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Application of Magnetic Suspension and Balance Systems to Ultra-High Reynolds Number Facilities

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Abstract

The current status of wind tunnel magnetic suspension and balance system development is briefly reviewed. Technical work currently underway at NASA Langley Research Center is detailed, where it relates to the ultra-high Reynolds number application. The application itself is addressed, concluded to be quite feasible, and broad design recommendations given.

Introduction

Wind tunnel Magnetic Suspension and Balance Systems (MSBS) have been under continuous investigation and development since 1957. A significant number of small-scale systems have been constructed and a variety of aerodynamic testing carried out [1]. This paper will briefly review the previous work in wind tunnel MSBSs and will examine the handful of systems currently known to be in operational condition or undergoing recommissioning. The ultra-high Reynolds number application will then be addressed in some detail, focusing on specific technical issues wherever possible. Technical developments currently emerging from research programs at NASA and elsewhere will be reviewed briefly, where there is potential impact on the ultra-high Reynolds number application. Finally, some opinions concerning this new application and based on the author's experience will be given.

Wind Tunnel Magnetic Suspension and Balance Systems

An aerodynamic test model can be magnetically suspended or levitated in the test section of a wind tunnel (Figure 1). The classical approach involves the use of a ferromagnetic core in the model, either soft iron or permanent magnet material, with the applied fields generated by an array of electromagnets surrounding the test section. This arrangement is always open-loop unstable in at least one degree-of-freedom, so the position and attitude of the model is continuously sensed, with the electromagnet currents adjusted via a feedback control system to maintain stability and the desired position/orientation (Figure

2). Optical sensing systems of various types have been prevelant, although electromagnetic and X-ray systems have also been used. Electromagnet power amplifers typically require modest bandwidths, but high reactive power capacity. The resulting system is referred to as a Magnetic Suspension and Balance System (MSBS), since aside from the suspension/levitation function, whole-body forces and moments can be recovered from calibrations of the electromagnet currents.

The governing equations for this type of suspension system (following notation in [2]) can be written as follows :

$$\vec{F}_c \approx \forall \left(\vec{M}.\nabla\vec{B}_o\right) \qquad -(1)$$

$$\vec{T}_c \approx \forall \left(\vec{M} \times \vec{B}_o\right) \qquad -(2)$$

- where $\vec{M}$ represents the magnetization of the magnetic core in A/m, $\vec{B}$ the applied magnetic field in Tesla, $\forall$ is the volume of the magnetic core in m^3, and the subscript o indicates that the field or field gradient is evaluated at the centroid of the magnetic core. Now, following the detailed development presented elsewhere [2], the effect of changes in relative orientation between the magnetic core and the electromagnet array can be incorporated as follows :

$$\vec{\bar{F}}_c \approx \forall\, [T_m][\partial B][T_m]^{-1}\vec{\bar{M}} \qquad -(3)$$

$$\vec{\bar{T}}_c \approx \forall\; \vec{\bar{M}} \times \left[[T_m]\vec{B}\right] \qquad -(4)$$

Where a bar over a variable indicates magnetic core coordinates, $[\partial B]$ is a matrix of field gradients and $[T_m]$ is the coordinate transformation matrix from electromagnet coordinates to suspended element (magnetic core) coordinates. Study of equations 2 and 4 reveals that, with a single magnetization direction it is only possible to generate two torque components by this "compass needle" phenomena. This gives rise to the well-known "roll control" problem in wind tunnel MSBSs, where the magnetization direction has usually been along the long axis of the magnetic core, in turn along the axis of the fuselage. Roll torque can be generated by a variety of methods involving tranverse magnetizations, or by applications of second-order field gradients to model cores with reduced levels of symmetry.

In wind tunnel applications, the primary motivation for MSBSs has been the elimination of the aerodynamic interference arising from mechanical model support systems [3]. The fact that the suspended model forms part of a feedback control system inherently permits predetermined motions of the suspended model to be created rather easily. This suggests great potential for studies of unsteady aerodynamic phenomena, although this potential has not yet been fully exploited (see later Section).

