Wind Tunnel Magnetic Suspension and Balance Systems with Transversely Magnetized Model Cores

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Abstract

This paper discusses the possibility of using vertically magnetized model cores for wind tunnel Magnetic Suspension and Balance Systems (MSBS) in an effort to resolve the traditional "roll control" problem. A theoretical framework is laid out, based on previous work related to generic technology development efforts at NASA Langley Research Center. The impact of the new roll control scheme on traditional wind tunnel MSBS configurations is addressed, and the possibility of demonstrating the new scheme with an existing electromagnet assembly is explored. The specific system considered is the ex-MIT, ex-NASA, 6-inch MSBS currently in process of recommissioning at Old Dominion University. This system has a sufficiently versatile electromagnet configuration such that straightforward "conversion" to vertically magnetized cores appears possible.

Background

For many years, the "roll control" problem has hindered the development of wind tunnel Magnetic Suspension and Balance Systems (MSBS). This problem arises due to the natural tendency to place magnetic cores in the fuselage of aircraft models, magnetized along their long axis, i.e. the axis of the fuselage. This leads to a problem in generation of roll torque (torque about the axis of the fuselage), since the relevant moment equation provides no direct torque component for axisymmetric model cores :

$$\vec{T} \approx Vol\,((M_x,0,0) \times \vec{B}) \quad (axial\ \vec{M}) \tag{1}$$

A wide variety of techniques for generation of roll torque have been tried over the years, usually based on the introduction of transverse magnetization of some kind, or on the reduction of the degree of axial symmetry of the model core. Previous techniques are briefly summarized in a Addendum to this paper.

During the last few years, a series of laboratory-scale demonstration magnetic levitation systems have been designed and constructed at NASA Langley Research Center, in support of a program aimed at developing improved technology required for magnetic suspension of objects at large gaps and over large ranges of orientation. The first of these systems was called the Large Angle Magnetic Suspension Test Fixture (LAMSTF [1,2]), and relied on control in five degrees-of-freedom, the equivalent of the "roll" axis being free (uncontrolled). Later systems have demonstrated that full six-component control can be achieved with a cylindrical permanent magnet core magnetized transversely. i.e. perpendicular to the axis of symmetry.

It is important to note that the choice of transverse magnetization has only been made practical by the introduction of new magnetic materials over the past two decades or so. For practical systems, high magnetizations (remanences) are required, eliminating ferrite materials from consideration. High remanence, but relatively low coercive force materials, such as the Alnico types, would be wholly unsuitable, due to the high demagnetizing factors developed by the proposed geometry. By contrast, rare-earth cobalt (ReCo) and neodymium-iron-boron (NdFeBo) materials exhibit high remanences and extremely high coercive forces and are therefore virtually immune to demagnetization.

Theoretical Framework

The force and torque on dipole-like permanent magnet cores is given by :

$$\vec{F} \approx Vol(\vec{M}.\nabla\vec{B}) \tag{2}$$

$$\vec{T} \approx Vol(\vec{M} \times \vec{B}) \tag{3}$$

Where the magnetic cores exhibit reduced levels of symmetry, such as a slender, transversely magnetized cylinder, additional contributions to torque arise, due to interactions between the core magnetization and second-order field gradients. A specific case of interest is that of a slender cylindrical core with its principal axis oriented along the suspension system's x-axis (the wind tunnel axis), but with transverse magnetization, aligned in the z-direction (vertical in the wind tunnel), as shown in Figure 1. The additional torque term (acting about the axis of magnetization) can be shown to be [3,4]:

$$T_z \approx \int_{length} M_z \left(B_{yz}\, x - B_{xz}\, y\right) d(Vol) \;\; (vertical\ \vec{M}) \tag{4}$$

or, where B_{yz} varies uniformly along the length (l) of a core of radius a :

$$T_z \approx Vol\left(M_z\left(\frac{l^2}{12} - \frac{a^2}{4}\right)B_{xyz}\right) \tag{5}$$

Inspection of equation 5 shows that the torque arises due mostly to a longitudinal gradient of lateral forces. As suggested above, a six-degree of freedom levitation system using this torque generation scheme for control of the magnetic core about its axis of magnetization has been built and demonstrated. The working designation of this system, which is illustrated in Figure 2, is the "6DOF 8C/2L" - referring to a 6 degree-of-freedom configuration with 8 control coils and two fixed-current levitation coils.

