Electromagnetic Modeling of a Wind Tunnel Magnetic Suspension and Balance System

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ELECTROMAGNETIC MODELING OF A WIND TUNNEL MAGNETIC SUSPENSION
AND BALANCE SYSTEM

by

Desiree Driver
B.S. May 2014, University of Virginia

A Thesis Submitted to the Faculty of
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ABSTRACT

ELECTROMAGNETIC MODELING OF A WIND TUNNEL MAGNETIC SUSPENSION AND BALANCE SYSTEM

Desiree Driver
Old Dominion University, 2022
Director: Dr. Colin Britcher

Wind tunnels are used to study forces and moments acting on an aerodynamic body. While most results involve some interference from the mechanical supports used to hold the model, a Magnetic Suspension and Balance System (MSBS) is void of these interferences and presents an ideal test scenario. To further investigate the feasibility of dynamic stability testing at supersonic speeds using a MSBS, a preliminary design idea is currently being developed using an existing MSBS in a subsonic wind tunnel. This review focuses on the development of a mathematical model to more accurately portray the capabilities of the 6 inch Massachusetts Institute of Technology/NASA MSBS used in the preliminary study. This finite element analysis is performed in COMSOL Multiphysics software and involves a representation of the coils and iron yoke assemblies that form the electromagnet array of the MSBS. Experimental validation of the model is also discussed, with field surveys used to validate COMSOL results.
ACKNOWLEDGEMENTS

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**NOMENCLATURE**

\[ \vec{A} \]  =  magnetic vector potential (Vs/m)

\[ \vec{B} \]  =  magnetic flux density (T)

\[ B_i \]  =  magnetic flux density in the i direction (T)

\[ B_{ij} \]  =  magnetic flux density gradient – i component in the j direction (T/m)

\[ \vec{D} \]  =  electric flux density (C/m²)

\[ \vec{E} \]  =  electric field intensity (V/m)

\[ \varepsilon \]  =  electric permittivity (F/m)

\[ \vec{F} \]  =  magnetic force on suspended core (N)

\[ \vec{H} \]  =  magnetic field intensity (A/m)

\[ I_i \]  =  current of the i field (A)

\[ I_{ij} \]  =  current of the ij field (A)

\[ \vec{J} \]  =  externally applied current density (A/m²)

\[ \vec{M} \]  =  magnetic field strength (A/m)

\[ N_{i,ij} \]  =  number of turns/coil of the i,ij field

\[ \rho \]  =  volume charge density (C/m³)

\[ \sigma \]  =  electric conductivity (Ωm)⁻¹

\[ Vol \]  =  volume of magnetic core (m³)

\[ \mu_0 \]  =  magnetic permeability of a vacuum (4𝜋 x 10⁻⁷ H/m)
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CHAPTER 1

1. INTRODUCTION

1.1 MAGNETIC SUSPENSION AND BALANCE SYSTEM DEVELOPMENT

Since the middle of the 20th century, magnetic suspension systems have been an attractive option in several engineering and science applications. The wind tunnel Magnetic Suspension and Balance System (MSBS) approach, in which an object is suspended while simultaneously recording the forces, moments, and torques acting on the aerodynamic body, quickly became desirable in aeronautical applications. Specifically, these systems have shown to be valuable in their reduction of the interference of mechanical model supports. Some other potential benefits of a MSBS in wind tunnel testing include dynamic testing with forces and torques continuously available and high productivity since various model positions and orientations can be selected rapidly [1].

At the Massachusetts Institute of Technology (MIT) the development of systems for such applications began in the early 1960s [2]. The MIT design approach was based on a five degree of freedom system introduced by Tournier and Laurenceau at ONERA in 1957 which controlled translational, pitch, and yaw movements [3]. An added set of coils gave the MIT system a sixth degree-of-freedom (roll). NASA’s Langley Research Center (LaRC) has partnered in related research efforts since the early 1960s, with applications in small (1970s) and large (1980s) gap magnetic suspension systems. The former include the Annular Momentum Control Device (AMCD), used for the stabilization of spacecraft, and a derivative, the Annular Suspension and Pointing System (ASPS) [4]. The ASPS was designed to provide orientation, mechanical isolation, and higher accuracy with multipurpose pointing of space experiments. Large gap
applications at LaRC began with a single degree of freedom magnetic suspension system [5] and have focused on technology development and use in wind tunnels.

Some notable research in MSBSs has taken place at Oxford University, the Korea Advanced Institute of Science and Technology (KAIST) and the University of Southampton in the U.K [6,7,8]. Particular mention should also be given to Tohoku University in Japan. Oxford University has placed consistent efforts in MSBS development to aid in low density, hypersonic flow research from the 1960s to the early 2000s with a two and a three degree of freedom system. Recent plans have been put in place to recommission the three degree of freedom MSBS to improve capability [6]. MSBS development was successfully implemented at KAIST in collecting aerodynamic forces and moments during wind tunnel tests without support interference [7]. In 2015, the Institute of Fluid Science (IFS) at Tohoku University in Japan presented the largest operational test section having a width of 1.01 meters (see Figure 1) [9]. Five degree-of-freedom control is available from the test model containing a main magnetic core. Control of the roll is added with the introduction of small magnets, giving the MSBS six degree-of-freedom control [10]. Tohoku University implemented a study using the forced oscillation approach to dynamic stability testing in a MSBS at low speeds [11].
1.2 6-INCH MSBS OVERVIEW

A sophisticated 6-inch MSBS system was developed at MIT in the late 1960s, and later moved to the NASA LaRC in 1980 [4]. Although designed for supersonic and subsonic operation, the system was mainly used at low speeds [2]. The six translational and rotational degree-of-freedom magnetic suspension system contains subsystems including a magnet coil assembly, a position sensor system, a compensation system, and a power amplifier system. A closed loop control system, shown in Figure 2 is used to communicate signals from a position sensing device to compensated error signals that are amplified and applied to the magnet coils [2]. This loop serves to minimize position error continuously. The Electromagnetic Position Sensing (EPS) system was based on a transducer coil design that operated as a multi-component Linear Variable Differential Transformer (LVDT) [2].
The electromagnet design consists of three symmetric sets of coil assemblies (Figure 3). As designed, a Helmholtz coil system generates the main magnetizing field and the axial gradient referred to as the drag field. A saddle coil system consisting of two coil pairs generates the transverse field components. Two iron yokes each hold four excitation coils, called side and lift coils, which generate the axial gradients of the lateral and vertical field. A more detailed description of the magnet assembly and overall MSBS system will be presented in Chapter 3. The functionality of some coil sets has changed, but no changes to geometry, resulting in a similar coil configuration [18].
1.3 PROJECT GOALS

Re-entry capsules have the capability to return through the atmospheres of Earth or other planets after flight and rely on a heat shield and natural aerodynamic stability for successful entry/re-entry. Some examples include the Mars Science Laboratory Spacecraft and previous crewed capsules such as Apollo and Gemini (see Figure 4 and Figure 5). Especially for manned capsules, it is clear that aerodynamic analysis and dynamic stability analysis is imperative for success. Due to the low length-to-diameter ratio of contemporary planetary entry capsules, dynamic stability at low supersonic Mach numbers is critical just before parachute deployment [12]. To optimize dynamic stability testing environments for improved accuracy in these scenarios, the use of a MSBS in a supersonic wind tunnel is a desirable approach.
The currently available MIT 6-inch MSBS electromagnet array, the EPS, and low speed wind tunnel (supported by NASA LaRC) have been revived as a preliminary proof-of-concept for use at subsonic speeds. A finite element model of the electromagnet array is pertinent to this proof-of-concept phase in order to understand the 6-inch MSBS capabilities before the next phase, which is projected to be an all-new system for an existing supersonic wind tunnel located at NASA Glenn Research Center for dynamic stability testing with a free-oscillation approach. The goal of this finite element model is to develop a mathematical model that accurately portrays the capabilities of the 6-inch MSBS. Due to the need for finite element calculation, COMSOL™ Multiphysics Software was chosen as the optimal software to describe the full electromagnet system. This finite element analysis will involve a representation of the 14 coils and iron yokes that form the complete electromagnet system. Experimental validation of the model at varying currents and positions will be performed to ensure accurate estimates for the performance capabilities of the 6-inch MSBS.