It should be noted that the configuration discussed above is not the only possibility. Inherently stable configurations are feasible, such as by using a.c. applied fields, or by inclusion of diamagnetic materials in various ways. Laboratory suspensions using these techniques have been demonstrated for many years [4], but not in configurations appropriate for the wind tunnel application. A major disadvantage has been the difficulty of arranging significant passive damping of unwanted motions. The feedback controlled approach relies on artificial damping, whose value is limited principally by the control algorithm and the power supply capacity.

A Perspective on Ultra-High Reynolds Number Tunnels

So that the rest of this paper be set in proper context, the author's perspective on the ultra-high Reynolds number tunnel development effort will now be presented.

Research has been underway for several years examining the possibility of constructing an ultra-high Reynolds number "wind" tunnel, concentrating on the use of liquid or gaseous helium as the working fluid. At one point, the tunnel was referred to by some researchers as the "infinite Reynolds number" wind tunnel, since operation with superfluid helium was contemplated and a promise of effectively zero viscosity of the working fluid was held out. Current work appears to be focused on slightly more modest performance (finite Reynolds number!) but could still result in a facility with a Reynolds number capability one order of magnitude higher than anything currently existing. With these more modest objectives, the option of employing gaseous helium as the working fluid becomes quite viable, as has been suggested many times over the years [5].

The engineering application is clearly to hydrodynamic studies of submersibles, with the particular item of interest perhaps being wake-related signature reduction. Fundamental studies of high Reynolds number turbulence are also attracting some interest. It has been assumed that an MSBS would be mandatory for this type of facility, since a conventional support system would create severe problems by corruption of the vehicle's wake. Application of MSBS technology to this problem was reviewed in the 1989 Workshop [6].

Another alternative has been suggested, that being an ultra-high pressure air tunnel. This approach poses a rather different set of design challenges, perhaps of a more traditional nature. An ultra-high Reynolds number pipe flow facility does already exist [7].

Current MSBS Activity Worldwide

NASA Langley Research Center 13-inch MSBS

This system, illustrated in Figure 3, is currently inactive, although remains in operational condition. It comprises a low-speed wind tunnel, 5 uncooled copper electromagnets, 4 with iron cores, bipolar thyristor power supplies, an optical model position sensing system with a minicomputer-based digital controller. The system has been used for a variety of drag studies of axisymmetric and near-axisymmetric geometries, as well as support interference evaluations. Support interference increments of up to 200% have been discovered, although this is hardly typical [8,9].

The ODU 6-inch MSBS

If this system were to be described as the ODU/NASA/MIT 6-inch system, then its history and identity would be clear to all workers in the MSBS field. The electromagnet assembly and low-speed wind tunnel, illustrated in Figure 4, from the original MIT "6-inch" MSBS [10,11] has found its way to Old Dominion University, and partial recommissioning is currently in progress. A unique feature is the use of electromagnetic position and attitude sensing. Here, the suspended model forms the core of a high frequency variable differential transformer. It is planned to restore the system to full operation with new power supplies and a digital control system.

International Efforts

The National Aerospace Laboratory in Japan currently operates the largest MSBS ever constructed, with a test section 60 cm square (roughly 2 feet). Together with a smaller system (15 cm), current research is focusing on rapid force and moment calibration procedures [12]. Researchers in Taiwan have recently completed construction of a small (10 cm) system and are commencing low-speed wind tunnel tests [13]. Russian activity is at a low level, but includes studies of data telemetry systems from suspended models. One MSBS is believed to remain operational, at MAI/TsAGI [14]. Low-density, high Mach number aerodynamic measurements are continuing at Oxford University in England with their nominally 7.5 cm system [15]. A recent development has been the discovery of a new system at the Changsha Institute of Technology in P.R. China, about which information is just becoming available [16].

Table 1 - "Operational" MSBSs, 1996

Organization	**Approx. Size[1]**	**Current Application**	**Current Status**
NASA Langley RC	13-inch	Low-speed, R&D	Inactive
Old Dominion University	6-inch	System R&D	Recommissioning
Oxford University	3-inch	Hypersonic aerodyn.	Active
MAI/TsAGI, Moscow	18-inch	System R&D	Inactive
NAL, Japan	4-inch	System R&D	Active
NAL, Japan	23-inch	System R&D	Active
NCKU, Taiwan	6-inch	System R&D	Active
CIT/CARDC, P.R. China	6-inch	System R&D	Active

New Technology

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[1] Square-root of wind tunnel test section cross-sectional area