Application to Wind Tunnel Magnetic Suspension and Balance Systems

This paper explores the possibility of applying the torque generation scheme described above to wind tunnel MSBSs. Specifically, the magnetic core is assumed to be mounted in the aerodynamic model's fuselage as usual, but magnetized vertically, instead of axially as has been the virtually universal practice. Large rolling moments can be now be generated by application of transverse fields. The governing equation for moment production from dipole-like interactions is similar to that shown previously :

$$\vec{T} \approx Vol\left((0,0,M_z) \times \vec{B}\right) \; (vertical\,\vec{M}) \qquad (6)$$

Inspection reveals that the "missing" torque component is now that about a vertical axis; the equivalent of "yaw" in the aerodynamic sense. Force and torque components are clarified in Figure 3.

The Old Dominion University 6-inch MSBS

This system was designed by Stephens et.al. in the 1960's and operated for many years at the MIT Aerophysics Laboratory [5,6]. In the 1980's the system was relocated to NASA Langley Research Center and was recommissioned in support of a wind tunnel MSBS research and development program. Limited aerodynamic testing was undertaken [7], prior to a termination of NASA's effort, and subsequent transfer of the entire facility to ODU. The MSBS with its low-speed wind tunnel are both illustrated in Figure 4.

Despite its age, the electromagnet assembly is still one of the most sophisticated ever constructed, with considerable efforts made in the original design to provide a significant degree of separation of field and field gradient components by choice of electromagnet configuration. Further, the Electromagnetic Position Sensor (EPS) is still the only successful example of its kind. Recommissioning efforts are currently proceeding, albeit rather slowly.

The electromagnet assembly comprises several subsystems. Two pairs of "saddle" coils[1] are configured to develop transverse fields within the test section. Two assemblies comprising four coils mounted on complex iron yokes are positioned at each end of the test section (upstream and downstream) with the intention of developing lateral gradients in axial fields[2] for generation of lift and lateral forces. A pair of axial (Helmholtz) coils are configured to generate an axial magnetizing field, and a final set of coils (two pairs upstream and downstream) provide an axial gradient in the axial field. These subassemblies and their design functions are illustrated in Figure 5.

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[1] Electromagnet windings are traditionally referred to as coils

[2] Equivalent to axial gradients in transverse fields

By removing existing electrical interconnections between coils, additional flexibility to generate independent field and field gradient components can be introduced. By way of example, Figure 6 illustrates that the lift coil assemblies, previously used only for production of the "lift" and "sideforce" field gradients, B_{xy} and B_{xz} are actually capable of developing two fields, three field gradients and one second-order gradient, B_x, B_z, B_{xy}, B_{xz}, B_{yz} and B_{xyz}, depending on the relative signs of current in each coil. In effect, each lift coil assembly can act as a dipole-like field source, or a quadrupole-like field source. Action as a monopole-like field source is ruled out on grounds of low efficiency, due to the configuration of the iron yokes.

Field and Field Gradient Generation

Preliminary computational (finite-element) models of the electromagnet sub-assemblies have been developed using the well-proven TOSCA package [8]. Some experimental validations have also been completed [9]. At the present time, each coil set has been modeled separately for convenience. Therefore, although the effect of the iron yokes within the lift coil sets is properly represented, the secondary influences of the yokes on the other coils sets is not. Further development and refinement of the model is clearly necessary.

In a preliminary analysis of system performance, it is acceptable to retain the notion that each coil set is assigned certain limited functions, i.e. develops one or more specific field or field gradient components, with secondary contributions neglected. Following this approach, Table 1 summarizes the principal coil sets involved in the development of each important field and field gradient term. It is seen that the generation of the necessary field and field gradient components for suspension and control of a vertically magnetized model core is possible with this system.