Figure 4: Mars Science Laboratory Spacecraft [12]
Figure 5: Gemini VII Capsule (left) [13] and Apollo 11 Capsule (right) [14]
CHAPTER 2

2. ELECTROMAGNETICS – BRIEF OVERVIEW

2.1 INTRODUCTION

As mentioned previously, the ability to track the forces, moments, and torques acting on an aerodynamic body in wind tunnel testing without interference from physical supports is desirable for adequate design of re-entry capsules. Accurately estimating performance of the 6-inch MSBS and subsonic wind tunnel will aid in the design effort of a new MSBS for a supersonic wind tunnel. Magnetic suspension is achieved by the interaction of an electromagnetic array and a magnetic field developed by a magnetic core in a levitated model. The purpose of this chapter is to give a brief overview of the principal relevant concepts of electromagnetism.

2.2 MAXWELL’S EQUATIONS

An assembly of stationary electric charges produce a vector field, the electric field, that is quantified by the electric field intensity, $\vec{E}$. Charges moving at a given velocity result in electric current and generate a different vector field. This is the magnetic field which can be quantified by the magnetic field intensity, $\vec{H}$. An electric field produced by static charges can be described by electrostatic theory. Magnetic fields produced by steady currents can be described by magnetostatic theory. This combination also represents a steady-state or low frequency subset of electromagnetics. Maxwell’s equations and the constitutive relations can be used to explain the fundamental principles of electromagnetics.

James Clerk Maxwell formulated the theory of electromagnetism as four main equations. Maxwell expounded on the theories of Ampere, Gauss, and Faraday with the introduction of “displacement currents” which makes Ampere’s law valid in all situations [15]. These equations
are commonly written in two forms, the local and the integral form. The local form is valid at every point and is relevant because vector fields are involved instead of point vectors. This is best used when there is a high degree of symmetry. The integral form is most applicable when the equation must be applied over a specific domain and takes volumes and surfaces into account [15]. The local form of these equations is

Ampere’s Law
\[ \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \] (1)

Gauss’ Law (for magnetism)
\[ \nabla \cdot \vec{B} = 0 \] (2)

Faraday’s Law
\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \] (3)

Gauss’ Law (for electricity)
\[ \nabla \cdot \vec{D} = \rho \] (4)

The constitutive equations are
\[ \vec{B} = \mu(\vec{H} + \vec{M}) \] (5)
\[ \vec{D} = \varepsilon\vec{E} \] (6)

Ohm’s Law
\[ \vec{J} = \sigma\vec{E} \] (7)

The two solution domains included in these equations are the high frequency domain, involving electromagnetic waves, and the low frequency domain, involving most electromagnetic devices. Since the low frequency domain applies to scenarios in which displacement currents can be neglected to emulate a quasi-static state, \( \partial \vec{D}/\partial t \) can be considered to be zero. This corresponds to solutions where the wavelength of any electromagnetic wave is very large compared to the physical problem scale. To simplify the explanation of these equations, Equation 1 states that the time derivative of the electric flux density can generate the magnetic field intensity. Equation 2 can be understood to mean that the magnetic flux that enters
and leaves a volume is equal (i.e. net magnitude of zero). Equation 3 denotes that the time derivative of the magnetic flux density can generate an electric field. Equation 4 can be understood to mean that the electric flux that enters and leaves a volume is not equal, when electric charge is present [16].

2.3 BIOT-SAVART’S LAW

Biot-Savart’s Law provides a way to calculate the magnetic field generated by a current. To avoid complex derivation, the Biot-Savart law is listed in Equation 8 and will be displayed in a simple application.

\[
\frac{d\vec{B}}{4\pi} = \frac{\mu_0 I \, d\vec{l} \times \hat{r}}{r^2}
\]

In Figure 6, \(d\vec{l}\) is a small length segment of current and \(\hat{r}\) is the distance from the current to the point where the magnetic field is to be measured. Here, \(d\vec{l}\) and \(\hat{r}\) are always perpendicular. The magnetic field measured at a point, \(P\), along the \(x\) axis, caused by a single current loop is demonstrated below.
The cross product of $d\vec{l} \times \hat{r}$ is the magnitude of $d\vec{l}$ times the magnitude of $\hat{r}$ times sin of the angle between them. The magnitude of the unit vector $\hat{r}$ is 1 and since the two are always perpendicular, that also equals 1.

$$d B_x = d\vec{B} \cos \theta = \frac{d\vec{B} \cdot R}{r}$$

$$d B_x = \frac{\mu_0 I}{4\pi} \frac{d\vec{l} \times \hat{r} R}{r^3} = \frac{\mu_0 I}{4\pi} \frac{dl R}{(R^2 + x^2)^{3/2}} = \frac{\mu_0 I}{4\pi} \frac{R (R \, d\theta)}{(R^2 + x^2)^{3/2}}$$

$$B_x = \int_0^{2\pi} dB_x = \frac{\mu_0 I}{4\pi} \frac{R^2}{(R^2 + x^2)^{3/2}} \int_0^{2\pi} d\theta = \frac{\mu_0 I}{4\pi} \frac{R^2}{(R^2 + x^2)^{3/2}} \cdot 2\pi$$

$$B_x = \frac{\mu_0 I R^2}{2(R^2 + x^2)^{3/2}}$$
Similar methodology was originally used to derive the formulae for performance estimation of the magnetic field for the MIT 6-inch MSBS [2].

2.4 FORCES AND TORQUES

The force on a moving charge produced by a magnetic field is given by the Lorentz Force equation.

\[ \vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \]  \hspace{1cm} (10)

The force and torque on a moving body as a function of the magnetic field can be calculated using Equations 11 and 12 where V is the volume of the body and M is the magnetization.