A program has been underway for some years at NASA Langley Research Center to develop technology for large-gap applications of magnetic suspensions. Applications include, but are not limited to, wind tunnel MSBSs, space payload pointing and vibration isolation systems, momentum storage and control devices, maglev trains and electromagnetic launch systems. Emphasis has been placed on the development of formalized dynamic models and the application of modern controller design techniques. Two small laboratory scale levitation systems have been constructed, with air-gaps between suspended element and electromagnets of 10 cm [17,18]. The first system is referred to as the Large-Angle Magnetic Suspension Test Fixture (LAMSTF) and is capable of 360-degree rotation of the levitated model about a vertical axis (Figure 5). Levitation here implies the use of magnetic forces of repulsion from below the test object, rather than the more traditional approach of attractive forces from above, or some combination. The second system, currently unnamed, utilizes a pair of concentric coils carrying steady currents, to provide a background force opposing gravity. An important novel feature is the use of a transversely magnetized permanent magnet core in the cylindrical suspended element. The magnetization direction is vertical is this application. This configuration, illustrated in Figure 6, provides full six degree-of-freedom control capability with passive stability in vertical translation and two rotations. The third rotation (about the vertical axis) is neutrally stable, and the remaining two translations (in the horizontal plane) are slightly unstable. A secondary array of electromagnets ("control" coils) provides stability and the capability for predetermined motions. A larger system of comparable configuration, the Large Gap Magnetic Suspension System (LGMSS), is close to completion, with a 1 meter air-gap [19]. This system includes superconducting coils to provide the background levitation force, with water-cooled copper control coils. It will represent the largest, large-gap magnetic suspension or levitation device ever constructed.

It should be realized that the tranversely magnetized magnetic core configuration is well suited to the wind tunnel application, where generation of magnetic roll torque has already been mentioned as being a long-standing problem. Using vertically magnetized permanent magnet cores within an aircraft model's fuselage would provide roughly equal (and large) pitch and roll torque capability. Lift, drag and sideforce capability will be largely unaffected compared to the conventional axial magnetization configuration. Only yaw torque is relatively reduced, although it is observed that aerodynamic yaw torques are seldom dominant. The additional torque is generated by a term of the form :

$$\vec{T}_z \approx \not{V} \int_{\not{V}} \vec{M}_z \left\{ \frac{\partial B_y}{\partial z} x \right\} \qquad -(5)$$

This can be non-zero if the core geometry is suitably chosen and $\frac{\partial}{\partial x}\left\{ \frac{\partial B_y}{\partial z} x \right\}$ is non-zero.

It can also be noted that magnetic suspension and levitation technology has made dramatic progress in other applications in recent years. Feedback-controlled magnetic bearings for rotating machinery applications are a viable commercial item [20], with a growing number of companies involved and regular International Symposia. Useful spin-offs from this work include specialized control hardware, algorithms and software, new sensing approaches, improved system modelling and analysis, and application of High Temperature Superconductors (HTS) to current-controlled electromagnets. Maglev "trains" are on the verge of revenue-generating operation, with sophisticated prototypes in operation in Germany and Japan. The German approach relies on feedback controlled copper electromagnets generating attractive levitation forces from below the "guideway" (track); the Japanese approach utilizes superconducting electromagnets generating repulsive levitation forces by inducing eddy currents in the guideway. Both approaches have a speed capability in excess of 300 m.p.h. The U.S. National Maglev Initiative (now defunct) spawned a range of design studies, with the Grumman Corporation hybrid magnet design perhaps being most notable.

Preliminary Considerations for MSBS Application to Ultra-High Reynolds Number Facilities

The magnitude of the engineering challenge is determined primarily by the test requirements and the choice of working fluid. By way of example, three low temperature design points and one high pressure design point have been chosen for a 10:1 length-to-diameter ratio quasi-axisymmetric, low-drag model. The target length Reynolds number is 10^9. Numerical values are derived largely from data in reference 6. The maximum model weight is estimated based on the weight of a steel or permanent magnet magnetic core occupying around 50% of the available volume. The drag force is estimated based on a drag coefficient (C_D) of 0.1.

