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Application of Magnetic Suspension Technology to Large Scale Facilities
- progress, problems and promises

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Abstract

This paper will briefly review previous work in wind tunnel Magnetic Suspension and Balance Systems (MSBS) and will examine the handful of systems around the world currently known to be in operational condition or undergoing recommissioning. Technical developments emerging from research programs at NASA and elsewhere will be reviewed briefly, where there is potential impact on large-scale MSBSs. The likely aerodynamic applications for large MSBSs will be addressed, since these applications should properly drive system designs. A recently proposed application to ultra-high Reynolds number testing will then be addressed in some detail. Finally, some opinions on the technical feasibility and usefulness of a large MSBS will be given.

Introduction

Wind tunnel Magnetic Suspension and Balance Systems (MSBS) have been under investigation and development by many organizations since 1957. A significant number of small-scale systems have been constructed and a variety of aerodynamic testing has been carried out[1]. Due to the undoubted technical challenges inherent in these systems, they have never been adopted for large-scale production testing. On the other hand, the idea is still too promising to abandon.

Current work in the U.S. is rather limited, but includes a serious investigation of a potential application for an "ultra-high Reynolds number" wind tunnel and a modest system recommissioning effort. The work is benefitting from a variety of "spin-off's" from generic large-gap magnetic suspension development work at NASA Langley Research Center, as well as

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technological progress in superconductivity and magnetic materials. Other work on MSBSs is currently known to be proceeding in Japan, Taiwan, P.R. China, England and Russia, with interest also being shown in other countries.

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, as illustrated in Figure 1. The classical approach involves the use of a ferromagnetic core in the model, of 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, as shown in 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 can be written as follows[2] :

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

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

- where $\vec{M}$ represents the magnetization of the magnetic core in A/m, $\vec{B}$ the applied magnetic field in

Tesla, V 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 :

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

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

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 2 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 been fully exploited at this time.

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, but not in configurations relevant to 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.

Current Research - United States

Ultra-High Reynolds Number Wind Tunnel MSBS

Research has been underway for several years examining the possibility of constructing an ultra-high Reynolds number "wind" tunnel with liquid helium as the working fluid. A Workshop was held in 1989 to coordinate early efforts[4]. At one point, the tunnel was referred to by some researchers as the "infinite Reynold's number" 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 focussed on slightly more modest performance (finite Reynold's number!) but could still result in a facility with a Reynold's number capability one order of magnitude higher than anything currently existing. Scientific application of a tunnel of this type could provide experimental data which is currently unobtainable, such as concerning high Reynolds number flows, particularly the evolution and decay of turbulence. The engineering application is clearly to hydrodynamic studies of submersibles, with a particular item of interest being wake-related signature reduction. 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 test article's wake.

An alternative avenue of development appears to be an ultra-high pressure wind tunnel, with normal temperature air as the working fluid[5]. This approach poses a rather different set of design challenges, perhaps of a more traditional nature.

Research is proceeding, with recent completion of a candidate preliminary design and the hosting of a second Workshop[6,7].

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, shown in Figure 3, from the original MIT "6-inch" MSBS[8,9] has found its way to Old Dominion University via NASA Langley Research Center[10], and is currently in process of partial recommissioning. A unique feature is the use of Electromagnetic Position and attitude Sensing (EPS). It is planned to gradually restore the system to full operation with new power supplies and a digital control system.

The NASA Langley 13-inch MSBS

This system, illustrated in Figure 4, is still in operational condition, although has been inactive since 1992. During its use at LaRC it has been used for a variety of drag studies of axisymmetric and near-axisymmetric geometries, as well as support interference evaluations. Support interference increments on model drag of up to 200% were discovered, although this is hardly typical[11,12].

Large-Gap Magnetic Suspension Systems

A program has been underway for some years at NASA Langley Research Center to develop technology for large air-gap 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. Two small laboratory scale levitation systems have been constructed, shown in Figures 5,6, with air-gaps between suspended element and electromagnets of 10 cm[13,14]. A larger system of comparable configuration, the Large-Gap Magnetic Suspension System (LGMSS), is close to completion, with a 1 meter air-gap[15]. 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.

Current Research - Rest of the World

Low-density, high Mach number aerodynamic measurements have been made for many years at Oxford University in England with their nominally 15 cm system. This system is arguably a "production" facility, since the main interest has been in the aerodynamic data generated, rather than the MSBS itself. Work is continuing up to the present time[16,17].