Magnetization is the magnetic moment per unit volume. Magnetization relates to the magnetic field as in Equation 5 [17].

\[ \vec{t} = \int (\vec{M} \times \vec{B})dV \]  \hspace{1cm} (11)

\[ \vec{F} = \int (\vec{M} \cdot \nabla \vec{B})dV \]  \hspace{1cm} (12)

In complex scenarios, the Lorentz Force calculation becomes cumbersome. A more versatile set of equations to determine magnetic forces in complex scenarios is the Maxwell Stress Tensor, T

\[ \vec{F} = \int (\nabla \cdot [T])dV \]  \hspace{1cm} (13)

(\begin{array}{l}
\text{force per unit area on a surface} \\
\end{array})

\[ \frac{F_i}{V} = \frac{\partial T_{ij}}{\partial x_j} \text{ where } T_{ij} = \left( \frac{B_i B_j}{\mu_0} - \frac{\delta_{ij} B_k B_k}{2\mu_0} \right) \]  \hspace{1cm} (14)

(\begin{array}{l}
\text{force per unit volume} \\
\end{array})

\[ F = \frac{1}{\mu_0} \int \begin{vmatrix}
B_x^2 - B_y^2 - B_z^2 \\
B_y B_x & B_y^2 - B_x^2 - B_z^2 \\
B_z B_x & B_z B_y & B_z^2 - B_x^2 - B_y^2
\end{vmatrix} \begin{bmatrix}
S_x \\
S_y \\
S_z
\end{bmatrix} \]  \hspace{1cm} (15)
Equation 15 is used to calculate the total force on the surface of an object or virtual surface, $S$ [15].
CHAPTER 3

3. THE 6-INCH MSBS

3.1 ELECTROMAGNET DESIGN

The electromagnet design consists of three symmetric sets of coil assemblies. Specific magnetic fields are produced by a variation of the coil currents in the subassemblies. All coil windings consist of hollow wet-wound “room temperature” copper windings of multiple turns [2]. The coil layers are hollow conductors with a square outer diameter and a circular inner diameter. The subassembly groups and their respective field influences are:

i. Helmholtz Coil System \( (B_x, B_{xx}) \)

ii. Saddle Coil System \( (B_y, B_z) \)

iii. Side and Lift Coil System \( (B_{yx}, B_{zx}) \)

Figure 7: Overall Magnet Structure [2]
3.1.1 HELMHOLTZ COIL SYSTEM

The main axial magnetizing (“bias”) field, $B_x$, and its axial gradient (“drag” field), $B_{xx}$, are controlled by a pair of identical solenoid coils whose main axial field varies symmetrically. The circular coils are each wound in three sections. The middle windings are isolated from the other coils by insulating material. These two coils, positioned on the same axis, connected in series, contain cross-sections separated axially by a distance approximately equal to the radius of one coil. Thus, the middle windings represent a Helmholtz pair providing a uniform field proportional to the magnetizing current, $I_x$.

The inner and outer winding sections of each coil are also connected to their respective counterpart in the other coil, in series. This forms a current path shown in Figure 8 that travels in the opposite direction in each coil, whereas the current travels in the same direction in the magnetizing coil pair. The inner and outer windings are positioned such that $B_x$ is 0 at the center of symmetry, thereby producing a uniform field gradient, $B_{xx}$, along the x-axis proportional to the drag current, $I_{xx}$ (See Figure 8).
3.1.2 SADDLE COIL SYSTEM

The transverse fields, $B_y$ and $B_z$, are produced by two pairs of Saddle coils arranged about the $x$ axis with fields produced at 45 degrees to the $y$ and $z$ axis. In this scenario the transverse field is produced by the vector addition of the field components. These pairs consist of two identical coils nested inside another set of identical coils (See Figure 9). These, referred to as the inner and outer saddle coils, are all positioned between the Helmholtz coil pair (See Figure 7).
3.1.3 SIDE AND LIFT COIL SYSTEM

Two pairs of iron-cored coil assemblies produce axial gradients of the transverse fields, $B_{yx}$ and $B_{zx}$. Each assembly contains a laminated silicon steel ring with four inward pointing and tapered poles and four mounted coils. The four coils in the vertical plane of the two mirror facing assemblies produce an axial gradient of the lateral field, referred to as the “slip” field, $B_{yx}$. The four coils in the horizontal plane produce an axial gradient of the vertical field, referred to as the “lift” field, $B_{zx}$ (See Figure 10). The magnetic field profile of $B_z$ produced by $B_{yx}$ and $B_{zx}$ are shown in Figure 11.
Figure 10: Side and Lift Force System Coil Arrangement [2]

Figure 11: Side and Lift Force Coil Field Profile [2]
3.2 RECENT MODIFICATIONS

As the development of the system has proceeded, the configuration has been changed by reassigning the functions of various electromagnets. Previously, an axisymmetric object with axial magnetization was able to freely rotate about the roll axis. Recent updates allow the model to be magnetized transversely and rotate about its pitch (or yaw) axis. Finite Element Analysis (FEA) analysis was performed with coils in the configuration of their original functionality and in the configuration of their re-allocated functionality. This MSBS has also received an updated EPS, new power supply, and an all-digital control system. Further details are given in references 18 and 19. These modifications place additional importance on the field characterization study reported herein.
CHAPTER 4

4. THEORETICAL ANALYSIS AND FEA

4.1 THEORETICAL ANALYSIS

This chapter will focus on the FEA approach to estimate magnetic field performance of the system. For context, the calculations from the original Stephens report on the MIT 6-inch MSBS [2] will be reiterated. The previous estimates for the magnetic field generated due to each coil set are shown below. Here, the geometry is simplified, and the iron cores are not considered. This will cause variations between theoretical calculations and the computational model. However, these calculations can be taken as a point of reference and comparison, although the COMSOL model results are considered to be the most accurate and useful due to the complexities of the magnet-coil system. Additional derivations and assumptions can be found in the Stephens report [2].

*Field Due to Helmholtz Coils*

$B_x$, the main axial field, is generated by the middle set of coils in the Helmholtz pair. These are the magnetizing coils.
Figure 12: Partial Section of Helmholtz Coils [2]

\[ B_x(0,0,0) = \kappa \mu_0 \frac{N_x I_x}{(x_2 - x_1)(r_3 - r_2)} \left( x_2 \ln \frac{r_3 + \sqrt{r_3^2 + x_2^2}}{r_3 + \sqrt{r_2^2 + x_2^2}} - x_1 \ln \frac{r_3 + \sqrt{r_3^2 + x_1^2}}{r_2 + \sqrt{r_2^2 + x_1^2}} \right) \] (16)

where \( N_x = 400 \) turns \( r^2 = 10 \) inches \( x_1 = 3.25 \) inches \( \kappa = 39.37 \) in/m (conversion to meters) \( r_3 = 14 \) inches \( x_2 = 7.25 \) inches

The calculated relation of current and magnetic performance of the main axial “bias” field without the iron core contribution is \( B_x/I_x = 12.65 \) Gauss/Amp.

\( B_{xx} \), the axial gradient of the bias field, is generated by the inner and outer pair of coils.

These are the drag coils.

\[ B_{xx}(0,0,0) = -\mu_0 x_0 \left[ \left( \frac{N_{xx} I_{xx}}{r_4 - r_3} \right) \left( \frac{r_4^3}{x_0^2 + \sqrt{(x_0^2 + r_4^2)^3}} - \frac{r_3^3}{x_0^2 + \sqrt{(x_0^2 + r_3^2)^3}} \right) \right] + \left( \frac{N_{xx} I_{xx}}{r_2 - r_1} \right) \]

* \( \left( \frac{r_2^3}{x_0^2 + \sqrt{(x_0^2 + r_2^2)^3}} - \frac{r_1^3}{x_0^2 + \sqrt{(x_0^2 + r_1^2)^3}} \right) \]

where \( N_x = 200 \) turns \( r_3 = 14 \) inches \( x_1 = 3.25 \) inches \( r_1 = 8 \) inches \( r_2 = 10 \) inches \( r_3 = 16 \) inches \( x_2 = 7.25 \) inches
The calculated relation of current and magnetic performance of the main axial gradient “drag” field without the iron core contribution is $B_{xx}/I_{xx} = -1.38$ Gauss/Amp

*Field Due to Saddle Coils*

The saddle coil geometry is complex, therefore was estimated by the “mean-turn” of the coils corresponding to the centroid of the coil cross-section [2]. The inner saddle coils form the transverse field, $B_y$, while the outer saddle coils form the transverse field, $B_z$.