	Gaseous Helium	Helium I	Helium II	High Pressure
Temperature, K	5.3	2.8	1.6	288
Pressure, atmospheres	1	1	1	100
Velocity, m/s	40	10	4	48.5
Unit Reynolds No., m^{-1}	3×10^8	3.8×10^8	4.4×10^8	3.3×10^8
Dynamic pressure, Pa	8725	7150	1160	288,000
Model length, m	3.3	2.63	2.27	3.0
Test section size, m	0.94 square	0.75 square	0.65 square	0.85 square
Max. model weight, N	8700	4400	2830	7190
Drag force, N	74.6	38.9	4.7	2992

The immediate conclusion is that this application is quite benign from a force perspective. The likely aerodynamic/hydrodynamic forces in the helium tunnel cases appear to be a small fraction of the upper limit of the deadweight of the model. This fact justifies some attention to passively stable suspensions in this application [such as 21]. Increasing attention is being paid to this possibility by the magnetic bearing community and progress is being made, although many difficulties remain to be solved [22]. Here, a smaller model core and relatively more unused volume than indicated in the Table would be called for.

In the pressure tunnel case, the dynamic pressure is quite high, leading to forces comparable to the deadweight of the model. Hoever, MSBSs have been successfully operated under these conditions in the past (in supersonic wind tunnels).

Some Opinions and Observations

The first consideration for this application is the extremely low temperature. Whatever the working fluid, the MSBS must either be designed for an environment around 2-4 K, or the test section must be designed such that the MSBS is essentially "outside" the cold zone. The latter approach was taken with the only MSBS to be used with a cryogenic wind tunnel to date [23]. It is thought, however, that the former would be preferable in this application, due to the extreme penalty in cooling power incurred should the thermal insulation of the test section be compromised. Immediately one might be concerned that the power dissipation of the suspension electromagnets might negate this advantage, but a.c. capable low-temperature and high-temperature superconducting coils have been demonstrated and the technology is advancing rapidly. HTS coils are perhaps the first choice, since they would be operated well below their transition temperature, providing huge stability margins and permitting considerable flexibility in design of cooling and insulation systems. The d.c. and a.c. field requirements in this application appear to be extremely modest compared to "conventional" wind tunnel MSBSs, suggesting no great problems in electromagnet or power supply design or procurement.

Two approaches for position and attitude sensing are viable, optically-based and the Electromagnetic Position Sensor (EPS, [10]). Optoelectronic devices can operate effectively at 2-4 K, but there are practical concerns relating to condensation of stray gases etc. For this reason, and also due to the perception that the typical model to be tested is naturally quasi-axisymmetric, and does not seem likely to be oriented at extreme angles relative to the test section axis, the EPS is recommended as a first choice. The electromagnetic behaviour of this system should be essentially temperature independent.

The ferromagnetic core of the model could be either soft iron or permanent magnet. It is known that either will operate without difficulty down to liquid nitrogen temperature, in fact exhibiting improved properties. Operation at the extremely low temperatures anticipated would have to be researched. There seems little point in resorting to the persistant superconducting solenoid model core [23,24] since the force requirements seem so modest. The purpose of this core design was to provide higher force capability in high dynamic pressure wind tunnel applications.

An important design issue is thought to be the selection of materials for the test section. First, the EPS must be located "inside" any electrically conducting structural shells. Further, it has been found that eddy currents in conducting material close to the suspension electromagnets can significantly degrade the system dynamics. Due to the low electrical conductivity of metals at the extremely low temperatures encountered here, this problem is likely ot be severe. Pending further study, it is therefore recommended that designs concentrate on the use of electrically non-conducting materials. It should be noted that passively stable suspension systems usually rely on eddy currents for damping of unwanted motions. Again, due to the low conductivities in this application, further study will be required.

Specialized Aerodynamic Testing

"Static" aerodynamic testing can be defined as where the model's geometric axis is fixed in space and with respect to the freestream velocity vector. This class of testing includes, but is not limited to, drag measurements. "Dynamic" testing is also of great significance in many cases, but is very challenging with mechanical model supports, and is usually done only sporadically. MSBSs of the feedback controlled type have long been recommended as a powerful altenative approach, since arbitrary model motions can be commanded rather easily through the feedback control system. At least three research teams have addressed dynamic testing with MSBSs over the years, though none recently. At MIT [9,25] and the University of Southampton [26,27], forced oscillation testing has been successfully carried out. The University of Virginia developed a special design of MSBS specifically for dynamic stability work [28,29] and conducted limited testing. With more modern control and data acquisition approaches, small-amplitude forced oscillation testing in an MSBS should be a quite viable test technique. A single facility could make measurements requiring an array of conventional mechanical rigs.

