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6. AUTHOR(S)
Britcher, Colin P., PhD.
Gonzalez, Oscar, PhD.
Gray, Steven, PhD.

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Old Dominion University Research Foundation
4807 Hampton Blvd.
Hughes Hall, Room 2033
Norfolk, VA 23529

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13. SUPPLEMENTARY NOTES
A Magnetic Suspension and Balance System (MSBS) has been designed, partially constructed and will be commissioned for use with the Princeton/ONR High Reynolds number Testing Facility (HRTF). This report reviews the background of the project (Section 1), the HRTF itself (Section 2), the current status of development of the MSBS (Section 3), and finally problems encountered and future plans (Section 4).

14. ABSTRACT

Princeton University has constructed a specialized wind tunnel, the Princeton/ONR High Reynolds number Testing Facility (HRTF) to be used for aero/hydrodynamic testing of submersible shapes. The facility is capable of operation at very high pressures, up to around 230 atmospheres, with relatively low test velocities. Old Dominion University is responsible for the design and commissioning of a Magnetic Suspension and Balance System (MSBS) for use with the HRTF. The design task encompasses configuration definition, detail design and documentation. Initial commissioning was undertaken at NASA Langley Research Center, with subsequent relocation to Princeton and installation in the HRTF.

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Interim Final Administrative Report

The Design, Construction and Commissioning of a Magnetic Suspension and Balance System for the Princeton/ONR High Reynolds Number Testing Facility (HRTF)

Dr. Colin P. Britcher†, Dr. Oscar Gonzàlez‡, Dr. Steven Gray‡
Old Dominion University
†Department of Aerospace Engineering,
‡Department of Electrical & Computer Engineering

Summary

A Magnetic Suspension and Balance System (MSBS) has been designed, partially constructed and will be commissioned for use with the Princeton/ONR High Reynolds number Testing Facility (HRTF). This report reviews the background of the project (Section 1), the HRTF itself (Section 2), the current status of development of the MSBS (Section 3), and finally problems encountered and future plans (Section 4).

1. Introduction

1.1 Technical Objectives

Princeton University has constructed a specialized wind tunnel, the Princeton/ONR High Reynolds number Testing Facility (HRTF) to be used for aero/hydrodynamic testing of submersible shapes. The facility is capable of operation at very high pressures, up to around 230 atmospheres, with relatively low test velocities. Old Dominion University is responsible for the design and commissioning of a Magnetic Suspension and Balance System (MSBS) for use with the HRTF. The design task encompasses configuration definition, detail design and documentation. Initial commissioning was undertaken at NASA Langley Research Center, with subsequent relocation to Princeton and installation in the HRTF.

1.2 Approach

The unique requirements of the project promoted the development of an unusual teaming arrangement. Purchase of capital equipment would be handled by Princeton University, using DURIP funds already awarded. ODU would receive funds through the subject ONR award, N00014-99-1-0298, plus a small subcontract from Princeton, 150-67555-1. ODU separately negotiated a Cooperative Agreement with NASA Langley Research Center, SAA #450, such that the design team would have access to specialized magnetic field analysis software already in place at LaRC, and such that the build-up and commissioning of the MSBS could take place in LaRC's dedicated MSBS laboratory. Personnel at ODU supporting the project included Dr.

Colin P. Britcher, Department of Aerospace Engineering, Drs. Oscar Gonzalez and Steven Gray, Department of Electrical and Computer Engineering, with a number of graduate and undergraduate students and an electronics technician involved at various times. The initial NASA point-of-contact for the Cooperative Agreement was Nelson J. Groom. Following Mr. Groom's retirement, Dan Moerder acted as an interim point of contact, with continued activity sanctioned under the NASA-sponsored Center for Experimental Aeronautics, NCC-1-394. Dr. Moerder is currently on full-time study leave from NASA.

2. The High Reynolds Number Test Facility (HRTF)

2.1 Overview

The HRTF was specified as operating at a maximum pressure of 3500 psi. (similar to the existing Superpipe). A representative test model would be a 12:1 length-to-diameter ratio quasi-axisymmetric, low-drag shape, with a target length Reynolds number of around $1.8*10^8$. These requirements could be satisfied with a test section diameter of around 18 inches (0.46 m) and a flow velocity below 65 ft/s (20 m/s). Due to restricted access to the interior of the tunnel, MSBS systems such as position sensors and the controller must be configured so as to reliably suspend models for long periods of time, with a variety of aero/hydrodynamic tests conducted in sequence. These considerations lead to a relatively conservative choice of system configuration and hardware.