Table 1 - Coil Sets Generating Individual Field and Field Gradient Components

Field	Traditional Function	Proposed Function	Traditional Coil Set Designation
B_x	Magnetizing field	Pitching moment	Magnetizing coils
B_{xx}[3]	Drag force	None	Drag coils
B_y	Yaw moment	Rolling moment	Saddle coils, lift assemblies
B_{xy}	Sideforce	None	Lift assemblies
B_z	Pitch moment	None	Saddle coils, lift assemblies
B_{xz}	Lift force	Axial force	Lift assemblies
B_{yz}	None	Sideforce	Lift assemblies
B_{xyz}	None	Yaw moment	Lift assemblies
B_{yy}	None	None	Saddle coils, drag coils
B_{zz}	None	Lift force	Saddle coils, drag coils

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[3] Of course $B_{xx} + B_{yy} + B_{zz} = 0$

The magnitude of the relevant field and field gradient components that can be generated with the existing electromagnet assembly are indicated in Table 2. Data is derived from a combination of original design information [5] with recent analysis and computation [9]. A maximum current of 100 Amps in each coil is used for reference, although this is well within the original design specifications of this system [5]. Note that transverse gradients in transverse fields (such as B_{zz}) can be generated by the saddle coil assembly, or as secondary components by the drag coil pair.

Table 2 - Baseline Capability for Specific Fields and Field Gradients ($I = 100A$)

Force or Moment	Field or Gradient	Magnitude	Data Source
Axial force	B_{xz}	$0.55\,T/m$	Ref. 5
Lateral force	B_{xy}	$0.55\,T/m$	Ref. 5
Lift force	B_{zz} (saddle coils)	$0.7\,T/m$	Estimated using Ref. 9
	B_{zz} (drag coils)	$0.33\,T/m$	Ref. 5
Rolling moment	B_y	$0.054\,T$	Ref. 5
Pitching moment	B_x	$0.14\,T$	Ref. 9
Yawing moment	B_{xyz}	$31.8\,T/m/m$	Computer model in Ref. 9

A typical model core used in this MSBS might be around 5 inches long and 0.75 inches in diameter. Typical core material (NdFeBo) has a working magnetization level around 800 kA/m ($\equiv$ 1 Tesla). The magnitude of the forces and torques that can be generated with axial and vertical magnetization configurations can now be estimated using Equations 2,3, and 5 and the information from Table 2 above. The estimated forces and moments are compared in Table 3.

Table 3 - Baseline Force and Moment Capability

Force or Moment	Magnitude
Axial force	$15.8\,N$
Lateral force	$15.8\,N$
Lift force	$29.7\,N$ (includes saddle and drag coils)
Rolling moment	$1.5\,Nm$
Pitching moment	$4.0\,Nm$
Yawing moment	$1.1\,Nm$
Deadweight	$3.2\,N$

Discussion

The largest force present in typical wind tunnel applications tends to be the aerodynamic lift force, which can be generalized to the aerodynamic normal force in cases where large angle-of-attack ranges are of interest. With transverse magnetization, it is seen that this force is developed by field gradients of the form B_{ii}, i.e. a vertical gradient in a vertical field, B_{zz}. It is suspected, but not yet proven by example, that this type of field gradient can be generated more efficiently than field gradients of the form B_{ij}, as required in the traditional case of axial magnetization. If this proves to be the case, then roll torque generation can be "added" to wind tunnel MSBSs with zero cost penalty. More detailed analysis of alternative configurations will be required to resolve this point.

Conclusions

The results presented above indicate that the transverse magnetization concept can be demonstrated using the existing 6-inch MSBS electromagnet configuration. By inference, the transverse magnetization concept is worthy of further study.