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 focussing on rapid force and moment calibration procedures[18].

Researchers in Taiwan have recently completed construction of a small (10 cm) system and are commencing low-speed wind tunnel tests[19]. Plans for larger systems are being discussed.

Russian activity is at a low level, but includes recent studies of data telemetry systems from suspended models. Current information suggests that one MSBS remains operational, at TsAGI[20].

A notable recent development has been the discovery of significant activity in P.R. China, about which information has just become available[21].

Some details concerning the abovementioned systems is given in Table I.

Aerodynamic Test Requirements and Capabilities

A fresh look at the inherent capabilities of MSBSs and perceived shortcomings in conventional wind tunnel test capability was recently undertaken (unpublished). The main points will be summarized here, with the important rider that they should be taken to represent only an expression of the personal views of this author.

The large system design studies undertaken in the 1980's, under the direction of NASA Langley Research Center, concentrated on application to a large, high Reynolds number, transonic wind tunnel. The main technical justification was the elimination of support interference, which is a major problem around the transonic regime. Design studies were made for large-scale systems by General Electric Company[22] and later by Madison Magnetics Incorporated[23,24,25], illustrated in Figure 7. The conclusions were that a very large system was technically feasible, though quite expensive. A major cost driver was the unsteady (control) force and torque requirement, producing large cryogen boil-off in conventional superconducting electromagnets.

It seemed (and indeed is) inevitable that the cost of a "large MSBS" would be a significant fraction of the cost of the wind tunnel in which it would be used. The system under consideration would have provided static aerodynamic data, free of support interference, but little else. The technical risk was perceived to be quite high, since the system would have been around 5 times larger in linear dimension than anything previously attempted (c.1985, NAL 23-inch system and NASA LaRC LGMSS not yet completed). The design was ultimately seen as constituting an insufficiently attractive program and work gradually slowed and eventually was stopped, in or around 1990.

Provision of an support interference-free aerodynamic test capability is a valuable goal and should be pursued. However, the precise application needs to be carefully considered. For instance, while there is no doubt that

support interference is major problem in the accurate evaluation of cruise drag in wind tunnel testing, there often exist strategies for its assessment, such as mounting normally sting-mounted models on blade, wing-tip or fin supports[26]. This is an expensive process, but it is difficult to construct a persuasive argument this should be replaced by another apparently expensive process (MSBS). Valuable generic data could, however, be generated at moderate Reynolds numbers in a smaller and less expensive facility. Some interesting information was generated using the 13-inch MSBS at LaRC, which included a demonstration of the fact that the drag correction for sting interference could be as high as 200% (though admittedly not typical, as mentioned previously[11,12]). It has also been known for some time that support interference can be particularly significant in cases where the support lies in a separated and/or unsteady wake or any type of vortex flows[27,28]. The understanding of high angle-of-attack and unsteady aerodynamics would be greatly improved by the provision of interference-free test data, especially with the possibility of including fully representative model motions, such as wing rock. The fundamental research to permit the use of MSBSs at high angles-of-attack has been done, and suspension at extreme attitudes has been demonstrated, but the systems have not yet been systematically applied to this type of testing.

New Technology

New Configurations
An important novel feature of the ACTF configuration is the use of a transversely magnetized permanent magnet core in the cylindrical suspended element. This can provide full six degree-of-freedom control capability. The additional torque is generated by a term of the form :

$$\vec{T}_z \approx V \int_V \vec{M}_z \left\{ \frac{\partial B_y}{\partial z} x \right\} \qquad - (5)$$

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 has since been realized that this configuration may be well suited to the wind tunnel application, where generation of magnetic roll torque has been a long-standing problem. Using vertically magnetized permanent magnet cores within the fuselage provides 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 proposed new arrangement is shown in Figure 8.

Electromagnets and Magnetic Materials
The forces and moments generated by a conventional MSBS tend to be proportional to the strength of the magnetic fields generated by the electromagnets external to the tunnel flow and the magnetic moment of the suspended element. The suspended element can have a magnetic core of soft iron or permanent magnet material. The former promises higher absolute levels of magnetization, but requires an external "magnetizing" field, and also presents some difficuties with system calibration, since the magnetization is not absolutely fixed. Within the last few months, information concerning a new permanent magnet material, doped acicular iron powder, has been widely circulated[29]. The claimed specifications of this new material suggest a doubling of some aspects of performance from anything previously available. Specifically, magnetization intensities well above 2 Tesla are claimed, whereas current Nd-Fe-Bo materials achieve about 1.2 Tesla. Should this prove to be realised in practice, the technical and economic feasibility of MSBSs will be profoundly improved.