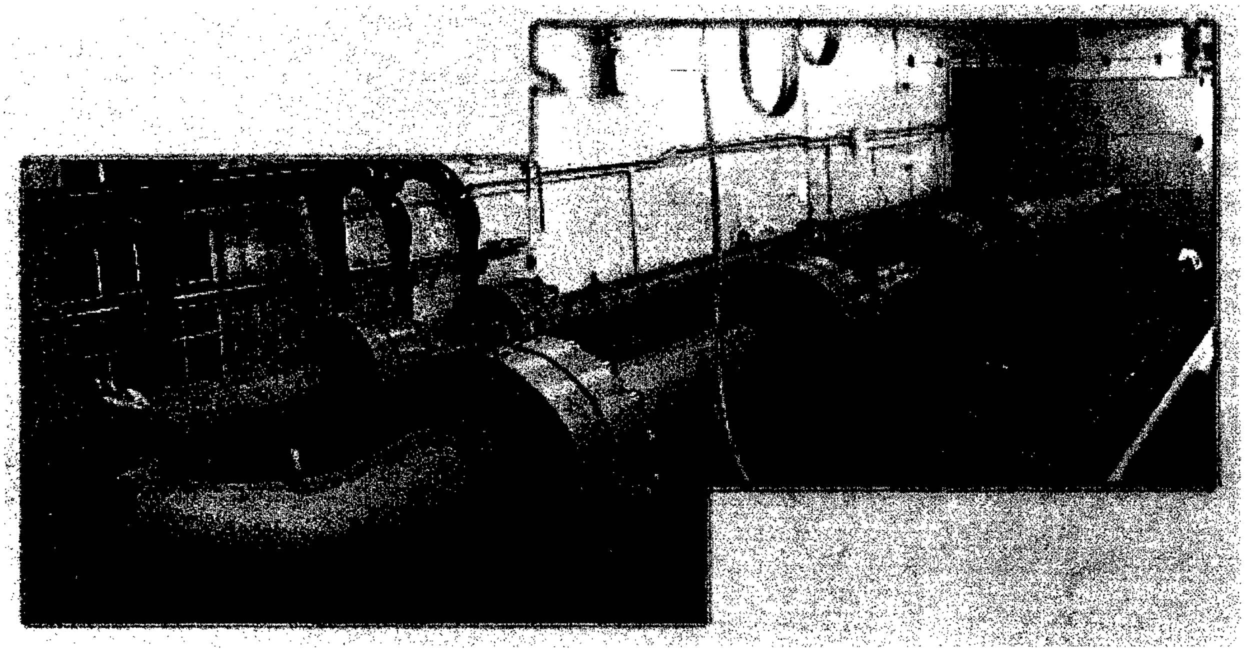


Figure 2.1 – The High Reynolds Number Test Facility, c.2001

A major design decision was whether to mount the MSBS electromagnets inside or outside the pressure shell. The pressure shell is fabricated from stainless steel, which is relatively conductive, but non-magnetic (see later comments concerning the weld). The former alternative was initially preferred for the MSBS, since it placed eddy currents induced in the pressure shell further away from the suspended model, while placing the electromagnets closer. However, the cost of the larger cross-section pressure shell required in the test section area proved prohibitive. Following some analysis of eddy current behavior, detailed below, it was concluded that electromagnets mounted outside the pressure shell would be practical. Model position sensor and other hardware would be located inside the pressure shell, shielded from the flow by an aerodynamic liner, so as to avoid a requirement for extensive viewing ports in the test section region.

The Test Section

Struthers Corporation designed the test section according to specifications supplied by Princeton. The stainless steel test section was fabricated by rolling a plate, with a welded seam, rather than by casting or extruding a tube as originally anticipated. Carbon steel flanges were added to each end, as shown in accompanying figures and drawings. This fabrication technique leads to some difficulties. First, the welded seam was discovered to be weakly magnetic, since the filler rods used apparently have to have some modest carbon content to avoid brittleness in the weld. Second, the rolled section was discovered to be non-circular and tapered along its length. Finite element analysis addressing the magnetic effect of the weld is presented later. Careful measurements were taken to quantify the geometry and are presented in accompanying figures.

