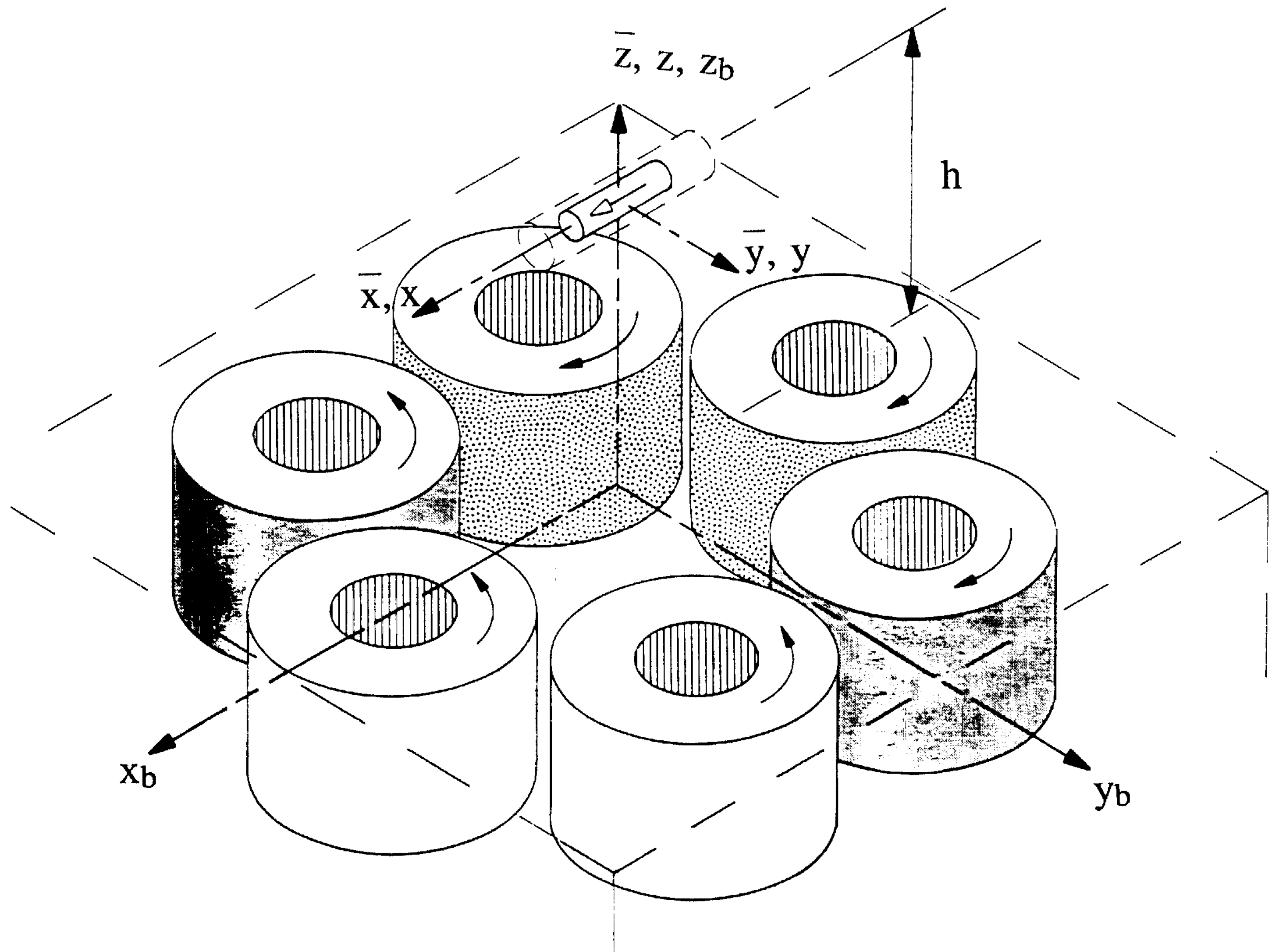

Figure 3.- LGMSS Six-Coil configuration.

