Design of a Magnetic Suspension and Balance System for the Princeton/ONR High Reynolds Number Testing Facility

Dr. Colin P. Britcher[†], Dr. Oscar Gonzàlez[‡], Dr. Steven Gray[‡]
Old Dominion University
Dr. Alexander J. Smits
Department of Mechanical and Aerospace Engineering, Princeton University
Oscar Gomeiz[†], James E. Barkley[‡], Adeel Jafri[‡]
Old Dominion University, [†]Department of Aerospace Engineering,
[‡]Department of Electrical & Computer Engineering

Abstract

Princeton University is currently constructing 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 will operate at very high pressures, up to 230 atmospheres, and relatively low 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 HRTF design and operational characteristics will be briefly described, then the paper will concentrate on the design challenges faced by the MSBS. The most unusual problems are related to the fact that the electromagnets will be located outside the wind tunnel pressure shell, with position sensing and other hardware inside. The test section is constructed of stainless steel, so eddy currents generated by unsteady magnetic fields are a serious concern. It is shown by analysis and confirmed by measurements that the system is practical, provided the eddy current effects are properly modeled and accounted for in the control system design. Due to restricted access to the interior of the tunnel, the position sensing and control systems must be configured so as to reliably suspend models for long periods of time, with a variety of aero/hydrodynamic tests conducted in sequence. This leads to a relatively conservative choice of system configuration and hardware. The general design of the MSBS will be presented and plans for completion, commissioning, calibration and operation of the facility will be reviewed.

Introduction

In the late 1980's, considerable interest was generated in the possibility of constructing an ultra-high Reynolds number wind tunnel dedicated to aero/hydrodynamic testing of submersibles. At the time, the leading proposal was an ultra-low temperature facility employing either gaseous or liquid helium as the test medium. From the outset, a Magnetic Suspension and Balance System (MSBS) was considered necessary in order to provide a test environment free of support interference. A publication derived from the proceedings of a Workshop which summarizes the position in 1989 is available [1]. Although a helium-based facility appeared feasible, the practical problems of operating flow diagnostic and other instrumentation at extremely low temperatures was apparently a barrier to further progress.

In the early 1990's, a research program at Princeton University resulted in the development of an ultra-high Reynolds number pipe flow apparatus, now known as the Princeton/DARPA-ONR SuperPipe (Figure 1), which has provided turbulent pipe flow data at the highest Reynolds numbers achieved to date (38×10^6 based on diameter) [2-4]. The SuperPipe achieves ultra-high Reynolds numbers by utilizing air at normal temperatures, but extremely high pressures, up to 3500 psi (24 MPa; above 230 atmospheres). Since the proposed application is not Mach number constrained, this approach could be applied to the ultra-high Reynolds number wind tunnel.

In the mid-1990's, following two further Workshops [5,6], it was apparent that the high pressure approach seemed to provide the best near-term opportunity for construction of a pilot facility and a project was started at Princeton University, funded by the Office of Naval Research (ONR). The new facility would share certain infrastructure already in place for the SuperPipe. The task of design and construction of the MSBS was assigned to Old Dominion University. The HRTF will begin operation in late 1999 and the MSBS is scheduled to be delivered as a "turnkey" system in late 2000.

Generation of High Reynolds Numbers

The submersible application is distinct from the perhaps better-known aerospace problem in one very important respect. This is that the test Mach number is simply very low and does not need to be held to any specific value. It is easily seen that since :

$$Re = \frac{\rho VL}{\mu} \; ; \; q = \tfrac{1}{2}\rho V^2$$

- then for a gaseous test medium :

$$Re \propto \sqrt{qp}\, L$$

Thus it is seen that high Reynolds numbers can be achieved with modest dynamic pressures and physical scales by utilizing very high test pressures. An implication is that the test velocity will be quite low, since the rise in ρ is offset by allowing V^2 to decline. This results in very low test Mach numbers; also relatively modest power consumption for conventional fan-driven wind tunnel layouts.