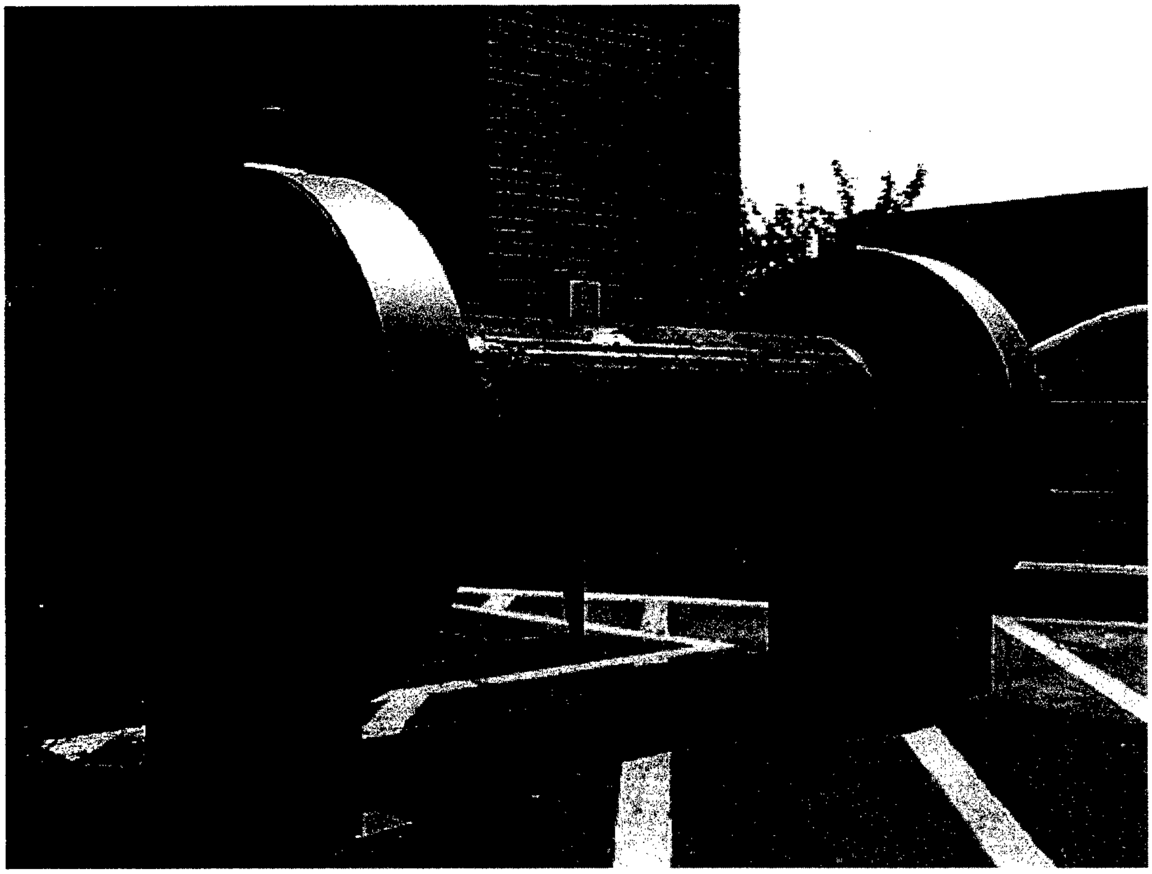


Figure 2.2 – The Test Section as Delivered to NASA LaRC, c.2000
- note weld visible along the side facing the camera

The test section is presumed to be fabricated from 304L stainless steel, with an electrical resistivity of $720\times10^{-9}\Omega$m and a magnetic permeability of 1.02. It should be noted that some early editions of the ASM Metals Handbook give an incorrect value for electrical resistivity of 72×10^{-9} Ωm. The flanges are presumed to be ASTM A105 carbon steel (AISI 1035 similar), with A 106 used for other sections of the pipe. Here, the electrical resistivity is taken to be around 170×10^{-9} Ωm, with the magnetic permeability unknown, but presumably of the order of 1000 or higher. The precise composition of the weld material is unknown, but based on anecdotal reports, is expected to be of modestly elevated carbon content compared to the 304L parent material, apparently to avoid embrittlement. The electrical and magnetic properties are clearly uncertain, but the weld is observed to be weakly magnetic.

The Aerodynamic Liner

As mentioned, the design concept is to mount MSBS position sensors inside the pressure vessel, thus avoiding the necessity for access ports or windows, other than those required to insert or retrieve the model. It was desired to retain the maximum practical flow cross section so as to maximize the size of the model that can be tested with acceptable levels of wind tunnel wall interference. The precise dimensions can be changed in the future, but a baseline design set the target flow area as between 220 and 230 square inches, as indicated in accompanying figures. This should be compared to the nominal cross sectional area of the pipe, which is just over 280 square inches based on a mean internal diameter of 18.897 inches. Spaces are allocated for optical position sensors of either 1.0 inch nominal "box" width/height or 1.26 inch nominal box width/height.

The aerodynamic liner is required to be constructed of non-magnetic material with optical viewing ports as appropriate. By venting the space between the liner and the pressure shell, loading of the walls due to the wind tunnel flow is minimal. A final version has not been constructed at the time of writing, but a design in detailed in accompanying drawings.

3. The Magnetic Suspension and Balance System for the HRTF

3.1 Preliminary Design

Overview

The initial design of the MSBS, particularly electromagnet sizing and placement, was driven by steady-state operating conditions. By incorporating substantial performance margins in the electromagnets, some dynamic capability was naturally introduced. The key issue affecting system dynamics is the provision of adequate power supply capacity. Within the circular pressure shell, some allowance must be made for location of model position sensor and other hardware. With the flow area set, the model size can be established based on a compromise between Reynolds number requirements (suggesting larger models) and test section blockage (suggesting smaller models). From the HRTF dimensions already stated, the specifications of the baseline model to be suspended in the MSBS were established as follows.