Turning now to the external electromagnets, progress in the development of practical high temperature superconductors continues to be steady and impressive. Small a.c. electromagnets have been fabricated and are being tested in magnetic bearing and other applications. Although future progress is not predictable, it seems likely that high temperature superconducting electromagnets will soon be feasible options at least for small and medium-scale wind tunnel MSBSs.

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 are a viable commercial item[30], 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 notable.

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

The magnitude of the engineering challenge of an MSBS is determined primarily by the aerodynamic 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 4. The 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. Results are shown in Table II.

The immediate conclusion is that this application is extremely benign from the perspective of aerodynamic forces and moments. The likely aerodynamic or hydrodynamic forces appear to be a small fraction of the deadweight of the model. This fact justifies some attention to passively stable suspensions in this application[6]. 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[31].

Turning to more detailed engineering design issues, the first consideration for this application is the extremely low temperature. Whatever the working fluid, an MSBS for helium tunnels 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[32]. 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. 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. In the case of an MSBS for a high pressure air tunnel, a similar design challenge is faced. Here, the MSBS must be placed inside the pressure shell, or the pressure shell must be designed such that it can easily be penetrated by magnetic fields. Due to the very high pressures involved, the latter option is probably the first choice (keeping the diameter of the pressure shell to a minimum), and seems feasible if composite materials are used. Conducting materials cannot be used extensively between the electromagnets and the suspended model, due to the induction of eddy currents by time-varying magnetic fields.

Two approaches for position and attitude sensing are viable, optically-based and the electromagnetic position sensor[8,9]. Optoelectronic devices can operate effectively at 2-4 K, or at high pressures, but there are practical concerns relating to condensation of stray gases and penetration of the pressure shell. 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. Here, the EPS coils could, perhaps should, be located inside the main structure of the wind tunnel. The electromagnetic behaviour of this system should be essentially independent of pressure or temperature changes.

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[25,32] since the force requirements seem so modest. The main purpose of this core design was to provide higher force capability in high dynamic pressure wind tunnel applications.

Some Opinions and Observations

It seems that a argument can be made that the earlier focus on large, high Reynolds number, transonic wind tunnels was flawed, insofar as the "cost-benefit ratio" for a system focused largely on support interference elimination in static testing was never favorable. Instead, it is now argued, at least by this author, that the focus should be on the areas of unsteady aerodynamics and dynamic stability, where conventional test facilities are arguably quite deficient. The unique ability of MSBSs to permit controlled motion through arbitrary trajectories (limited only by force and moment capability) represents an enormous untapped potential.

At least three research teams have addressed dynamic stability testing over the years, though none recently. At MIT[9,33] and the University of Southampton[34,35], forced oscillation testing has been successfully carried out. The University of Virginia developed a special design of MSBS specifically for dynamic stability work[36,37] 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. Although not so far pursued beyond the point of speculation, "modal" testing (i.e. directly forcing model motion in representative natural modes) or on-line system identification with random excitation might prove to be viable alternative approaches.

Acknowledgements

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Table I - "Operational" MSBSs, 1996/7

Organization	Approx. Test Section Size	Current Application	Current Status
NASA Langley Research Center	13-inch	Low-speed, R&D	Inactive
Old Dominion University	6-inch	System R&D	Recommissioning
Oxford University	3-inch	Hypersonic aerodynamics	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

Table II - Characteristics of Candidate Designs for Ultra-High Reynolds Number Wind Tunnels

