



**Force and Moment Measurements Applicable to
a Flexible Weapons System**

THESIS

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AFIT-ENY-MS-16-M-237

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FORCE AND MOMENT MEASUREMENTS APPLICABLE TO A FLEXIBLE
WEAPONS SYSTEM

THESIS

Presented to the Faculty
Department of Aeronautical Engineering
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in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Aeronautical Engineering

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Abstract

Continuing the development of the 6-DOF Motion Test Apparatus (MTA) for performing dynamic wind tunnel tests revealed the importance of a capable data acquisition (DAQ) system for collecting and analyzing data. Assembling and testing the DAQ system in conjunction with the MTA, AFIT Low-Speed Wind Tunnel, and a selection of high-performance sensors was the primary focus of this research. Specifically, acquiring time-accurate aerodynamic force and moment measurements on a variety of test models was of high importance. With the established real-time DAQ system hardware, a National Instruments (NI) LabVIEW program was created to acquire data from an ATI Nano25-E force transducer and a second LabVIEW program was modified to communicate with a MicroStrain[®] 3DM-GX4-15[™] Inertial Measurement Unit (IMU). The complete DAQ hardware and software system was employed in both static and dynamic wind tunnel tests to collect the aerodynamic forces and moments acting on a NACA 0012 wing model. Dynamic testing involved pitch oscillation motions, which were tracked with the IMU, as well as pitch-plunge oscillation motions. Static tests yielded results that matched traditional sting mounted wind tunnel tests, despite minor angle-of-attack differences. Dynamic measurements of the lift, drag, and pitch moment coefficients were within expectations for the pitch oscillation tests and the highest flow velocity case of the pitch-plunge oscillation test.

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James B. A. Sellers

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List of Symbols

α Angle of Attack

β Sideslip Angle

η Angle from c to y_1 in Figure 7

θ Pitch Rotation Angle

θ_{ab} Angle from a to b in Figure 7

θ_{tr} Torso Yaw Angle

θ_{sp} Shoulder Pitch Angle

θ_{ep} Elbow Pitch Angle

θ_{er} Elbow Roll Angle

θ_{wp} Wrist Pitch Angle

θ_{wr} Wrist Roll Angle

λ Angle from c to a in Figure 7

ξ Angle from a to y_1 in Figure 7

ϕ Roll Rotation Angle

ψ Yaw Rotation Angle

a Torso Yaw to Shoulder Pitch Distance

b Shoulder Pitch to Wrist Pitch Distance

c Torso Yaw to Wrist Pitch Distance

F_x, F_y, F_z Force Vectors

$model_x, model_y, model_z$ Model position

T_x, T_y, T_z Torque Vectors

${}^0_7T$ Transformation Matrix from Inertial to Model Reference Frame

${}^0_7P$ Translational Component of Transformation Matrix

${}^0_7R$ Rotational Component of Transformation Matrix

x, y, z Cartesian Coordinate Position

x_b, y_b, z_b Body Reference Frame

x_i, y_i, z_i Inertial Reference Frame

x_m, y_m, z_m Model Reference Frame

x_w, y_w, z_w Wind Reference Frame

x_0, y_0, z_0 MTA-Inertial Reference Frame

x_1, y_1, z_1 Torso Yaw Reference Frame

x_2, y_2, z_2 Shoulder Pitch Reference Frame

x_3, y_3, z_3 Elbow Pitch Reference Frame

x_4, y_4, z_4 Elbow Roll Reference Frame

x_5, y_5, z_5 Wrist Pitch Reference Frame

x_6, y_6, z_6 Wrist Roll Reference Frame

x_7, y_7, z_7 MTA-Model Reference Frame

List of Acronyms

AEDC	Arnold Engineering Development Complex
AFIT	Air Force Institute of Technology
AFRL	Air Force Research Laboratory
AHRS	Attitude and Heading Reference System
AKF	Adaptive Kalman Filter
AOA	Angle of Attack
ATI-IA	ATI Industrial Automation
BLDC	Brushless Direct Current
CAD	Computer Aided Design
CTS	Captive Trajectory System
DAQ	Data Acquisition
DOF	Degree-of-Freedom
EDM	Electrical Discharge Machining
F/T	Force/Torque
HV	High Voltage
IMU	Inertial Measurement Unit
MTA	Motion Test Apparatus
NACA	National Advisory Committee for Aeronautics

NI	National Instruments
REEF	Research and Engineering Education Facility
ssh	Secure Shell
U.S.	United States
USAF	United States Air Force
VI	Virtual Instrument
VTOL	Vertical Take-off and Landing

FORCE AND MOMENT MEASUREMENTS APPLICABLE TO A FLEXIBLE WEAPONS SYSTEM

I. Introduction

1.1 Motivation

In an effort to streamline the weapon acquisition process, and improve the operational efficiency of weapons operated by the United States Air Force (USAF), the Air Force Research Lab (AFRL) began research and development of flexible weapons systems. The term ‘flexible’, in this instance, is a collective term that Mehta describes as the automatic synchronization of particular technologies to the core of the weapon (a missile) [21]. This synchronization could include a wide variety of technologies and has the potential to significantly reduce the time between weapon development and platform integration.

A subset of the flexible weapons system defined above is multi-body interaction. This is the interaction of multiple bodies, such as missiles, in a given phase of flight, including store separation or free-stream flight. This type of system may also be described as a composable system. The term ‘composable’ is often used in the field of software engineering, referring to the system design principle concerned with the inter-relationships of system components [11]. Based on this definition, a highly composable system yields components that can be assembled in many different combinations to satisfy requirements [19]. The term may easily be used in the context of multi-missile interactions, representing a network of missiles in a desired combination or a reconfiguration of the system to meet requirements [23]. The various possible

configurations of a flexible or composable weapons system can introduce challenges in the testing phase of development. Testing multiple configurations can significantly increase workload and costs of the project. The implementation of dynamic wind-tunnel testing can mitigate these increased workloads and costs. In prescribed motion dynamic wind tunnel testing, a model can be moved in a user-specified trajectory, while collecting force and moment data in real time [20].

In addition to testing flexible weapons systems, dynamic wind-tunnel testing may also be beneficial in testing store separation (weapon release) or the operation of small unmanned aircraft. A dynamic wind tunnel test facility commonly used for store separation testing is the captive trajectory system (CTS) at the Arnold Engineering Development Complex (AEDC). The CTS is capable of performing store separation tests at pressures of almost 2000 lb/ft^2 . The tunnel can operate between Mach 0.05 and Mach 2.5 for these tests as well as conventional sting-mounted force and pressure model tests [13].

Applying the dynamic testing concepts discussed will include pairing a six-degree of freedom (DOF) Motion Test Apparatus (MTA) with the Air Force Institute of Technology (AFIT) Low-Speed Wind Tunnel. The 6-DOF MTA, shown in Figure 1, is a large robotic manipulator with full range-of-motion capabilities over several cubic feet. Space constraints and the relatively small size of the wind tunnel test section at AFIT currently limits the operation of the MTA to motions within approximately 1-2 cubic feet.



Figure 1. Motion Test Apparatus installed next to the AFIT Low-Speed Wind Tunnel

1.2 Problem Statement

The goal of the current research effort is to assemble, test, and evaluate the performance of multiple elements of the data acquisition system in order to utilize dynamic testing in the AFIT Low-Speed Wind Tunnel, providing results for a variety of applications—including flexible weapons systems (multi-body flow interaction), store separation, or the operation of small unmanned aircraft. Pertaining to the primary topic of interest, the thesis will also include both assessing the performance of the MTA and acquiring aerodynamic force and moment data for the dynamic wind tunnel testing of a model with a focus on prescribed-motion tests. These investigations will incorporate specific methods for acquiring quantitative results, such as aerodynamic force and moment measurements on the model and pressure measurements at select locations. An accompanying objective of the research is to obtain time-accurate measurements during testing with the use of real-time data acquisition hardware components. Additionally, the assessment will involve trajectory verification by tracking

the orientation and acceleration of the MTA with an independent Inertial Measurement Unit (IMU) and comparing with actual MTA motor positions and orientations. Although the intended use of the MTA is for complex and potentially aperiodic model maneuvers, most of the work herein was focused on simplified cyclic motions. For these cases, the focus was on the development of data acquisition methods and integration of sensors with anticipation that these results would directly apply to general complex maneuvers.

1.3 Methodology

From a data acquisition standpoint, the goal of the experiment is to collect all data, to include aerodynamic forces and moments, local pressures, and inertial measurements, from the dynamic tests using the same primary computer. Equipment setup will include the MTA positioned next to the AFIT Low-Speed Wind Tunnel. The experimental model will be attached to the MTA using the force balance and positioned inside the wind tunnel test section from the side. Analog voltage signals will be collected from the force balance, using the National Instruments (NI) data acquisition system (DAQ) and will be processed using NI LabVIEW software installed on the primary computer. The pressure transducers also provide analog data signals to the DAQ system. The IMU is installed on the model and provides the inertial measurements through an RS-232 connection on the DAQ system.

The operation of the MTA is achieved with a second computer system, which calculates and transmits trajectory commands for the MTA to perform. A variety of dynamic test trajectories are envisioned for the MTA system, such as linear translations, oscillatory rotations, radial translations (arcs), or figure-8 motions. These trajectories would be performed to simulate operations such as weapons store separation.

The post-processing step of the project will ideally be performed immediately after data collection using the NI LabVIEW software to obtain desired results. The data may then be compared with any existing data for accuracy. The post-processing step will also include the verification of the MTA trajectories by comparing the IMU data with the actual MTA encoder data.

1.4 Limitations

The ultimate goal of the system is to acquire force and moment data in order to provide feedback to the MTA so that motion can be dictated by the force and moment vectors acting on the model. In the current investigation, testing is limited to prescribed motion only. This limitation has little influence on the data acquisition process, which is a primary focus of this thesis. Range of motion constraints are another concern of this research. Physical and programmable rotation constraints are implemented to prevent damage or harm. A safety cage was installed around the MTA, as well as several emergency shut-off switches as additional safety precautions.

1.5 Overview of Subsequent Chapters

The organization of the remaining chapters is as follows. Chapter II addresses the important aspects and background information on the pairing of the MTA with the AFIT Low-Speed Wind Tunnel; background information and studies performed on flexible weapons systems; background information and studies performed on dynamic wind tunnel testing; and the operation of force balance, pressure transducers and inertial measurement units. Chapter III includes the description of the experimental setup to include: required materials and equipment; the design, operation and specifications of the MTA; the specifications of the AFIT Low-Speed Wind Tunnel; and the methodology of acquiring data using the data acquisition system in conjunction with

specific sensors. Chapter IV provides the results from conducting both static and dynamic wind tunnel tests and acquiring quantitative data from aerodynamic force and balance measurements and trajectory verification from an independent IMU. Chapter V discusses: conclusions on acquiring useful data from dynamic testing in the AFIT Low-Speed Wind Tunnel; the assessment of the MTA performance during experiments; and conclusions reached based on quantitative results from sensors.

II. Background and Literature Review

This chapter begins by defining the multiple reference frames applicable to the AFIT Low-Speed Wind Tunnel and Motion Test Apparatus (MTA). Additionally, the chapter presents the theory behind coordinate transformations between these reference frames and the robot kinematics of the MTA. The literature on dynamic wind-tunnel testing is discussed next and finally, an overview is presented regarding the measurements that apply to a flexible weapons system subjected to dynamic wind tunnel testing.

2.1 Reference Frames

In any experiment that incorporates complex dynamics, coordinate reference frame definitions are essential. Wind tunnel tests generally have a standard definition of reference frame axes—a wind reference frame and a body-fixed reference frame. The wind reference frame designates the x-axis, x_w , pointing upstream into the wind, the y-axis, y_w , pointing right when looking upstream and the z-axis, z_w , pointing down. This reference frame definition assumes a horizontal wind tunnel orientation and is centered horizontally and vertically in the test section. Additionally, this reference frame, and all subsequent reference frames to be discussed, follow the right-hand coordinate convention [7].

The body-fixed reference frame is a reference frame that is fixed for all time to the model in the wind tunnel test section. This reference frame is similar to the wind reference frame in terms of axis direction. However, the body-fixed frame moves with the model and can be described relative to the wind reference frame [7]. The axes of the body-fixed frame are denoted in the x-, y-, and z-directions as x_b , y_b , and z_b , respectively [20]. The body-fixed reference frame also describes the components of

force on the model, with drag in the negative x_b -direction, side force in the positive y_b -direction, and lift in the negative z_b -direction [7]. The wind and body-fixed reference frames are depicted in Figure 2. These two reference frames are valid for the AFIT Low-Speed Wind Tunnel alone, although two additional reference frames must be defined to sufficiently describe the wind tunnel and MTA coupled dynamic system.

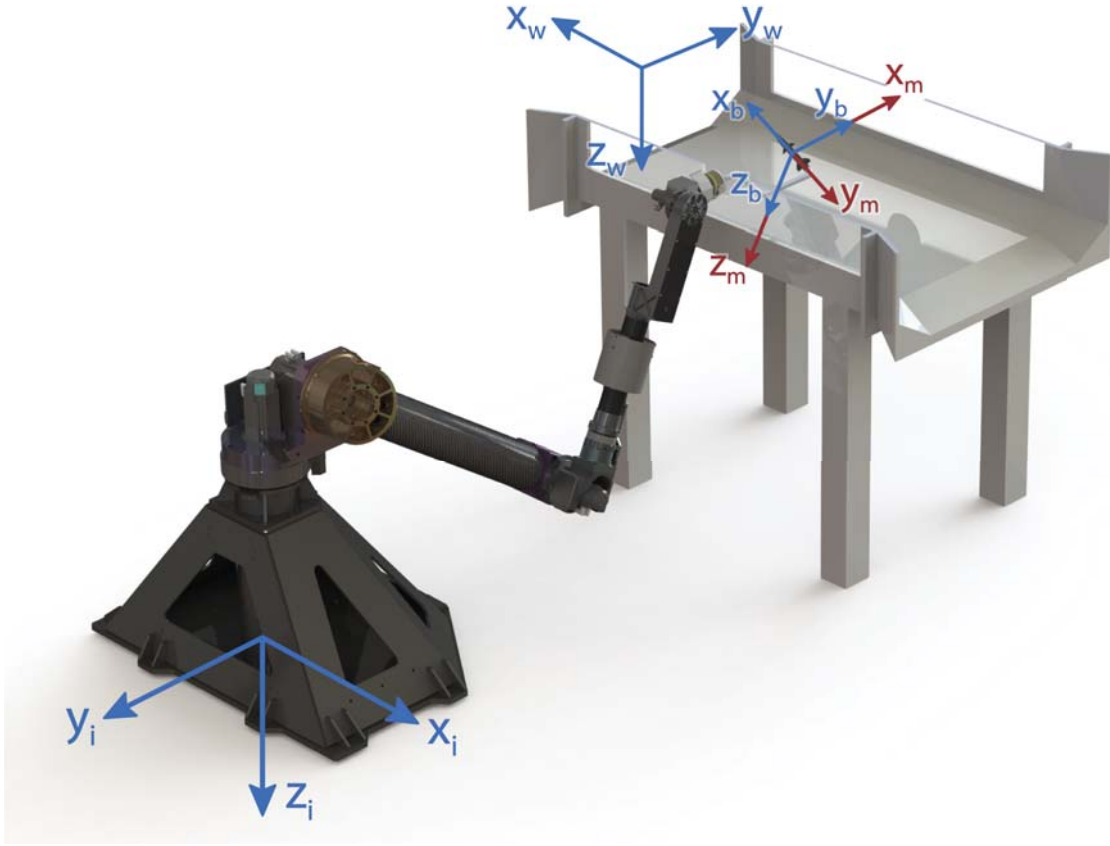


Figure 2. Wind Tunnel and MTA Reference Frames (CAD model acquired from RE2, Inc.) [9]

The two primary reference frames of the MTA are the MTA-model reference frame and the inertial reference frame. The MTA-model reference frame, like the body-fixed frame, is fixed to the model. The only difference is the MTA-model frame is rotated positive 90 degrees about the z_b -axis, creating the z_m -axis in the same direction as

the z_b -axis, the x_m -axis in the positive y_b -direction, and the y_m -axis in the negative x_b -direction. The origin of this frame is specified as the model control point [20].

Defining an inertial reference frame for this system is important for describing the position and orientation of the model. An inertial reference frame is a non-accelerating reference frame that is fixed for all time. The MTA inertial reference frame is positioned at the base of the MTA, where it is secured to the laboratory floor. The origin is centered under the torso yaw joint of the MTA, as depicted in Figure 2 [20]. The z_i -axis points down from the inertial origin with the x_i -axis pointing in the negative x_w -direction, and the y_i -axis in the negative y_w -direction [29]. Desired MTA trajectories, which describe the motion of the model in the wind tunnel, are designed with respect to the inertial reference frame [20].

2.2 Coordinate Transformations

The determination of aerodynamic forces acting on a wind tunnel model is based exclusively on the relative orientation of the model to the free-stream flow velocity [18]. Thus, a transformation between the body-fixed and wind reference frame is required. In aerodynamics, standard convention specifies the attitude of a model with an Euler-rotation angle sequence. With respect to the free-stream velocity, the orientation is specified in terms of roll, pitch, and yaw. Yaw (ψ) is a rotation about the z_w -axis, pitch (θ) is a rotation about an intermediate axis formed from the yaw rotation, and roll (ϕ) is a rotation about the x_b -axis [7]. These Euler-rotation angles are shown in Figure 3. Equation 1 is the transformation matrix used to express vectors in the body-fixed frame with respect to the wind reference frame with ‘c’ referencing ‘cosine’ and ‘s’ referencing ‘sine’ [30].

$$\begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}_w = \begin{bmatrix} c\theta c\psi & c\theta s\psi & -s\theta \\ (-c\phi s\psi + s\phi s\theta c\psi) & (c\phi c\psi + s\phi s\theta s\psi) & s\phi c\theta \\ (s\phi s\psi + c\phi s\theta c\psi) & (-s\phi c\psi + c\phi s\theta s\psi) & c\phi c\theta \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}_b \quad (1)$$

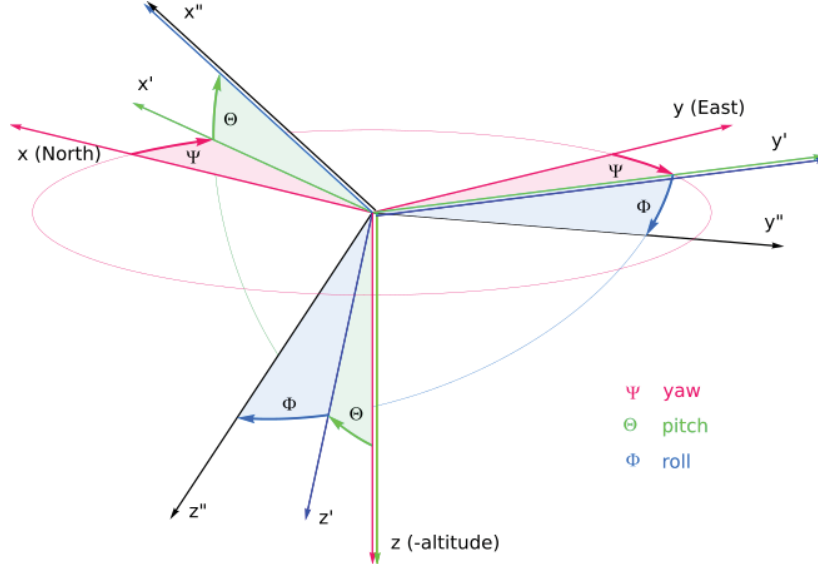


Figure 3. Standard Euler Rotation Angles [22]

Additional angles for describing the model orientation with respect to the free-stream velocity are angle of attack, α , and sideslip angle, β . Figure 4 depicts these angles measured from the projection of the x_a -axis (x_w) onto the x_b - z_b plane. Angle of attack is measured from this projected vector to the x_b -axis, and sideslip is measured from the projected vector to the x_a -axis (x_w), which is aligned with the velocity vector [18]. The angle of attack is directly correlated with model pitch, while sideslip is negatively correlated with model yaw. The roll rotation, as previously discussed, is correlated with the bank angle of the model. However, in wind tunnel testing, the bank angle is generally assumed to have no effect on the measured aerodynamic forces. Thus, the bank angle is neglected when expressing the forces with respect to the wind reference frame [18]. With the rotation sequence of $(-\beta-\alpha-0)$, referring to

a rotation of negative yaw then positive pitch and no roll, Equation 1 can then be replaced with Equation 2 [20].

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}_w = \begin{bmatrix} \cos \alpha \cos \beta & -\cos \alpha \sin \beta & -\sin \alpha \\ \sin \beta & \cos \beta & 0 \\ \sin \alpha \cos \beta & -\sin \alpha \sin \beta & \cos \alpha \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}_b \quad (2)$$

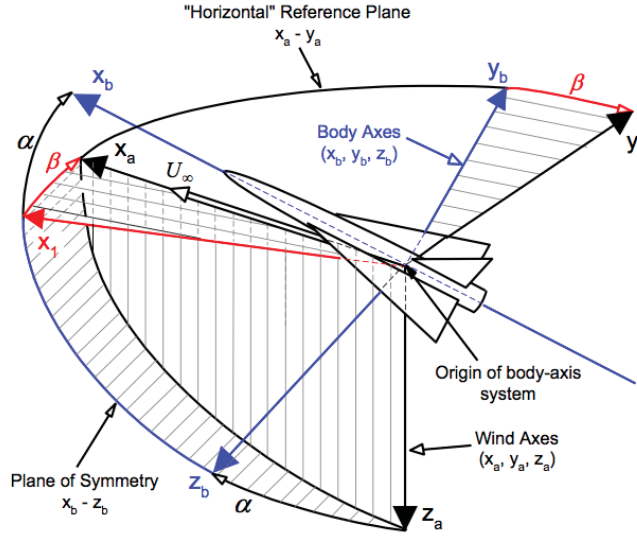


Figure 4. Model Orientation Relative to the Wind and Body Frames [18]

2.3 Robot Kinematics

Successful operation of the MTA requires an understanding of the procedures for determining both the model position and the angles of each MTA joint. This information at each time step of the commanded trajectory describes the MTA kinematics.