Initial Development of the HRTF MSBS Design

The HRTF was specified as operating at a maximum pressure of 3500 psi, thereby remaining within the range already used for the SuperPipe. A representative test model would be a 12:1 length-to-diameter ratio quasi-axisymmetric, low-drag model[1]. The target length Reynolds number was 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). In turn, the drive power requirements of such a facility would be comparable to those of the SuperPipe, permitting the use of common electrical drives and cooling systems.

A major design decision was whether to mount the MSBS electromagnets inside or outside the pressure shell. The pressure shell would be fabricated from stainless steel; relatively conductive, but non-magnetic. The former alternative was 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, it was concluded that electromagnets mounted outside the pressure shell would be practical, as discussed more fully later. This configuration was therefore chosen. Model position sensor and other hardware would be located inside the pressure shell, so as to avoid a requirement for extensive viewing ports in the test section region[2]. Figure 2 shows the HRTF layout. Note that an aerodynamic liner, not shown, is to be fitted inside the test section leg.

The pressure shell dimensions in the test section region were fixed at 24 inches outside diameter (0.61 m), nominally 19 inches inside diameter (0.48 m). The shell material was 304L stainless steel. Due to the unavailability of cast or drawn stainless steel pipe of these dimensions, the section was fabricated by rolling a plate, with a welded seam. For metallurgical reasons, the weld material was stainless steel with 10% ferrous addition. This results in the weld being weakly magnetic. Massive carbon steel flanges were attached to each end by welding. Figure 3 shows the dimensions of the test section, and the fabricated part is illustrated in Figure 4.

Dynamic Analysis

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 attentuation and guidance for development of a dynamic model.

A simple finite element model of the test section pressure shell is shown in Figure 5, with a representative air-cored electromagnet located externally. ELEKTRA™ can solve the magnetodynamic problem either as a series of single frequency, quasi-steady problems, or as the time response to a prescribed electromagnet current transient. In both cases, only the electromagnet current is assumed, all other fields and currents are computed. Figure 6

---

[1] An ellipsoid is currently used as the basline geometry

[2] Optical position sensing is assumed, as discussed later

shows the computed magnitude and phase of the magnetic field on the axes of both the electromagnet and the test section (the nominal centroid of the suspended model). Also shown is the field development in response to a step change in electromagnet current. It should be noted that the reliability of these solutions decreases as the frequency increases, or at shorter times following the step, due to concentration of the eddy current near the surface of the conducting material - the "skin effect". These degradations can be alleviated to some extent by adjustments to the finite element mesh.

It is seen that a simple first-order lag provides 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 [7, etc.] has shown that the form of the eddy current effect is perhaps more accurately described by a "half-order" pole[3]. As system development proceeds, more attention will be paid to development of high-fidelity dynamic models.

MSBS Design Synthesis

The initial design of the MSBS, particularly electromagnet sizing and placement, is driven by steady-state operating conditions. By incorporating substantial performance margins, in the electromagnet sizing, dynamic capability is introduced. The key issue affecting system dynamics is the provision of adequate power supply capacity. The system design procedure will be briefly reviewed here.

Test Section Cross-Section

Within the circular pressure shell, some allowance must be made for location of model position sensor and other hardware. Figure 7 illustrates one possible choice, giving a flow area of around 220 square inches (0.142 m^2).

Model Size

With the flow area set, the model size can now be established based on a compromise between Reynolds number requirements (larger models) and test section blockage (smaller models). From other dimensions stated, we have :

Table 1 - Baseline Model Specifications

Length	35.4 in (0.9 m)	Volume	162 cu.in ($2.65 \times 10^{-3} m^3$)
Diameter	2.95 in (0.075 m)	Weight	45.6 lbs (202.8N)
Blockage	$\approx$ 3%	C_D	0.1 to 0.3

---

[3] For instance, see also the paper by Fukata et al in this symposium

The estimated dynamic pressure in the HRTF is only 5.8 psi (40 kPa; < 0.4 atmospheres), so typical model aerodynamic drag loads are only of the order of 3.8 to 11.7 lbs (17 to 52 N). It is seen that the model deadweight is the dominant force in this application.