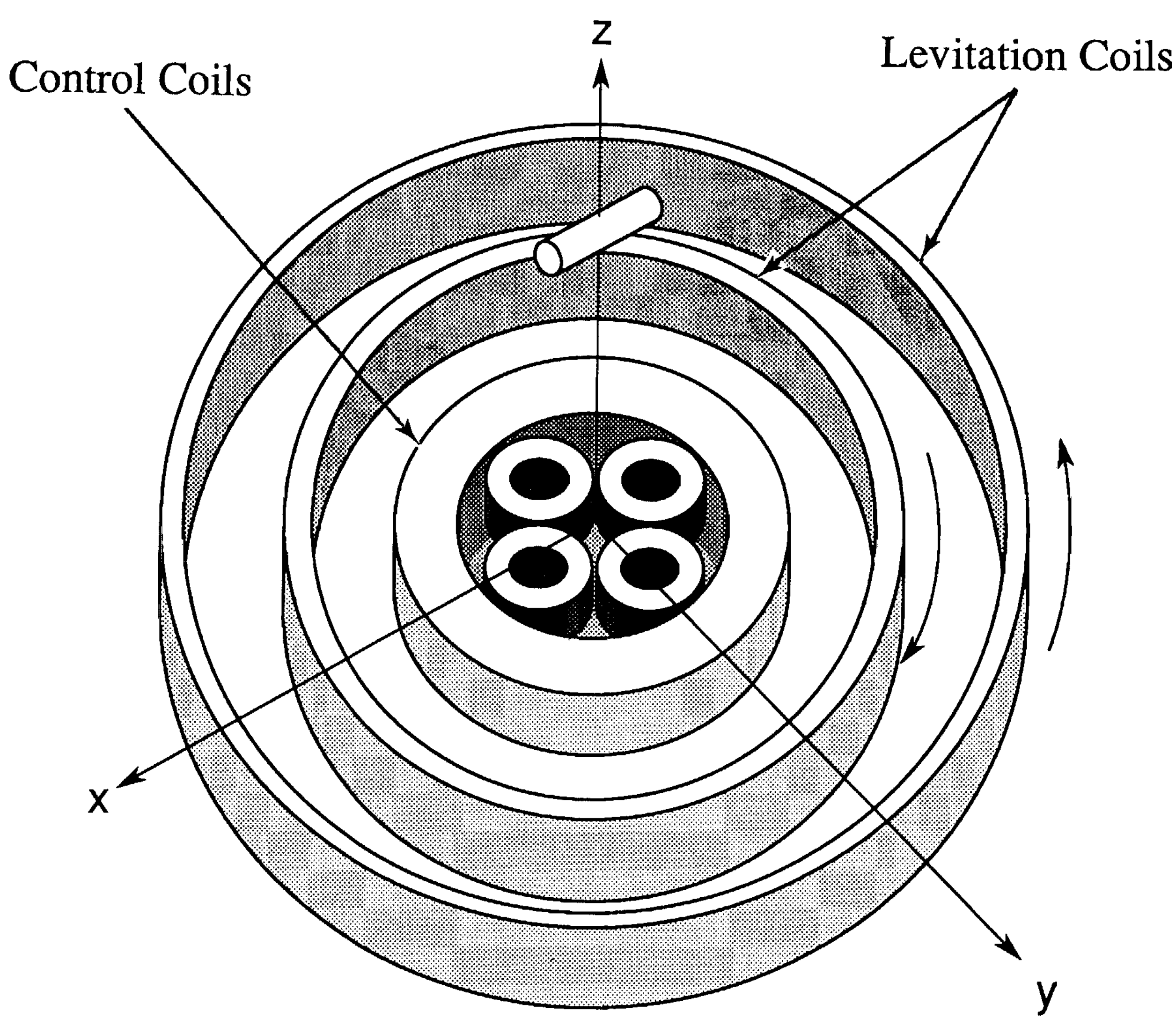

Figure 4.- Selected configuration for LGMSS ground-based experiment.