The suspension of models through large ranges of angles-of-attack has been demonstrated in wind tunnels [21] and through large ranges of orientation in other laboratory facilities [15]. This can now be considered rather standard practice. Based on the authors understanding of the application of the ultra-high Reynolds number facility, this possibility is not further emphasized here.

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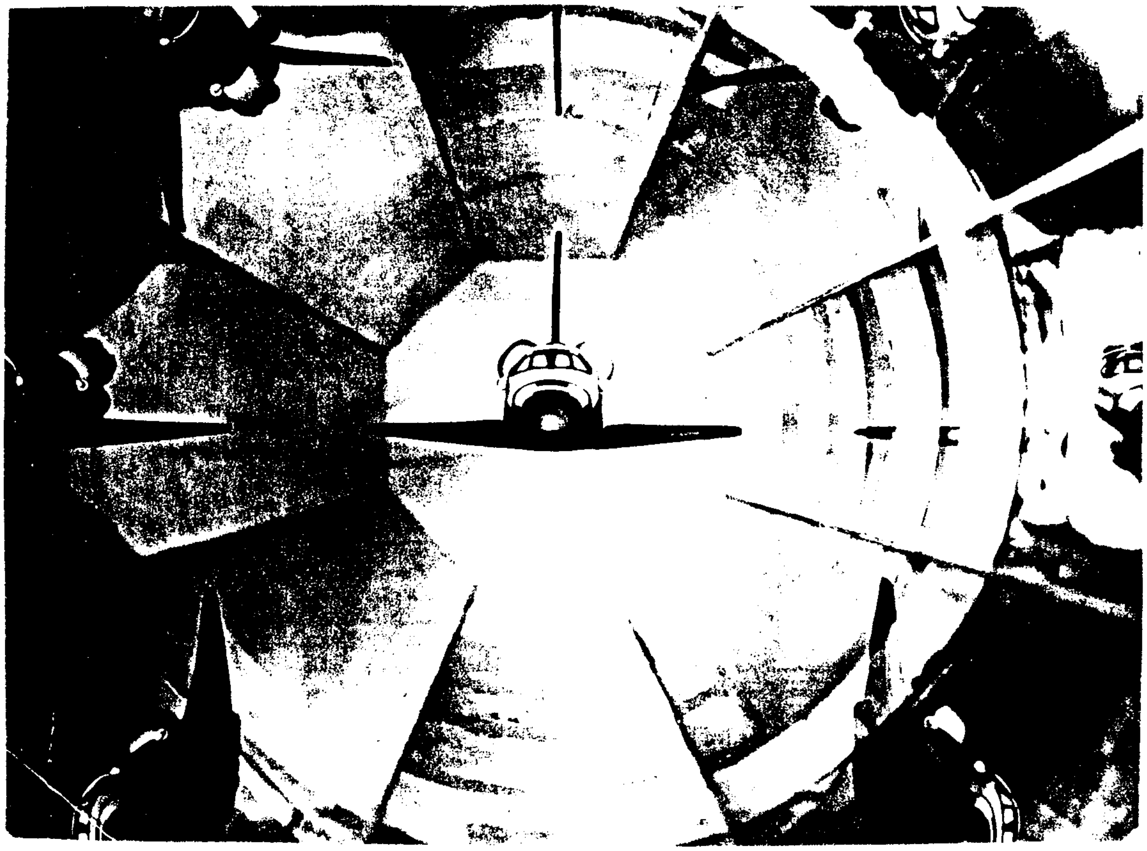
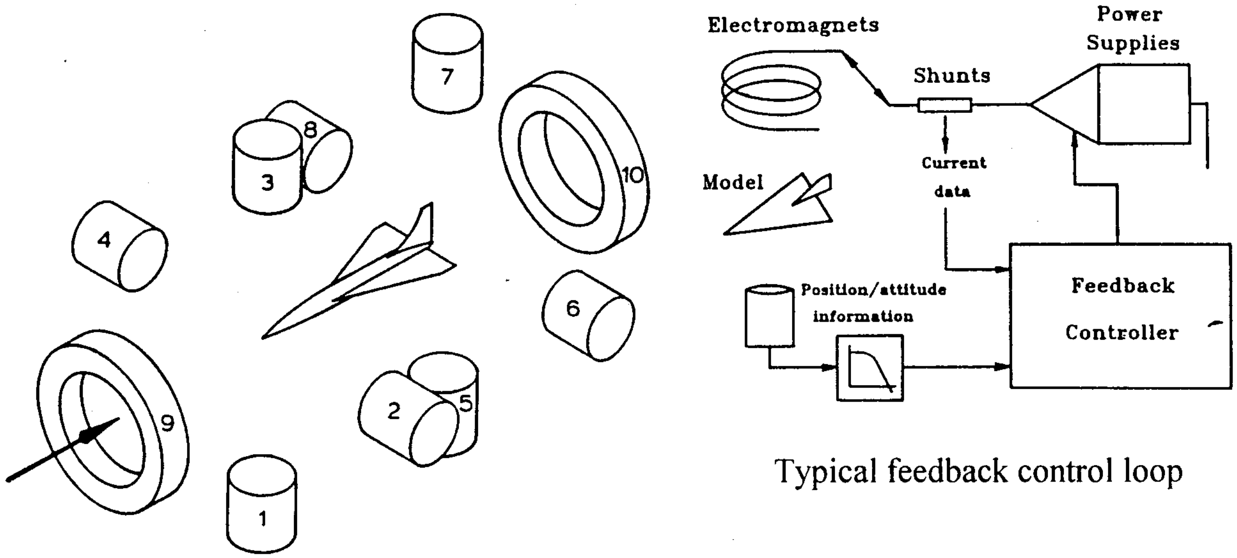