Magnetic Fields and Forces

A permanent magnet model core was chosen with a view to minimizing steady-state power consumption (i.e. no magnetizing coils needed). Taking the classical axial model magnetization and using the axis system shown in Figure 8, we have :

$$\vec{F} = \int_V \vec{M}.\nabla\vec{B}\,dV \approx V\,\vec{M}.\nabla\vec{B}_o \quad ; \quad \vec{T} = \int_V \vec{M} \times \vec{B}\,dV \approx V\,\vec{M} \times \vec{B}_o$$

$$\vec{M} = (0, 0, M_z) \quad \text{(see Figure 8)}$$

$$\begin{aligned} F_x\,\text{(sideforce)} &= V\,M_z B_{xz_o} \\ F_y\,\text{(vertical force)} &= V\,M_z B_{yz_o} \\ F_z\,\text{(axial force)} &= V\,M_z B_{zz_o} \end{aligned}$$

$$\begin{aligned} T_x\,\text{(pitching moment)} &= -\,V\,M_z B_{y_o} \\ T_y\,\text{(yawing moment)} &= V\,M_z B_{x_o} \\ T_z\,\text{(rolling moment)} &= 0 \end{aligned}$$

- where V is the magnetic core volume, M its magnetization and B the external magnetic flux. A subscript of o indicates evaluation at the model centroid. Rolling moment capability will be required, but will be addressed later, as is traditional practice. The target maximum force capability and corresponding nominal field and field gradient values are shown below, based on a "1 Tesla" magnetic core (i.e. $M_z = 796{,}000$ A/m). The drag and sideforce 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.

Table 2 - Design Forces and Corresponding Field Gradients

F_x	$106\,N$	B_{xz_o}	$0.1\,T/m$
F_y	$106\,N$	B_{xz_o}	$0.3\,T/m$
F_z	$308.8\,N$	B_{xz_o}	$0.1\,T/m$

A baseline set of air-cored electromagnets has been developed, by trial-and-error, using the OPERA/TOSCA™ magnetostatic package. The general configuration follows the classical "+" arrangment and is shown in Figure 9. Considerable further refinements are to be expected prior to the design "freeze", such as the introduction of iron cores to the vertical and lateral electromagnets.

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[4]. 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.

Sensor System

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 [9,10]. If other types of magnetizations are included, or if the magnet is made non-axisymmetric, then roll control is also possible. Several techniques are still being considered for the measurement of the roll angle; the technique to be used will depend on the test model. For example, X-shaped stern control surfaces of a submarine model can be used with shadow position sensors. The currently selected

---

[4] To simulate dynamic maneuvers

sensors are SUNX™ Model No. LA-511. Each sensor consists of an 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 are attached to rings that are fitted inside the tunnel. Each ring can hold one or two sensors. Figure 10 shows the front view of a ring with two sensors and a cylindrical three inch diameter model. This figure does not show the aerodynamic liner. This liner will have portholes to allow the light beams to pass. Since the laser beam width is 15 mm, with this configuration it is possible to measure ± 7.5 mm displacements in each direction. The sensors will be placed to give about a ± 5° angle variation for pitch and yaw.

Controller Hardware

The hardware selected for the data acquisition and control is a dSpace™ 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 testing and analyzing 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 will also be used to develop a custom GUI interface for the production turnkey system.

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.