![Mean-Turn Geometry of Saddle Coils](image)

**Figure 13: Mean-Turn Geometry of Saddle Coils [2]**

$$B_y(0,0,0) = \frac{\mu_0}{4\pi} N_y I_y \left( \frac{4\bar{r}}{\bar{r}} \right) \left( \frac{1}{1 + (\bar{r}/L/2)^2} \right) \left( \frac{1}{1 + (L/2/\bar{r})^2} \right) \cos \phi$$

where $N_x = 88$ turns $\bar{r} = 5.2$ inches $L/2 = 5.5$ inches $\phi = 15$ degrees
The calculated relation of current and magnetic performance of the $B_y$ transverse field without the iron core contribution is $B_y/I_y = 5.5$ Gauss/Amp.

$$B_y(0,0,0) = \frac{\mu_0}{4\pi} N_x I_x \left( \frac{4}{\bar{r}} \right) \left( \frac{1}{1 + \left( \frac{\bar{r}}{L/2} \right)^2} \right)^{1/2} \left( \frac{1}{1 + \left( \frac{L/2}{\bar{r}} \right)^2} \right) \cos \phi$$

where $N_x = 133$ turns $\bar{r} = 7$ inches $L/2 = 5$ inches $\phi = 15$ degrees

The calculated relation of current and magnetic performance of the $B_z$ transverse field without the iron core contribution is $B_z/I_z = 5.8$ Gauss/Amp.

Approximation of the Side-Lift Coil Pairs was not performed in the aforementioned report due to the presence of iron cores, which cannot be modeled in any simple way. For future references, $N_x = 290$/coil for the Side-Lift Coils.

4.2 COMSOL MODEL

COMSOL Multiphysics is a simulation software that allows for calculation of complex scenarios using the finite element method. The AC/DC Module is used to simulate the magnet-coil system as it gives the ability to model electromagnetics by solving Maxwell’s equations. Pre-defined characteristics in COMSOL produce a streamlined modeling process.

4.2.1 GEOMETRY

A cylinder with a radius and length of 120 inches is used to simulate the air domain with standard material properties of air applied. This was found to be an acceptable size that caused negligible variations in the magnetic flux results compared to an infinite far-field boundary. The Helmholtz coil pair is modeled as a simple set of circular coils in COMSOL, as the coils are axisymmetric and can be modeled as a circular loop of the coils’ cross section. The Saddle
Coils, Side-Lift Coils, and iron yokes were modeled in Autodesk Inventor 3D CAD software and imported into COMSOL. Coil wires are not modeled individually; instead, the coil is one block, with current flowing in the direction of the wires and negligible flow in other directions. This is a standard approach in analysis of this kind. Major geometries are considered, excluding impacts from thin spaces between coil sets and fillets in the iron yokes. Material properties of all coils are copper and soft iron (without losses), all with standard material properties applied. See Figure 14 through Figure 18 for reference geometries. Additional details are given in Appendix A.

Figure 14: Helmholtz Coil Cross-Section and Geometry in COMSOL (Looking Down)
Figure 15: Helmholtz Coil Geometry in COMSOL

Figure 16: Side-Lift Coils with Iron Yokes Imported in COMSOL
Figure 17: Inner Saddle Coil Geometry Imported in COMSOL

Figure 18: Outer Saddle Coil Geometry Imported in COMSOL
4.2.2 MODEL INTERFACES

The magnetic fields interface in COMSOL’s AC/DC module applies Ampere’s Law and magnetic insulation across the coils. The “multi-turn coil” domain applies in this case as it takes into account the wire cross section and number of wires. This eliminates the need to model each wire individually. COMSOL performs an analysis of the coil geometry and allows for user defined inputs of the number of turns per coil and coil excitation. Varying levels of current are applied as the coil excitation source. The Coefficient Form PDE (partial differential equation) interface is applied as a precedent to the coil geometry analysis study.
step in which the dependent variables are defined as in Figure 20. This interface assists with solving for the axial gradients of the specified fields.

Figure 20: COMSOL Model Builder (Helmholtz Coil-Iron Yokes Example)

4.2.3 MESH

The Mesh interface within COMSOL applies an initial mesh size and shape based on the created geometry. The intent of the mesh is to assist in calculation of coil geometry as well as solve for the applied physics nodes at discrete points. Optimal mesh size was accomplished by slightly varying COMSOL’s automatic mesh sizes and shapes until effects on the magnetic field results of small mesh changes were minimal. An example mesh is shown
below in Figure 21. All meshes are a free tetrahedral shape with coarse mesh used for the yokes and a fine to extremely fine mesh applied to the coils, as pre-defined by COMSOL. Normal to fine mesh was sufficient for all remaining areas (air domain surrounding coils). The coil geometry study steps are solved where the combination of the physics interfaces are applied to a specified coil and solved. See Figure 23.

Figure 21: Helmholtz Coil Mesh with Iron Yokes (Air Domain Mesh Not Shown for Clarity)
Figure 22: Saddle Coil Mesh with Iron Yokes, Air Domain Shown
4.2.4 RESULTS

Coils were modeled with and without contribution of the iron core at varying current levels. Some sharp changes are seen in the field plots at certain boundary points. Additional mesh refinement studies could be performed to mitigate any spikes in the field plots with the understanding that more mesh elements call for more computation time and more memory. For example, adaptive mesh refinement could be performed to estimate where error is high and re-mesh geometry to more discrete points. Corner mesh refinement can be used to decrease the element size at sharp corners. For this study, a manual mesh refinement was performed, and polynomial curve fits applied to data sets which provided sufficient information. See Figure 24 through Figure 27 for COMSOL plots showing the small spikes mentioned previously.
Figure 24: Magnetic Flux Density, Fwd Pair of Lift Coils at 50A

Figure 25: Magnetic Flux Density, Aft Pair of Lift Coils at 50A
Figure 26: Magnetic Flux Density, Drag Coils at 50A

Figure 27: Magnetic Flux Density, Saddle Coils at 50A
Additional 3D plots of magnetic flux density on the $xy$ plane are shown in Figures 27 and 28 below.