	Gaseous Helium	Helium I	Helium II	High Pressure
Temperature, K / Pressure, atmospheres	5.3 / 1	2.8 / 1	1.6 / 1	300 / 100
Velocity, m/s	40	10	4	48.4
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
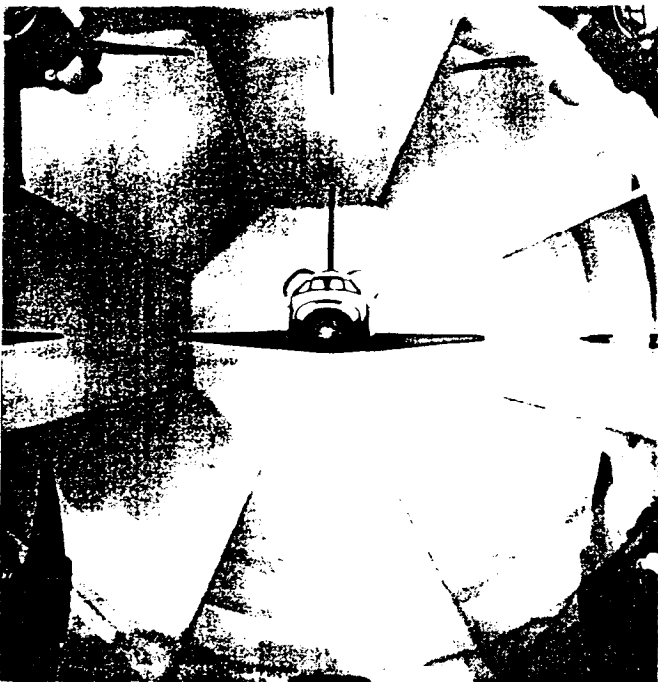