Acknowledgements

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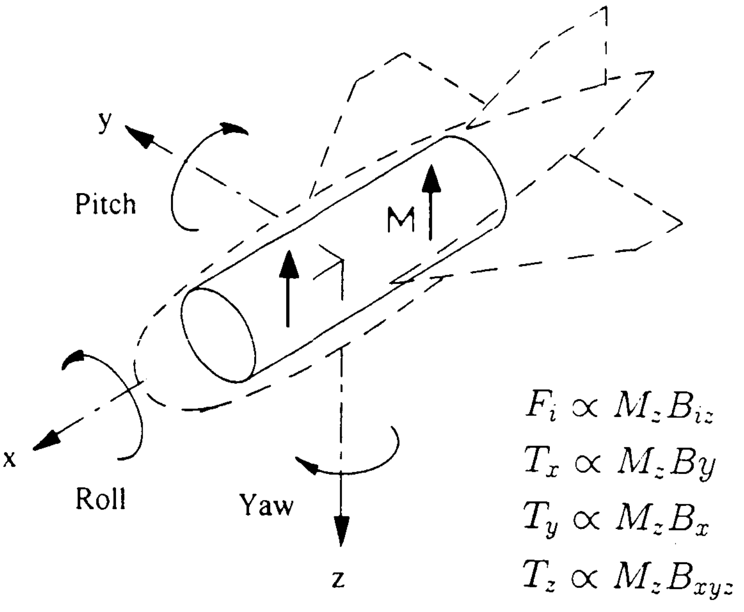


$$F_i \propto M_z B_{iz}$$
$$T_x \propto M_z B y$$
$$T_y \propto M_z B_x$$
$$T_z \propto M_z B_{xyz}$$