Figure 28: $B_x$ in Gauss, Inner Saddle Coils and Iron Yokes, All Coils Excited at 100A
Results from the FEA analysis are summarized below. Table 1 shows a comparison of the Magnetic Flux from COMSOL in their originally intended functionality compared to the theoretical values calculated in section 4.1. Table 2 shows the target field components after re-configuring the coil sets to their current state. As mentioned previously, note that effects of the iron core and simplified geometry elements can cause variations between theoretical and computational results. Low variation between results in the Helmholtz coils is expected as the geometry is inherently simple.
Table 1: Magnetic Flux Density Comparison, Original Coil Functionality

(Coils in Isolation and Iron Yokes in Place)

<table>
<thead>
<tr>
<th>Coil Set</th>
<th>Field Component</th>
<th>Theoretical Calculation</th>
<th>COMSOL Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetizing</td>
<td>( B_y/I_y ) (isolation, G/A)</td>
<td>12.65 G/A</td>
<td>12.6 G/A</td>
</tr>
<tr>
<td>Magnetizing</td>
<td>( B_y/I_y ) (iron yokes in place, G/A)</td>
<td>17.48 G/A</td>
<td>17.48 G/A</td>
</tr>
<tr>
<td>Drag</td>
<td>( B_{yx}/I_{yx} ) (isolation, G/in/A)</td>
<td>1.38 G/in/A</td>
<td>1.30 G/in/A</td>
</tr>
<tr>
<td>Drag</td>
<td>( B_{yx}/I_{yx} ) (iron yokes in place, G/in/A)</td>
<td>1.72 G/in/A</td>
<td>1.72 G/in/A</td>
</tr>
<tr>
<td>Inner Saddle</td>
<td>( B_y/I_y ) ' (isolation, G/A)</td>
<td>5.5 G/A</td>
<td>3.79 G/A</td>
</tr>
<tr>
<td>Inner Saddle</td>
<td>( B_y/I_y ) ' (iron yokes in place, G/A)</td>
<td>3.81 G/A</td>
<td>3.81 G/A</td>
</tr>
<tr>
<td>Outer Saddle</td>
<td>( B_z/I_z ) ' (isolation, G/A)</td>
<td>5.8 G/A</td>
<td>3.84 G/A</td>
</tr>
<tr>
<td>Outer Saddle</td>
<td>( B_z/I_z ) ' (iron yokes in place, G/A)</td>
<td>3.85 G/A</td>
<td>3.85 G/A</td>
</tr>
<tr>
<td>Lift</td>
<td>( B_{zx}/I_{zx} ) (iron yokes in place, G/in/A)</td>
<td>1.44 G/in/A</td>
<td>1.44 G/in/A</td>
</tr>
<tr>
<td>Side</td>
<td>( B_{yx}/I_{yx} ) (iron yokes in place, G/in/A)</td>
<td>Assumed same as ( B_{zx} )</td>
<td>Assumed same as ( B_{zx} )</td>
</tr>
</tbody>
</table>
Table 2: Magnetic Flux Density at (0,0,0), 50A Applied, Re-Allocated Coil Functionality

<table>
<thead>
<tr>
<th>Target Field Component</th>
<th>Helmholtz (Drag Coils)</th>
<th>All Lift</th>
<th>Forward Lift</th>
<th>Aft Lift</th>
<th>All Saddle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_x$</td>
<td>0.338 T/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_y$</td>
<td>0.003 T/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_z$</td>
<td>0.013 T/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_{xz}$</td>
<td></td>
<td>0.283 T/m</td>
<td>-0.151 T/m</td>
<td>-0.019 T/m</td>
<td></td>
</tr>
<tr>
<td>$B_{yz}$</td>
<td></td>
<td>0.262 T/m</td>
<td>-0.143 T/m</td>
<td>0.002 T/m</td>
<td></td>
</tr>
<tr>
<td>$B_{zy}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.003 T/m</td>
</tr>
<tr>
<td>$B_{xy}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.041 T/m</td>
</tr>
</tbody>
</table>
CHAPTER 5

5. VALIDATION

COMSOL results for magnetic fields are verified using experimental measurements. These are carried out using Hall-effect gaussmeter probes traversed within the volume of interest. This process yields magnetic fields, with gradients estimated from the spatial variations.

A mount was constructed to hold one of three gaussmeter probes (axial or transverse field probes, or a newer three-axis probe positioned atop a traverse driven by a stepper motor to record continuous field measurements along the x axis at the line of symmetry. This motor-probe system is positioned on a platform with vertical and lateral adjustments formed from slotted aluminum framing as shown in Figure 30. Software written in LabView (discussed later) was used to record measurements and control motor movement. Table 2 shows the results of field surveys for the drag, slip, and lift fields across an 8-inch range. The Saddle coils were not operational during the initial test run; therefore these fields were not recorded. The initial runs were performed using the test rig described in Section 5.1. More recent data was taking using the three-axis gaussmeter and a revised setup as described in section 5.2.

5.1 TEST RIG 1 FOR INITIAL RUNS

The frame for magnetic field surveys is constructed with 80/20 aluminum framing. Four holes are counterbored in the two main frame supports for the 4 frame mounting points on the MSBS side profile. 80/20 frame profiles included in Figure 30 and Figure 31 are roller wheel assemblies, flanges, and L-handle bearing brakes. This allows for manual vertical and lateral adjustments to correctly position the gaussmeter probe and stepper motor. Surveys were completed using a one-axis gaussmeter with a transverse probe to capture vertical or lateral field and additional surveys captured with an axial probe.
Frame mounted onto 4x existing bolt holes in MSBS

Lateral adjustment

Vertical adjustment

Figure 30: Motor-Probe Mount
5.2 TEST RIG 2 USING NEW GAUSSMETER

The frame for recent magnetic field surveys using the three-axis probe is constructed with 80/20 aluminum framing, of similar style to Figure 30 and Figure 31. Similar mounting points and 80/20 profiles. See below for reference.
Figure 32: Motor-Probe Mount, Recent Setup
5.3 LABVIEW SOFTWARE

Figure 34 shows the LabView software for the TM4500 stepper motor control to record measurements during the initial test runs at specific increments along with the PMD-1208FS data acquisition device. The data acquisition device automatically records the gaussmeter values as the stepper motor transports the attached probe across the MSBS test section. User inputs of number of steps, step frequency, and samples/cycle are relayed to a wave function in LabView to create a pulse. These inputs and pulses control the number of data points taken, distance between each data point, and the speed of the motor.
Figure 34: LabView Software

Figure 35: Component Setup
5.4 FIELD SURVEYS

Data from the drag coils, all lift coils, and all saddle coils for Rig 1 were received from the one axis or axial gaussmeters. All scenarios from Rig 1 depict the magnetic field at approximately 33.3 amps in the appropriate coils. Data from the drag coils, forward (Fwd) pair of lift coils, aft pair of lift coils, and all saddle coils for Rig 2 were acquired from the axial gaussmeter. All scenarios from Rig 2 depict the magnetic field at 50 amps in the appropriate coils. The following discussion and charts reflect data from COMSOL, Rig 1 field surveys, and Rig 2 surveys in a line scan and grid sweep.

Figure 36 through Figure 38 were performed with coils in the state of their originally intended functionality. Coils were excited at 33.3A. These figures were quite reasonable and lined up well with Rig 2 data given the change in functionality of coils, proving that doing so caused no major error in system performance.
Figure 36: Measured Drag Field Across the x-axis, 8-inch Range, Rig 1

Figure 37: Measured Vertical Field Gradient Across the x-axis, 8-inch Range, Rig 1
Figure 38: Measured Lateral Field Gradient Across the x-axis, 8-inch Range, Rig 1

The upcoming figures for Rig 2 show line sweeps of data taken of the system with coils in their re-allocated functionality.

Figure 39 shows measured data of the drag coils excited with 50A.
Figure 39: Measured Magnetic Flux Density Across x-axis, Rig 2

Figure 40 and Figure 41 show measured data of the forward and aft lift coils, respectively, excited with 50A.
Figure 40: Measured Magnetic Flux Density Across $x$-axis, Rig 2

Figure 41: Measured Magnetic Flux Density Across $x$-axis, Rig 2
Figure 42 shows measured data of both the inner and outer saddle coils excited with 50A.