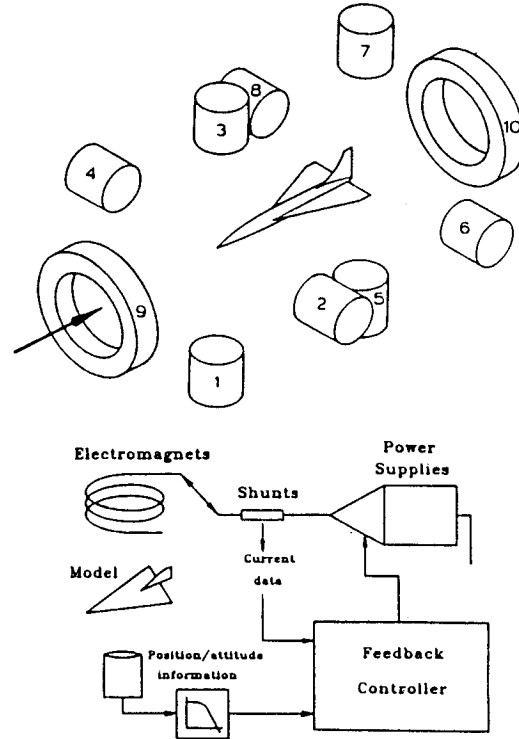Figure 1 - Wind Tunnel Magnetic Suspension and Balance System (ODU 6-inch MSBS)
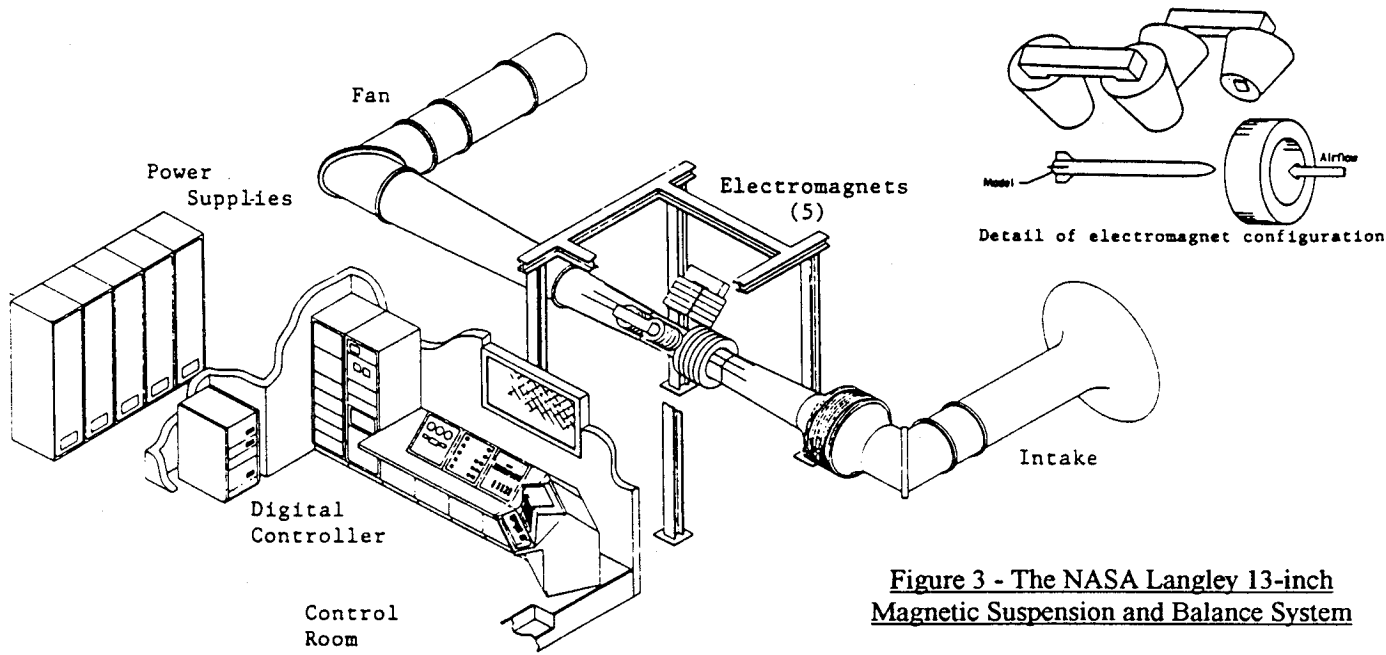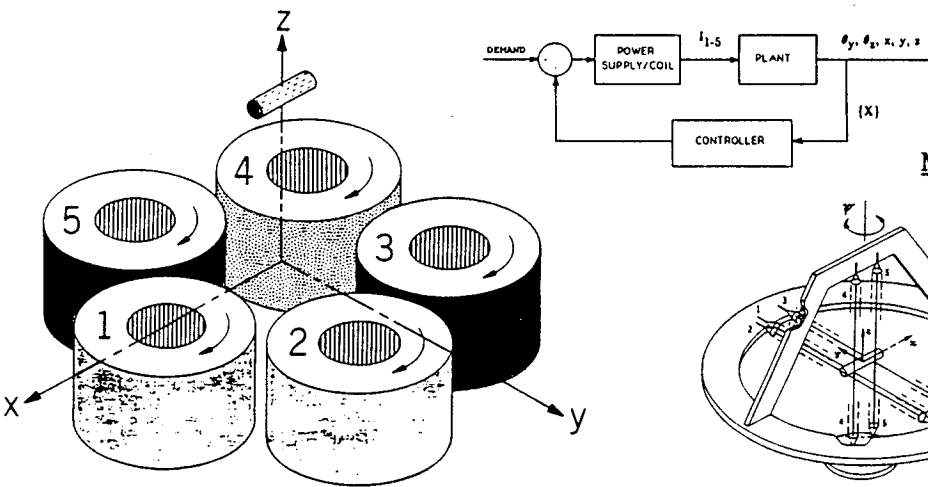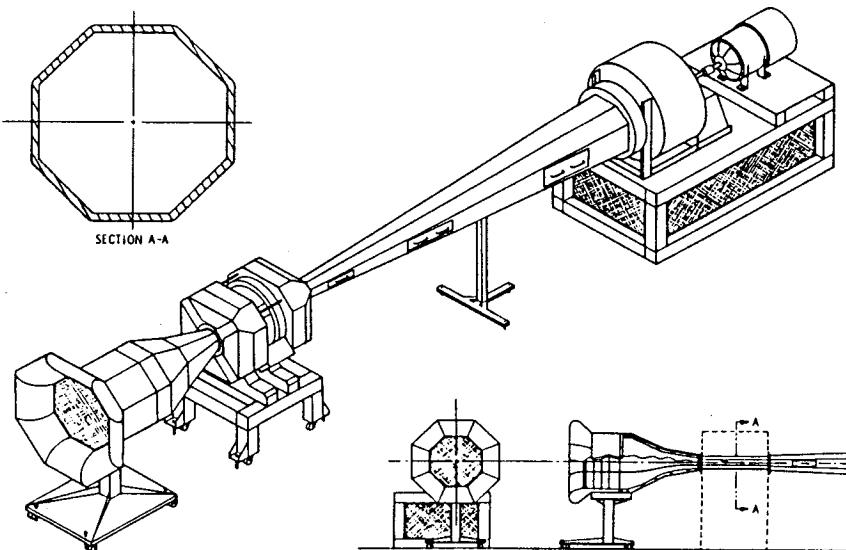