Table 1 - Baseline Model Specifications

Length	35.4 in (0.9 m)	Weight	45.6 lbs (202.8N)
Volume	162 cu.in (2.6510m)	Blockage	3%
Diameter	2.95 in (0.075 m)	C_D	0.1 to 0.3
Dynamic pressure	5.8 psi (40 kPa)	Drag	3.8 to 11.7 lbs. (17 to 52 N)

Note that the model length-to-diameter (L/D) ratio is 12. It is seen that the model deadweight is the dominant force in this application.

Models

Suspended models are typically fabricated from non-magnetic material, with embedded magnetic cores. This is preferred so as to minimize cost (magnetic cores can be simple cylindrical shapes) and to simplify adaptation to different models (the magnetic configuration can be essentially unchanged between several models).

The preferred magnetic core is a permanent magnet material with high remanence and high coercive force. Contemporary Neodymium-Iron-Born (NdFeBo) material is ideal, with typical values for remanence around 1.2 Tesla, and coercive forces so high as to render the material immune to demagnetization in normal handling (except by heating). The material is readily available in large sizes from a number of suppliers.

A commissioning model has been constructed from PVC pipe with embedded NdFeBo cores supplied by Edmunds Scientific

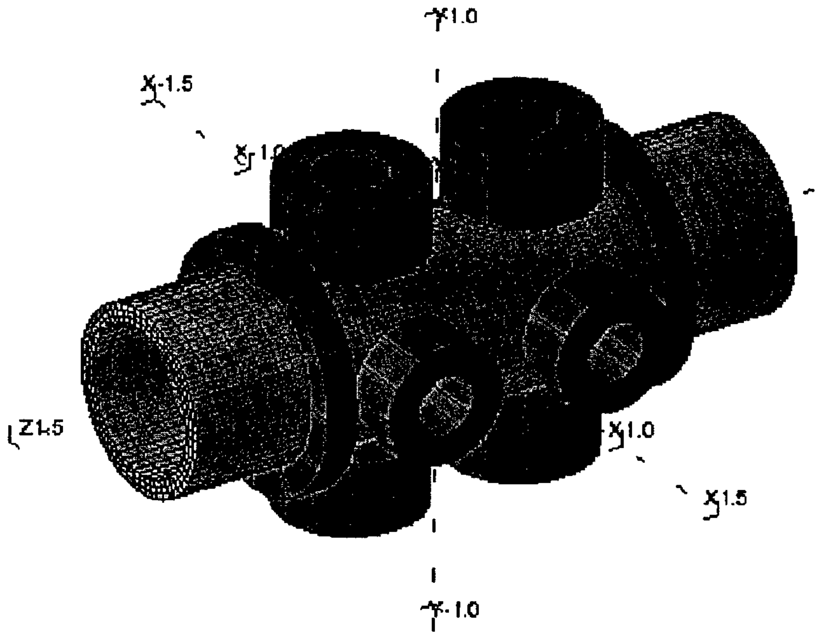
Magnetic Fields and Forces

A permanent magnet model core was chosen with a view to minimizing steady-state power consumption (i.e. no external magnetizing coils needed). Currently available Neodymium-Iron-Boron material exhibits a magnetization of around 955,000 A/m (1.2 Tesla). Half the model volume and weight is assigned for the magnetic core, following classical "rules of thumb" for MSBS designs. Choosing a classical axial model magnetization and using an axis system where z is upstream, y vertical, it is found that target values for the field gradients B_{zz}, B_{yz}, and B_{xz} are around 0.085 T/m, 0.26 T/m, and 0.085 T/m respectively. The magnetic drag and side force targets are twice the maximum expected steady-state aero/hydrodynamic forces. The vertical force target is the deadweight of the model, plus twice the maximum expected steady-state aero/hydrodynamic force. The aero/hydrodynamic moments are expected to be relatively small and hence a weak design driver. The sizing of the electromagnet array can now proceed.

Configuration

A baseline set of air-cored electromagnets was been developed using the OPERA/TOSCA™ magnetostatic package available at NASA LaRC. The general configuration follows the classical "+" arrangement and is shown in Figure 3.1 below. Problems were experienced with steady-state power consumption in the four coils in the vertical plane, so the configuration was changed to an "X" type, shown in Figure 3.2.