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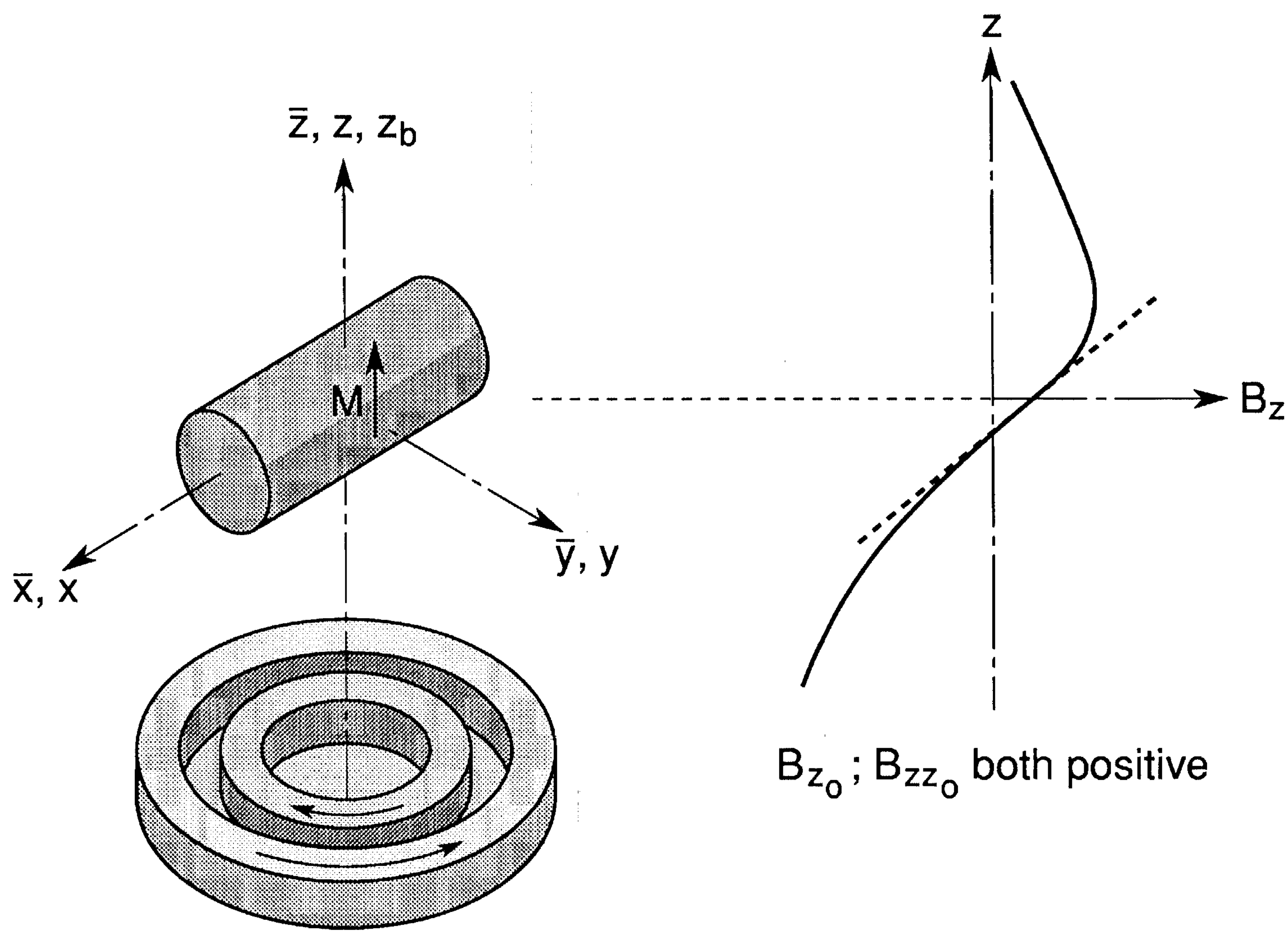

Figure 5.- Permanent magnet core and levitation coil detail for selected LGMSS configuration.