A trajectory command to the MTA contains a time-step series of Cartesian waypoints that describe the desired position and orientation of the model. The position coordinates (x, y, z) describe the location of the MTA-model reference frame relative to the inertial reference frame while the orientations (ϕ, θ, ψ) are defined relative to the inertial reference frame [29].

Two methods are used to transform between the Cartesian waypoints and the six MTA joint angles. Using the method of forward kinematics, the six MTA joint angles, along with the offset of the model from the MTA, are used to calculate the Cartesian waypoints. The second method simply describes the inverse of the first method, appropriately called inverse kinematics. Inverse kinematics uses the Cartesian waypoints of the model to calculate the six MTA joint angles. Using the six calculated MTA joint angles to perform the desired trajectory is the preferred method for operation of the MTA [20]. These two methods were employed by the MTA manufacturer, RE2, Inc., and are detailed in the following subsections.

2.3.1 MTA Notation and Reference Frames

As previously mentioned, the position of the model can be described by the six MTA joint angles. These angles are the torso yaw (θ_{tr}), shoulder pitch (θ_{sp}), elbow pitch (θ_{ep}), elbow roll (θ_{er}), wrist pitch (θ_{wp}), and wrist roll (θ_{wr}) [20]. The location of each of these joints is depicted in Figure 5.

Each joint has a corresponding reference frame, specified by a subscript number. The MTA-inertial reference frame, centered along the torso yaw z-axis, z_1 , and level with the laboratory floor, is denoted with x_0 , y_0 , and z_0 . Proceeding to each joint, the torso yaw reference frame (x_1 , y_1 , z_1) is centered 1.2764 meters above the MTA-inertial frame in the negative z_0 -direction and rotated -90 degrees about the z_0 -axis. The shoulder pitch frame (x_2 , y_2 , z_2) is offset 0.2413 meters in the positive x_1 -direction and 0.2539 meters in the positive y_1 -direction, elbow pitch (x_3 , y_3 , z_3) is offset 1.3335 meters in the positive x_2 -direction and 0.2282 meters in the positive y_2 -direction, elbow roll (x_4 , y_4 , z_4) is offset 0.2889 meters in the positive x_3 -direction, wrist pitch (x_5 , y_5 , z_5) is offset 1.0572 meters in the positive x_4 -direction, and wrist roll (x_6 , y_6 , z_6) is offset 0.2683 meters in the positive x_5 -direction.

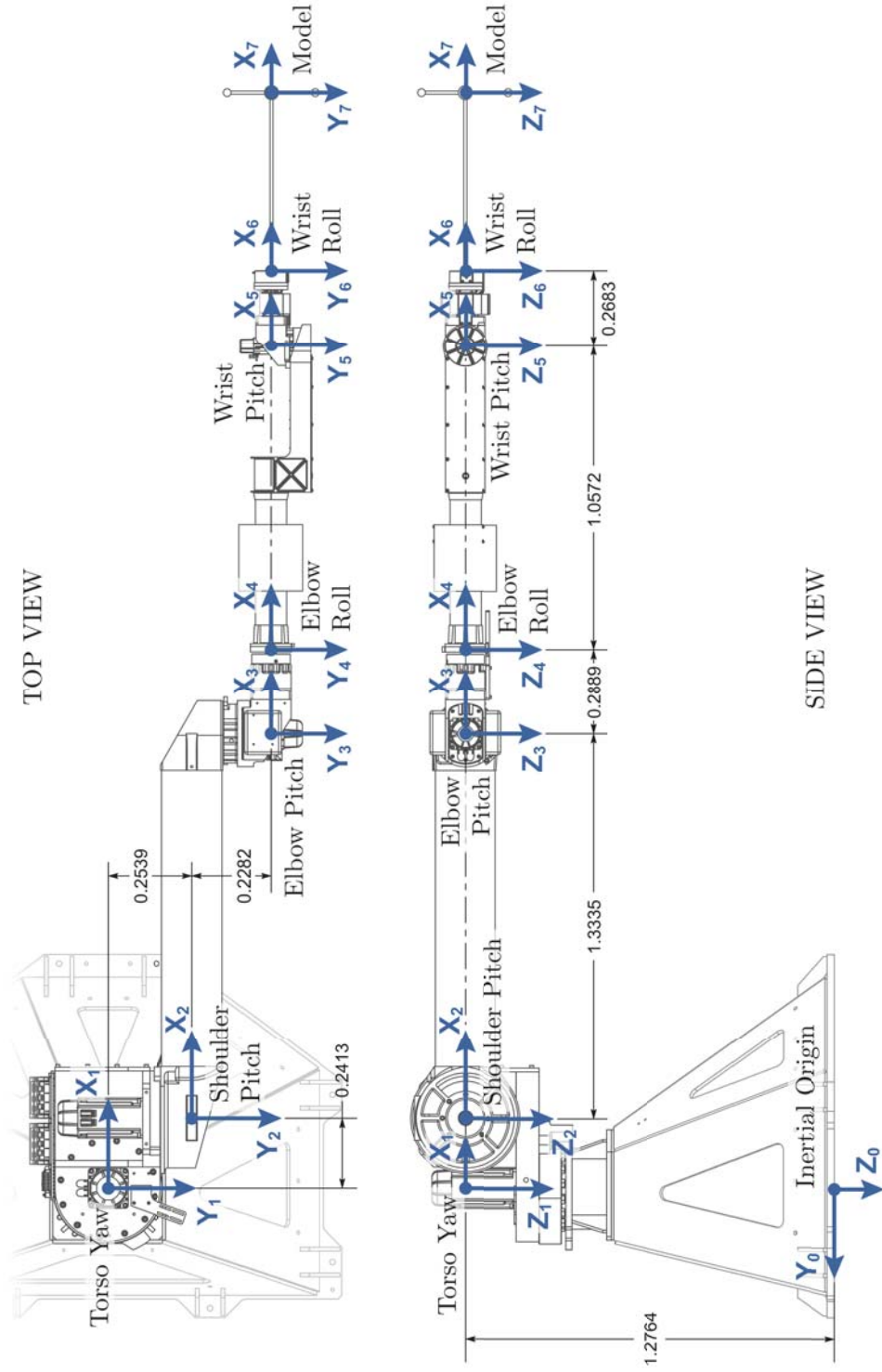


Figure 5. MTA reference frame locations for robot kinematics. All angles are zero for displayed joint positions and orientations (units in meters) [9].

The position and orientation of the MTA-model reference frame (x_7, y_7, z_7) is user-specified. In Equation 9, the model position is denoted by $model_x$, $model_y$, and $model_z$, with units in meters [29].

2.3.2 Forward Kinematics

The following equations are the rotation and position transformation matrices used to transform from the inertial reference frame to the MTA-model reference frame. Each 4x4 matrix transforms from the specified reference frame to the next frame along the MTA [29]. These 4x4 matrices are typically referred to as homogeneous transforms and are used for rotation, translation, and scaling, however, scaling is not used in this work. In the matrices, rotation transformations (θ) in the first three columns and top three rows, a 3x3 matrix, have units of degrees and the position transformations in the fourth column and fourth row have units in meters.

$${}^0_1T = \begin{bmatrix} \cos(\theta_{tr} - 90^\circ) & -\sin(\theta_{tr} - 90^\circ) & 0 & 0 \\ \sin(\theta_{tr} - 90^\circ) & -\cos(\theta_{tr} - 90^\circ) & 0 & 0 \\ 0 & 0 & 1 & -1.2764 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$${}^1_2T = \begin{bmatrix} \cos(\theta_{sp}) & 0 & \sin(\theta_{sp}) & 0.2413 \\ 0 & 1 & 0 & 0.2539 \\ -\sin(\theta_{sp}) & 0 & \cos(\theta_{sp}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$${}^2_3T = \begin{bmatrix} \cos(\theta_{ep}) & 0 & \sin(\theta_{ep}) & 1.3335 \\ 0 & 1 & 0 & 0.2282 \\ -\sin(\theta_{ep}) & 0 & \cos(\theta_{ep}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$${}^3_4T = \begin{bmatrix} 1 & 0 & 0 & 0.2889 \\ 0 & \cos(\theta_{er}) & -\sin(\theta_{er}) & 0 \\ 0 & \sin(\theta_{er}) & \cos(\theta_{er}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

$${}^4_5T = \begin{bmatrix} \cos(\theta_{wp}) & 0 & \sin(\theta_{wp}) & 1.0572 \\ 0 & 1 & 0 & 0 \\ -\sin(\theta_{wp}) & 0 & \cos(\theta_{wp}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

$${}^5_6T = \begin{bmatrix} 1 & 0 & 0 & 0.2683 \\ 0 & \cos(\theta_{wr}) & -\sin(\theta_{wr}) & 0 \\ 0 & \sin(\theta_{wr}) & \cos(\theta_{wr}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

$${}^6_7T = \begin{bmatrix} 1 & 0 & 0 & model_x \\ 0 & 1 & 0 & model_y \\ 0 & 0 & 1 & model_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9)$$

Multiplying the above equations, represented by Equation 10 below, results in a single complex transformation matrix for the transformation between the inertial reference frame and the MTA-model reference frame [29]. This transformation matrix calculates the test model position and orientation relative to the MTA-inertial reference frame [20].

$${}^0_7T = {}^0_1T * {}^1_2T * {}^2_3T * {}^3_4T * {}^4_5T * {}^5_6T * {}^6_7T \quad (10)$$

2.3.3 Inverse Kinematics

As discussed, the method of inverse kinematics transforms the Cartesian waypoints of the model $(x, y, z, \phi, \theta, \psi)$ to the six MTA joint angles, where x, y , and z represent the position of the model and ϕ (roll), θ (pitch), and ψ (yaw) represent the orientation of the model, all with respect to the MTA-inertial reference frame. Since the MTA is a 6-DOF manipulator, multiple solutions exist for this transformation. RE2, Inc. developed a closed-form solution for performing the inverse kinematic calculations. Working with the user-designed trajectory file, each line from the file is converted to a homogeneous transform, which is shown below in Equation 11 as a single complex transformation matrix [29]. It is noted here that the following series of equations and methods originated from the MTA User Manual [29]. However, for consistency, a portion of the notation used in these equations originates from Lancaster's description of the methods [20].

$${}^0_7T = \begin{bmatrix} \cos \psi \cos \theta & \cos \psi \sin \theta \sin \phi - \sin \psi \cos \phi & \cos \psi \sin \theta \cos \phi + \sin \psi \sin \phi & x \\ \sin \psi \cos \theta & \sin \psi \sin \theta \sin \phi + \cos \psi \cos \phi & \sin \psi \sin \theta \cos \phi - \cos \psi \sin \phi & y \\ -\sin \theta & \cos \theta \sin \phi & \cos \theta \cos \phi & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11)$$

The first step of the solution is to find an expression for the position of the MTA wrist pitch reference frame at the final specified orientation of the model. Beginning with Equation 10, the offset of the model (${}^6_7T$) and the translational component of the wrist pitch to endpoint transform are removed. The model offset transform is removed by multiplying Equation 10 by its inverse, ${}^6_7T^{-1}$. The wrist pitch transform (${}^5_6T$) is split into a rotational (${}^5_{5'}R$) and translational (${}^5_6P$) component. These modifications are shown in Equation 12.

$${}^0_6T = {}^0_1T * {}^1_2T * {}^2_3T * {}^3_4T * {}^4_5T * ({}^5_{5'}R * {}^5_6P) * {}^6_7T * {}^6_7T^{-1} \quad (12)$$

Multiplying Equation 12 by the inverse of the translational component (${}^5_6P^{-1}$) and performing cancellations results in Equation 13.

$${}^0_5T' = {}^0_1T * {}^1_2T * {}^2_3T * {}^3_4T * {}^4_5T * {}^5_{5'}R \quad (13)$$

The solution for all six MTA joint angles is possible partially due to the Pieper Solution Method described by Williams [31]. Pieper's solution proved that a closed-form solution to the inverse kinematics exists as long as the 6-DOF robotic manipulator contains at least three consecutive joint axes which intersect. Along with the MTA, most industrial robotic manipulators have this arrangement [31]. In the case of the MTA, the three joint axes which consecutively intersect are the elbow roll, wrist pitch, and wrist roll joint axes. The solution is then split into two parts to solve for all six joint angles. The lower three MTA joints, including torso yaw, shoulder pitch, and elbow pitch, are solved to result in the desired model position. The desired model orientation is achieved by solving for the upper three MTA joints, which includes the elbow roll, wrist pitch, and wrist roll joints [29].

An intermediate step in solving for the lower three MTA joint angles involves a geometric analysis of the torso yaw and shoulder pitch joint offset depicted in Figure 6. For the geometrical calculations, it is assumed that the x-axis of the shoulder pitch reference frame becomes collinear with the x-axis of the wrist pitch reference frame [20]. Unlike the relationship between the torso yaw and shoulder pitch joints in which the axes of rotation are oriented differently, this assumption has no effect on the inverse kinematics because the axes of rotation for both the shoulder pitch and wrist pitch joints are oriented in the same direction.

Based on the assumptions discussed above, Figure 7 below provides a representation of the angles and lengths between the torso yaw, shoulder pitch, and wrist pitch joints.

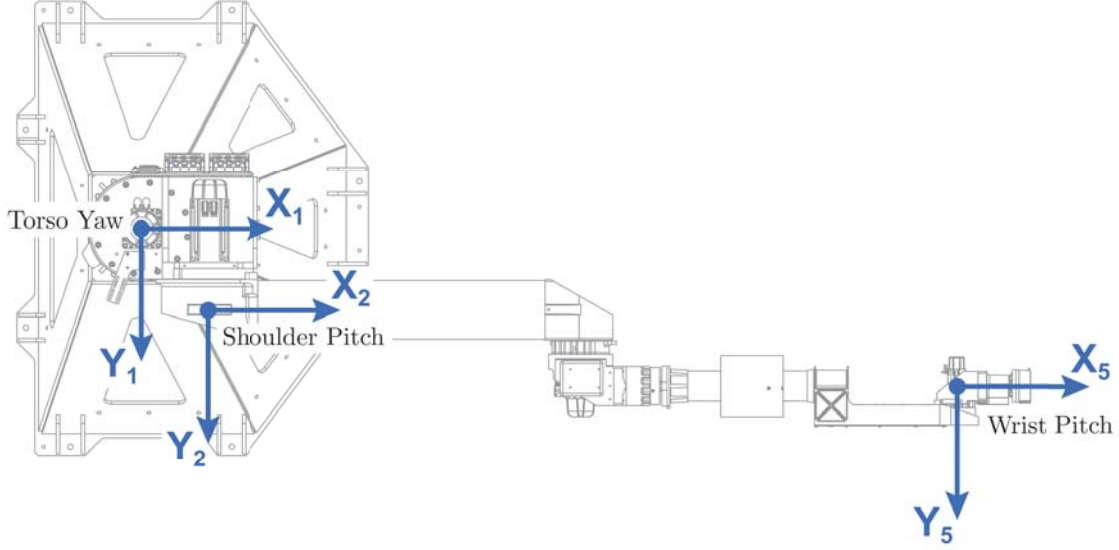


Figure 6. Offset of the shoulder pitch joint from the torso yaw joint in the x-directions and y-directions and location of the wrist pitch joint [9].

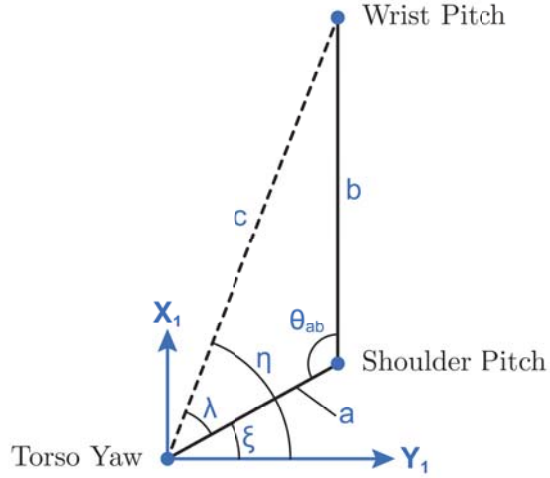


Figure 7. Geometrical definitions of angles and lengths between the torso yaw, shoulder pitch, and wrist pitch joints [29].

Since the location of the shoulder pitch joint is fixed with respect to the torso yaw joint, plus the coordinate change assumption discussed above, length a is calculated with Equation 14. Additionally, length c can be calculated using Equation 15.

$$a = \sqrt{0.2413^2 + (0.2539 + 0.2282)^2} = 0.5391 \text{ meters} \quad (14)$$

$$c = \sqrt{x_{wp}^2 + y_{wp}^2} \quad (15)$$

Where x_{wp} and y_{wp} are the x- and y-locations, respectively, of the wrist pitch reference frame (x_5, y_5, z_5) with respect to the MTA-inertial reference frame (x_0, y_0, z_0) . Next, the angle θ_{ab} is calculated using known lengths between the MTA links, represented by Equation 16.

$$\theta_{ab} = 180^\circ - \tan^{-1} \left(\frac{0.2539 + 0.2282}{0.2413} \right) = 116.589^\circ \quad (16)$$

Length b is calculated using the law of cosines for the triangle of Figure 7, rearranging to equate the terms to zero, and solving the quadratic equation.

$$c^2 = a^2 + b^2 - 2 a b \cos(\theta_{ab}) \quad (17)$$

$$b^2 + (2 a \cos(\theta_{ab})) b + (a^2 - c^2) = 0 \quad (18)$$

$$b = \frac{-(2 a \cos(\theta_{ab})) + \sqrt{4 a^2 \cos^2(\theta_{ab}) - 4(a^2 - c^2)}}{2} \quad (19)$$

The remaining angles of Figure 7 (η , λ , ξ) are calculated from the equations below.

$$\eta = \tan^{-1} \left(\frac{y_{wp}}{x_{wp}} \right) \quad (20)$$

$$\lambda = \cos^{-1} \left(\frac{a^2 + c^2 - b^2}{2 a c} \right) \quad (21)$$

$$\xi = \eta - \lambda \quad (22)$$

The calculated angle above is used to find the x- and y-location of the shoulder pitch frame (x_2, y_2, z_2) , shown in the two equations below, with respect to the MTA-inertial reference frame (x_0, y_0, z_0) .

$$x_{sp} = a \cos(\xi) \quad (23)$$

$$y_{sp} = a \sin(\xi) \quad (24)$$

The torso yaw joint angle can now be calculated from Equation 35 below.

$$\theta_{tr} = -\tan^{-1}\left(\frac{y_{sp} - y_{wp}}{x_{sp} - x_{wp}}\right) \quad (25)$$

To calculate the next two joint angles, shoulder pitch and elbow pitch, the MTA is regarded as a 2-DOF robotic manipulator, temporarily ignoring the remaining MTA joints, reference frames 4-7. Furthermore, the height of the shoulder pitch reference frame, which is the z-direction offset from the MTA-inertial frame, is removed from the transform to account for this distance in the angle computation [29]. This offset is represented by the homogeneous transform in Equation 26.

$$z_{sp} = {}^0_5T'(z) + 1.2764 \text{ meters} \quad (26)$$

Again using the law of cosines, the elbow pitch angle is calculated first, shown in Equation 27. Two solutions are possible with this equation, a positive and negative solution. The positive solution represents an elbow down orientation with the elbow joint positioned below the shoulder joint in the z-direction, while the negative solution represents an elbow up orientation with the elbow joint positioned above the shoulder joint in the z-direction. Since both solutions are viable options for MTA operation, they both are tracked by the software algorithm. Equation 28 calculates the shoulder

pitch joint angle for either solution of the elbow pitch angle calculation. The variable L_1 in the two equations below is the MTA section length from the shoulder pitch reference frame (x_2, y_2, z_2) to the elbow pitch frame (x_3, y_3, z_3) , which is $L_1 = 1.3335$ meters. The variable L_2 is the combined section length from the elbow pitch frame (x_3, y_3, z_3) to the elbow roll frame (x_4, y_4, z_4) , and to the wrist pitch frame (x_5, y_5, z_5) , which is $L_2 = 0.2889 + 1.0572 = 1.3461$ meters.

$$\theta_{ep} = \cos^{-1} \left(\frac{b^2 + z_{sp}^2 - L_1^2 - L_2^2}{2 L_1 L_2} \right) \quad (27)$$

$$\theta_{sp} = \tan^{-1} \left(\frac{-z_{sp}}{b} \right) - \tan^{-1} \left(\frac{L_2 \sin(\theta_{ep})}{L_1 + L_2 \cos(\theta_{ep})} \right) \quad (28)$$

Since the lower three joint angles have been determined up to this step, they can be substituted into the first three transforms (Equations 3 - 5) to form ${}^0_3T$ [20]. The upper three joint angles are represented by the transform ${}^3_5T'$. The equations below demonstrate the method for calculating the transform ${}^3_5T'$, with Equation 31 representing the resulting transformation matrix layout.

$${}^0_5T' = {}^0_3T * {}^3_5T' \quad (29)$$

$${}^3_5T' = {}^0_3T^{-1} * {}^0_5T' \quad (30)$$

$${}^3_5T' = \begin{bmatrix} t_{1,1} & t_{1,2} & t_{1,3} & t_{1,4} \\ t_{2,1} & t_{2,2} & t_{2,3} & t_{2,4} \\ t_{3,1} & t_{3,2} & t_{3,3} & t_{3,4} \\ t_{4,1} & t_{4,2} & t_{4,3} & t_{4,4} \end{bmatrix} \quad (31)$$

The components of the transform ${}^3_5T'$ shown in Equation 31 are used in calculating the final three joint angles in the following equations.

$$\theta_{wp} = \tan^{-1} \left(\frac{\sqrt{(t_{2,1})^2 + (t_{3,1})^2}}{t_{1,1}} \right) \quad (32)$$

$$\theta_{er} = \tan^{-1} \left(\frac{t_{2,1} / \sin(\theta_{wp})}{-t_{3,1} / \sin(\theta_{wp})} \right) \quad (33)$$

$$\theta_{wr} = \tan^{-1} \left(\frac{t_{1,2} / \sin(\theta_{wp})}{t_{1,3} / \sin(\theta_{wp})} \right) \quad (34)$$

Equations for all six joint angles are now defined and can be calculated for any set of desired Cartesian waypoints of the test model. With this understanding of forward and inverse kinematics, desired model trajectories for use in dynamic wind tunnel tests can be effectively designed.