Figure 1 - Wind Tunnel Magnetic Suspension and Balance System (ODU 6-inch MSBS)



Typical array of electromagnets surrounding the wind tunnel test section

Typical feedback control loop

Figure 2 - Generic Configuration and System Block Diagram for a Wind Tunnel MSBS

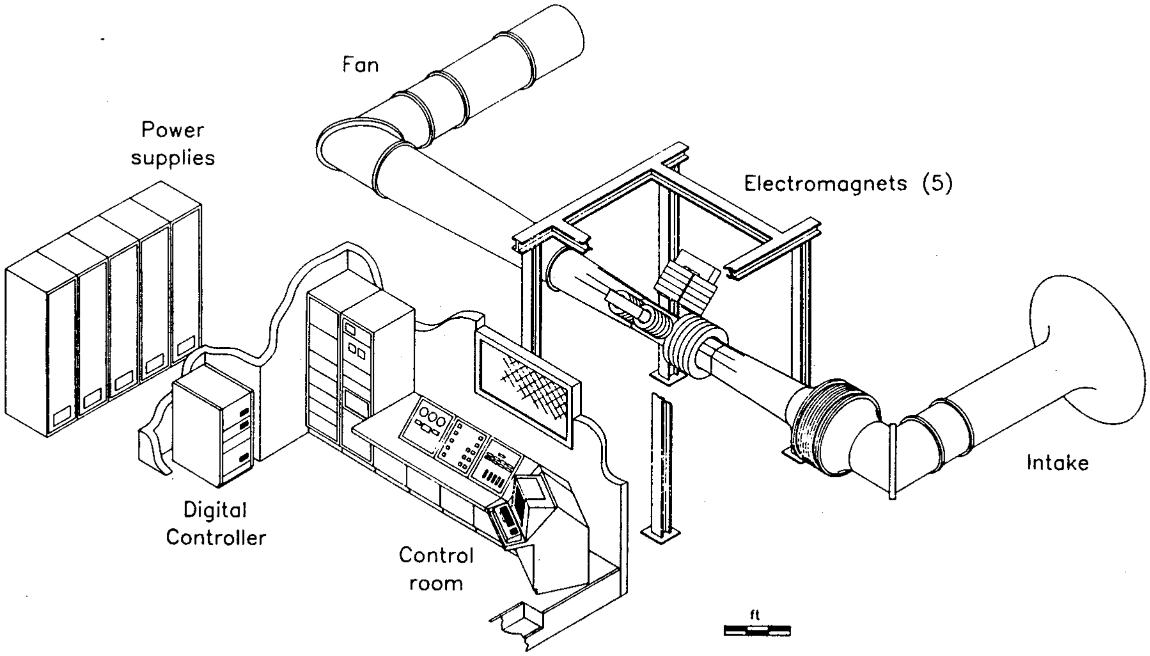


Figure 3 - The NASA Langley 13-inch Magnetic Suspension and Balance System

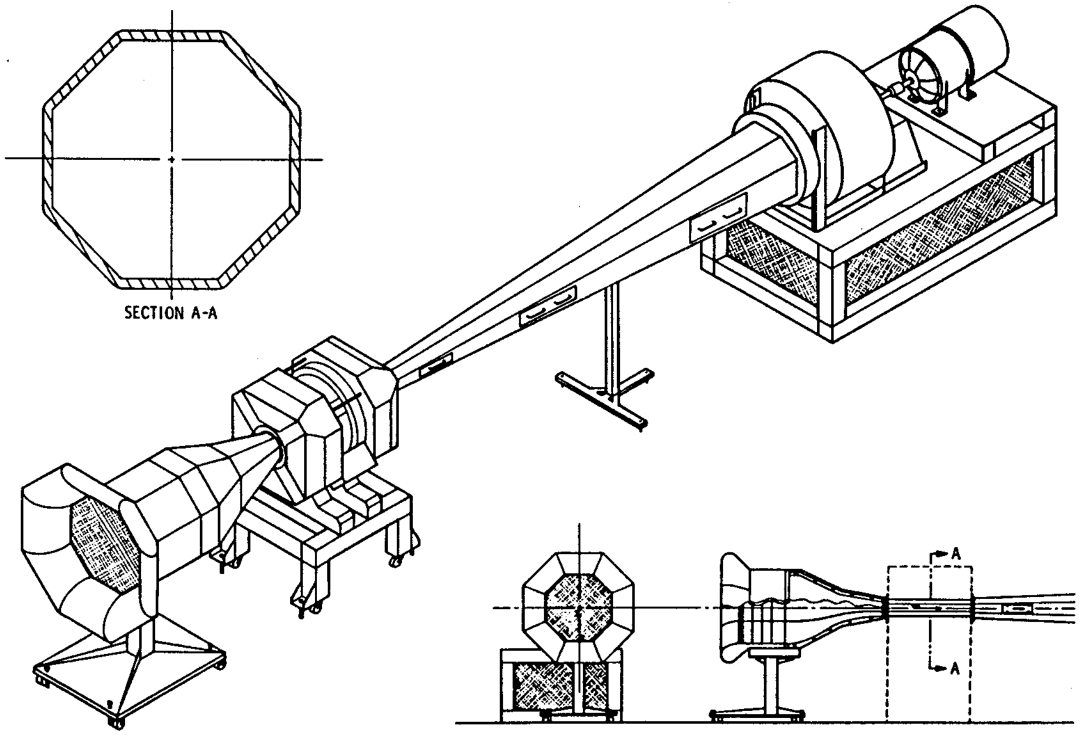


Figure 4 - The ODU/NASA/MIT 6-inch Magnetic Suspension and Balance System