Discussion - Project Status

A significant analysis effort is underway to fully model the effect of the weakly magnetic test section weld. Following completion of this effort, the design presented will be refined, such as by inclusion of iron electromagnet cores, principally to minimize the steady-state power consumption and capital cost. The final specifications will then be frozen and hardware procurement started. It is currently planmed to complete asembly of all major componets in Summer 2000, with delivery to Princeton around the end of 2000. *(Authors note - shortly after the Symposium, the electromagnet confiuration was changed to an "X" layout, as shown in Figure 11. This distributes the model deadweight more evenly across the electromagnet array)*

Acknowledgements

This work is supported by the Office of Naval Research, under Grant No. N00014-99-1-0298, by Princeton University under Grant No. 150-67555-1 and by NASA Langley Research Center under Cooperative Agreement No. SAA #450.

References

1. Donnelly, R. (ed.): High Reynolds number flows using liquid and gaseous helium - Proceedings of the 7th Oregon conference on low-temperature physics. Springer-Verlag, 1991.
2. Zagarola, M.V.; Smits, A.J.: Scaling of the mean velocity profile for turbulent pipe flow. Physical Review Letters, Vol.78, No.1, 1997.
3. Smits, A.J.; Zagarola, M.V.: The issue of roughness in he Princeton Superpipe experiment. Physics of Fluids, Vol. 9, 1977.
4. www.princeton.edu/~gasdyn/Facilities/Facilities.html#SuperPipe.
5. Donnelly, R. (ed.): Flow at ultra-high Reynolds and Rayleigh numbers - a status report - Proceedings of the international workshop on ultra-high Reynolds number flows, Brookhaven National Laboratory, June 1996. Springer-Verlag, 1998
6. ONR Workshop on needs for high Reynolds number facilities to design the next generation of sea and air vehicles. Arlington, VA, October 1997.
7. Britcher, C.P.: Eddy current influences on the dynamic behaviour of magnetic suspension systems. 4th International Symposium on Magnetic Suspension Technology, Gifu City, Japan, October 1997. NASA CP-1998-207654.
8. Covert, E.E.; Finston, M.; Vlajinac, M.; Stevens, T.: Magnetic suspension and balance systems for use with wind tunnels. Progress in Aerospace Sciences, Vol. 14, 1973.
9. Groom, Nelson J. and Britcher, Colin, P., Open-Loop Characteristics of Magnetic Suspension Systems Using Electromagnets Mounted in a Planar Array, NASA TP-3229, 1992.
10. Groom, Nelson J. , Expanded Equations for Torque and Force on a Cylindrical Permanent Magnet Core in a Large-Gap Magnetic Suspension System, NASA TP-3638, 1997.