Figure 1 - Transverse Magnetization

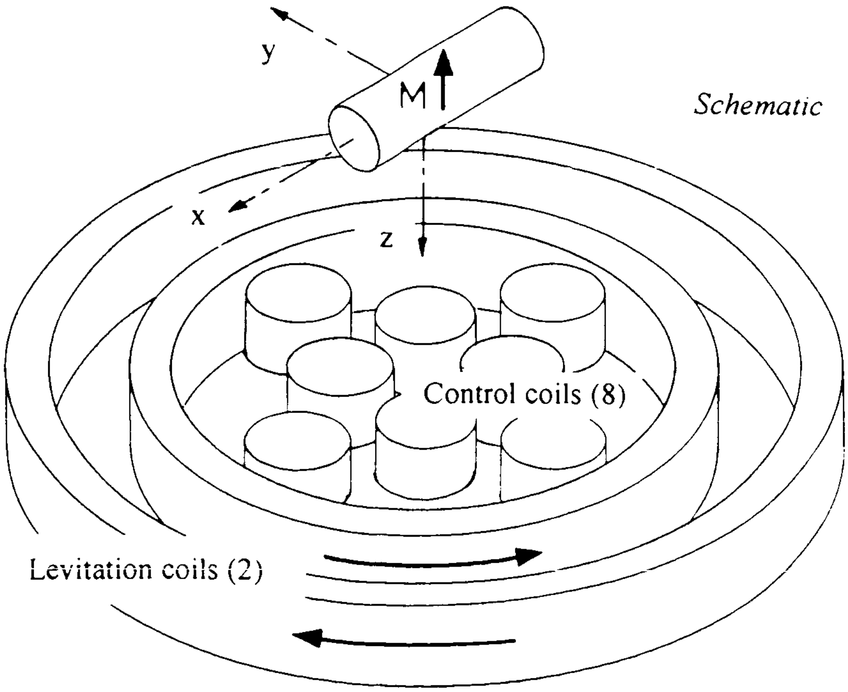


Figure 2 - Schematic Layout of the 6DOF-8C/2L System