Figure 3.1 – Initial "+" Configuration



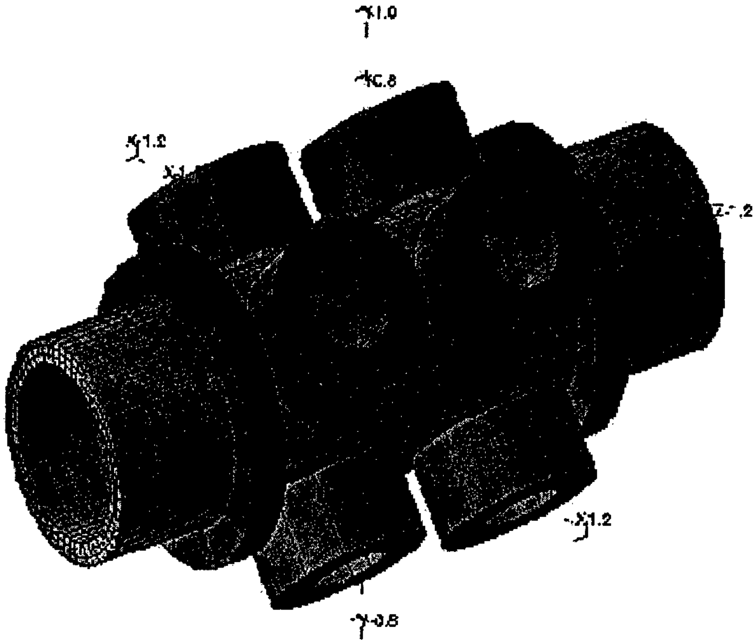


Figure 3.2 – Final "X" configuration

3.2 Analysis

Eddy Currents

The critical issue arising from the choice of the placement of MSBS electromagnets outside the pressure shell is that of eddy currents induced in the stainless steel walls. A series of finite element models were developed using the magnetodynamic analysis package OPERA/ELEKTRA™ in order to provide preliminary estimates of the field attenuation and guidance for development of a dynamic model. It was found that a simple first-order lag provided an order-of-magnitude representation of the eddy current effects. Further, the time constant, around 0.009 seconds, is acceptable from a system dynamics point of view. Previous analysis has, however, shown that the form of the eddy current effect could be more accurately described in by a "half-order" pole, so further analysis will be required if high fidelity dynamic models are to be developed

3.3 Single Degree-of-Freedom Verification

In order to remove some uncertainties concerning the modeling of pressure shell eddy currents, the operation of a suspension system in connection with the pressure shell (including the effect of the weld) and the operation of the dSpace controller software and hardware, it was decided to develop a single degree-of-freedom demonstration system. A simple permanent magnet cored model (a gray sphere is the photo below) was suspended inside the actual test section, using the actual controller hardware, simplified software, with the remaining hardware chosen from available items with characteristics similar to that specified for the HRTF MSBS. The electromagnetic coil was a prototype coil from the Large Angle Magnetic Suspension System (LAMSTF), around 6 inches diameter with around 500 turns. The power amplifier was a Copley

Controls Model 241, with a maximum steady-state current output of 30 A. A SUNX LA-511 infra-red optical position sensor was used.

Suspension was successfully achieved with minimal difficulty, as shown in Figure 3.3 below. Full details of the design and evaluation process have been reported separately.

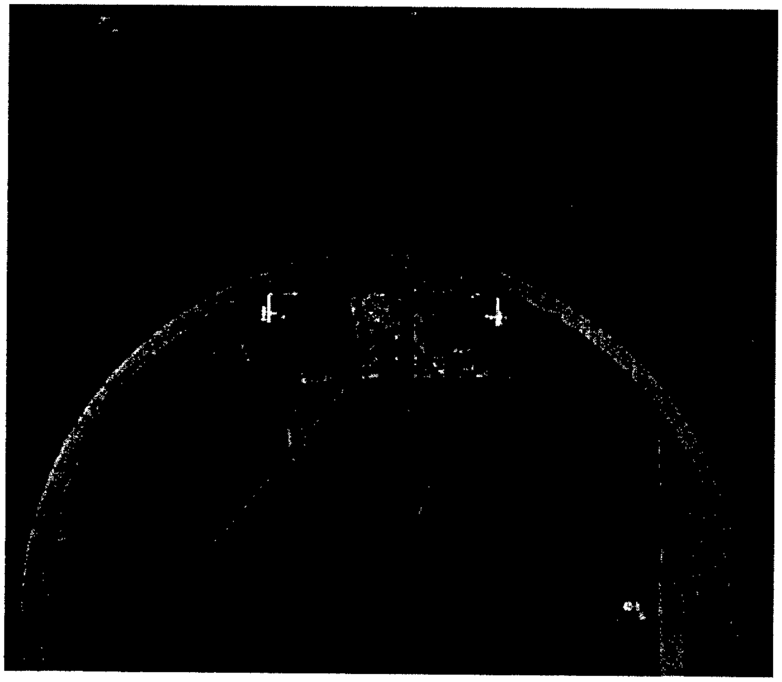


Figure 3.3 - Demonstration Levitation Inside the HRTF Test Section

3.4 Design Details

Electromagnets
The 8 main electromagnets were procured from Stangenes Engineering Inc., following in-house designs. The two axial electromagnets had to be wound in place and have contributed to the considerable delays experienced by the project (discussed more fully later).