2.4 Dynamic Wind Tunnel Testing

The purpose of dynamic wind tunnel testing is to analyze the dynamic characteristics of a given model in a non-static aerodynamic environment. Measurements from dynamic wind tunnel testing include aerodynamic forces and moments, dynamic pressure, and model orientation [20]. Dynamic test configurations have been widely used in the past to obtain data for evaluating controllability or dynamic stability. These configurations can be described as motion test rigs and can be categorized by forced-motion rigs, free-flying wind tunnel models, or free-motion rigs—each capable of multiple degrees-of-freedom [26].

The MTA is classified as a forced-motion rig, in which wind tunnel models are forced along prescribed trajectories defined by the researcher. Another example of a

forced-motion rig is described in Reference [8]. This 6-DOF rig was used for research on the aerodynamics of unsteady moving aircraft [26].

The captive trajectory system (CTS) at the AEDC is another example of a 6-DOF forced-motion test rig primarily used for store separation testing and conventional sting-mounted force and pressure model testing [13]. Store separation testing ensures any kind of store separates cleanly from the aircraft. Testing with the CTS involves an aircraft model mounted inverted in the wind tunnel with a specific store model mounted on the CTS sting. The store model is positioned relatively close to the aircraft model before it is separated from the aircraft model by moving the CTS along a prescribed trajectory. Figure 8 below presents a multi-exposure image of a CTS store separation test. The CTS is commonly used in two separate wind tunnels at the AEDC, allowing for transonic and supersonic testing [6].

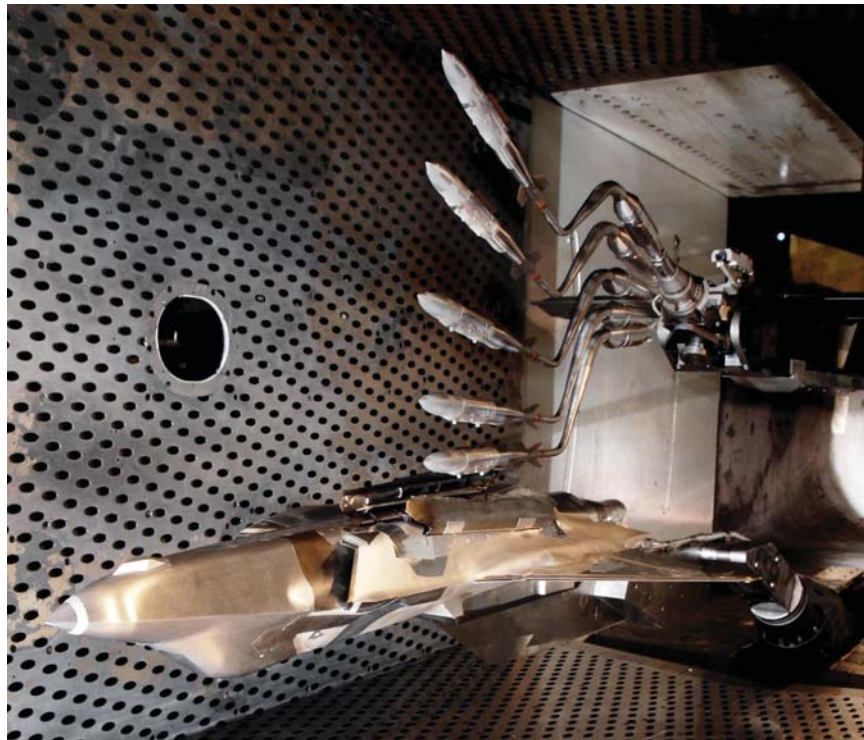


Figure 8. Multi-exposure image of initial F-35 weapon integration testing using the captive trajectory system in the AEDC 4-foot transonic wind tunnel [24].

Ideally, free-flying wind tunnel models would provide the most accurate test results due to the absence of model support structure. However, difficulty arises when attempting to control a free-flying model in a confined space. Furthermore, decreasing the model scale increases the rate of motions [26]. Despite these difficulties, successful free-flight dynamic investigations have been performed as detailed in References [15] and [10].

Finally, free-motion rigs position models in the wind tunnel allowing at least one DOF. The majority of free-motion rigs, due to simplicity, involve a single degree-of-freedom (1-DOF) allowing researchers to control only the pitch or roll motion of the model. One example, described in Reference [27], demonstrated high angle of attack and dynamic rate effects during rapid pitch-up maneuvers [26]. Higher DOF free-motion rigs have been used successfully but are not as prevalent as the single DOF rigs [14], [25]. One such example is a 5-DOF robotic arm used to examine the transition between forward flight and near-hover in fixed-wing vertical-takeoff-and-landing (VTOL) micro air vehicles. The test rig pitched the wing model about the aerodynamic center at constant rates. The theory and operation of this robotic manipulator is much like the methods applied for the MTA [28].

2.5 Experimental Measurements

A variety of experimental measurements are applicable to dynamic wind tunnel testing; the most common being time-accurate aerodynamic forces and moments. Additional measurements include time-accurate pressure measurements as well as position, orientation, and acceleration of the test model. Results from the combination of these measurements provide a quantification of the aerodynamic performance of the model under test.

2.5.1 Aerodynamic Forces and Moments

The measurement of forces and moments acting on a model in a wind tunnel environment is one of the most important components of quantifying the performance of the model [17]. This becomes even more apparent in dynamic wind tunnel tests where the effects of the dynamic motion in particular must be accounted for to analyze only effects of the air flow on the model, most commonly known as dynamic tare runs. Completing a dynamic tare run before and after the test with the wind tunnel operating provides results on the inertial forces and moments due to the motion. Linearly interpolating between the two tare runs results in corrections that can be applied to the tare data. This final tare data is subtracted from the “wind-on” test data during the post-processing step of the analysis [12].

The acquisition of force and moment data requires a force transducer, which measures forces and torques about a defined reference point using a series of strain gauges attached to the sensor’s internal structure. As the force transducer is flexed or twisted, the resistance of the strain gauges change, resulting in a measurable difference in the output voltages being collected once connected through a Wheatstone bridge or similar circuitry [5].

2.5.2 Position, Orientation, and Acceleration Tracking

In prescribed motion tests, it is beneficial to measure and track the movement of the object being tested in order compare the results with the commands sent to the motion test rig. The comparison reveals the accuracy of the motion, or how well the motion follows the prescribed trajectory, as well as the precision or repeatability of the trajectory. A typical free-flying, single DOF simplifies this since the DOF position can be obtained with a single sensor. For complex trajectories, the tracking of this motion is generally accomplished with an Inertial Measurement Unit (IMU). An IMU

generally consists of an accelerometer for measuring triaxial linear accelerations and a gyroscope for measuring Euler angles and angular rates [3]. The combination of these measurements support the verification of the motion and ultimately validates the test.

2.5.3 Time-Accurate Pressure Measurements

The incorporation of time-accurate pressure measurements provides a means for analyzing flow characteristics on or around the wind tunnel model. An ideal location for measuring pressure during testing is the surface of the model. Analysis of the flow region at the model's surface, for example, can provide insight into areas of flow separation. Collecting these measurements requires the pressure transducer to be small and capable of mounting flush with the surface of the model. This is accomplished with the use of piezoresistive materials that vary in resistance when a pressure is applied, either positive or negative [20]. Like the force transducer, the output voltages from the pressure transducer, after passing through appropriate circuitry, change in value depending on the pressures applied to the sensor.

2.6 Summary

This chapter provided a detailed background of the AFIT Low-Speed Wind Tunnel and Motion Test Apparatus coupled system. The sections detailed the necessary reference frames, coordinate transformations, and robot kinematics for appropriately describing the motion of the MTA, with respect to the wind tunnel and inertial reference frame. The chapter also described past research on dynamic wind tunnel testing and the three different types of motion test rigs. Finally, a variety of measurement techniques applicable to dynamic wind tunnel testing was introduced for the purpose of collecting important aerodynamic and kinematic data.

III. Experimental Setup and Methodology

3.1 Motion Test Apparatus Design

The Motion Test Apparatus is an advanced 6-DOF robotic manipulator classified as a forced-motion test rig. The primary purpose of the MTA is to maneuver a wind tunnel model along a desired trajectory within the flow of the wind tunnel test section. This motion is accomplished using a combination of six joint motors, each of which are detailed in this chapter. The size and capabilities of the joint motors were selected based on achieving realistic motions in low Reynolds number wind tunnel flow for wind tunnel models. Each motor receives angular velocity commands from an Elmo[®] controller and contains a digital encoder for joint orientation output [20].

With limited operational space, ensuring the safety of personnel and equipment is essential. This is accomplished using joint rotation limitations, both software and hardware, as well as the installation of a safety fence around the operational space. Multiple emergency shutdown switches are located around the safety fence and next to the MTA control computer. Additionally, the MTA access gate is equipped with an interlock that prevents operation of the MTA if the gate is open [20].

3.1.1 MTA Joints and Hardware

Shown in Figure 9, the six operational joints of the MTA include torso yaw, shoulder pitch, elbow pitch and roll, and wrist pitch and roll. Hardware component descriptions for each joint are provided in Table 1. The torso and shoulder joints each use identical motors, controllers, and gear boxes. These hardware components are the largest and most capable components of the MTA system because of the large amount of torque required to move the remaining MTA links [20]. The torso motor assembly is positioned directly above the origin of the inertial reference system, centered on the

base [29]. As previously mentioned, the torso joint is limited in rotation, using both software and hardware, to $10^\circ \leq \theta_{tr} \leq 20^\circ$. The torso rotation hard stop configuration is pictured in Figure 10.

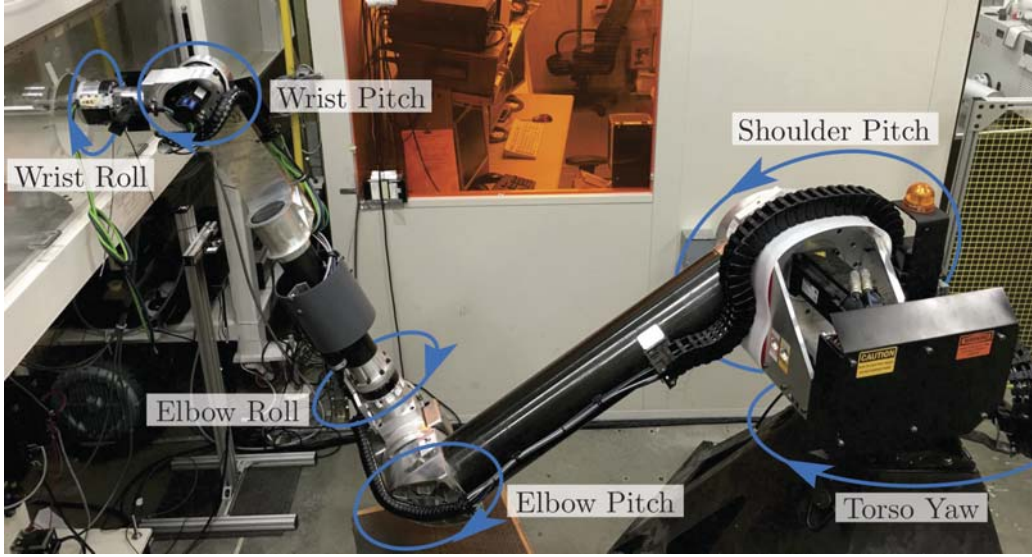


Figure 9. MTA Joint Rotation Axes

Table 1. MTA Joint Hardware Components [29]

Joint	Motor	Controller	Gearbox
Manufacturer:	Kollmorgen ¹	Elmo	Onvio ²
Torso Yaw	AKM65N	Drum HV (G-DRU-A35)	DM10090
Shoulder Pitch	AKM65N	Drum HV (G-DRU-A35)	DM08055
Elbow Pitch	AKM52K	Trombone (G-TRO12)	DN05078
Elbow Roll	AKM22E	Trombone (G-TRO6.1)	DN03055
Wrist Pitch	AKM22E	Trombone (G-TRO6.1)	DN03055
Wrist Roll	AKM22E	Trombone (G-TRO6.1)	DM02015

¹Each BLDC motor includes an EnDat Absolute Encoder

²Zero Backlash

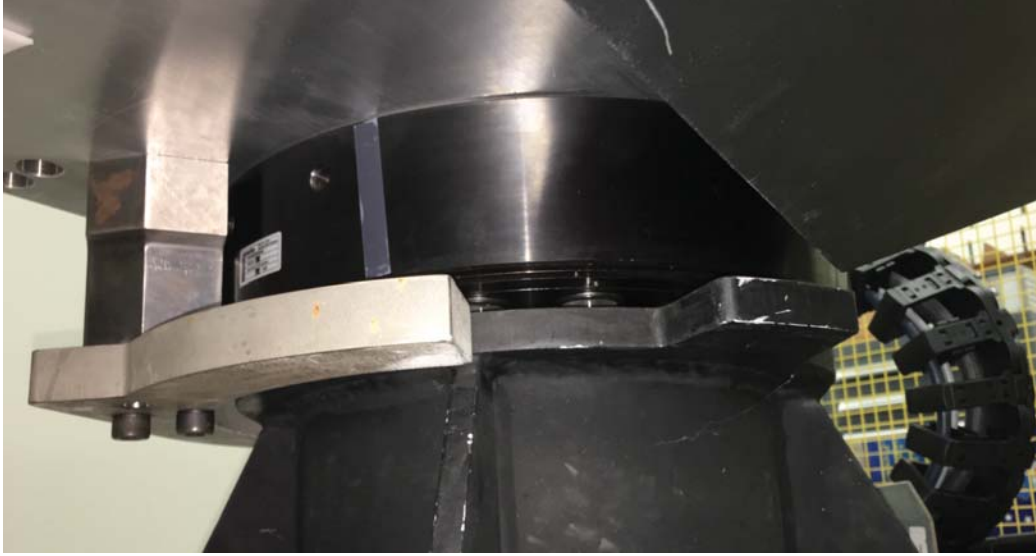


Figure 10. Physical hard stop mechanism to prevent over-rotation.

To ensure sufficient rigidity and to prevent unnecessary link deflections, the MTA is secured to the floor with a large steel base. The base is 46x60 inches at the floor, 32.35 inches tall, and weighs about 1500 pounds. The base is secured to the floor using six leveling bolts to ensure proper orientation and eight concrete bolts, each 6 inches long [20].

The elbow and wrist joints each consist of a motor to control pitch and roll rotations, respectively. The motors that control the elbow and wrist roll rotations are enclosed within the MTA joint while the pitch motors are externally located. The final MTA link, which is directly controlled by the wrist roll motor, contains a mounting interface for securing a sting and model assembly [20].

3.1.2 MTA Control System

The MTA is directly connected to a custom-built computer control unit, referred to as the MTA computer. This control unit, shown in Figure 11, sends angular velocity commands to each joint controller, which in turn, controls each joint motor. The digital encoders, built into the motors, output orientation data for each joint.



Figure 11. MTA Computer Assembly Cabinet

3.1.3 MTA Operation

Proper operation of the MTA system requires the researcher to comply with specific instructions as detailed in the MTA User Manual [29]. This begins with a key turn and then a switch turn on the MTA computer to power on the MTA. After a short time, the researcher is able to log on to the MTA computer using secure shell (ssh) within the terminal on the Linux-powered host computer. Once logged on, the MTA is now ready for operation and commands can be sent to the MTA through the MTA computer.

Following a series of commands to prepare for trajectory execution, a trajectory file is loaded on the MTA computer. This trajectory file is formatted into seven

columns containing a time step column in seconds, three coordinate position columns (X, Y, Z) in meters, and three orientation columns (ϕ , θ , ψ) in radians. A sample section of a trajectory file is provided in Figure 12.

Time	X	Y	Z	Phi	Theta	Psi
0.0000	-0.0640	-2.5120	-1.7930	0.0000	0.0000	-1.6718
0.0080	-0.0640	-2.5110	-1.7930	0.0000	0.0000	-1.6718
0.0160	-0.0640	-2.5100	-1.7930	0.0000	0.0000	-1.6718
0.0240	-0.0640	-2.5090	-1.7930	0.0000	0.0000	-1.6718
0.0320	-0.0641	-2.5079	-1.7930	0.0000	0.0000	-1.6718
0.0400	-0.0641	-2.5069	-1.7930	0.0000	0.0000	-1.6718
0.0480	-0.0642	-2.5059	-1.7930	0.0000	0.0000	-1.6718
0.0560	-0.0642	-2.5049	-1.7930	0.0000	0.0000	-1.6718
0.0640	-0.0643	-2.5030	-1.7930	0.0000	0.0000	-1.6718
0.0720	-0.0644	-2.5029	-1.7930	0.0000	0.0000	-1.6718
0.0800	-0.0645	-2.5019	-1.7930	0.0000	0.0000	-1.6718

Figure 12. Sample section of a trajectory file. Column headers are for reference only.

Each row of the trajectory file specifies the desired location and orientation of the wind tunnel model at a time step of 0.008 seconds. Once the trajectory file is loaded, a command is sent to “home” the model, positioning it at the first point of the trajectory file. The trajectory can then be executed as described in the MTA User Manual.

During operation, the researcher must pay close attention to the movements and be prepared to press the emergency stop switch if undesired motions occur that might lead to damage of equipment. The MTA computer is also recording joint angle and joint angular velocity command data at each time step. At the conclusion of motion, the MTA computer disables the joint motors, engages the joint brakes, and saves forward kinematic data to memory. This data must then be copied to the host computer for reference and analysis.

3.2 Model Support Sting and Experimental Models

The model support sting for interfacing between the MTA and a model was originally designed with the objective of taking force and moment measurements relative

to the quarter-chord, or aerodynamic center, of a wing model. The design proved to be remarkably useful for performing pitch oscillation and pitch-plunge oscillation experiments [20]. The sting design is shown in Figure 13 below.



Figure 13. Model support sting with F/T transducer interface (right).

The base plate attaches securely to the end of the MTA interface plate with 1/4"-20 socket head bolts. The model connection point at the end of the sting is designed to interface with the ATI Nano25 Force/Torque Transducer. An extruded pin on the sting ensures proper orientation and connection of the Nano25.

Previous research with the sting by Lancaster used solely the wrist roll motion of the MTA to perform the pitch oscillations about the quarter-chord of the wing model. This was possible due to the alignment of the MTA wrist roll axis with the wing quarter-chord. Detailed dimensional drawings for the sting and each model discussed below are provided in Appendix C.

3.2.1 NACA 0012 Wing Model

The NACA 0012 wing models used in testing were based on a design by Lancaster for performing the pitch oscillation maneuvers [20]. Two models were manufactured initially, one for interfacing directly with the aforementioned sting and the second for interfacing with a force transducer. Research by Lancaster was based on the first model. However, for the purposes of the current research, the second model is ideal due to force transducer compatibility. This model is pictured in Figure 14.

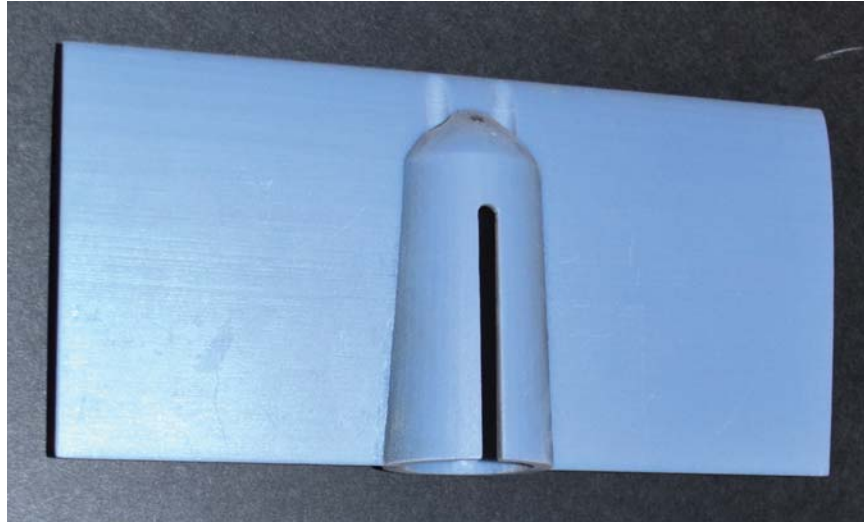


Figure 14. NACA 0012 wing model for interfacing with the Nano25 force balance [20].

Additionally, a third NACA 0012 wing model was made to interface with the wind tunnel force balance. Because of design differences in each transducer, the designs of the wing model varied slightly, although the primary wing geometry remained identical. Each wing has an 8-inch wing span and 4-inch chord length. The force balance interface within the fuselage section is located at the quarter-chord of the wing to simplify post-processing as pitch moment measurements are in reference to the quarter-chord. The third wing model is pictured in Figure 15.

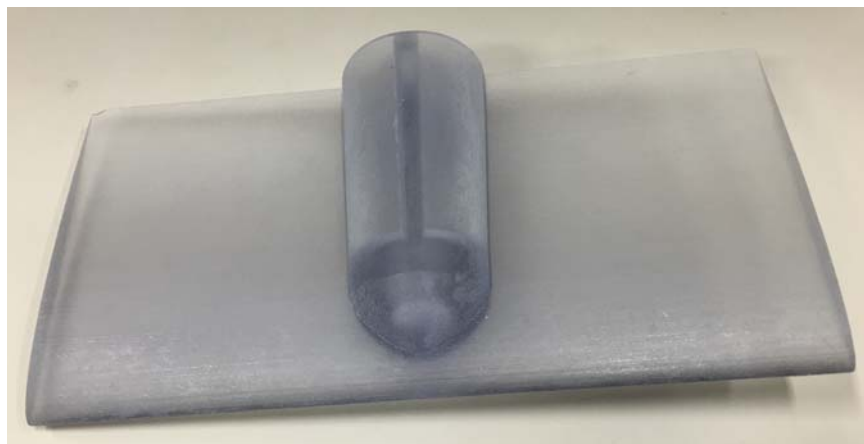


Figure 15. NACA 0012 wing model for interfacing with the AFIT force balance.