![Figure 42: Measured Magnetic Flux Density Across x-axis, Rig 2](image)

Figure 43 through Figure 45 show drag coils and lift coil comparisons of Rig 1 and Rig 2 data.
Figure 43: Magnetic Flux Density Comparisons, Drag Coils at 50A

Figure 44: Magnetic Flux Density Comparisons, Fwd Pair of Lift Coils at 50A
Figure 45: Magnetic Flux Density Comparisons, Aft Pair of Lift Coils at 50A

The data for Rig 2 in Figure 46 was calculated by adding the data for the Forward Pair and Aft Pair of lift coil line sweeps. The saddle coil line scans in Figure 47 show the greatest alignment between Rig 1 and Rig 2.
Figure 46: Magnetic Flux Density Comparisons (Rig 2 Field Calculated)

Figure 47: Magnetic Flux Density Comparisons, Saddle Coils at 50A
The following grid sweeps did not behave as well as the line scans and therefore show the necessary step of reflecting data in more than one fashion. Performing the grid sweep even more so revealed the complex nature of grid mesh and its importance on the resultant data. Abnormal shapes in the COMSOL grid sweeps, $B_z$ of Figure 49 for example, are due to COMSOL’s effort to solve for the desired data points with influence of an inadequate mesh. Grid sweeps in Figure 48 and Figure 49 compare the Rig 2 and COMSOL FEA magnetic flux densities.

Figure 48: Magnetic Flux Density Grid, Rig 2, Drag Coils at 50A
The saddle coil mesh proves to be sufficient as there are no sharp changes in the COMSOL line scan or warped graph in the COMSOL grid sweep. See Figure 50 and Figure 51.
Figure 50: Magnetic Flux Density Grid, Rig 2, Saddle Coils at 50A

Figure 51: Magnetic Flux Density Grid, COMSOL, Saddle Coils at 50A
Grid sweeps in Figure 52 and Figure 53 compare the Rig 2 and COMSOL FEA magnetic flux densities for the forward pair of lift coils excited at 50A.

Figure 52: Magnetic Flux Density Grid, Rig 2, Fwd Lift Coils at 50A
Grid sweeps in Figure 54 and Figure 55 compare the Rig 2 and COMSOL FEA magnetic flux densities for the aft pair of lift coils excited at 50A.
Figure 54: Magnetic Flux Density Grid, Rig 2, Aft Lift Coils at 50A

Figure 55: Magnetic Flux Density Grid, COMSOL, Aft Lift Coils at 50A
Gradient values were derived using a linear regression model fits of the matrixed data from points taken in a grid sweep. All field gradients in the tables below are from Rig 2 grid sweeps. See Appendix B for curve fitting MATLAB script. The gradients in Table 5 are the main components of interest for this system. These values were also impacted strongly by the mesh imperfections discussed earlier. To get more accurate values, additional mesh refinement can be performed to improve grid sweep data and therefore improve the gradient values shown below to reduce the percent difference between COMSOL and field gradient values. An additional option is to reduce the small faces and edges where possible in the geometry in order to avoid high numbers of mesh elements and having small boundaries that cause an error due to an area being smaller than the minimum element size allowed by COMSOL’s mesh node.

Table 3: Magnetic Flux Density, Original Performance and COMSOL, Original Coil Functionality

<table>
<thead>
<tr>
<th>Coil Set</th>
<th>Field Component</th>
<th>Original System Performance</th>
<th>COMSOL Results</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetizing</td>
<td>$B_x/I_x$</td>
<td>14 G/A</td>
<td>17.48 G/A</td>
<td>24.9%</td>
</tr>
<tr>
<td>Drag</td>
<td>$B_{xx}/I_{xx}$</td>
<td>1.7 G/in/A</td>
<td>1.72 G/in/A</td>
<td>1.2%</td>
</tr>
<tr>
<td>Inner Saddle</td>
<td>$B_y'/I_y'$</td>
<td>3.8 G/A</td>
<td>3.81 G/A</td>
<td>0.3%</td>
</tr>
<tr>
<td>Outer Saddle</td>
<td>$B_z'/I_z'$</td>
<td>3.5 G/A</td>
<td>3.85 G/A</td>
<td>1.4%</td>
</tr>
<tr>
<td>Lift</td>
<td>$B_{zx}/I_{zx}$</td>
<td>1.4 G/in/A</td>
<td>1.44 G/in/A</td>
<td>2.9%</td>
</tr>
<tr>
<td>Side</td>
<td>$B_{yz}/I_{yz}$</td>
<td>Same as Byx</td>
<td>Assumed same as Bzx</td>
<td>2.9%</td>
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Table 4: Magnetic Flux Density, Original Performance and COMSOL, Re-Allocated Coil Functionality

<table>
<thead>
<tr>
<th>Coil Set (Vertical Force)</th>
<th>Field Component</th>
<th>Original System Performance</th>
<th>COMSOL Results</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drag</td>
<td>$B_{zz}/I_{zz}$</td>
<td>0.85 G/A</td>
<td>0.89 G/A</td>
<td>4.7%</td>
</tr>
<tr>
<td>Saddles (Side Force)</td>
<td>$B_{yz}/I_{yz}$</td>
<td>0.78 G/in/A</td>
<td>0.79 G/in/A</td>
<td>1.3%</td>
</tr>
<tr>
<td>Lift (Align)</td>
<td>$B_z/I_z$</td>
<td>8.15 G/A</td>
<td>6.89 G/A</td>
<td>15.5%</td>
</tr>
<tr>
<td>Lift (Drag)</td>
<td>$B_{xz}/I_{xz}$</td>
<td>1.7 G/in/A</td>
<td>1.54 G/in/A</td>
<td>9.4%</td>
</tr>
</tbody>
</table>

Table 5: Magnetic Flux Density, Gradient Comparison, Re-Allocated Coil Functionality

<table>
<thead>
<tr>
<th>Coil Set (Flux Density Component)</th>
<th>Field Gradients (T/m)</th>
<th>COMSOL Gradients (T/m)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drag ($B_{zz}$)</td>
<td>0.16218</td>
<td>0.17588</td>
<td>8.4</td>
</tr>
<tr>
<td>Saddle ($B_{yz}$)</td>
<td>-0.17292</td>
<td>-0.15666</td>
<td>9.4</td>
</tr>
<tr>
<td>Forward Lift Pair ($B_{xz}$)</td>
<td>-0.11898</td>
<td>-0.13667</td>
<td>14.8</td>
</tr>
<tr>
<td>Aft Lift Pair ($B_{xz}$)</td>
<td>-0.11908</td>
<td>-0.16611</td>
<td>39.5</td>
</tr>
</tbody>
</table>

5.5 ERROR ANALYSIS

The error in modeling of the 6-inch wind tunnel MSBS relies on three major areas of concern: 1. Computational model. 2. Experimental data. 3. Effect of probe alignment.
There is no one or simple answer to calculate error in a computational model. In this work, grid refinement was checked to the extent possible within available computational resources. The sensitivity of the far-field boundary was checked by varying the size of the computational volume. Regarding modeling details, the iron yokes consist of a laminated silicon steel ring with each inward pointing “pole” modeled as one solid. The properties of the laminations are difficult to model and this aspect should be studied in the future work. Additional error that is difficult to quantify is error in geometry. It was noted that the as-built geometry differs in some cases from the as-designed.