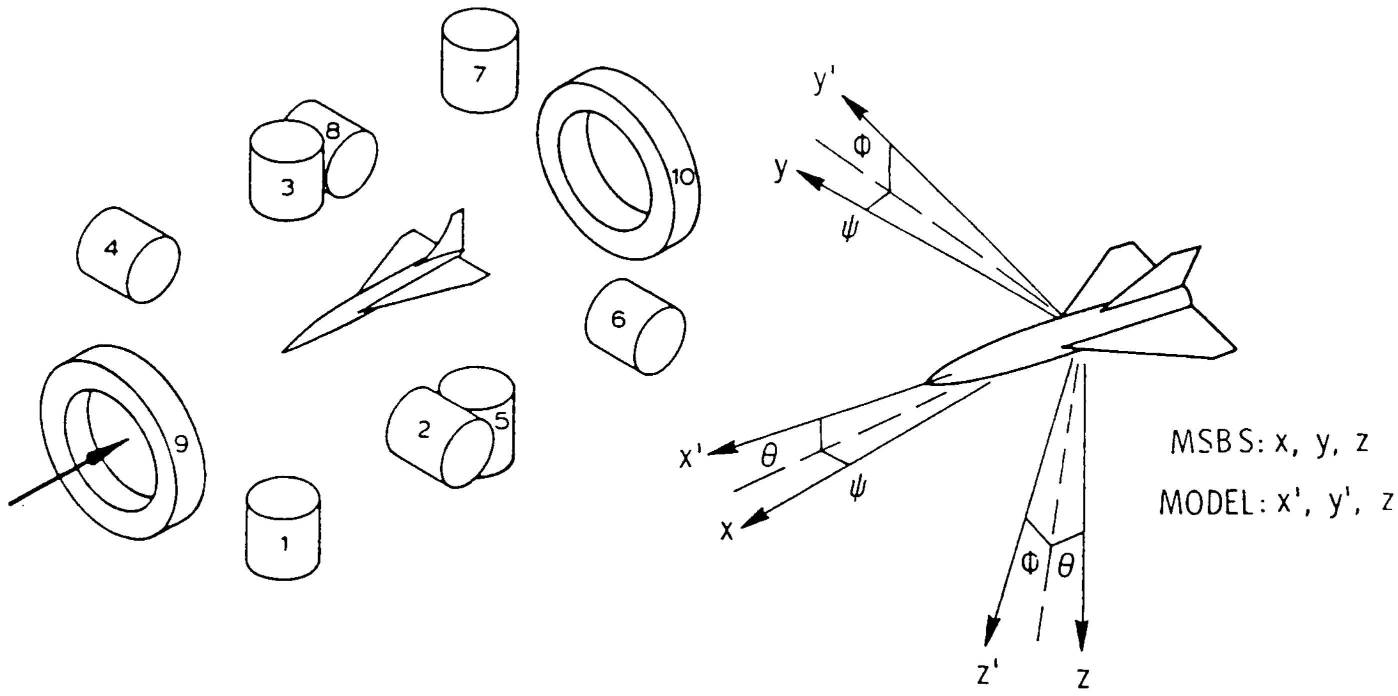


Figure 3 - Force and Torque Components

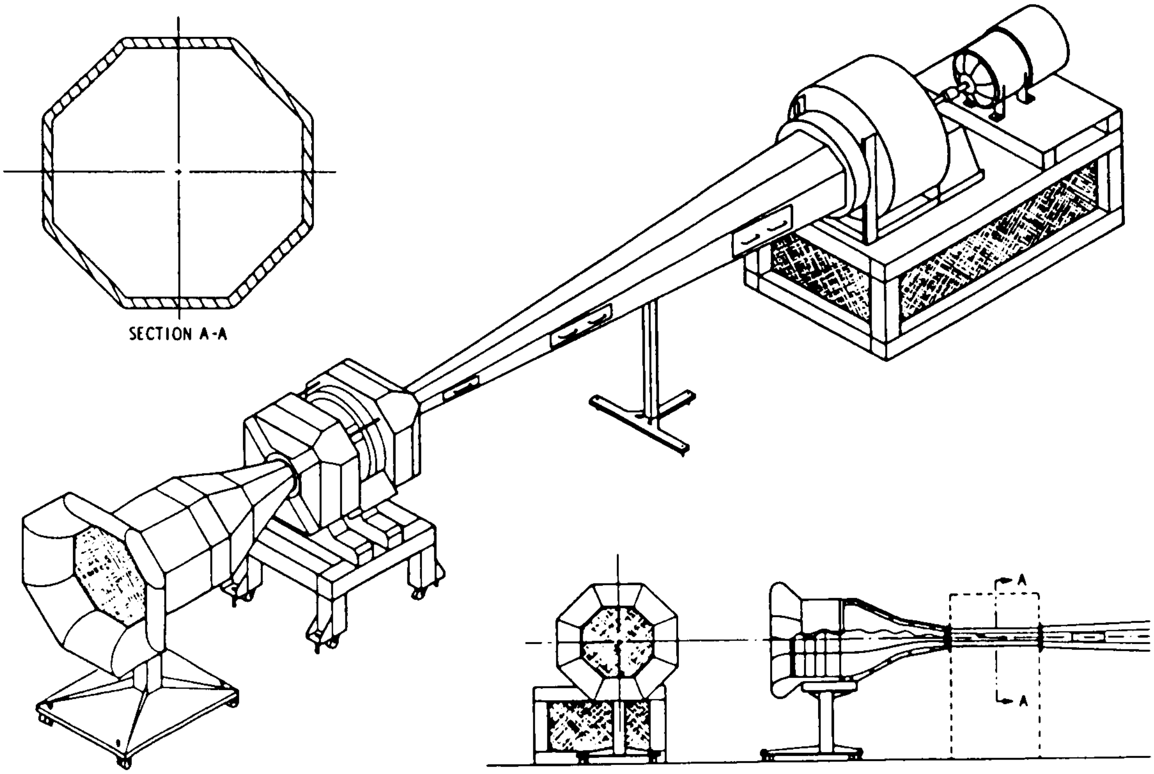
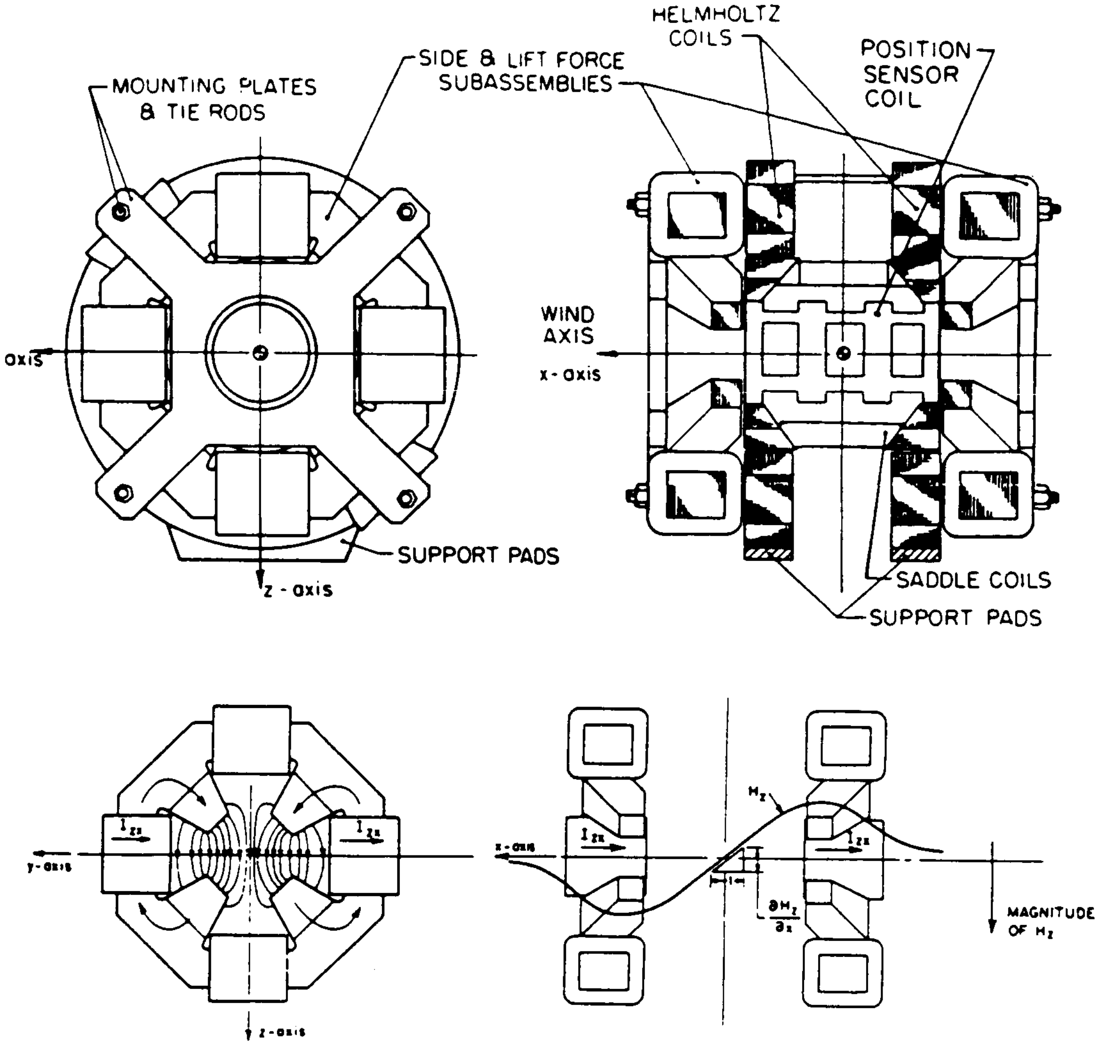