3.2.2 Missile Model for Store Separation

To perform weapon store separation experiments, a small missile model was created to interface with the Nano25 force balance and model support sting. Additionally, the missile model was sized to fit inside a previously manufactured mock weapon bay. Because of these sizing limitations, the missile model does not accurately represent any existing weapons system. The model is 9.25 inches in length and 1.29 inches in diameter. Figure 16 below shows the missile body and interface access plate.

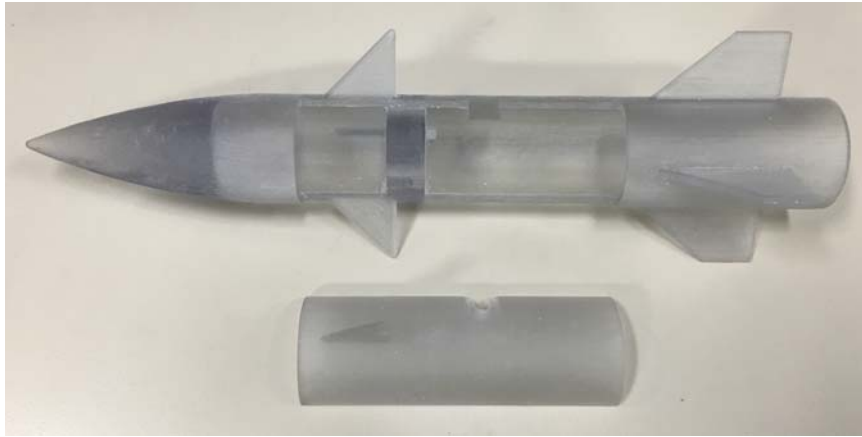


Figure 16. Small missile model (top) with interface access plate (bottom) detached.

3.3 Sensors and Measurements

A variety of measurements are of interest when performing dynamic wind tunnel tests. Aerodynamic force and moment measurements are among the most important and are obtained with a force/torque (F/T) transducer. Measurements of acceleration and orientation tracking are also essential, and this is obtained herein with an inertial measurement unit (IMU). Finally, time-accurate local pressure measurements are useful for additional aerodynamic analysis. The following sections detail each of these measurements and the sensors used to obtain the data.

3.3.1 Force/Torque Transducer

In order to acquire aerodynamic force and moment measurements for a variety of experimental wind tunnel tests, both static and dynamic, a robust and highly capable force transducer was required. Manufactured specifically for robotic applications, the ATI Nano25 F/T Sensor offers all desired capabilities. Pictured in Figure 17, the Nano25 is one of the smallest 6-axis transducers currently available. For its size, it is an extremely high strength sensor due to the electrical discharge machining (EDM) wire-cut manufacturing process. Using this process with high yield-strength stainless steel, single-axis overload values are significantly greater than rated capacities [2].



Figure 17. Nano25 F/T Sensor, model interface shown [2].

Internally, the Nano25 uses silicon strain gauges, instead of commonly used foil gauges, to provide a much larger signal strength and to maximize noise reduction, resulting in a high signal-to-noise ratio [2]. Table 2 below lists the technical specifications of the Nano25 F/T sensor. In the table, the variables Fx , Fy , and Fz represent forces in the x-, y-, and z-directions, respectively. Variables Tx , Ty , and Tz represent torques about the x-, y-, and z-axes, respectively. Finally, the variable Fxy denotes any combination of forces in the x- and y-directions and the variable Txy denotes any combination of torques about the x- and y-axes [2]. These coordinates and their relation to the wind tunnel and test models are discussed later in this section.

Table 2. Nano25 F/T Sensor Technical Specifications [2]

Calibration Specifications		
	Sensing Ranges	Resolution
Fx, Fy	25 lbf	1/224 lbf
Fz	100 lbf	3/224 lbf
Tx, Ty	25 lbf-in	1/160 lbf-in
Tz	25 lbf	1/320 lbf-in
Single-Axis Overload		
Fxy	±520 lbf	
Fz	±1600 lbf	
Txy	±380 lbf-in	
Tz	±560 lbf-in	
Physical Specifications		
Weight	0.14 lb	
Diameter	0.984 in	
Height	0.85 in	

Additional specifications such as data output rates and measurement units are dependent on the specific data acquisition hardware and setup. These types of specifications are detailed in the data acquisition system section.

An important part in using force transducers is understanding the defined coordinate reference frame for the sensor. The Nano25 uses a standard right-hand coordinate system with the sensing reference frame origin centered on the surface of the model interface plate, with the positive z-axis oriented normal to this surface. A detailed dimensional drawing of the Nano25 transducer is provided in Appendix C showing the specific orientation of each coordinate axis.

Understanding the orientation of the Nano25 coordinate system in relation to the wind tunnel and test models ensures the aerodynamic forces and moments are calculated correctly. In the majority of dynamic wind tunnel tests performed with the MTA and AFIT wind tunnel system, the orientation of the Nano25 is consistent. Figure 18 below displays the Nano25 sensing coordinate reference frame.

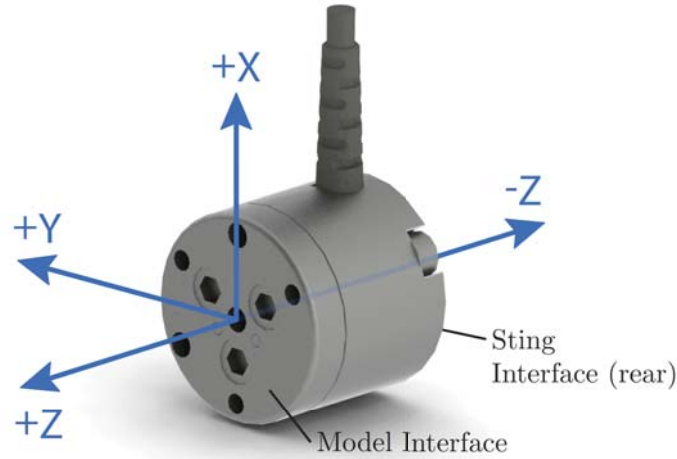


Figure 18. Nano25 Coordinate Reference Frame (CAD model acquired from ATI-IA)
[2]

The Nano25 sting interface and desired orientation of the model interface governed the design of the model support sting as discussed previously in this section. With regard to the MTA-model reference frame of Figure 2 in Section 2.1, as well as the location of the MTA in relation to the wind tunnel, the positive z-axis on the Nano25 was aligned in the negative y_m -direction. The positive y-axis on the Nano25 was

aligned in the negative z_m -direction, resulting in the Nano25 positive x-axis in alignment with the positive x_m -axis. With zero rotation angles, x_b aligned with x_w of the wind tunnel, the Nano25 reference frame is oriented +90 degrees about the y_m -axis. This default orientation of the Nano25 results in $+Fx$ forces representing model lift, $+Fy$ forces representing side force, and $-Fz$ forces representing model drag. Additionally, $-Tx$ torque represents positive yaw moment, $+Ty$ torque represents positive pitch moment, and $+Tz$ torque represents positive roll moment.

Flexibility in how the Nano25 is mounted can result in different coordinate frame orientations specific to the individual experimental setup. Sections included later in this chapter describe each experimental setup in detail, including whether the orientation of the Nano25 is different from the relations described above.

3.3.2 Inertial Measurement Unit

To verify and track dynamic movements of the MTA during operation, an inertial measurement unit is used. The nature of the experiments require a small sensor with exceptional capabilities and accuracy. The MicroStrain[®] 3DM-GX1[™] IMU successfully used by Lancaster was upgraded in order to reduce the size with the intention of mounting it directly upon a model as well as to increase the sample rate. The MicroStrain[®] 3DM-GX4-15[™] is an industrial-grade micro IMU. It contains a triaxial accelerometer and gyroscope with on-board processors running an Adaptive Kalman Filter (AKF) to take high quality static and dynamic measurements [3]. The IMU is pictured in Figure 19 and specifications are listed in Table 3. A major improvement from the 3DM-GX1[™] is that the data output rate of the 3DM-GX4-15[™] reaches 1000 Hz.



Figure 19. MicroStrain® 3DM-GX4-15™ IMU [3]

Table 3. 3DM-GX4-15™ IMU Technical Specifications [3]

	Accelerometer	Gyroscope
Range	± 5 g	$300^\circ/sec$
Resolution	<0.1 mg	$<0.008^\circ/sec$
Bias Instability	± 0.002 g	$\pm 0.05^\circ/sec$
Sampling Rate	4 kHz	4 kHz
Data Output Rate	1 Hz to 1000 Hz	
Dimensions	36.0 x 24.4 x 11.1 mm	
Weight	16.5 grams	

3.3.3 Dynamic Pressure Transducers

Taking dynamic pressure measurements at any location in the experimental setup requires a relatively small sensor. For this research, up to four Endevco Model 8515C-15 piezoresistive pressure transducers and one Kulite XTL-190-15A ruggedized pressure transducer will be used that can measure absolute pressure. Figure 20 shows the Endevco transducer flush mounted in Lancaster’s experimental wing model. The Endevco transducer is 6.30mm in diameter, 0.76mm in thickness, can be sampled at up to 180 kHz, and has a range from 0 to 15 psia. Figure 21 shows the Kulite transducer installed in the internal aft section of the small weapons bay. Refer to Figure 29 for a detailed image of the adaptor that positions the pressure transducer

in the bay. The sensing portion of the Kulite transducer is 3.8mm in diameter and the entire unit, up to the cable, is 21.3mm long. The data sampling rate is dependent on the data acquisition hardware and the pressure sensing range is 0 to 25 psia.

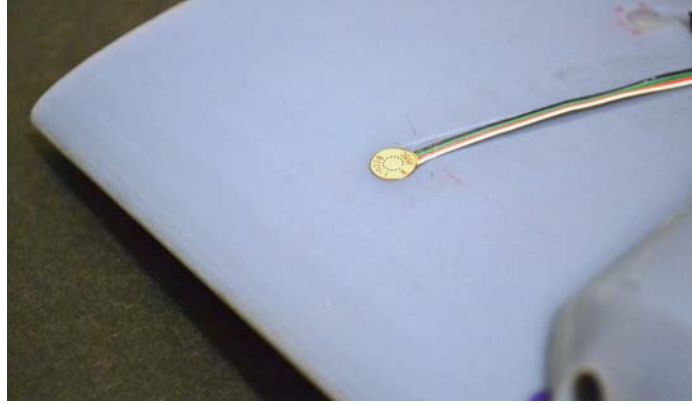


Figure 20. Endevco Model 8515C-15 pressure transducer installed on wing model [20].

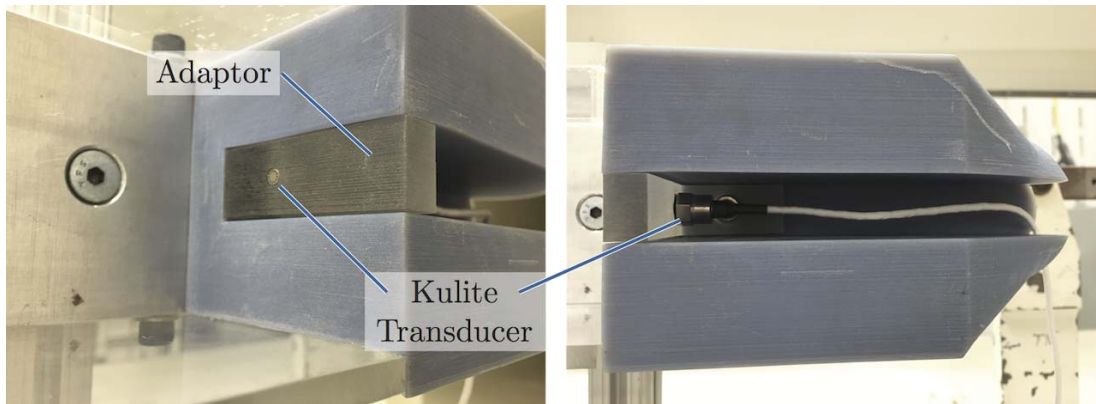


Figure 21. Kulite XTL-190-15A pressure transducer installed in adaptor in small weapons bay.

3.4 Real-Time Data Acquisition

A principal objective of this research is to obtain time-accurate force and moment measurements on a wind tunnel model during testing. A significant resource in reaching this level of data acquisition is the use of Real-Time data acquisition software and equipment manufactured by National Instruments (NI). The NI LabVIEW Real-Time

module enables a user to create graphical programs that can be loaded and reliably executed on embedded hardware devices.

The following sections describe in detail the setup of the data acquisition (DAQ) system, both hardware and software. Screenshots of the graphical program sets developed for this research are provided in Appendix B.

3.4.1 DAQ System Hardware

Figure 22 shows the complete DAQ system setup with connected sensors and model support sting. Each hardware component is described below.

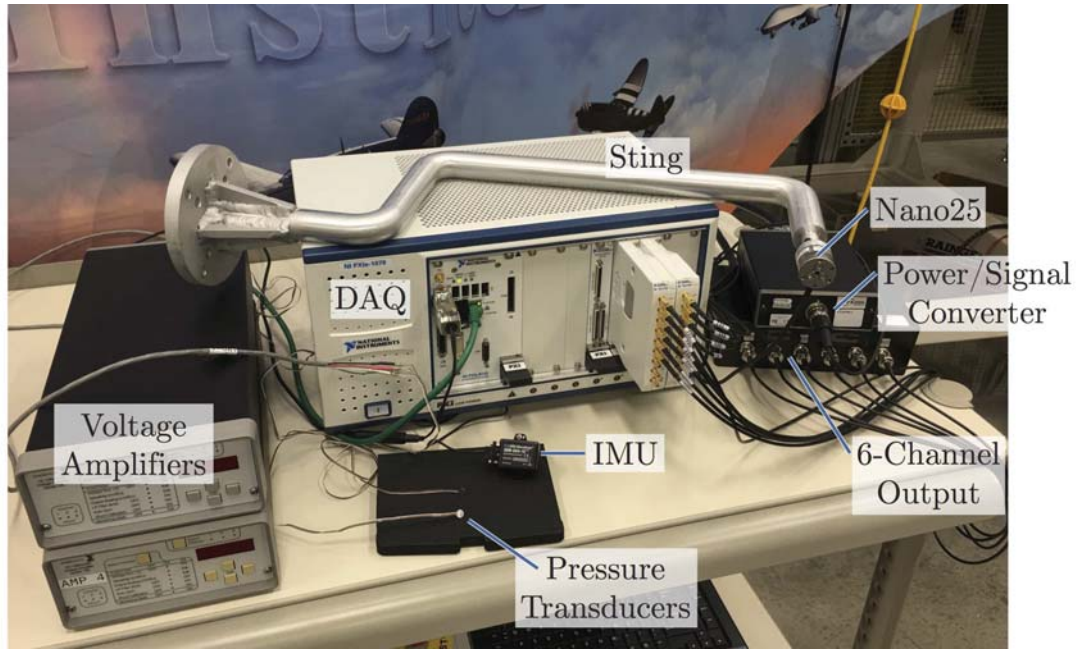


Figure 22. Complete DAQ System hardware with sensors and sting.

The primary component of the DAQ system, which is connected directly to the computer by Ethernet, is the PXIe-8133 Embedded Controller, labeled in Figure 23. This controller includes a built-in hard drive and operating system and acts as a remote system for the advanced real-time data acquisition this research entails. The controller is installed in a PXIe-1078 chassis which enables communication with other

DAQ cards installed. Installed in slot numbers 6 and 7 of the chassis are two PXI-6123 DAQ cards, hidden in Figures 22 and 23 due to installed hardware. These DAQ cards provide an interface for installing two TB-2709 terminal blocks which provide direct connections to individual analog input wires for acquiring raw voltage signals.

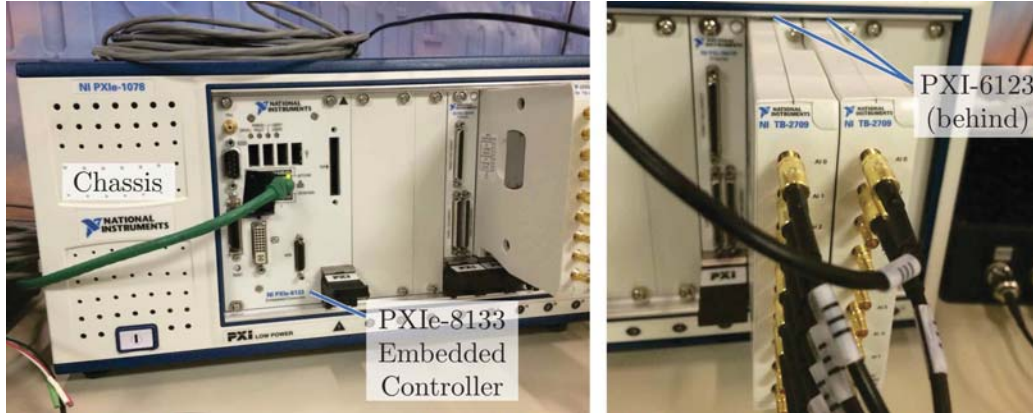


Figure 23. Front Instrument Interface of DAQ Hardware

To communicate between the Nano25 force transducer and the embedded controller, ATI-provided hardware was necessary. The Nano25 sensor connects directly into the signal converter box, which also provides power to the internal sensor electronics. A long cable from this signal converter box connects to the 6-Channel output box which splits the six channels from the Nano25 (F_x , F_y , F_z , T_x , T_y , T_z) into individual analog voltage wires. It is these wires that connect to the input connectors of the TB-2709 terminal block providing six separate signals to analyze with the NI LabVIEW software.

The pressure transducers communicate in a similar manner as the Nano25 sensor. Each pressure transducer contains four small wires, two wires for input signals (+ & -) and two wires for output signals (+ & -). The four wires are connected to a custom RS-232 cable for interfacing with an Endevco® Model 136 DC Differential Voltage Amplifier. The voltage amplifier supplies the pressure transducer with a 10V excitation signal, the output is filtered with a 10 kHz low-pass filter and the signal is

amplified to output a 200mV/psi analog voltage signal [20]. This amplified signal is collected by the NI LabVIEW software for analysis and conversion.

The inertial measurement unit (IMU) connects directly to the PXIe-8133 embedded controller using a standard RS-232 serial port. The IMU communicates with the NI LabVIEW software much differently than the analog voltage signals of the Nano25 sensor. The basic concept for communication requires commands to be sent from the software to the IMU for data collection setup and once the commands are executed onboard the IMU, the IMU sends data packets back to the software program, which must be interpreted.

3.4.2 NI LabVIEW Graphical Program Overview

The LabVIEW graphical program environment provides a user-friendly method for writing code compared to traditional line-by-line writing. Instead of writing lines of code to perform computer or instrument tasks, a user arranges a series of functions in a block diagram format, including connectors between the functions, quickly creating an effective program for data acquisition purposes. Based on the block diagram, LabVIEW automatically and internally generates the code required to perform the functions. The majority of programs are contained within a file referred to as a 'VI', or 'Virtual Instrument', with a '.vi' extension. Each VI includes a block diagram environment for editing and debugging the code and a front panel editor for operating the VI code. The front panel can feature items such as switches, indicators, charts, digital or analog data displays, and VI controls, among many other items. A large assortment of functions are available for developing the data acquisition system to meet requirements.

Organized below is an overview of the methods used to create the DAQ system specifically for acquiring data from the various sensors. Based on the type of output

signals from the sensors, which were discussed above, two separate VIs are used that can run concurrently. The first VI acquires analog signals from the Nano25 force transducer and pressure transducers. The second VI, which contains an extensive library of subVIs, sends and receives information from the IMU.

Nano25 and Pressure Transducer VI

The layout of the entire front panel and block diagram for this VI is provided in Appendix B, Figures 111 - 115. The design of this VI is based loosely on the Producer/Consumer design pattern, which is a pattern primarily used to decouple data acquisition processes that collect data at different rates. In a Producer/Consumer design pattern, parallel loops run concurrently, with one loop producing or collecting the data and the other loop consuming or manipulating the data [1]. However, in the Nano25 and Pressure transducer VI, this design pattern was modified to instead include two producer loops which manipulate the data within the loop itself instead of a separate consumer loop. One loop collects and processes the Nano25 voltage data and the other loop collects and processes the pressure transducer voltage data. This design maintains the ability to collect data from each sensor at different rates.

Acquiring signals from the Nano25 begins with the DAQmx program which is a supplement to LabVIEW that enhances the data acquisition process. Incoming voltage signals from the Nano25 are formatted by the DAQmx program as Analog 1D Waveform signals and are sampled at 1 kHz. The voltage waveform signals are both written to file for reference and converted to user-specified units of force and torque. The signal conversion process depends on a SubVI that calculates a calibration matrix based on the specified units and a SubVI that applies a tool transform to ensure measurements are referenced correctly. Also included in the program is the ability to acquire the bias load from the Nano25 in order to define a zero-load orientation which

is subtracted from the voltage signals before conversion. The calibration matrix, specific only to the current Nano25 transducer (FT1570), is multiplied by the biased voltage signals and passed through a moving average smoothing filter to reduce signal noise. Finally, the filtered force and torque measurements are written to file for post-processing.

For the pressure transducer signals, the DAQ Assistant Express VI was used, which is a contained VI function that performs the processes of the DAQmx. Using the DAQ Assistant restricts some customization of the data acquisition program compared to DAQmx, however, it performs similarly to the DAQmx format. The DAQ Assistant was placed in a Timed Loop and sampled the pressure transducer voltage signals at 10 kHz. The signals are then written to file for post-processing.

MicroStrain[®] 3DM-GX4-15[™] IMU VI

The acquisition of data from the IMU required modification of LabVIEW sample code designed for the 3DM-GX3[®]-25 IMU, which was obtained from the manufacturer. At the time of writing, no manufacturer-developed LabVIEW code exists for the 3DM-GX4-15[™] IMU model. To accompany the descriptions of the code below, screen shots of the most relevant VIs in the code are provided in Appendix B.

The series of VIs for handling IMU communications is controlled by a primary host VI (Figure 120). The host VI uses a series of While Loop structures and Timed Loop structures with varying priorities to send commands and receive information from the IMU. Priorities of Timed Loops specify the order of execution relative to other functions and loops. Two While Loops control the tasks of sending messages to the IMU and distributing incoming messages from the IMU.