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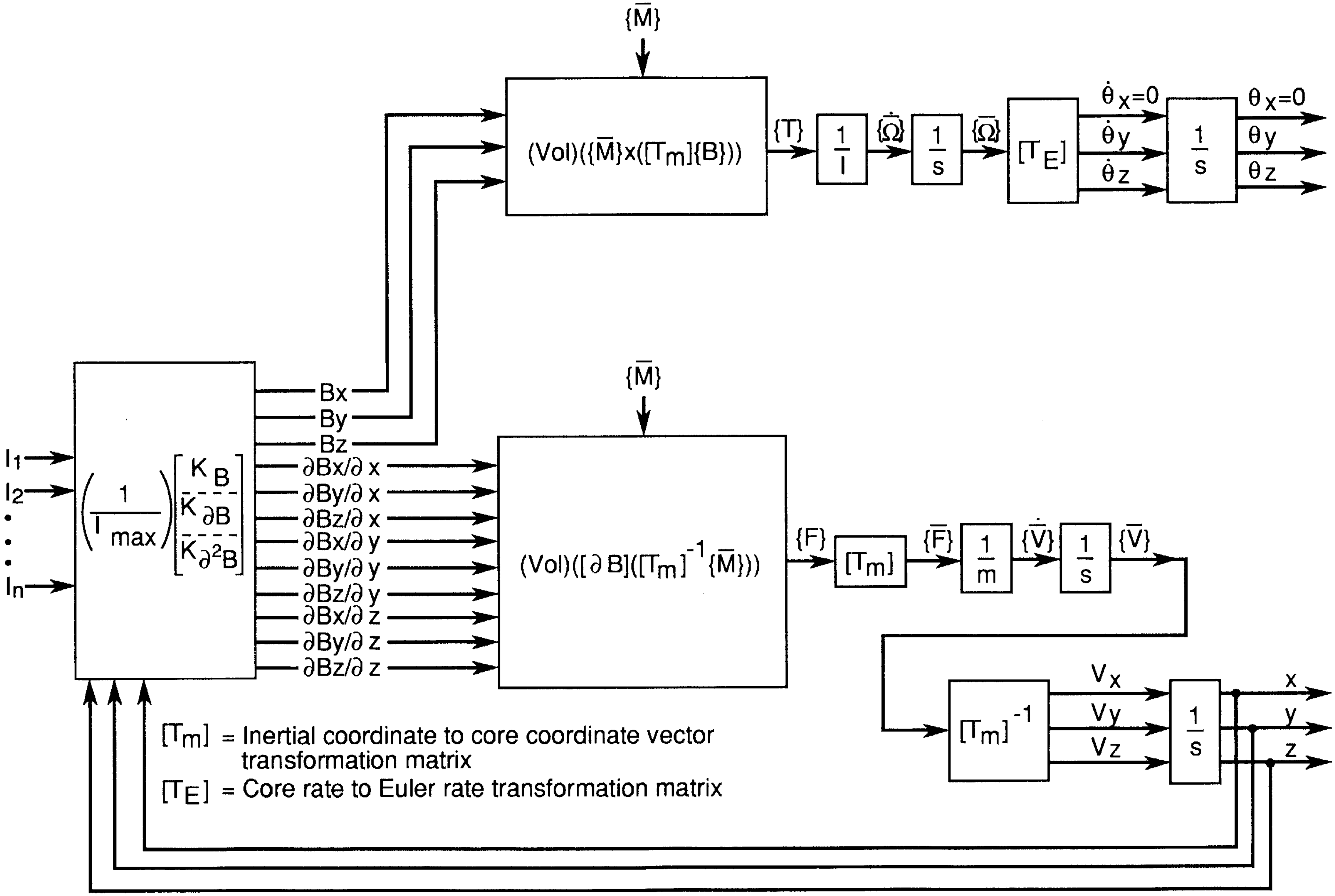

Figure 6.- Block diagram of LGMSS analytical model (horizontal magnetization vector).

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