Power Supplies
Current is supplied to the main electromagnets from Copley Controls Corporation Model 232P high capacity switching power amplifiers. These are rated for full four-quadrant operation, at 150 V maximum output (with a 150 V D.C. supply bus) with a maximum continuous current rating of 120 A. Short-term transients are allowed up to 250 A, with the load factor limited by thermal. Only six supplies were specified for cost reasons, with the 10 electromagnets fed in 5 pairs, with the sixth supply reserved for generation of roll control fields, as discussed elsewhere. The supplies are mounted in two groups of 3 with fan cooling of each group. Individual supplies have on/off controls and status indicators on a front panel.

The 150 V D.C. bus is fed from a Clinton Power Model S600/150B bulk D.C. power supply. This is basically an unregulated, 3-phase, full-wave rectifier, with a remote control panel and various fault protections. The full continuous power rating of 600 amps is thought to considerably exceed the normal requirements of the existing MSBS system, but provides minimum ripple under normal load, as well as some expansion capability. The start-up surge current when connected to the amplifier assembly can be large, due to the total 0.156 Farad capacitance located in the Copley amplifiers (described earlier). The energy required to bring this capacitance to full charge is around 1755 Joules. A "soft-start" circuit has therefore been added, which slow charges the capacitors from a simple 120 V A.C. bridge rectifier with a series resistor for current limiting. The Clinton supply can then be brought on line with greatly reduced surge current.

Cooling System

At maximum operating current each of the 10 electromagnets can dissipate around 6kW each by resistive heating. This power must be removed by passing a cooling fluid through the hollow conductor. De-ionized water is the usual choice for systems of this (relatively modest) power level. The heart of the cooling system is a NESLAB Instruments Ltd.., System II water-to-water heat exchanger. A closed "primary" cooling loop is thereby formed, to be operated with de-ionized water only. The NESLAB heat exchanger has all necessary de-ionizing equipment, including monitoring sensors, mounted internally.

Structure

A fiberglass structure has been fabricated to support the electromagnets and associated hardware. It is assembled in a modular fashion to facilitate rapid installation and removal of the electromagnets at the appropriate time.

Position Sensors

Initially, five laser light sheet sensors will be used to provide measurements for pitch and yaw angles, and longitudinal, lateral, and vertical displacements. These five degrees of freedom control are the only ones possible if the permanent magnet magnetization is along its axis and the magnet is cylindrical. If other types of magnetizations are included, or if the magnet is made non-axisymmetric, then roll control is also possible, when a sixth sensor would be added. The selected sensors are SUNX™ Model No. LA-511, each consisting of an infrared emitter and receiver element with side-view mirror attachments that bend the beam through 90°. The mirrors are needed to improve packaging of the sensors in the narrow space between the inside wall of the pressure shell and the flow liner, hence maximizing the flow area through the middle of the tunnel. The sensors have a nominal sensing range (beam width) of 15 mm and a repeatability under optimal conditions of 10μm.

For system commissioning, the sensors are attached to mounting rails that are located inside the test section, aligned with the flow direction. With a beam width of 15 mm, this configuration it is possible to measure roughly ±7.5 mm displacements in each direction. With a typical fore-and-aft spacing of 160 mm, the sensors will also give a maximum angular range of around ±5°.

It was hoped that the sensors could be made tolerant of the high-pressure environment inside the HRTF by "venting" all cavities in the optical and electronic assemblies. Based on advice and with guidance from Princeton University, this was carried out on a prototype, which was subsequently tested in a small pressure vessel loaned by Princeton. After some failures, a sensor pair that could survive pressure cycling was developed. However, the sensor calibration (output voltage for a given level of beam obstruction) was never constant through the pressure cycling. Further details are given in separate reports. As a result, "anti-pressure" chambers have been designed to accommodate the SUNX LA-511 electronics with the cases removed. Each chamber consists of as a steel sleeve, with a very thick Plexiglas window, and is able to withstand the full operational pressure of the HRTF. To maintain the interior at atmospheric pressure, a small diameter tube is lead out to ambient pressure environment. Until such time as improved sensors can be developed, these chambers will have to be used in the HRTF.

Controller

The hardware selected for the data acquisition and control is dSpace's™ Advanced Control Kit 1103 which includes a micro-controller board with a Motorola PowerPC, a TI DSP subsystem, and an integrated real-time software environment. The main advantage of the software is that it interfaces with Matlab™ and Simulink™ to simplify development, testing and analysis of control algorithms in real-time. The hardware includes 8 DACs (14 bit, 5 μs settling time) and several ADCs, including 16 high performance ADCs (16 bit, 4 μs conversion time). If necessary, the hardware can be used to implement high order controllers while maintaining sampling rates between 0.5-2 kHz. The dSpace software environment has been used to develop a custom GUI interface for the final turnkey system.

During system development, it was discovered that an error existed, suspected to be in the 1103 firmware, which resulted in intermittent "lockup" of the user interface. This has recently been diagnosed and rectified by dSpace.