Figure 4 - The ODU 6-inch MSBS



MAGNETIC FLUX PATH IN FORWARD COIL ASSEMBLY DUE TO LIFT CURRENT, I_{zz}

AXIAL PROFILE OF H_z DUE TO I_{zz}, ON AXIS

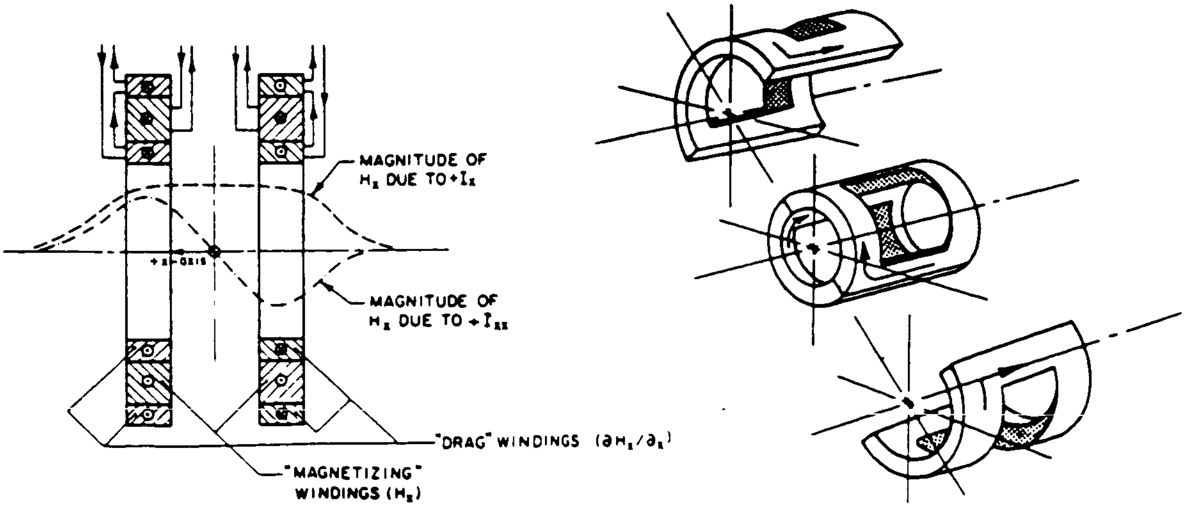
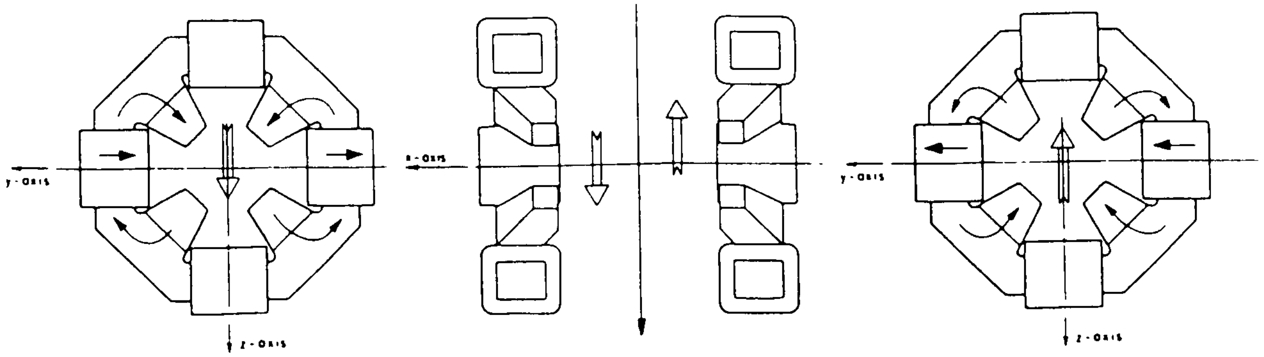
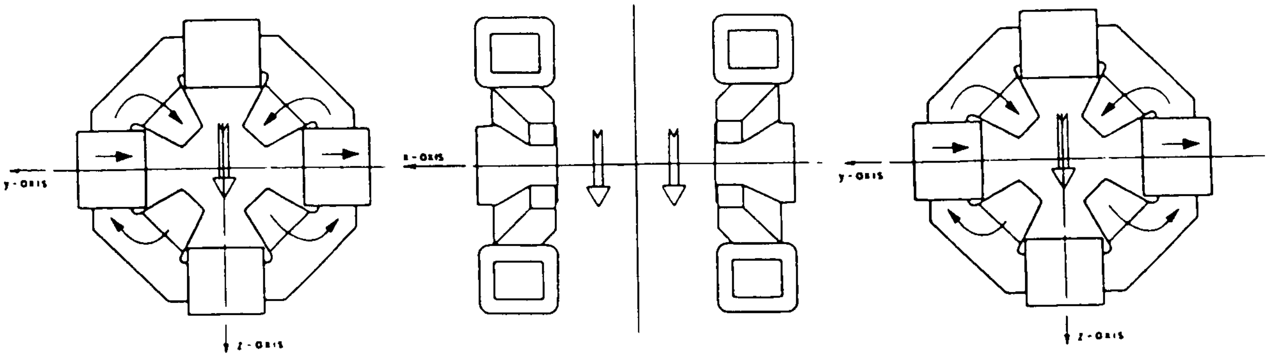