Figure 2 - Generic Configuration and System Block Diagram for a Wind Tunnel MSBS
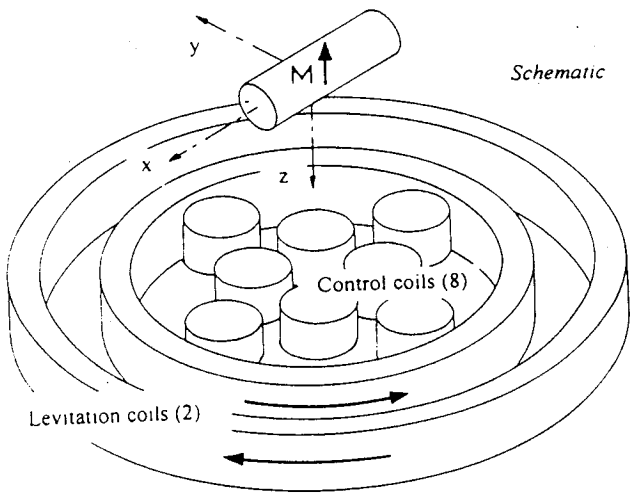
American Institute of Aeronautics and Astronautics

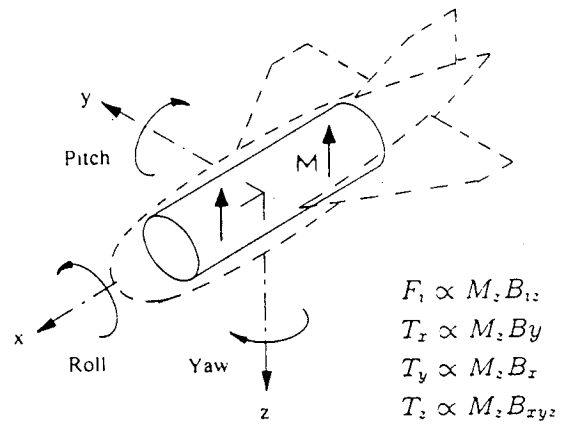Figure 3 - The NASA Langley 13-inch
Magnetic Suspension and Balance System

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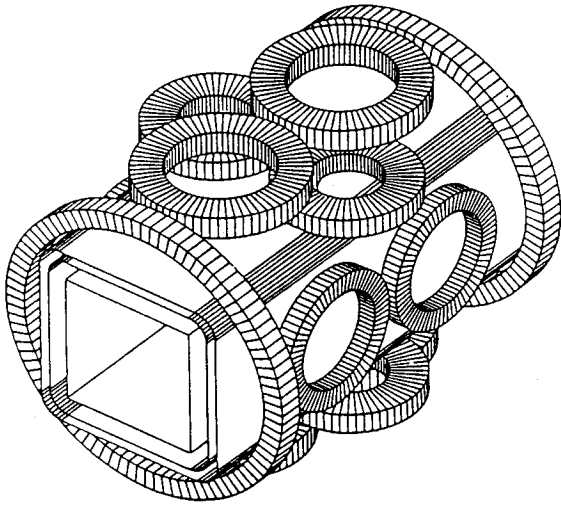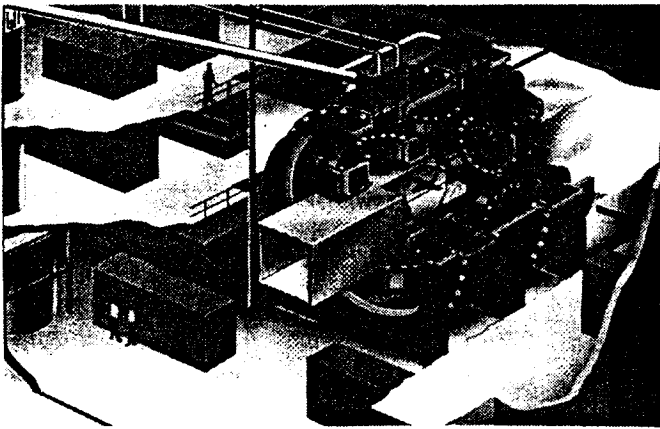

Figure 5 - The NASA LaRC Large Angle
Magnetic Suspension Test Fixture (LAMSTF)

Figure 6 - The 6 Degree-of-Freedom
LAMSTF Electromagnet Configuration

$$F_t \propto M_z B_{tz}$$
$$T_x \propto M_z By$$
$$T_y \propto M_z B_x$$
$$T_z \propto M_z B_{xyz}$$

Figure 8 - Transverse Magnetization
Configuration

Figure 7 - Large System Design Studies,
General Electric and Madison Magnetics