3.5 System Integration

Control Laws

The main goal for the control law is to robustly meet the regulation and tracking control specifications. The design will be very challenging because of the large-gap magnetic suspension requirement and the placement of the coils on the outside of the tunnel. This coil placement induces eddy currents, which add a layer of uncertainty, and will probably increase the coupling of the multivariable dynamics. Due to limited access to the inside of the tunnel and the high degree of uncertainty of the models, robustness will be emphasized over performance at first. Once the equipment is in operation and system identification gives models and uncertainty descriptions that are more accurate, then the control laws will be redesigned to have improved performance, trading-off robustness for performance. The initial control laws to be designed will be based on linear perturbation models. These include classical sequential loop closure and robust multivariable controllers. The nonlinear plant models that are being derived will permit the design of nonlinear controllers such as sliding mode controllers, which have well known robustness properties.

MSBS Control Law Design and Synthesis

The objective of the MSBS is to reliably suspend and position in six degrees of freedom a test model with a cylindrical permanent magnet core. In addition to regulating the position in six degrees of freedom, the system should also allow tracking of slow time-varying signals. Due to restricted access to the interior of the tunnel, the control system must maintain the test model in suspension for long periods of time while a variety of aero/hydrodynamic tests are conducted in succession. These constraints place special requirements on the hardware as well as on the control law design. For example, the electromagnet coils will need a built-in cooling system, and the control law will need to be robust and able to regulate the disturbance effects of the aero/hydrodynamic tests being conducted. Additional constraints are imposed on the sensor system, which is inside the tunnel where the maximum pressure can reach 3500 psi. The sensor elements will need to be prepared to withstand the pressure, such as by venting enclosed air cavities. In this section, the plan for the design of the regulation and tracking control law is described.

Plant Model

For control purposes, the plant consists of the actuators and load, that is, ten suspension/control electromagnets, six (or more) power supplies, and the test model. The equations of motion of the cylindrical magnet inside the test model can be derived starting with the nonlinear torque and force equations developed in References 8-10. The torque and force equations will first need to be modifed to properly include the effect of the eddy currents induced on the walls of the pressure shell as explained earlier. In addition, analytical models are being developed for the fields and their gradients acting on the permanent magnet that fit numerical data generated by the OPERA/TOSCA/ELEKTRA™ package. The plant model derivation will yield nonlinear equations that characterize the plant's response from the commanded power supply currents to the three displacement and three rotational outputs. These nonlinear equations are being derived for the design of nonlinear controllers. The nonlinear model will also be linearized to develop perturbation models for linear control design.

4. Current Status and Future Plans

4.1 Current Status

As previously reported, the project has fallen far behind any original schedule. A host of technical problems have been previously reported, including :

- Failure of the position sensors to perform adequately under high pressure.
- Failure of the Clinton DC power supply due to a manufacturing defect.
- Extreme challenges in winding the axial electromagnets in situ.
- Significant underestimation of the magnitude of the task.

Additional problems have been encountered, not previously reported :

- Firmware defects in the dSpace 1103 control board.
- Lost time is "transfer of knowledge" from one generation of students to the next.

Administrative difficulties, also previously reported and beyond the control of ODU or ONR, have further slowed hardware development :

- Loss of the NASA Cooperative Agreement No. SAA #450
- Consequent loss of NASA technician support.
- Retirement of Nelson J. Groom
- Temporary "freeze" on activity in the current laboratory space.
- Loss of Dr. Dan Moerder (interim NASA monitor)

Further issues, not previously reported, continue to delay the project :

- Loss of functionality of the NASA computer system running the OPERA software.
- Difficulties in arranging technician support through Johnson Controls, although tentative agreements were made for ONR to fund limited support directly to permit completion of the axial coil-winding task.

At the time of writing, all major hardware items are in hand, with final assembly on hold, pending completion of the axial coil winding. Development of the controller hardware continues. All funding from the subject award has been expended, so work continues using internal resources.

4.1 Future plans

ODU is, of course, ultimately responsible for the project, and is committed to complete the MSBS system and deliver it to Princeton. Accompanying documents demonstrate that best efforts have been made, with 17 individuals working on the project to date, far in excess of the original commitment and far exceeding the funding level available from ONR or Princeton. Further, 11 major documents have been produced (not including presentation material relating to formal reports), including 1 PhD dissertation and 3 Masters theses (2 approved).

The current complement of faculty and students is as follows :

- Dr. Colin P. Britcher (faculty, PI, part-time)
- Dr. Oscar Gonzalez (faculty, Co-I, part-time)
- Dr. Steven Gray (faculty, Co-I, part-time)
- Mark Adams (graduate research assistant, full-time)
- Lance Breitenbach (graduate research assistant, part-time)

If the axial coil winding can be completed in the near future, final assembly will quickly follows, with levitation and system commissioning anticipated to run through the Fall semester 2003. The current graduate student is assigned to the project until Spring 2004.