The prioritized Timed Loops handle the interpretation of incoming messages, resulting in the desired data. The high priority loop runs with a one-millisecond period

and handles the Attitude and Heading Reference System (AHRS) data, or the orientation of the sensor. Moderate loops, running with ten-millisecond periods, handle data sets from additional sensor features. For the 3DM-GX4-15TM, the moderate priority loops are not configured or needed in the current iteration of the code, however, these loops can be used to handle additional output data from the iMU such as angular rates. Finally, the low priority loop, with a 100-millisecond period, handles the command responses.

3.5 Setup of Wind Tunnel Experiments

The following sections, in order, describe the setup of various wind tunnel experiments performed for this research. The initial wind tunnel tests were static tests using the NACA 0012 8-inch-span wing model. Next, wind tunnel tests were performed with the small weapons bay in an attempt to analyze the resonance of the bay. The final tests were dynamic wind tunnel tests including both pitch oscillation and pitch-plunge oscillation.

3.5.1 Static Test of NACA 0012 Wing Model with AFIT Balance

In order to analyze and compare results from the Nano25 force balance, a static wind tunnel test was performed using the AFIT-3 force balance and existing data acquisition system. The AFIT-3 force balance is the primary balance used for traditional sting mounted tests in the AFIT Low-Speed Wind Tunnel. Tests were performed at wind speeds of 60 mph and 120 mph, with an angle-of-attack sweep from -5 degrees to +20 degrees. Post-processing of the results was performed using existing MATLAB code developed by previous AFIT students and widely used in AFIT courses and research. The results from this test are provided in Chapter IV.

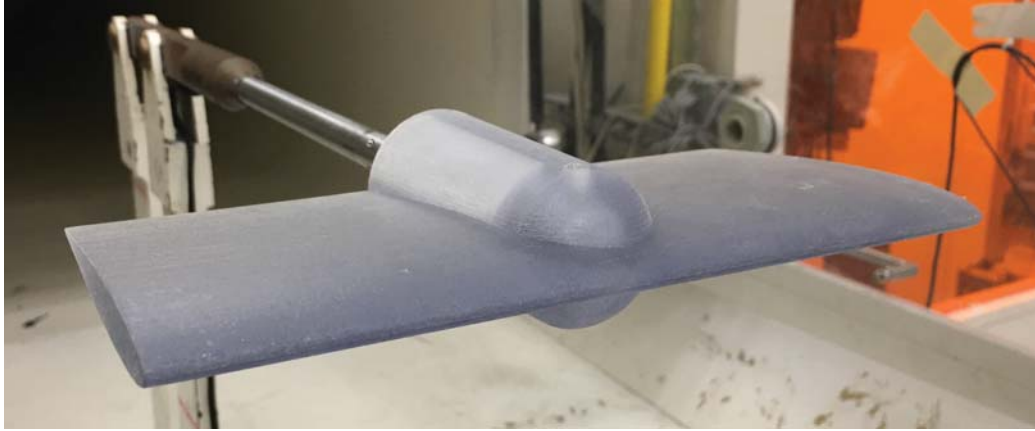


Figure 24. NACA 0012 wing model mounted to the AFIT-3 force balance for static wind tunnel testing.

3.5.2 Static Test of NACA 0012 Wing Model with Nano25 Balance

The next step in the comparison was statically testing the NACA 0012 wing model with the Nano25 and model support sting. To eliminate any adverse effects from mounting the wing model to the MTA, such as disturbances from the open test section port access or deflections in the MTA links, the model and sting were mounted as pictured in Figure 25. This ensured that the comparison between the two tests was as identical as possible, apart from the sting. The angle-of-attack of the model was adjusted manually and measured several times with a digital level, with respect to the tunnel floor, to achieve the desired angle within ± 0.02 degrees.

Shown in Figure 26, the cable from the Nano25 exited from the lower surface of the wing model and was attached to the back of the sting out of the airflow, down the support structure, and out the floor of the wind tunnel. The signal converter box was mounted to a rack placed under the wind tunnel test section so the cable could fasten to the box without an extension.

Aerodynamic force and moment results from this test are compared with results from the AFIT force balance test in Chapter IV.



Figure 25. NACA 0012 Wind Tunnel test rig for taking measurements from the Nano25 at various angles of attack.



Figure 26. Rear of NACA 0012 wing model showing cable exit and path along sting.

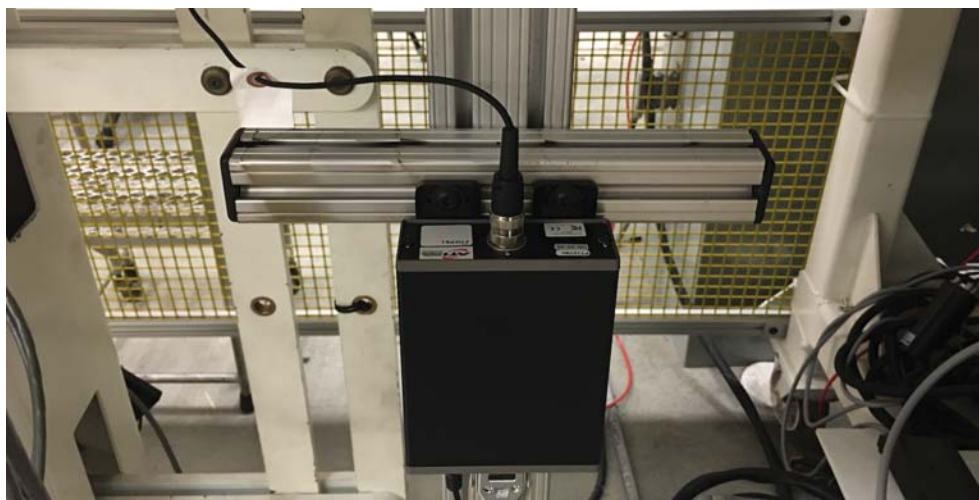


Figure 27. Signal converter box mounted to rack under wind tunnel test section.

3.5.3 Resonance Test of Small Weapons Bay

In preparation for store separation wind tunnel testing, the small weapons bay, pictured in Figure 28, was mounted in the wind tunnel in an attempt to measure the pressure power spectrum of the cavity. The Kulite pressure transducer was installed in the aft interior surface of the bay as this location was expected to experience the greatest fluctuation in pressure within the cavity. Initially, the transducer was centered on the aft surface, however, it was moved within 0.25 inches from the outside edge of the opening. The change was made in an effort to detect a stronger signal from any resonance occurring in the cavity. The pressure transducer adapter for mounting in the aft surface of the bay is pictured in Figure 29.



Figure 28. Installation of the small weapons bay for resonant frequency testing (shown with old Kulite transducer adaptor).



Figure 29. New adaptor for installing Kulite pressure transducer in rear surface of the small weapons bay.

To measure and collect the pressure power spectrum, the Kulite pressure transducer was connected to the voltage amplifier and then to an Agilent 35670A Dynamic Signal Analyzer, pictured below. At each wind speed, the signal was averaged 30 times then saved for post-processing. Results from this test are discussed in Appendix A.



Figure 30. Agilent 35670A Dynamic Signal Analyzer used for resonant testing.

3.5.4 Pitch Oscillation Test of NACA 0012 Wing Model with Nano25

The first dynamic wind tunnel test performed for this research was a pitch oscillation motion. The NACA 0012 wing model designed by Lancaster [20] was used for this test because it was adapted for the Nano25 interface. Additionally, the 3DM-GX4-15TM IMU was mounted on the sting for secondary motion verification. The uploaded trajectory file was also created by Lancaster for similar dynamic tests with flush mounted pressure transducers. The trajectory was a 1.5 Hz sinusoidal oscillation from a -25 to +25 degree pitch angle, starting from level. The test motion was conducted for 15 seconds with force and moment data and IMU data continually collected. Furthermore, the same oscillation test was performed at tunnel wind speeds of 0, 30, 60, 90, and 120 mph. Figure 31 below shows the starting position for this dynamic test.

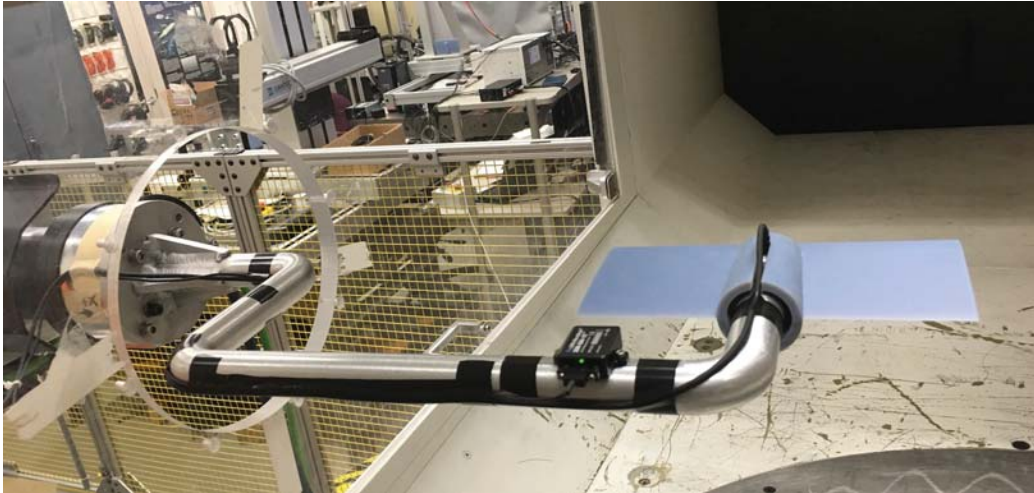


Figure 31. Starting position for pitch oscillation dynamic motion test.

Ensuring minimal interference to the airflow by the sensors is ideal, however, with the current state of equipment, the Nano25 cable protrudes from the wing model and the IMU is mounted on the sting behind the wing. Securely routing the sensor cables is also important to prevent damage by the high flow speeds. Figure 32 shows the routing of the cables along the sting.



Figure 32. Detail of cable routing on back of sting.

3.5.5 Pitch-Plunge Oscillation Test of NACA 0012 Wing Model with Nano25

The second dynamic motion performed was a pitch-plunge oscillation test. The experimental setup was identical to the pitch oscillation test discussed above, however, the IMU was not prepared for testing, therefore no motion verification was performed for this test. The trajectory file for this test was also created by Lancaster for similar dynamic tests. It involved a 1 Hz pitch oscillation from -20 to +20 degree pitch angles, with the model pitch angle starting from +25 degrees. The plunge motion also oscillated with a frequency of 1 Hz with a vertical distance of about 7 cm. At the peak or valley of every plunge, the pitch angle of the model was zero, representing a plunging motion rather than a flapping motion. Figure 33 shows the starting position of the wing model at +25 degrees in pitch.

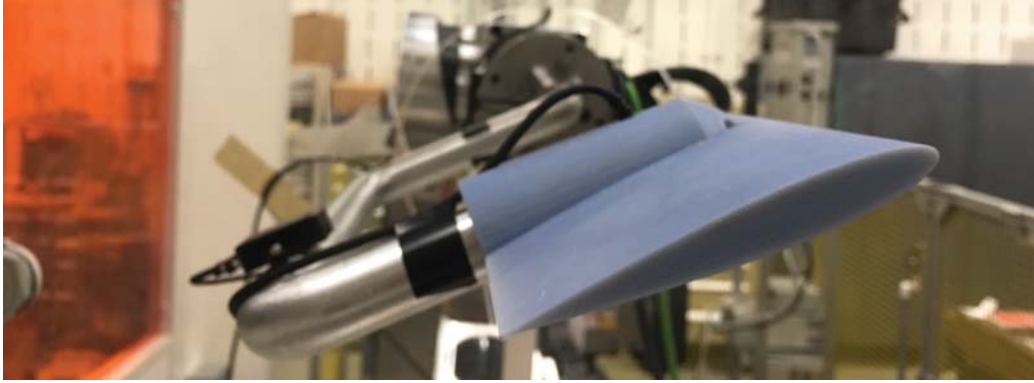


Figure 33. Starting position for pitch-plunge oscillation dynamic motion test.

3.6 Summary

This section discussed the experimental setup for this thesis research. Specifically, the design and operation of the MTA was presented, the model support sting and experimental models were described in detail, and the various sensors used were described. The majority of the effort applied to this research revolved around the setup of the data acquisition hardware components and development of the NI LabVIEW graphical program. This section described in detail each of the important components of the complete data acquisition system. The final portion of this chapter was the description of the various wind tunnel experiments performed in order to test and verify the data acquisition system. Table 4 provides a compact summary of each test performed and results from these static and dynamic tests are presented in the next chapter.

Table 4. Summary of tests performed, commanded trajectories, measured quantities, and sensors.

Static Test, NACA 0012 Variable Pitch	
Input	Flow speed: 60 mph, 120 mph; -5° to 20°
Measurement	Forces/Moments
Equipment	NACA 0012 model, AFIT-3 balance
Static Test, NACA 0012 Variable Pitch	
Input	Flow speed: 60 mph, 120 mph; -5° to 20°
Measurement	Forces/Moments
Equipment	NACA 0012 model, Nano25 balance
Static, Small Bay Resonance Test	
Input	Flow speed: 0-120 mph
Measurement	Pressure power spectrum
Equipment	Small bay, Kulite pressure transducer, Agilent 35670A
Dynamic Test, Pitch Oscillation	
Input	Pitch trajectory: 1.5Hz, 15 sec, $\pm 25^\circ$, 0-120 mph
Measurement	Forces/Moments, Euler Angles
Equipment	NACA 0012 model, Nano25 balance, 3DM-GX4-15 TM IMU
Dynamic Test, Pitch-Plunge Oscillation	
Input	Pitch-Plunge trajectory: 1.0Hz, 15 sec, $\pm 20^\circ$, 0-120 mph
Measurement	Forces/Moments
Equipment	NACA 0012 model, Nano25 balance

IV. Results

The following sections provide experimental results and analysis from the various wind tunnel tests, both static and dynamic, performed in order to establish the data acquisition system. The static results are analyzed and compared with data known to be accurate based on experimental and data acquisition methods widely used in AFIT courses and previous thesis research. The initial wind tunnel test using the developed data acquisition system evaluated the performance of the Nano25 force balance in comparison to the AFIT-3 force balance, with the control as a NACA 0012 wing model. Dynamic testing was performed with the same wing model, which included pitch oscillation testing and pitch-plunge oscillation testing. Reporting of the peak measured forces is important for ensuring loads are within the Nano25 sensing ranges and for understanding the effect of equipment noise on the results. Results from the resonance testing of the small weapons bay are also presented.

4.1 Static Test of the NACA 0012 Wing Model

Provided in Figures 34 to 41 are the experimental results from static wind tunnel tests performed with the NACA 0012 wing models. The tests were performed using both the Nano25 F/T transducer and the AFIT-3 force transducer. Results from these two transducers are compared from -5 to +25 degree pitch angles and at 60 and 120 mph flow speeds. Lift and drag coefficient results are also provided for the 120 mph test case.

Figures 34 and 35 show aerodynamic lift measurements for the 60 mph and 120 mph test cases, respectively. Individual values show slight errors and the trends show slight deviations, possibly attributable to imprecision in the angle measurements or small differences between the two wing models. The lift curve slopes for each

case are identical, verifying that the developed data acquisition system is performing properly. The values plotted for the Nano25 force transducer are averaged values from 10 seconds of data at an input rate of 1 kHz, a total of 10,000 data points.

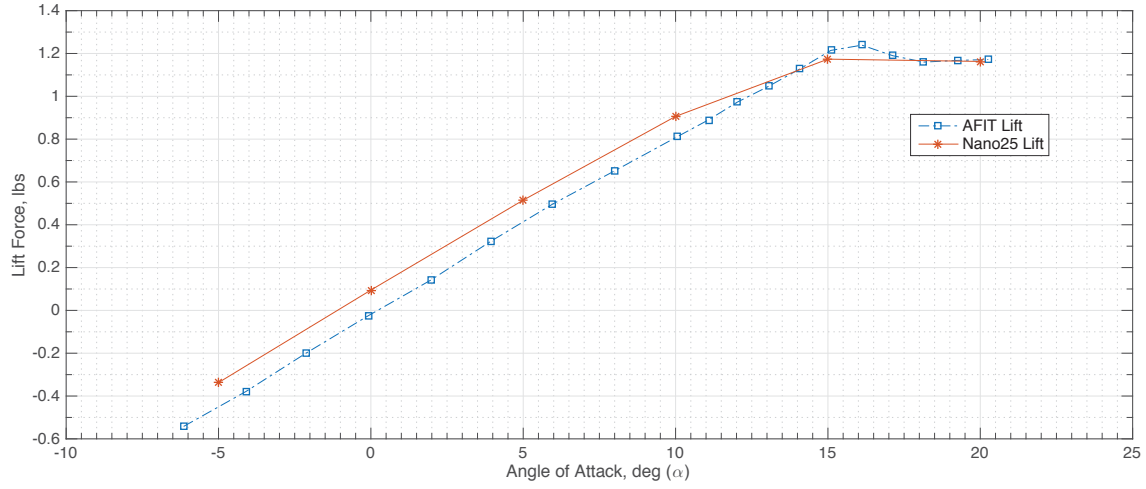


Figure 34. Angle of Attack to Lift Force Comparison - 60 mph

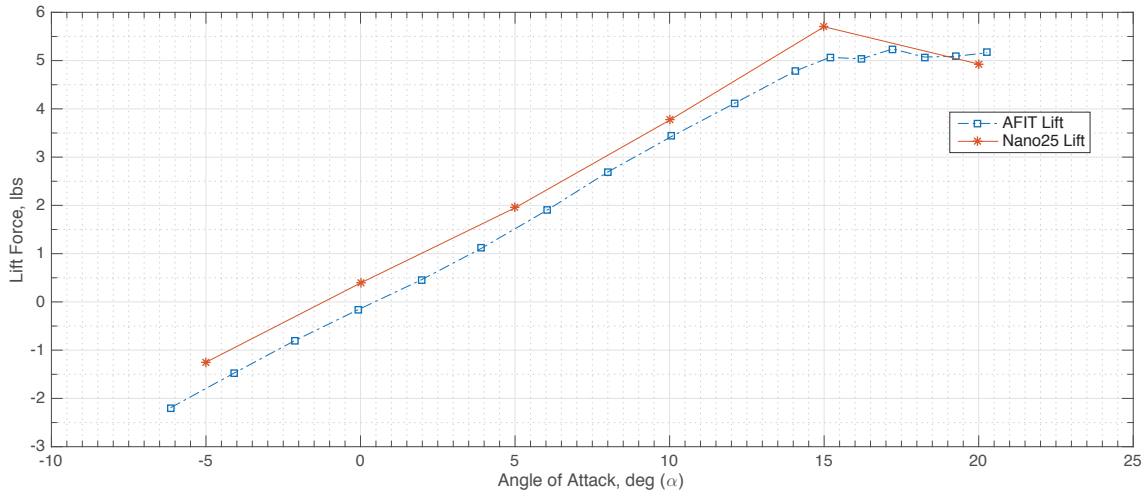


Figure 35. Angle of Attack to Lift Force Comparison - 120 mph

A likely source of error between the results of the two force transducers can be attributed to electrical and vibrational noise caused by surrounding equipment, especially the wind tunnel motor. Differences could also exist in the measurement of

the pitch angle of the model, specifically differences between physical measurements taken on the Nano25 test rig (see Section 3.5.2) and digital angle read-outs on the wind tunnel control system. Furthermore, differences between the two wing models, such as the Nano25 cable access slot (Figure 14) and the protruding Nano25 cable itself (Figure 26), are expected to be some of the leading causes for differences in the comparison.

Figure 36 shows the lift coefficients for the various angles of attack. Error bars are included, however, they are extremely small and do not represent the sources of uncertainty discussed above. The uncertainty analysis performed was based on the methods of Reference [7], which takes into account the tolerances for the three force components and the three moment components for each transducer. The analysis also includes tolerances for the angle of attack, α , and dynamic pressure, q .

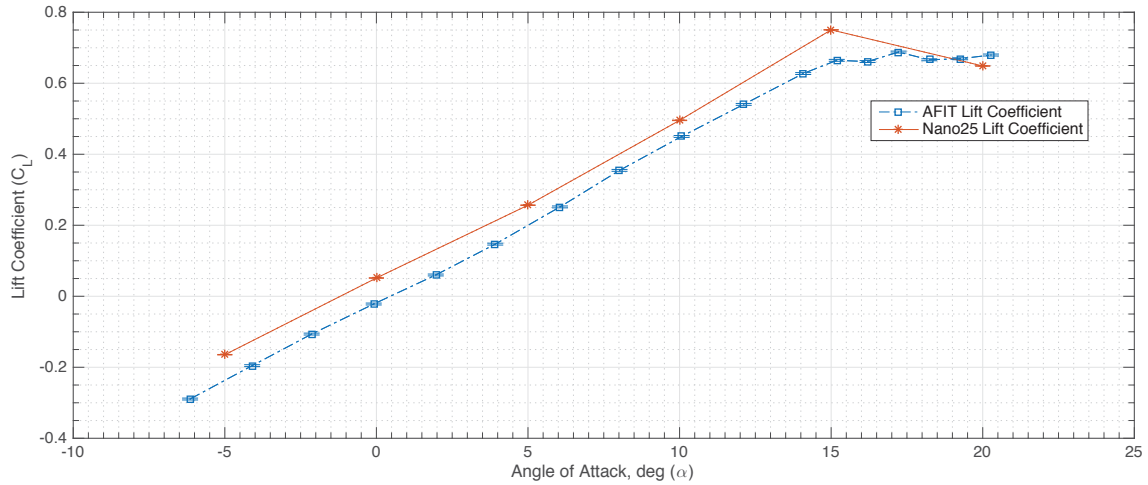


Figure 36. Angle of Attack to Lift Coefficient Comparison - 120 mph

Figures 37 and 38 show drag measurements for the 60 mph and 120 mph test cases, respectively. As with the lift measurements, the trends of the drag plots are nearly identical, with small differences likely due to the same reasons as discussed above for the lift measurements.