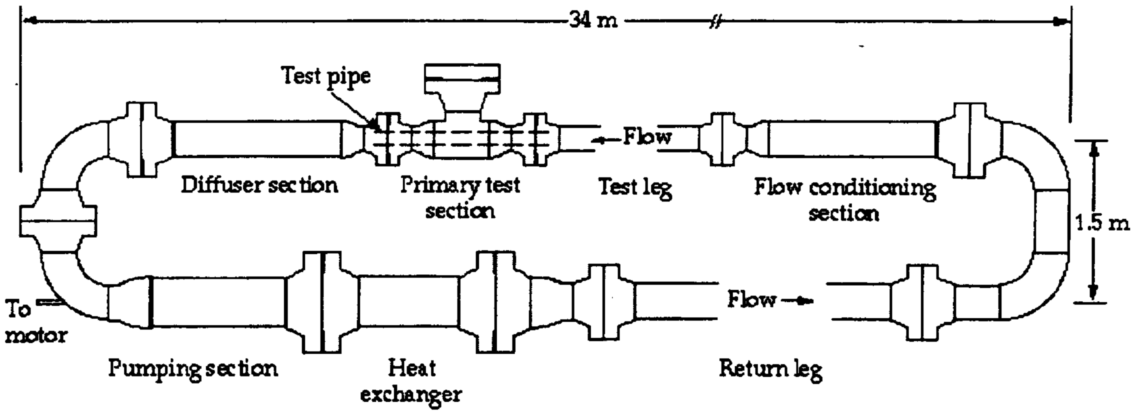


Figure 1 - The Princeton/DARPA-ONR SuperPipe

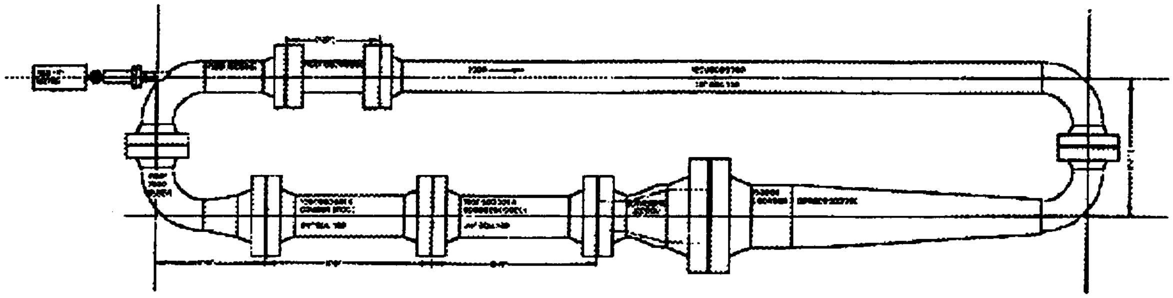


Figure 2 - The Princeton/ONR High Reynolds Number Test Facility (HRTF) Circuit

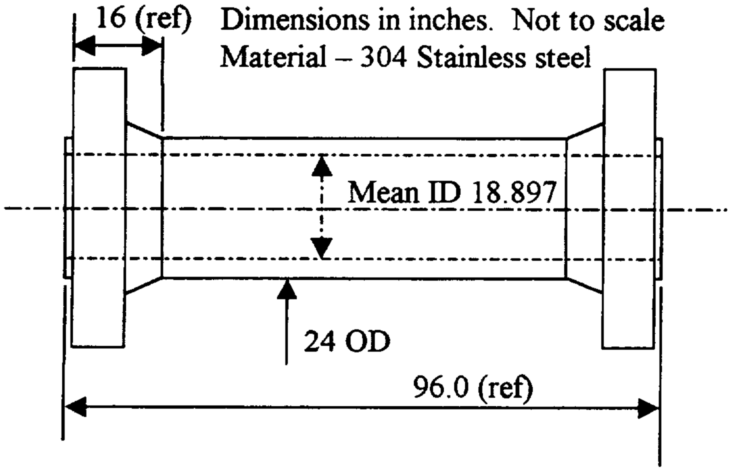


Figure 3 - The HRTF Test Section Schematic

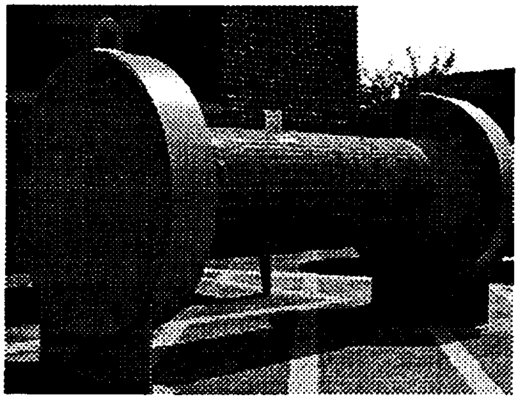


Figure 4 - The HRTF Test Section