List of ODU Personnel Involved in Work under ONR N00014-99-1-0298

(**bold** denotes those currently active)

Faculty

1) **Dr. Colin P. Britcher**, Aerospace Engineering.
Project Principal Investigator.

2) **Dr. Oscar Gonzalez**, Electrical and Computer Engineering
Co-Investigator

3) **Dr. Steven Gray**, Electrical and Computer Engineering
Co-Investigator

Graduate Students

4) Dr. V. Dale Bloodgood, Aerospace Engineering
Graduate (Doctoral) Research Assistant
(Financially supported through NASA GSRP program and Virginia Space Grant Consortium)

5) **Mark Adams**, Electrical and Computer Engineering
Graduate Research Assistant
(On paid study leave from the U.S. Coastguard)

6) Oscar Gomeiz, Aerospace Engineering
Graduate Research Assistant
(partial support through the subject Grant)

7) James E. Barkley, Electrical and Computer Engineering
Graduate Research Assistant
(partial support through the subject Grant)

8) Adeel Jafri, Electrical and Computer Engineering
Graduate Research Assistant
(partial support through the subject Grant)

9) **Lance Breitenbach**, Aerospace Engineering
Graduate Research Assistamt
(financial support through Aerospace Engineering)

Undergraduate Students

10) Peter T. Welch, Electrical and Computer Engineering
Undergraduate Student
(no financial support)

11) Robert Boller, Electrical and Computer Engineering
Undergraduate Student
(no financial support)

12) Corey Freeman, Electrical and Computer Engineering
Undergraduate Student
(no financial support)

13) John Furbee, Electrical and Computer Engineering
Undergraduate Student
(no financial support)

14) Ron Dinoso, Electrical and Computer Engineering
Undergraduate Student
(no financial support)

15) Randy Volante, Electrical and Computer Engineering
Undergraduate Student
(no financial support)

16) Robert Gibson, Mechanical Engineering
Undergraduate Research Assistant
(partial support through the subject Grant)

17) Chris Lott, Mechanical Engineering
Undergraduate Research Assistant
(partial support through the subject Grant)

List of Documents Submitted under ONR N00014-99-1-0298

(most recent first)

High Reynolds Number Test Facility Magnetic Suspension and Balancing System
Dinoso, R. A.; Volante, R.C.
- Discusses detail development of the control software and hardware interfacing

High Reynolds Number Test Facility Magnetic Suspension and Balancing System
Dinoso, R. A.; Volante, R.C.
- PowerPoint presentation relating to above

Status of the Magnetic Suspension and Balance System for the Princeton/ONR High Reynolds Number Test Facility (HRTF)
Britcher, C.P.; Gonzalez, O.; Gray, S.
- PowerPoint presentation giving status as of summer 2002

Design of a Cooling System for a Magnetic Suspension and Balance Control System
Boller, R.; Freeman, R.; Furbee, J.:
- PowerPoint presentation showing testing and interfacing of the cooling system

Modeling Aspects of Magnetic Actuators and Magnetic Suspension Systems
Bloodgood, V.D.:
- PhD Dissertation, includes analysis of eddy current issues on the HRTF
-

Modeling Aspects of Magnetic Actuators and Magnetic Suspension Systems
Bloodgood, V.D.:
- PowerPoint presentation relating to above

An Update on the Magnetic Suspension and Balance System for the Princeton/ONR High Reynolds Number Test Facility (HRTF)
Britcher, C.P.; Gonzalez, O.; Gray, S.
- PowerPoint presentation giving status as of summer 2001

Design of a Graphical User Interface for a Magnetic Suspension and Balance Control System
Welch, P.T.:
- Discusses the user interface to the controller software

Design of a Graphical User Interface for a Magnetic Suspension and Balance Control System
Welch, P.T.:
- PowerPoint presentation relating to above

Studies Related to the Design and Implementation of a Magnetic Suspension and Balance System

Jafri, S.A.A.:
- Masters thesis, addressing key aspects of the overall control approach

Studies Related to the Design and Implementation of a Magnetic Suspension and Balance System
Jafri, S.A.A.:
- PowerPoint presentation relating to above

Modeling of Magnetic Suspension and Balance Systems for the Purpose of Control Design
Barkley, J.E.Jr.:
- Masters thesis (never formally approved), addressing system modeling and single d-o-f validation

Status Report on the Magnetic Suspension and Balance System for the Princeton/ONR High Reynolds Number Test Facility (HRTF)
Britcher, C.P.; Gonzalez, O.; Gray, S.
- PowerPoint presentation giving status as of fall 2000

Annual Report (N00014-99-1-0298)
Britcher, C.P.:
- First ONR progress report

Studies Related to the Design of a Magnetic Suspension and Balance System for an Ultra-High Reynolds Number Flow Facility
Gomeiz, O.M.M.:
- Masters thesis addressing overall configuration and top-level design issues