Experimental error is based on measurement tools, user error, and geometry. For the most recent data taken with coils in their re-allocated functionality, a F.W. Bell 8130 Hall-effect gaussmeter and F.W. Bell 3-axis 8000 series probe was used to measure the magnetic field. The probe and instrument accuracy from the manufacturer’s specifications are +/- 0.05% of the reading and +/- 0.25%/10kG linearity, respectively. This would have a minor effect on the field readings reported in Figure 39 through Figure 47 with minimal effect on calculated gradients. Probe position error is entirely human error in the ability to pick the starting point for the traverse gaussmeter probe/motor. This error can be estimated to be +/- 2mm. Once the origin is established, position error is estimated as +/- 0.1mm at each point.

Probe alignment uncertainty is estimated as +/- 1 degree relative to the x-axis and +/- 2 degrees in rotation around the x-axis. This will have minimal effect on primary fields due to the behavior of cosines. Secondary fields would be affected. Correction for probe misalignment may be possible and is discussed in Section 6.1.
6. CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

A COMSOL Multiphysics finite element analysis method for the ODU/MIT 6-inch magnetic suspension and balance system was discussed. A brief mention of the theoretical performance calculations from the initial MIT thesis was made and compared to the COMSOL values. It is recommended that the theoretical calculations remain as a point of reference and not a point of verification of an FEA model for this system due to over-simplification of complex geometry. Both the experimental validation process and FEA model presented themselves with a number of issues.

Alignment and Position

In the experimental model, alignment of the probe and orientation include an element of human error as the exact \( xyz \) positioning of the gaussmeter probe was done manually. No tool is used to “level” the gaussmeter. In addition, the \((0,0,0)\) position in the MSBS is based on the user’s ability to visibly verify the center in reference to the system. This could cause some of the measured data from more than one direction to be reported within each field. \( B_x \) could show some slight influence of \( B_y \) or \( B_z \), etc. In regard to the position, some magnetic flux data that is theoretically zero could show as a value not equal to zero. See Figure 56 for examples. In order to correct probe alignment, field survey runs should be performed to calculate uncertainty in probe alignment and corrections made as a follow up response.
Notable difficulties in the COMSOL model involved the balance between a more refined mesh and keeping a reasonable number of elements. Since mesh is memory intensive, an unreasonably high number of mesh elements will result in a model that will not compute as the amount of memory becomes inefficient. Another factor to consider is computation time as a more refined mesh results in much longer computation time. Although the computation takes longer, more refined mesh smooths out some of the sharp jumps in magnetic flux and would result in an even more accurate result. Particularly, in cases for the grid scans shown previously and for gradient fields. Additional mesh refinement at long boundary edges by “splitting” mesh was performed on the forward lift coils and shown in Figure 58. As additional mesh refinement is performed, additional changes to the air domain may be necessary. Incremental changes in size
of the cylinder of air should be executed until the change in the magnetic field is considered to be negligible as performed in the current model.

Figure 57: COMSOL Magnetic Flux Density, All Lift Coils, 50A, Original Mesh
Figure 58: COMSOL Magnetic Flux Density, All Lift Coils, 50A, Refined Mesh

_Model Builder_

One Coefficient Form PDE “study physics” was applied to solve for all $B_x$, $B_y$, and $B_z$ gradients (see Figure 20). An example analysis was performed to apply three separate Coefficient Form PDE’s. This ultimately did smooth out the gradient fields with some additional promise shown using polynomial patch recovery. This method is suggested for future adjustments to the COMSOL model.
Figure 59: COMSOL Model Builder – Three Coefficient Form PDE’s

Figure 60: $B_{x\alpha}$ (T/in), Drag Coils at 50A, Model Builder Configuration shown in Figure 20
Figure 61: $B_{x1}$ (T/in), Drag Coils at 50A, Model Builder Configuration shown in Figure 59

Figure 62: $B_{x3}$ (T/in), Drag Coils at 50A, Model Builder Configuration shown in Figure 59 and Polynomial Patch Recovery
Figure 63: $B_{bx}$ (T/in), Drag Coils at 50A, Model Builder Configuration shown in Figure 59

3D Plot of $xy$ Plane (left), 3D Plot of $yz$ Plane (right)

Figure 64: $B_{bx}$ (T/in), Drag Coils at 50A, Model Builder Configuration shown in Figure 59 and Polynomial Patch Recovery, 3D Plot of $xy$ Plane (left), 3D Plot of $yz$ Plane (right)
6.2 FUTURE WORK

Validation of the COMSOL model was performed using a 3-axis gaussmeter and frame rig with motor controlled by LabVIEW in initial runs and more recently controlled by MATLAB. The COMSOL model was validated within a reasonable range of error in most cases, but future potential work involves additional computations after performing mesh refine and geometry simplification if at all possible. Small differences in the model and field data may include small differences at boundary meshes and coil modeling assumptions stated previously. With more refined data, the model can accurately portray the performance capabilities of the current MSBS design in a subsonic wind tunnel and will be pertinent to the design at a supersonic level.

Refurbishment of the MSBS for a supersonic wind tunnel is ongoing with the goal of improving digital control, further improvements to the EPS, and simulating a “free-to-oscillate” model with a full six degree of freedom system to study dynamic stability. The 6-inch MSBS is confirmed to be a viable test facility and is operational. Successful levitation of entry capsule models with vertical magnetization was achieved. Next steps include work to perform aerodynamic testing of a free to yaw scenario and exploration of horizontal magnetization [18]. Additional work is to be done on the circuitry and the position sensing algorithm to expand the one degree of freedom EPS into six degrees of freedom [19]. It is recommended that additional work is done to make improvements on the FEA model to lessen error between the computational ad experimental values. This includes but is not limited to adjustments of boundary conditions, modeling separate PDE nodes to adjust gradients of $B_x$, $B_y$, and $B_z$ independently, comparing flux values at multiple current inputs, and mesh adjustments. Upon
successfully reducing error, field values from the COMSOL FEA model will be used to continue work on the control algorithm and continue to explore performance estimation.
REFERENCES


APPENDIX A

UPDATED GEOMETRIES - COILS AND IRON YOKES

Figure 65: Updated Geometry, Helmholtz Coils
Figure 66: Updated Geometry, Saddle Coils
Figure 67: Updated Geometry, Saddle Coils (Iron Yokes Present)
Figure 68: Updated Geometry, Iron Yokes (Saddle Coils Present)
% Helmholtz (drag)
% Field Survey (Rig 2)
positions=dataX_HCoil.rigpos;
fields=dataX_HCoil.field;
for i=1:21
    FieldBx(i)=fields(i,3);
    FieldBy(i)=fields(i,2);
    FieldBz(i)=-fields(i,1);
    FieldBmag(i)=fields(i,4);
    positions(i,1)=-positions(i,1);
    Fieldx(i)=positions(i,1);
    Fieldy(i)=positions(i,2);
    Fieldz(i)=positions(i,3);
end
% Comsol
positions2=Hcoil_comsolpos;
fields2=Hcoil_comsolfield;
for i=1:17
    ComsolBx(i)=fields2(i,1);
    ComsolBy(i)=fields2(i,2);
    ComsolBz(i)=-fields2(i,3);
    ComsolBmag(i)=fields2(i,4);
    positions2(i,1)=-positions2(i,1);
    Comsolx(i)=positions2(i,1);
    Comsoly(i)=positions2(i,2);
    Comsolz(i)=positions2(i,3);
end
figure
title('Helmholtz');
xlabel('x(mm)');ylabel('B(T)');grid;
hold on
coefficients=polyfit(Fieldx,FieldBx,3)
y=polyval(coefficients,Fieldx)
plot(Fieldx,y,'--ob')
plot(Comsolx,ComsolBx,'-xr');
hold off
legend('Rig 2 FieldBx','ComsolBx');
Grid Scan Line Scan Plotting and Polynomial Fit Example