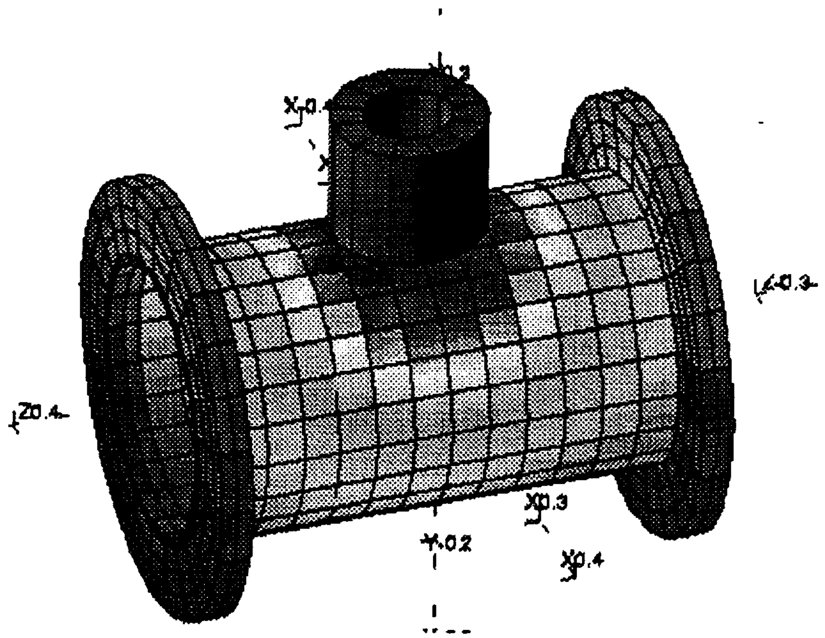
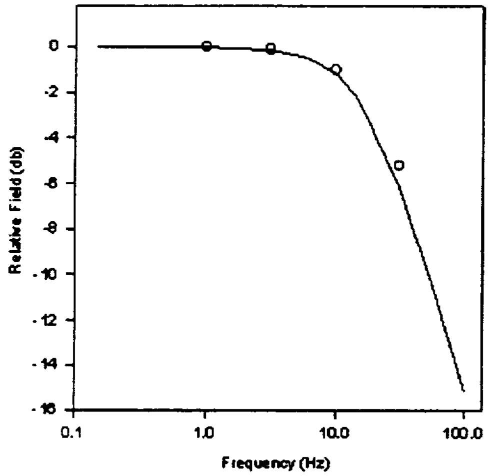


Figure 5 - Finite Element Model Representative of the HRTF Test Section
(Shaded contours represent eddy currents)



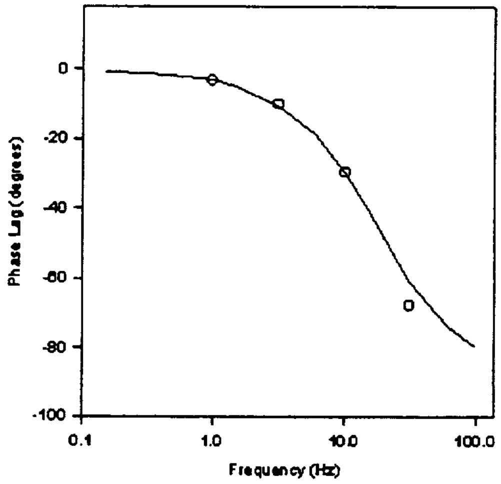
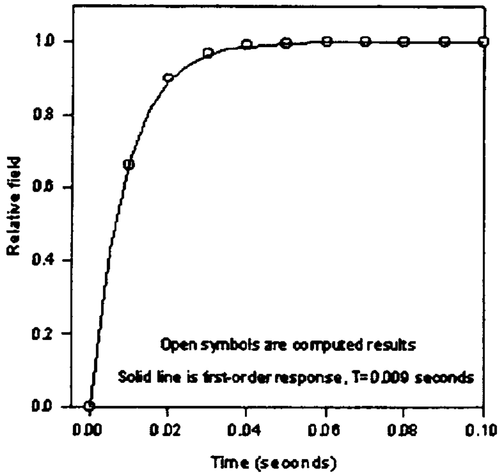


Figure 6 - Field Behavior on Electromagnet and Test Section Axes

(Magnitude - above, Phase - top right, Step response, right)