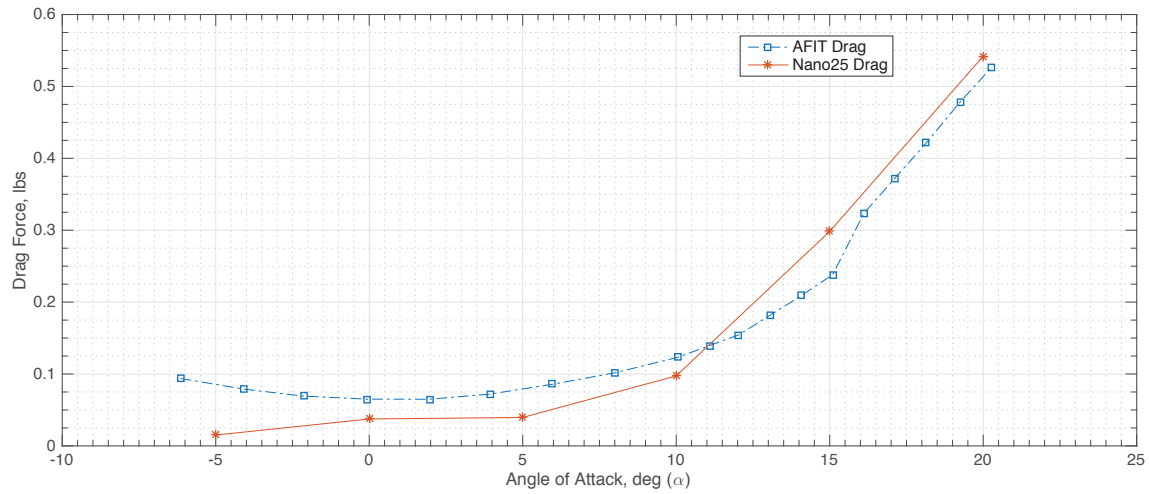


Figure 37. Angle of Attack to Drag Force Comparison - 60 mph

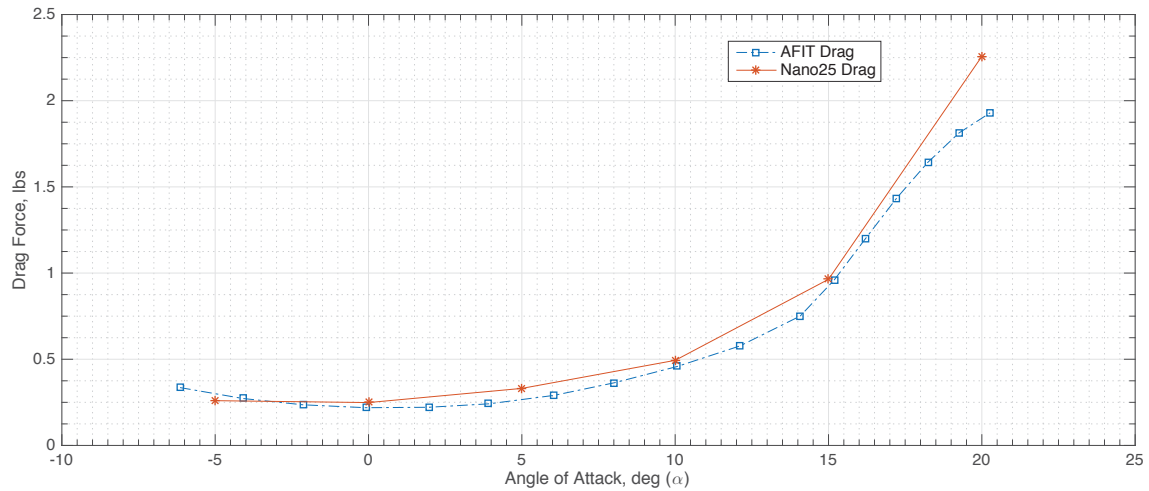


Figure 38. Angle of Attack to Drag Force Comparison - 120 mph

Figure 39 shows the drag coefficients for the various angles of attack. The error bars for this figure are also small, and as before, do not represent the sources of uncertainty previously discussed.

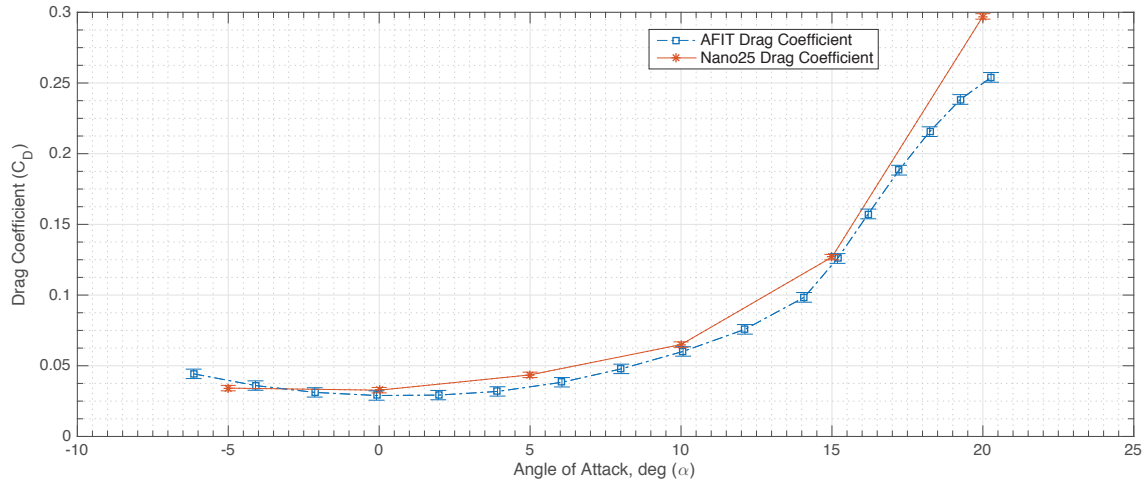


Figure 39. Angle of Attack to Drag Coefficient Comparison - 120 mph

Figures 40 and 41 on the next page show the pitch moment coefficients for the 60 mph and 120 mph test cases, respectively. These trends are also very similar, especially when observing the y-scales on the plots, which show the coefficient values are relatively small numbers. As expected, the pitch moment coefficient is nearly zero until the AOA reaches 15 degrees, where it then trends more negative. Error bars are more visible in these figures because of the small scale of the measurements.

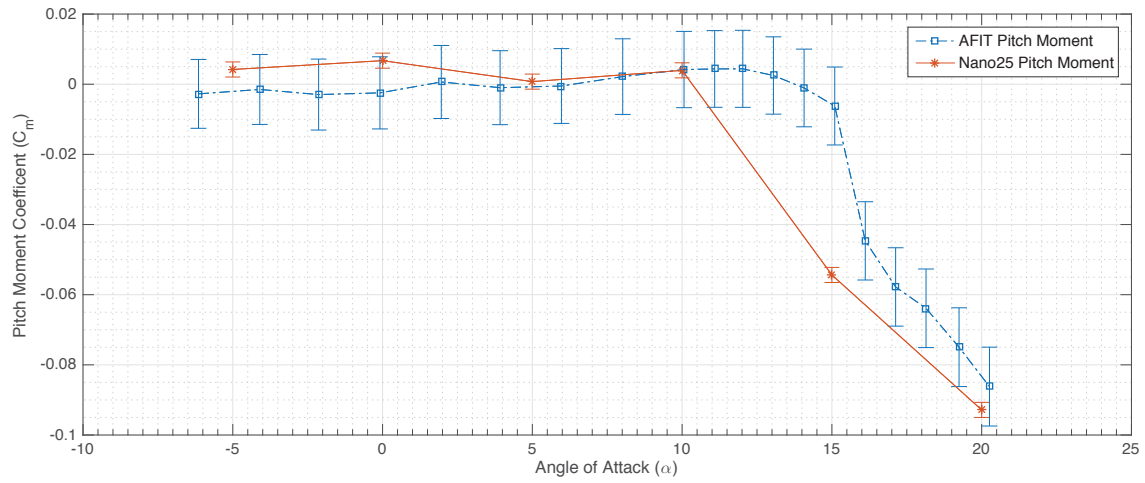


Figure 40. Angle of Attack to Pitch Moment Coefficient Comparison - 60 mph

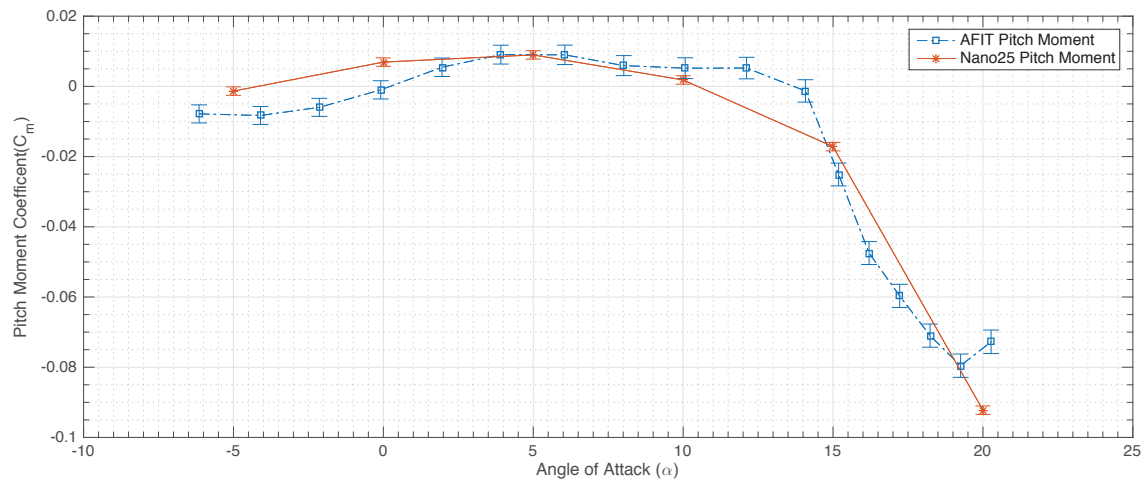


Figure 41. Angle of Attack to Pitch Moment Coefficient Comparison - 120 mph

4.2 IMU Euler Angle Output Comparison with MTA Encoder Data

Before proceeding to the dynamic testing, a comparison is provided between the IMU Euler angle output, the MTA encoder angle output, and the trajectory file angle input. The first five seconds of the 0, 60, and 120 mph test cases are shown below in Figures 42-44, while the 30 and 90 mph test cases are provided in Appendix A. For all dynamic test cases performed, the sensor start time was not yet synchronized with the start time of the MTA motion, as the system does not currently share a common trigger. Because of this, all data required a manual time shift to align motions with the results. The method for completing this involved examining the data to locate the first data point that motion was detected. Clearly, there exists uncertainty in the selection of this point for each case, so it is expected that the manual adjustment might be offset by up to 0.05 seconds for a 500 Hz sampling rate.

A majority of the time, all angles match well in value and time location. During the 120 mph case, high angles are expected to show some errors due to the greater forces acting on the model and MTA links. However, in every test case performed, errors are seen in the IMU Euler angle output values that show a deviation in angle. The cause for these errors relate to the input data rate that the computer and software can handle, referred to as the baud rate. If the baud rate of the computer is not set high enough, then incoming data packets from the IMU can be dropped. Evidence that data packets are being dropped is seen in Figure 42 between 1.3 seconds and 1.6 seconds where the IMU angles linearly jump forward in time, but then return to correctly tracking the oscillating motion. The conventional solution to the baud rate problem is to verify the baud rate setting within the LabVIEW code matches the port settings on the computer or embedded controller. Additionally, the baud rate should be set to a sufficient rate in order to handle all incoming data packets and prevent any dropping or the sampling rate should be reduced.

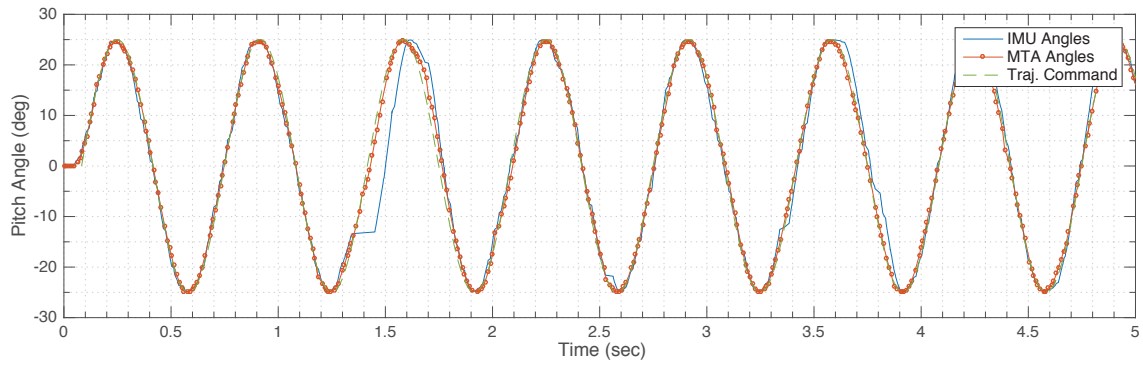


Figure 42. IMU Pitch Angle to MTA Encoder Pitch Angle, 1.5 Hz/ $\pm 25^\circ$ oscillation - 0 mph

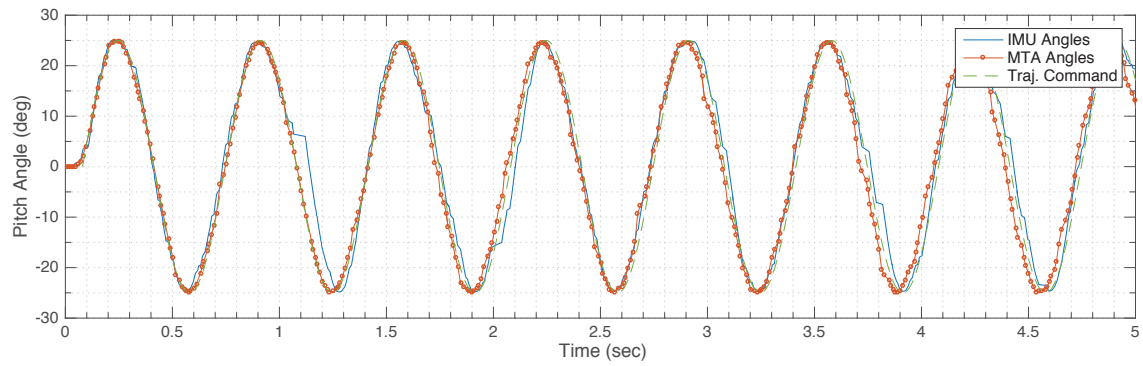


Figure 43. IMU Pitch Angle to MTA Encoder Pitch Angle, 1.5 Hz/ $\pm 25^\circ$ oscillation - 60 mph

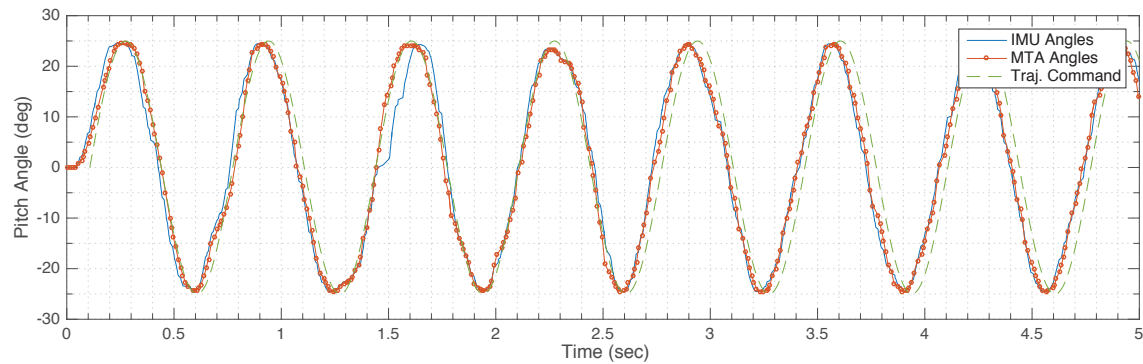


Figure 44. IMU Pitch Angle to MTA Encoder Pitch Angle, 1.5 Hz/ $\pm 25^\circ$ oscillation - 120 mph

For testing, the baud rate was set to 115,200 baud within the LabVIEW code. However, after testing was completed, the baud rate was discovered to be 9,600 baud in the embedded controller port settings, instead of 115,200 baud. Correcting the embedded controller port settings to a rate of 115,200 baud improved data collection, but did not completely eliminate dropped data packets. An additional suspected cause for these dropped data packets is the limited data transfer rates of the Ethernet ports and cable transferring all data to the primary computer from the embedded controller. The transfer of additional data not related to direct sensor data from the embedded controller might be using a portion of the Ethernet data rate, reducing the maximum possible data collection rate from the sensor.

4.3 Pitch Oscillation Dynamic Testing with the MTA

This section presents pitch oscillation dynamic test results for lift forces, drag forces, and pitch moments at 60 and 120 mph flow speeds. Raw converted data signals from the 0, 60 and 120 mph test cases are shown here, whereas the coefficient data is shown for the 30, 60, 90, and 120 mph cases. The raw converted data signals for the 0 mph test case act as the dynamic tare for the motion. The roll moment result for the 120 mph test case is also included at the end of this section. In each figure, the frequency of oscillation is 1.5 Hz and the pitch angle oscillates between -25 and +25 degrees. Oscillatory test data was collected for 15 seconds, however, the first 5 seconds of the test are shown in the figures for improved visibility of the curve shapes. Additionally, pitch angle scales (left y-axes) for each figure remain consistent throughout, while the output scales (right y-axes) are adapted to each result. The raw data collected for 30, 60, and 90 mph are given in Appendix A.

Figures 46 and 47 are lift force results for 60 and 120 mph flow speeds, respectively. Peak lift for the 60 mph case, before the wing stalls, averages around ± 1.75 lbf and occurs between 16° and 20° pitch angles. Observation of the slope in the region of decreasing pitch shows the flow reattaches between 12° and 13° pitch angles. The peak lift for the 120 mph case averages around ± 7.0 lbf, occurring consistently between 16° and 18° pitch angles. As the wing approaches stall, the peak lift force is higher compared with the lift force when the flow reattaches due to the additional time it takes to completely reattach.

The shape of each result follows the expected lift curve slope of the wing model based on increasing pitch angle. Additionally, the peak lift force increases by a factor of four when the wind speed is doubled from 60 mph to 120 mph. An important observation in Figures 46 and 47 above, as well as Figure 48 below of the 120 mph lift coefficient, is the slight offset of the lift force curve with respect to the pitch

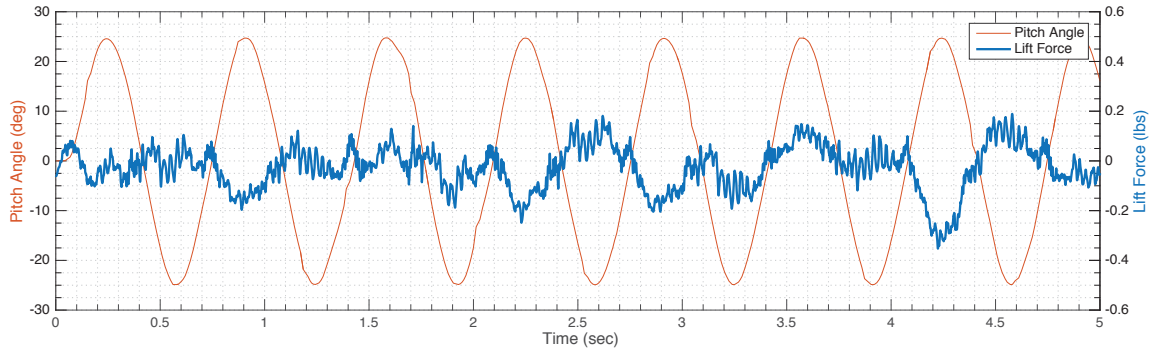


Figure 45. Pitch Angle to Lift Force, 1.5 Hz/ $\pm 25^\circ$ oscillation - 0 mph Tare

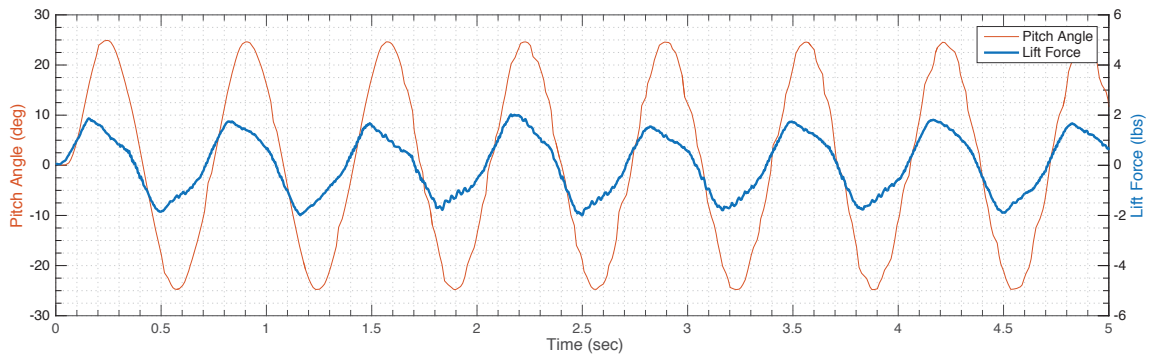


Figure 46. Pitch Angle to Lift Force, 1.5 Hz/ $\pm 25^\circ$ oscillation - 60 mph

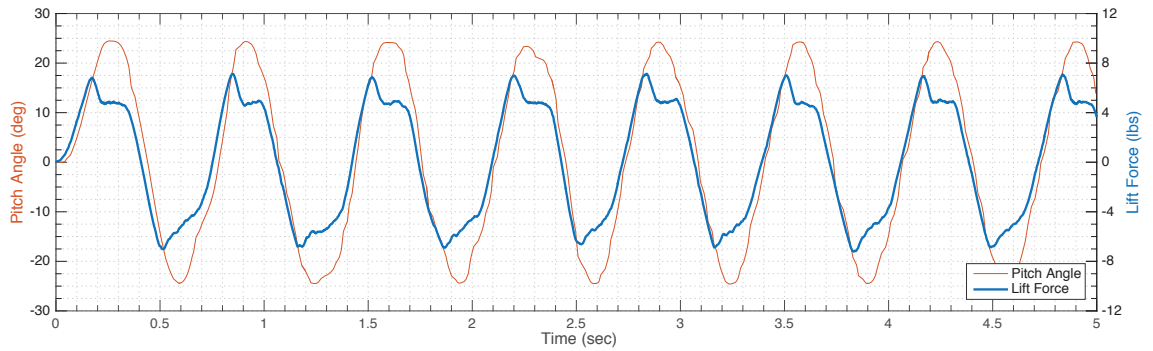


Figure 47. Pitch Angle to Lift Force, 1.5 Hz/ $\pm 25^\circ$ oscillation - 120 mph

angle curve. The lift curve seems to show increasing lift forces roughly 0.05 seconds before the wing begins to pitch up. The zero-lift point also seems to occur about 0.05 seconds before the zero pitch angle point. This slight shift exists most likely due to the point in the data that was defined as the start point. Additionally, a small

portion of this offset might be attributed to the protruding Nano25 cable and access slot on the top of the wing. If the offset is corrected, the location of peak values could change between 2° and 4° . Figure 49 compares the lift coefficients for the 30, 60, 90, and 120 mph test cases. As the flow speed is increased, the lift curve slope becomes more clear because the effect of noise on the sensor is reduced due to the larger forces.