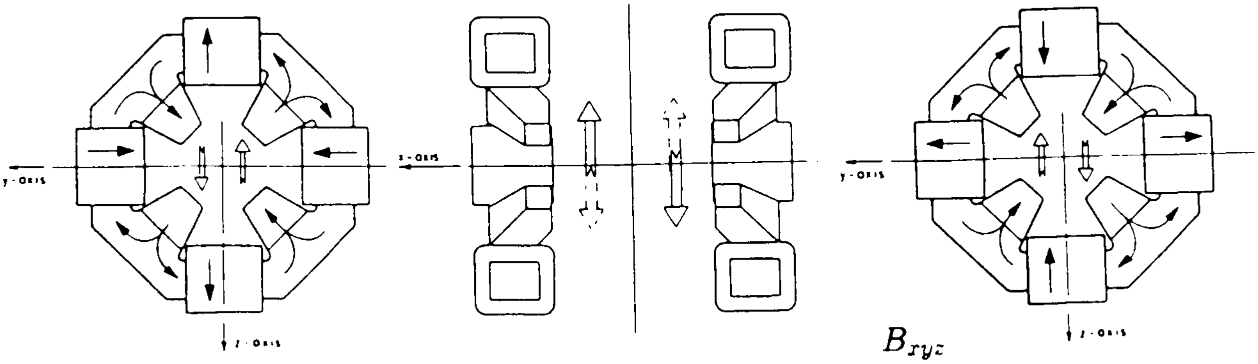
Figure 5 - Electromagnet Cofiguration of the 6-inch MSBS



B_{xz} (B_{yz} *similar*)



B_z (B_y *similar*)



B_{xyz}

Figure 6 - Field and Field Gradient Component Production

ADDENDUM

Roll control techniques suggested or demonstrated in past years include at least the following :

Transverse magnetization methods (interactions with transverse fields)
- 1.1 "Bent" fuselage cores [A.1, 6]
- 1.2 Through-wing magnetized wing cores [A.2]
- 1.3 Spanwise magnets [A.3]

Methods based on reduction in axial symmetry
- 2.1 Shaped fuselage cores [A.2]

Model-mounted coils
- 3.1 Passive (battery-powered) wing or fin coils [A.2]
- 3.2 Active (controlled-current) wing or fin coils [A.2]
- 3.3 A.C. excited, phase-controlled model-mounted coils [A.1, 6]
- 3.4 Secondary windings in superconducting solenoids [A.4]

Aerodynamic Systems
- 4.1 Active aileron control [A.2]
- 4.2 C_{l_β} control [A.2]

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