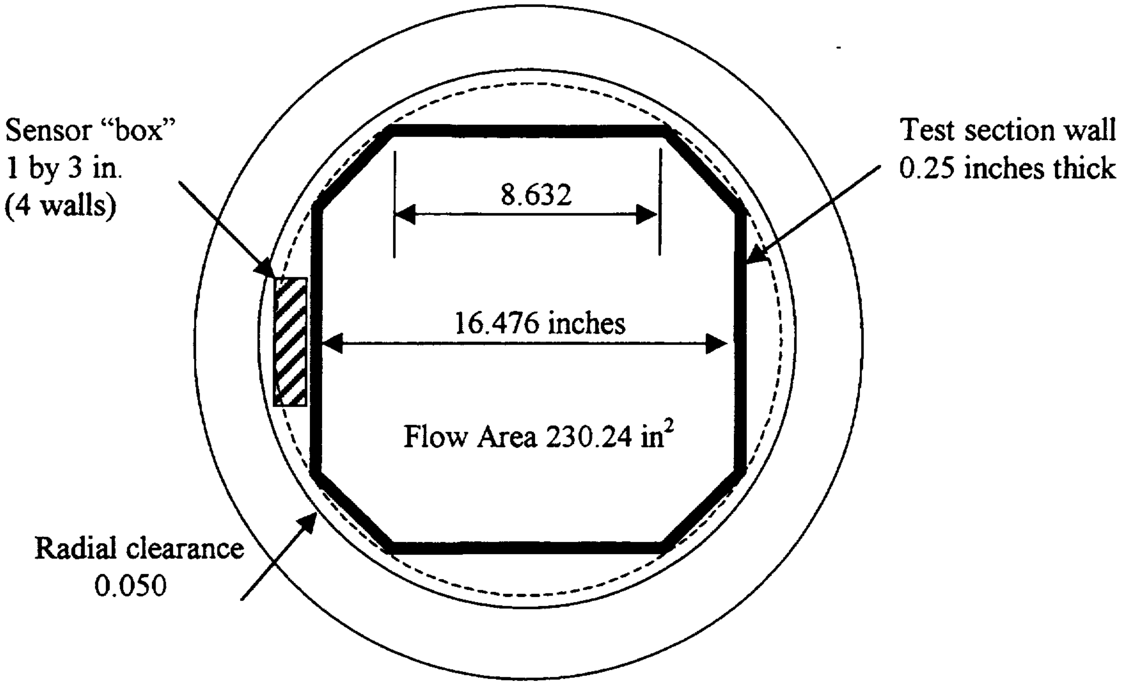
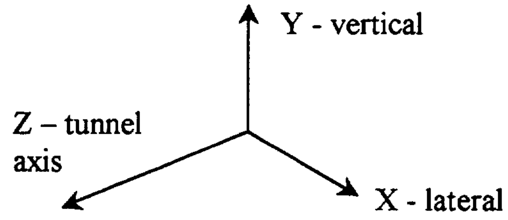