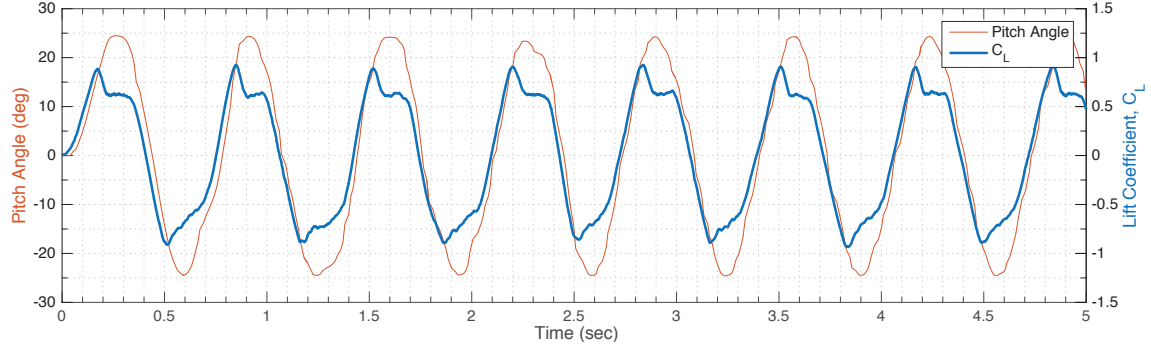


Figure 48. Pitch Angle to Lift Coefficient, 1.5 Hz/ $\pm 25^\circ$ oscillation - 120 mph

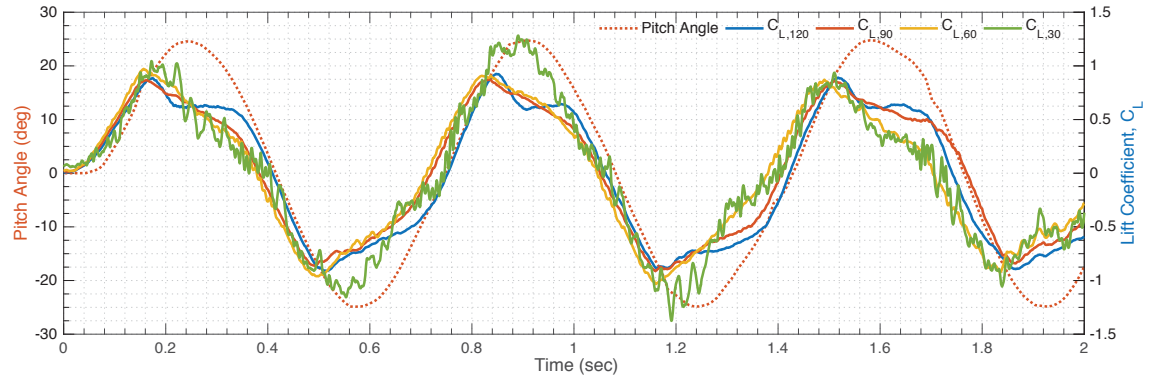


Figure 49. Pitch Angle to Lift Coefficient for 30, 60, 90, and 120 mph Cases

Another representation of the lift coefficient data is shown in Figures 50 and 51. These plots compare each oscillation for the first five seconds of testing, or the first 7.5 oscillations. This comparison shows small variations in lift coefficient results between each oscillation. However, regardless of these variations, the general trend of the results match the expected shape for this type of data. This is observed in the high and low pitch angle regions where, after flow separation, the flow takes additional

time to reattach as the pitch angle decreases. This is known as hysteresis, which can be observed in most of the lift force and lift coefficient plots provided here.

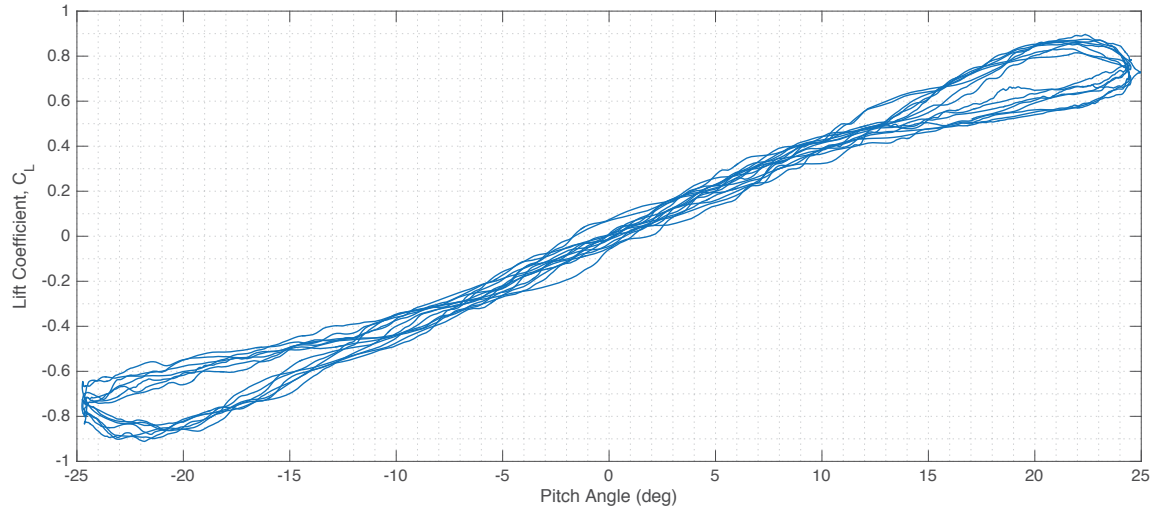


Figure 50. Lift Coefficient vs. Pitch Angle for 90 mph Case (first 5 seconds)

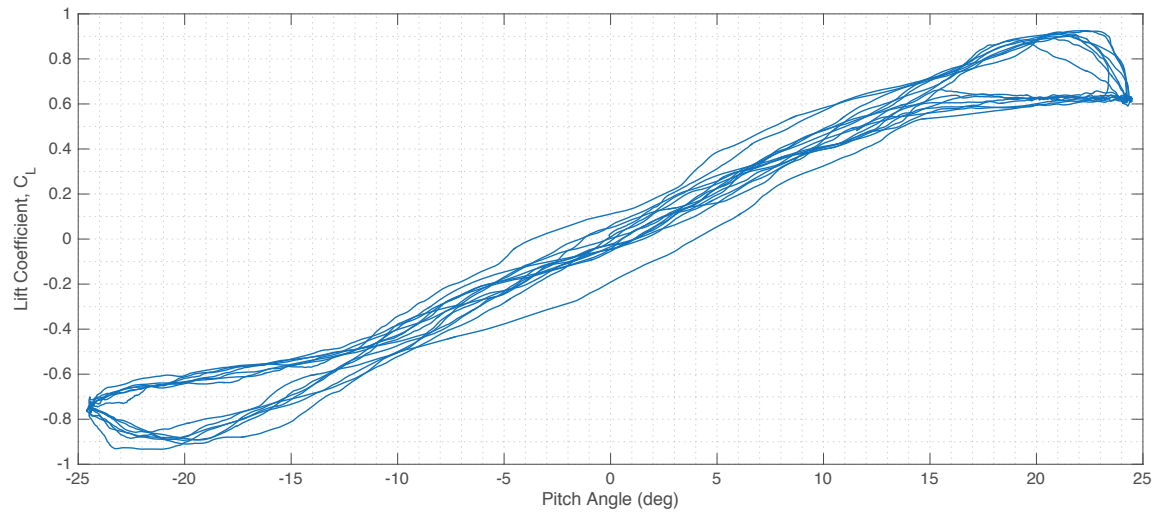


Figure 51. Lift Coefficient vs. Pitch Angle for 120 mph Case (first 5 seconds)

Figures 53 and 54 are drag force results for 0, 60, and 120 mph flow speeds, respectively, and Figure 55 is the drag coefficient for the 120 mph case. At 60 mph, the drag force curve shows significant errors, likely due to equipment noise and instrument uncertainty. Since the majority of the signal for calculating the drag force comes from the F_z -axis of the Nano25, which has a higher range but lower resolution (Table 2), it

is expected that noise and uncertainty will obscure actual loads due to aerodynamic loading. The 120 mph case supports this observation because the aerodynamic loads are about four times greater in value, reducing the effect of uncertainty and equipment noise. Furthermore, the drag forces remain mostly positive throughout the test, except for a small number of points that are negative due to the aforementioned uncertainty in the F_z -axis.

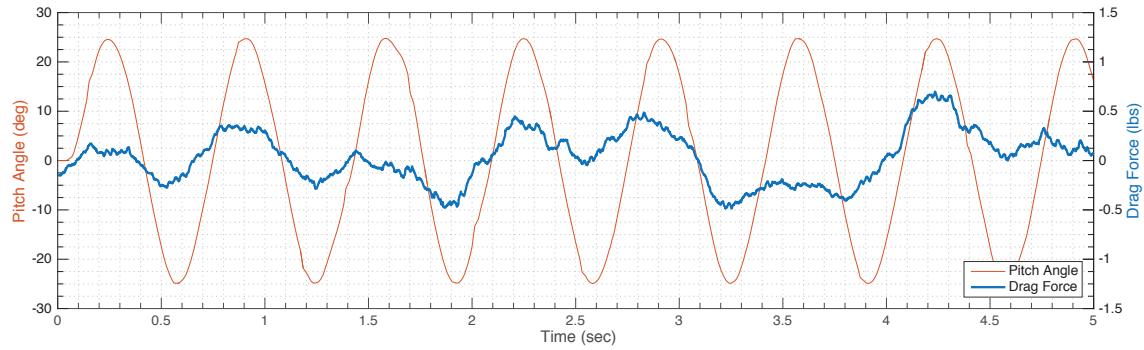


Figure 52. Pitch Angle to Drag Force, 1.5 Hz/ $\pm 25^\circ$ oscillation - 0 mph

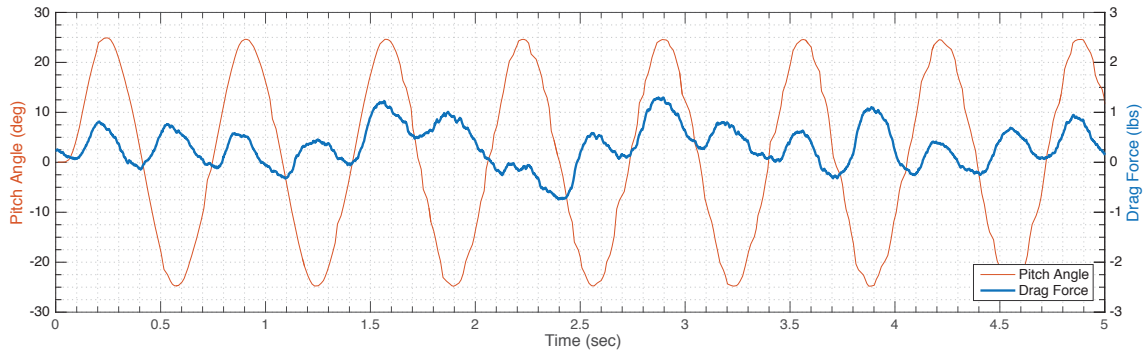


Figure 53. Pitch Angle to Drag Force, 1.5 Hz/ $\pm 25^\circ$ oscillation - 60 mph

From the 120 mph case above, peak drag forces are measured between 2.25 lbf and 3.25 lbf, all occurring at peak pitch angles of $\pm 25^\circ$, as expected. As discussed with the lift force results, the drag force results also include alignment error with the pitch angle curve, however, it is not as evident in Figures 52 - 54.

The next set of results are the pitch moment results at 0, 60, and 120 mph and

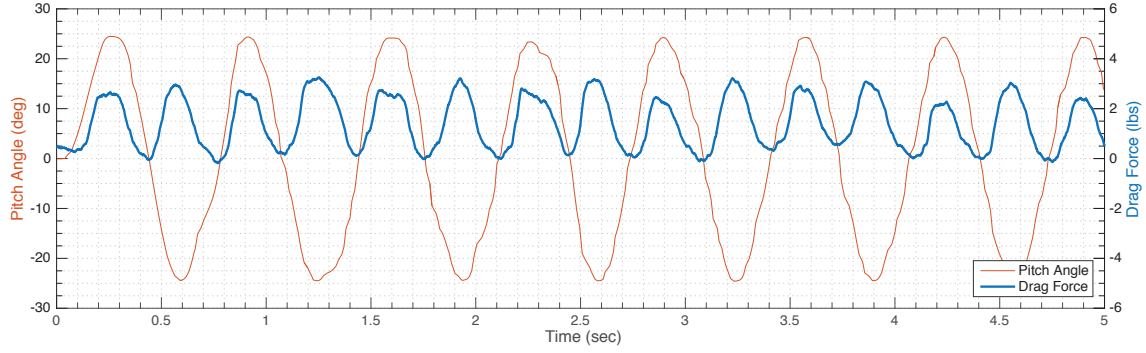


Figure 54. Pitch Angle to Drag Force, 1.5 Hz/ $\pm 25^\circ$ oscillation - 120 mph

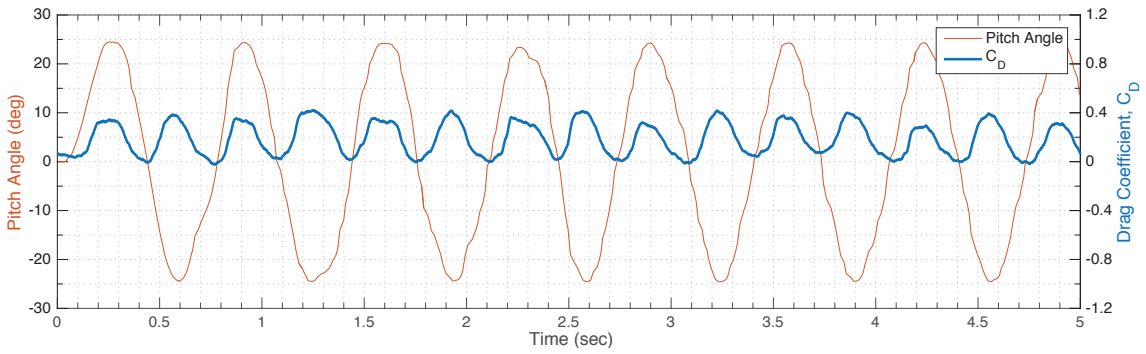


Figure 55. Pitch Angle to Drag Coefficient, 1.5 Hz/ $\pm 25^\circ$ oscillation - 120 mph

pitch moment coefficient results at 30, 60, 90, and 120 mph flow speeds. The pitch moment magnitudes were higher than expected based on the static results of the NACA 0012 wing model. At 60 mph, the maximum pitch moment averaged around ± 3 in-lbs and at 120 mph, the maximum was around ± 9 in-lbs. Each maxima or minima is centered on the peak pitch angle, which is expected.

Theoretically, since the pitch moment is measured at the aerodynamic center of the wing model, the magnitudes should not be as significant as they are. The most probable reason for the higher magnitudes is the center body section of the wing model that interfaces the quarter-chord of the wing with the Nano25 force transducer. Since this section of the model is relatively bulky, it is likely resulting in a greater torque about the y-axis of the Nano25.

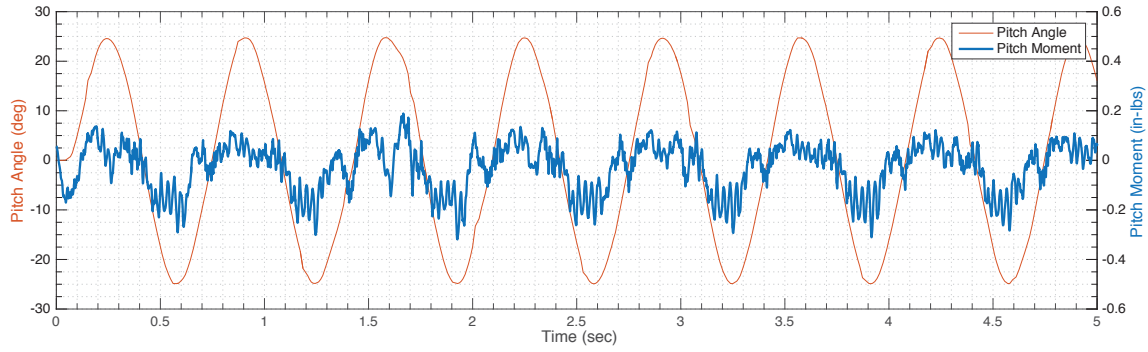


Figure 56. Pitch Angle to Pitch Moment, 1.5 Hz/ $\pm 25^\circ$ oscillation - 0 mph

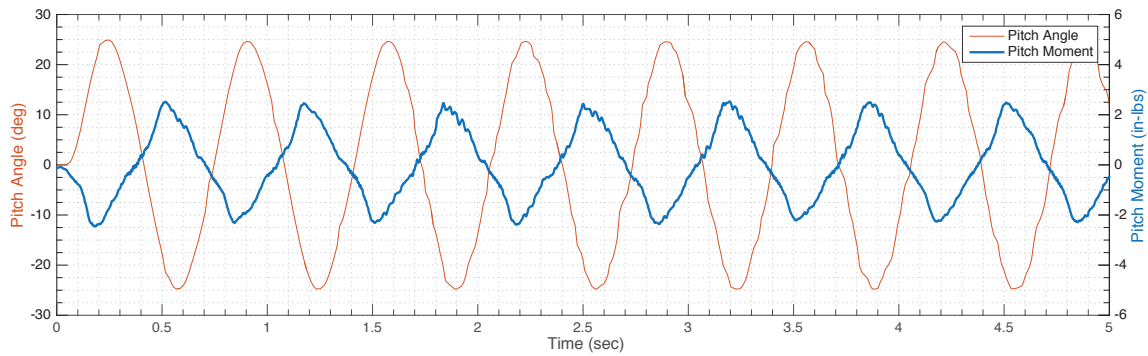


Figure 57. Pitch Angle to Pitch Moment, 1.5 Hz/ $\pm 25^\circ$ oscillation - 60 mph

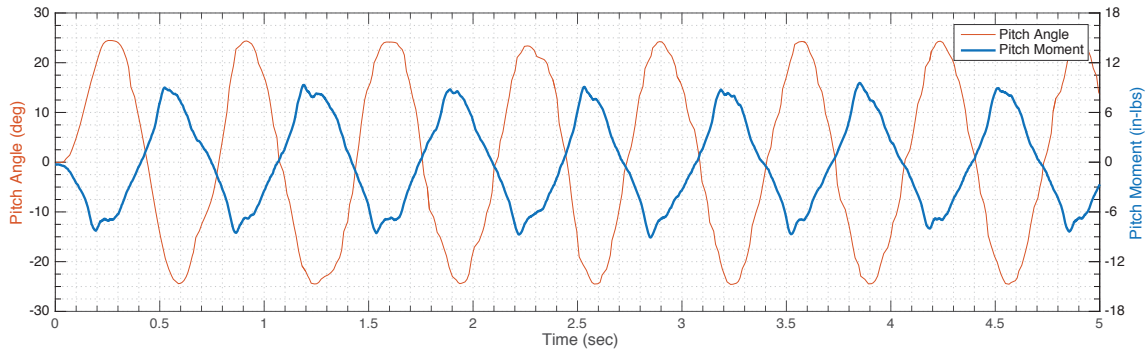


Figure 58. Pitch Angle to Pitch Moment, 1.5 Hz/ $\pm 25^\circ$ oscillation - 120 mph

Figure 59 below shows the pitch moment coefficient for the 120 mph case and Figure 60 compares the pitch moment coefficients for all cases. The magnitudes are relatively low as expected, however, they are about two times greater in magnitude than the pitch moment coefficients measured in the static test (Figures 40 and 41).