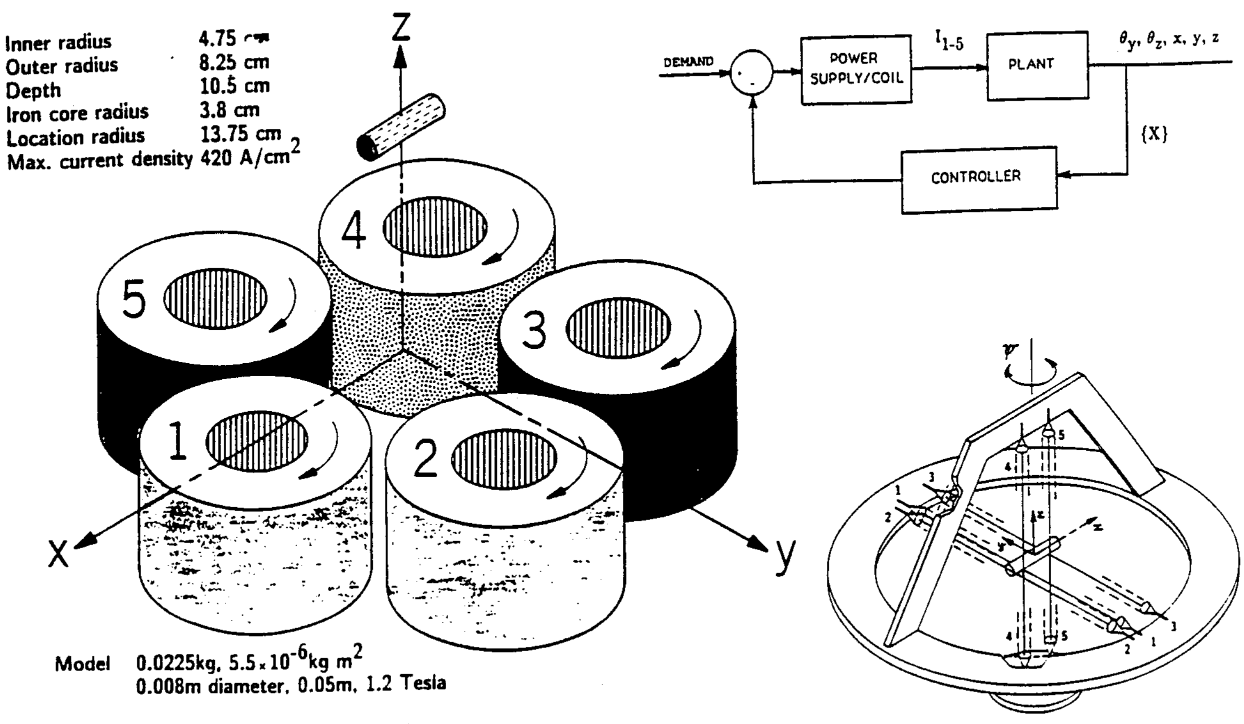


Figure 5 - The NASA LaRC Large Angle Magnetic Suspension Test Fixture

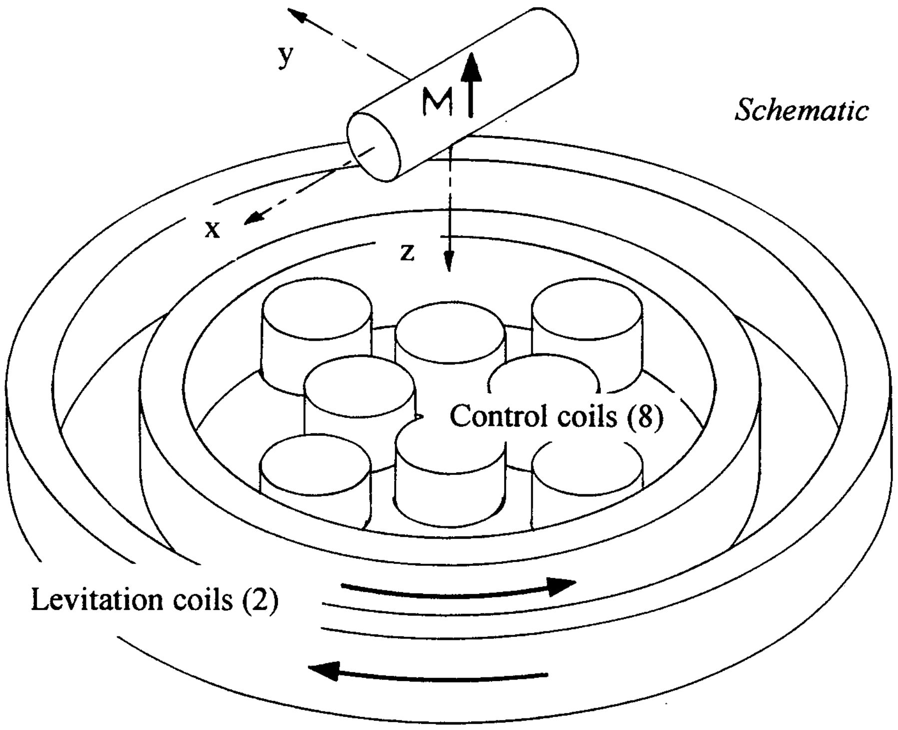


Figure 6 - 6 degree-of-freedom Electromagnet Configuration