% Helmholtz
figure
positions=data_Hcoil.rigpos;
fields=data_Hcoil.field;
positions2=Hcoilsweep_comsolpos;
fields2=Hcoilsweep_comsolfield;
%ang=28.5;
for i=1:175
    Bx(i)=fields(i,3);
    By(i)=fields(i,2);
    Bz(i)=-fields(i,1);
    Bmag(i)=fields(i,4);
    positions(i,1)=-positions(i,1);
    x(i)=positions(i,1);
    y(i)=positions(i,2);
    z(i)=positions(i,3);
end
% pick off middle Z first
for i=1:5
    % sweep in y
    yy(i)=y(64+7*i);
    for j=1:7
        % sweep in x
        xx(j)=x(70+j);
        BBz(i,j)=Bz(63+7*i+j);
        BBx(i,j)=Bx(63+7*i+j);
        BBy(i,j)=By(63+7*i+j);
        BBmag(i,j)=Bmag(63+7*i+j);
    end
end
subplot(2,2,1)
mesh(xx,yy,BBz);title('Bz');
xlabel('X');ylabel('Y');zlabel('Bz')
subplot(2,2,2)
mesh(xx,yy,BBmag);title('Bmod');
xlabel('X');ylabel('Y');zlabel('Bmod')
subplot(2,2,3)
mesh(xx,yy,BBx);title('Bx');
xlabel('X');ylabel('Y');zlabel('Bx')
subplot(2,2,4)
mesh(xx,yy,BBy);title('By');
xlabel('X');ylabel('Y');zlabel('By')
sgtitle('Helmholtz')
% Comsol Helmholtz
figure
for i=1:175
    ComsolBx(i)=fields2(i,1);
    ComsolBy(i)=-fields2(i,2);
    ComsolBz(i)=-fields2(i,3);
    ComsolBmag(i)=fields2(i,4);
positions2(i,1) = -positions2(i,1);
Comsolx(i) = positions2(i,1);
Comsoly(i) = positions2(i,2);
Comsolz(i) = positions2(i,3);
end

% pick off middle Z first
for i = 1:5
    for j = 1:7
        Comsolxx(j) = Comsolx(70+j);
        Comsollxx(i,j) = ComsolBx(63+7*i+j);
        ComsolBy(i,j) = ComsolBy(63+7*i+j);
        ComsolBBmag(i,j) = ComsolBmag(63+7*i+j);
    end
end

subplot(2,2,1)
mesh(Comsolxx,Comsoly,ComsolBBz);title('Bz');
xlabel('X');ylabel('Y');zlabel('Bz')
subplot(2,2,2)
mesh(Comsolxx,Comsoly,ComsolBBmag);title('Bmod');
xlabel('X');ylabel('Y');zlabel('Bmod')
subplot(2,2,3)
mesh(Comsolxx,Comsoly,ComsolBBx);title('Bx');
xlabel('X');ylabel('Y');zlabel('Bx')
subplot(2,2,4)
mesh(Comsolxx,Comsoly,ComsolBBy);title('By');
xlabel('X');ylabel('Y');zlabel('By')
sgtitle('Comsol Helmholtz')

% Now curve fits
mdl_Helmholtz_Bx = fitlm(positions,Bx,'quadratic')
mdl_Helmholtz_By = fitlm(positions,By,'quadratic')
mdl_Helmholtz_Bz = fitlm(positions,Bz,'quadratic')

Helmholtz_B(:,1) = mdl_Helmholtz_Bx.Coefficients.Estimate;
Helmholtz_B(:,2) = mdl_Helmholtz_By.Coefficients.Estimate;
Helmholtz_B(:,3) = mdl_Helmholtz_Bz.Coefficients.Estimate;

for i = 1:3
    Helmholtz_B(i+1,:) = Helmholtz_B(i+1,:)*1000;
    Helmholtz_B(i+4,:) = Helmholtz_B(i+4,:)*1000000;
    Helmholtz_B(i+7,:) = Helmholtz_B(i+7,:)*1000000;
end

mdl_Helmholtz_ComsolBx = fitlm(positions2,ComsolBx,'quadratic')
mdl_Helmholtz_ComsolBy = fitlm(positions2,ComsolBy,'quadratic')
mdl_Helmholtz_ComsolBz = fitlm(positions2,ComsolBz,'quadratic')

Helmholtz_ComsolB(:,1) = mdl_Helmholtz_ComsolBx.Coefficients.Estimate;
Helmholtz_ComsolB(:,2) = mdl_Helmholtz_ComsolBy.Coefficients.Estimate;
Helmholtz_ComsolB(:,3) = mdl_Helmholtz_ComsolBz.Coefficients.Estimate;

for i = 1:3
    Helmholtz_ComsolB(i+1,:) = Helmholtz_ComsolB(i+1,:)*1000;
    Helmholtz_ComsolB(i+4,:) = Helmholtz_ComsolB(i+4,:)*1000000;
    Helmholtz_ComsolB(i+7,:) = Helmholtz_ComsolB(i+7,:)*1000000;
end
VITA

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Education
Master of Science in Mechanical Engineering, Expected Spring 2022
Old Dominion University (ODU), Batten College of Engineering and Technology, Norfolk, VA GPA 3.50
Bachelor of Science in Mech Engineering, African American/African Studies Minor, May 2014
University of Virginia (UVa), School of Engineering and Applied Science, Charlottesville, VA GPA 3.05

Professional Experience
Leidos, Bridgewater, Virginia  Feb 2018 - Present
Project Management Support  Jan 2022 - Present
- Support the project manager in day-to-day activities and status reports, assess opportunities for streamlining efforts, and communicate across teams and programs to execute project plans. Support tracking of technical internal research and development projects.

Mechanical Engineer (Manufacturing Engineer)  Feb 2018 - Jan 2022
- Provide aviation manufacturing support to production vendors. Including but not limited to: submitting engineering change requests, submitting request for deviations, writing technical reports, managing engineering drawing lists, and providing onsite support. Release and manage work orders and instructions. Support design reviews.

Wind Tunnel Lab, Old Dominion University  Aug 2015 - March 2017
Graduate Research Assistant
- Construction of a finite element model using COMSOL Multiphysics and Autodesk Inventor for a Magnetic Suspension and Balance System (supplied by NASA Langley) to be used in the ODU Wind Tunnel for dynamic stability measurements.

Norfolk Southern Corporation, Roanoke, Virginia  May - Aug 2015
Mechanical Department Intern
- Assist locomotive facility maintenance department in project modifications, mainly with the use of shop tools and some welding. Creation and revision of mechanical drawings in Autodesk Inventor CAD Software.

Professional Publications
Modeling of a Wind Tunnel Magnetic Suspension and Balance System
AIAA Region I Student Conference, April 2017
Desiree Johnson
Feasibility of Dynamic Stability Measurements of Planetary Entry Capsules Using a Magnetic Suspension and Balance System
AIAA Aviation, June 13-17, 2016, AIAA 2016-4162
Colin P. Britcher, Desiree Johnson