Figure 7 - Candidate Test Section Cross-Section

Figure 8 - Axis System



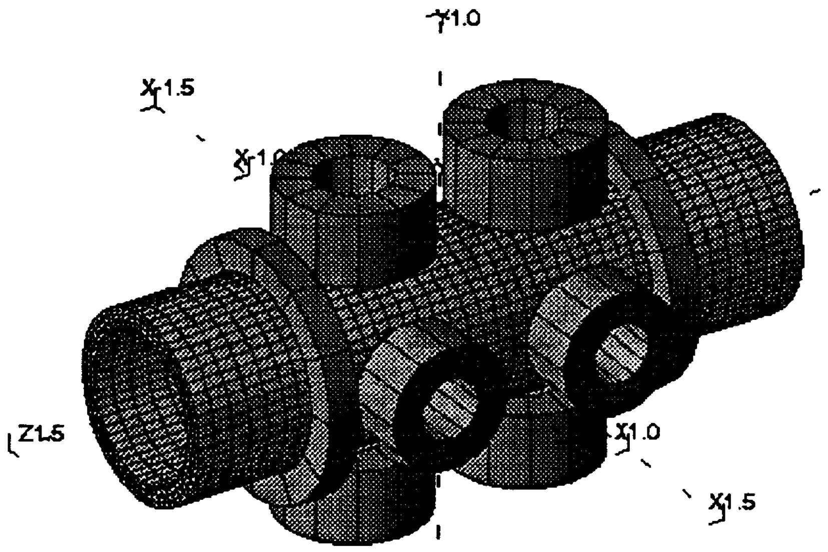


Figure 9 - Baseline Electromagnet Configuration ("+" layout)

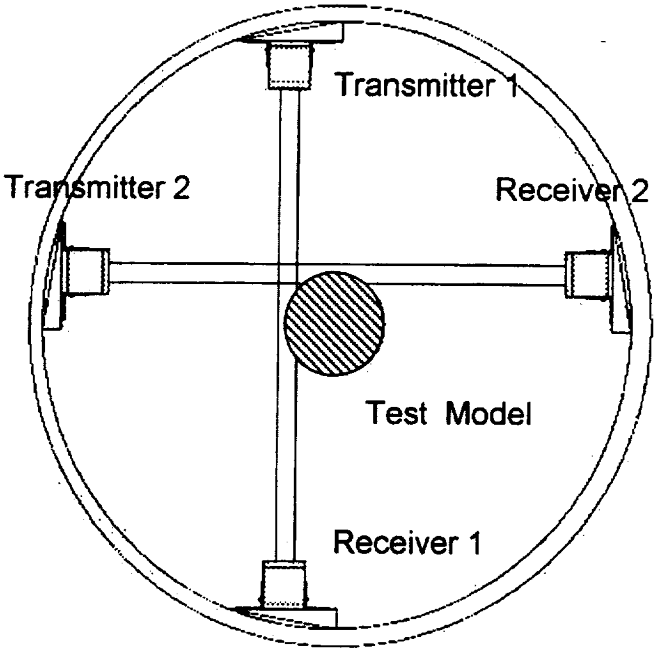


Figure 10 - Front View of the Sensor System - showing two sensors and a 3 in. dia. model.

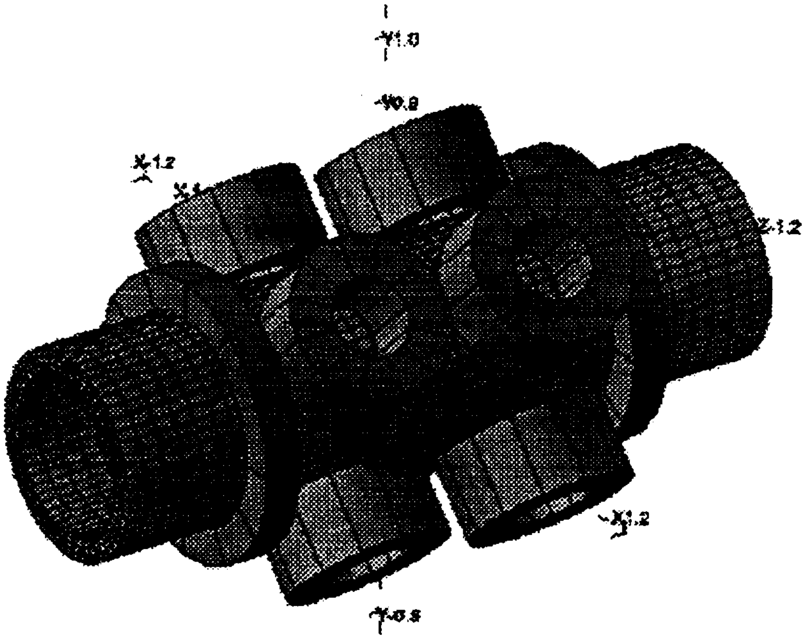


Figure 11 - Recently Modified Electromagnet Configuration ("X" layout)