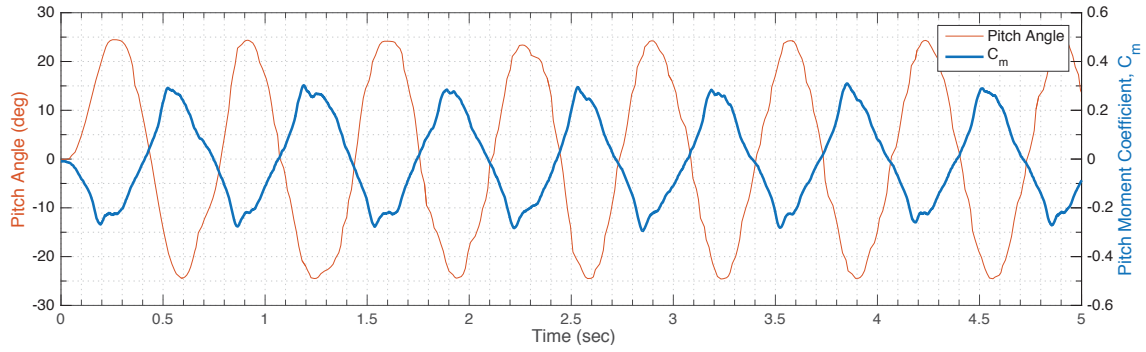


Figure 59. Pitch Angle to Pitch Moment Coefficient, 1.5 Hz/ $\pm 25^\circ$ oscillation - 120 mph

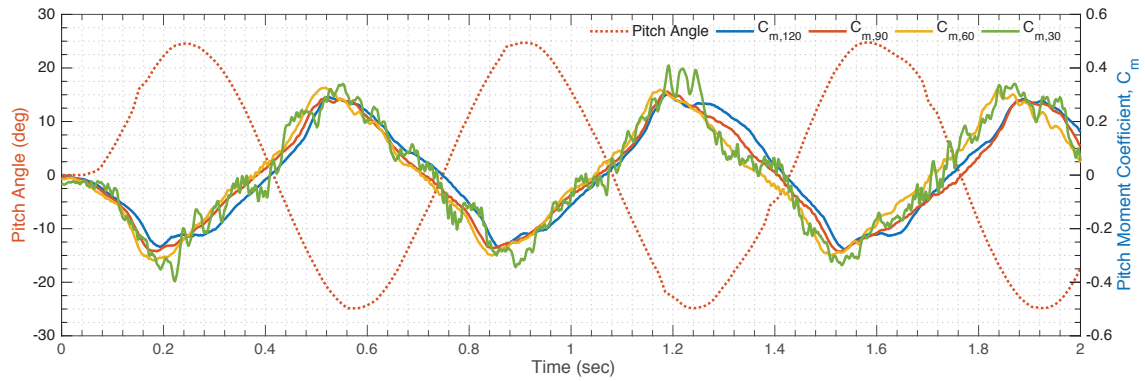


Figure 60. Pitch Angle to Pitch Moment Coefficient for 30, 60, 90, and 120 mph Cases

The final figure in this section, Figure 61, shows the roll moment on the wing due to pitch oscillation at 120 mph. This figure is included here because of the relatively large magnitude measured when no rolling motions were intended. This result reveals imperfections in dynamic testing of the pitch-only movement using the current equipment, specifically at higher pitch angles. The roll moment begins to rise in magnitude significantly around 15° , which may be correlated with the pitch angle at which the wing begins to stall. If the wing model is not mounted perfectly level in reference to the flow direction, stall could occur at one wing tip before the other and induce a rolling moment in one direction for every occurrence of that pitch angle. Another possibility is disturbances in the flow caused by the model support sting passing behind only one side of the model as well as disturbances from the open

MTA access port in the side of the wind tunnel. At higher pitch angles, a greater surface area of the sting is introduced to the incoming flow.

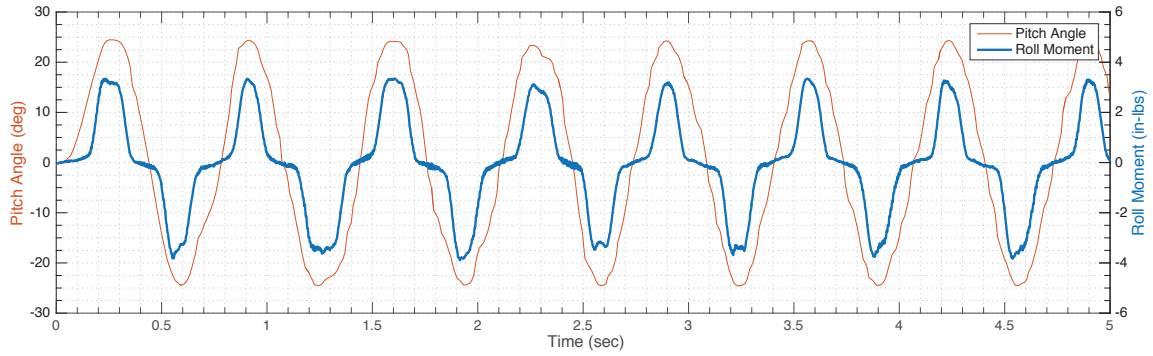


Figure 61. Pitch Angle to Roll Moment, 1.5 Hz/ $\pm 25^\circ$ oscillation - 120 mph

4.4 Pitch-Plunge Oscillation Dynamic Testing with the MTA

Pitch-plunge oscillation dynamic test results are shown below for lift forces, drag forces, and pitch moments at 0, 60, and 120 mph flow speeds. Lift, drag, and pitch moment coefficient results are included for the 120 mph test case as well as a comparison of coefficient results for all test cases. The roll moment result for the 120 mph test case is also included at the end of this section. In each figure, the frequency of oscillation is 1 Hz and the pitch angle starts at +25 degrees then oscillates between -20 and +20 degrees. The plunge motion also occurs at a frequency of 1 Hz, which is depicted in each figure as a dotted green line. As the model moves from its lowest to highest position, the pitch angle rises to +20° at the midpoint then falls back to 0°. Next, as the model moves from its highest to lowest position, the pitch angle drops to -20° by the midpoint then rises back to 0°. This movement defines one cycle of the pitch-plunge dynamic motion. Oscillatory test data was collected for 15 seconds and the first 5 seconds of the test are shown for all figures in this section. Pitch angle and plunge distance scales (left y-axes) for each figure remain consistent throughout, while the output scales (right y-axes) are again adapted to each result. All remaining test cases are provided in Appendix A for reference.

In Figures 63 and 64, as well as the remaining figures in this section, an apparent offset of the data exists due to uncertainty in defining the start of measurements, as discussed in the previous section about the pitch-only results. Just as before, a shift in the data to correct the offset could show a change in the location of peak values with respect to the pitch angle.

The lift force results for the 0, 60, and 120 mph test cases are shown in Figures 62 to 64, respectively. The results look similar to the pitch-only test results, however, the oscillation rate is slower at 1 Hz so the figures show the first five oscillations of the dynamic test. Peak lift for the 60 mph case, before the wing stalls, occurs around

1.5 to 2.0 lbf and between 18° and 20° pitch angles. For this case, it is not evident at which pitch angle the flow reattaches. The peak lift for the 120 mph case consistently averages around ± 6.5 lbf, occurring between 15° and 18° pitch angles, and the flow reattaches between 16° and 18° pitch angles.

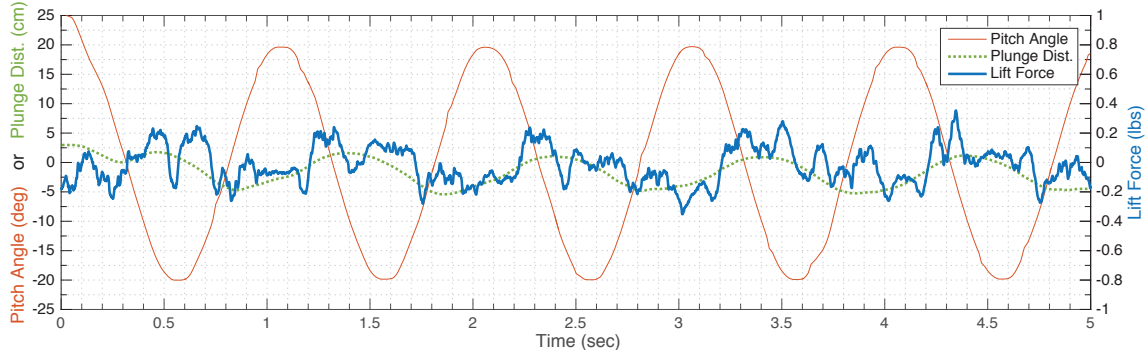


Figure 62. Pitch Angle & Plunge Dist. to Lift Force, 1 Hz/ $\pm 20^\circ$ oscillation - 0 mph

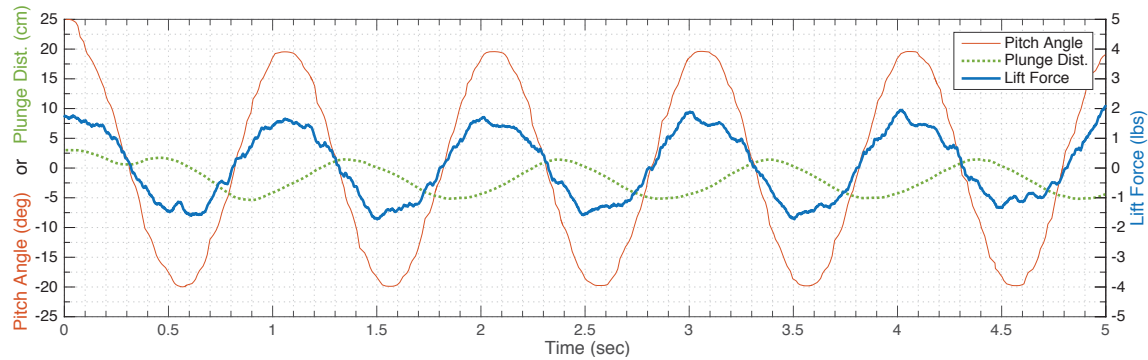


Figure 63. Pitch Angle & Plunge Dist. to Lift Force, 1 Hz/ $\pm 20^\circ$ oscillation - 60 mph

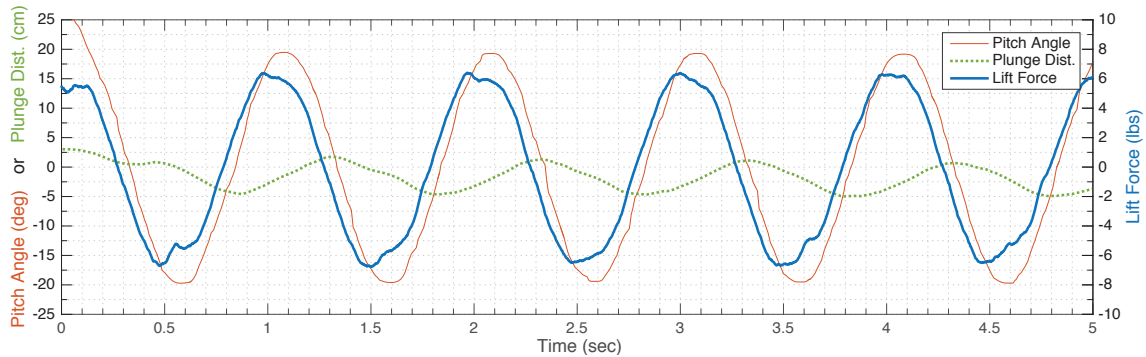


Figure 64. Pitch Angle & Plunge Dist. to Lift Force, 1 Hz/ $\pm 20^\circ$ oscillation - 120 mph

Peak magnitudes for the 120 mph lift coefficient case are nearly identical to the peak lift coefficient measured in the static tests. The maximum lift coefficient in the figure below reaches 0.8 around a pitch angle of 15° , which matches the angle of attack location of maximum lift coefficient for the static cases. However, the remaining values for the case below do not compare exactly with the static results. This could be due to many reasons, including the definition of the angle of attack for the model. Unlike the static tests, the pitch-plunge motion of this test causes the angle of attack to differ from the pitch angle based on the relative direction of the incoming air flow. Furthermore, the dynamic motion of the model may be a considerable factor in the difference between values.

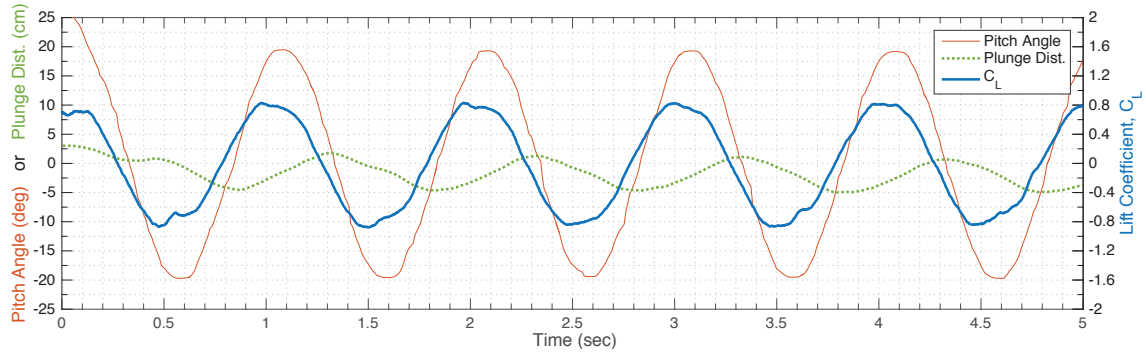


Figure 65. Pitch Angle & Plunge Dist. to Lift Coefficient, 1 Hz/ $\pm 20^\circ$ oscillation - 120 mph

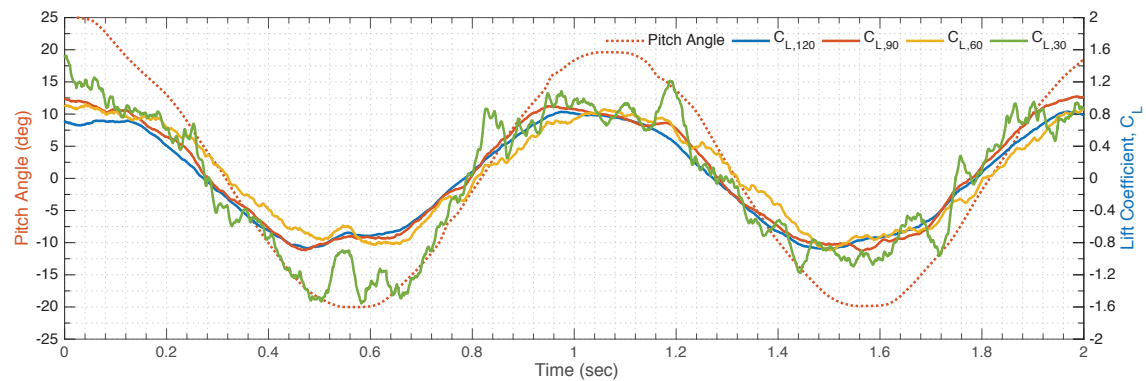


Figure 66. Pitch Angle & Plunge Dist. to Lift Coefficient for 30, 60, 90, and 120 mph Cases

The analysis of the drag results for the pitch-plunge test was considerably more difficult, primarily because the magnitudes were too low to overcome the equipment noise and instrument tolerances. Additionally, since the pitch angle peaked at ± 20 degrees rather than ± 25 degrees, drag forces were much lower in magnitude. The 60 mph test case barely shows any correlation between the pitch angle and drag force, while the 120 mph case begins to show pitch angle effects. Although a portion of the drag curves often go negative, a general trend can be observed where the drag forces spike around peak pitch angles, both positive and negative.

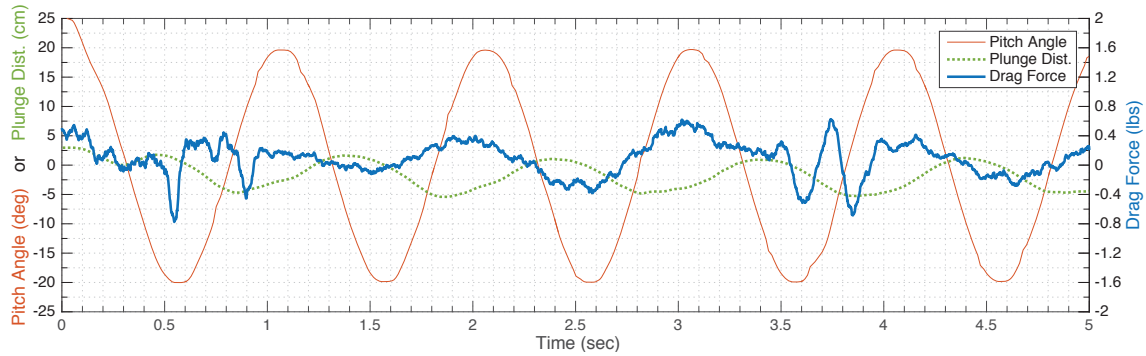


Figure 67. Pitch Angle & Plunge Dist. to Drag Force, 1 Hz/ $\pm 20^\circ$ oscillation - 0 mph

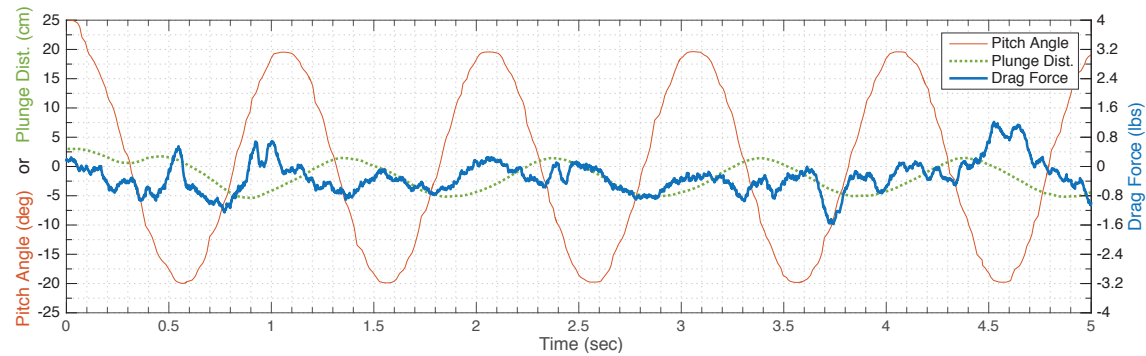


Figure 68. Pitch Angle & Plunge Dist. to Drag Force, 1 Hz/ $\pm 20^\circ$ oscillation - 60 mph

In order to measure more accurate drag forces, either the flow speed must be increased, or a different model must be used that is designed to result in significantly higher drag forces.

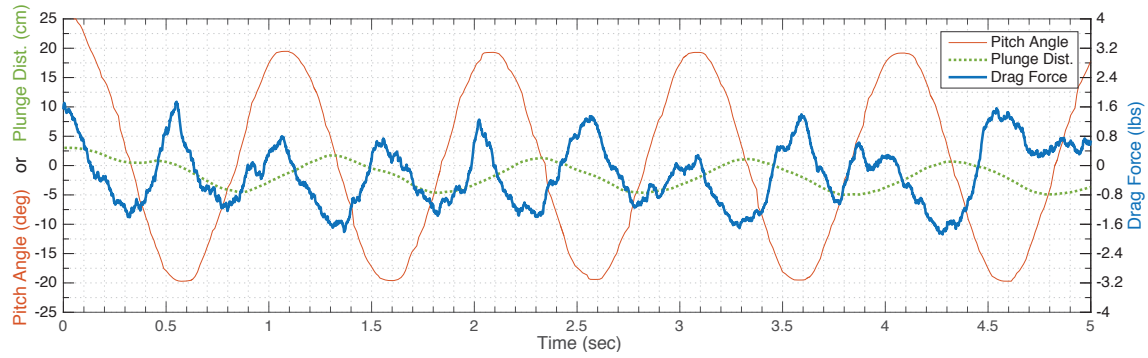


Figure 69. Pitch Angle & Plunge Dist. to Drag Force, 1 Hz/ $\pm 20^\circ$ oscillation - 120 mph

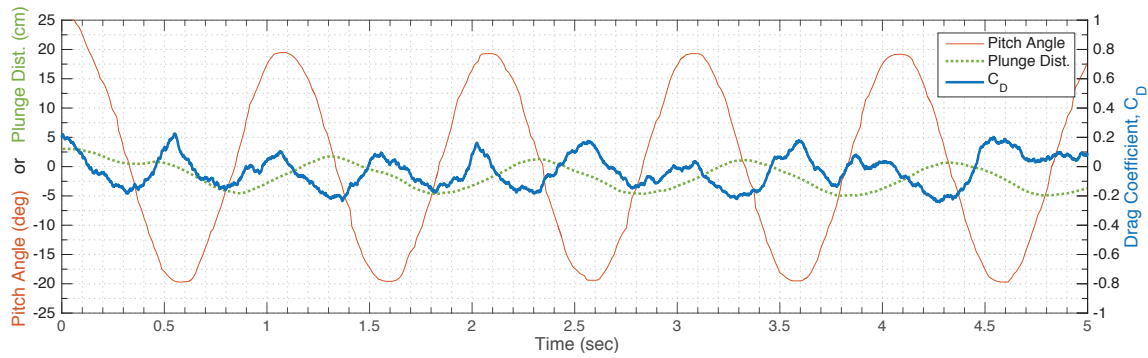


Figure 70. Pitch Angle & Plunge Dist. to Drag Coefficient, 1 Hz/ $\pm 20^\circ$ oscillation - 120 mph

Figures 71 to 73 show the pitch moment results for the 0, 60, and 120 mph test cases, respectively, Figure 74 is the pitch moment coefficient results at 120 mph, and Figure 75 is a comparison of all coefficient results. The results are very similar to the pitch-only results except the magnitudes are lower due to the lower pitch angles. At 60 mph, the maximum pitch moment is around 1.5 in-lbs and at 120 mph, the maximum pitch moment is around 6.5 in-lbs.

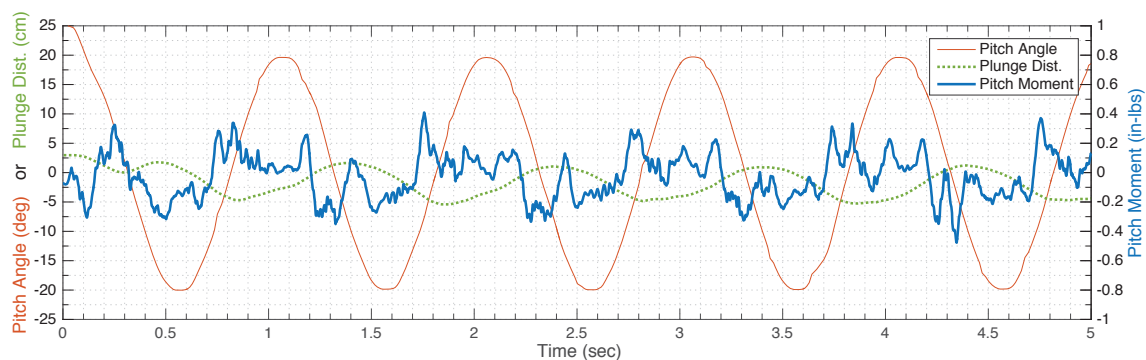


Figure 71. Pitch Angle & Plunge Dist. to Pitch Moment, 1 Hz/ $\pm 20^\circ$ oscillation - 0 mph

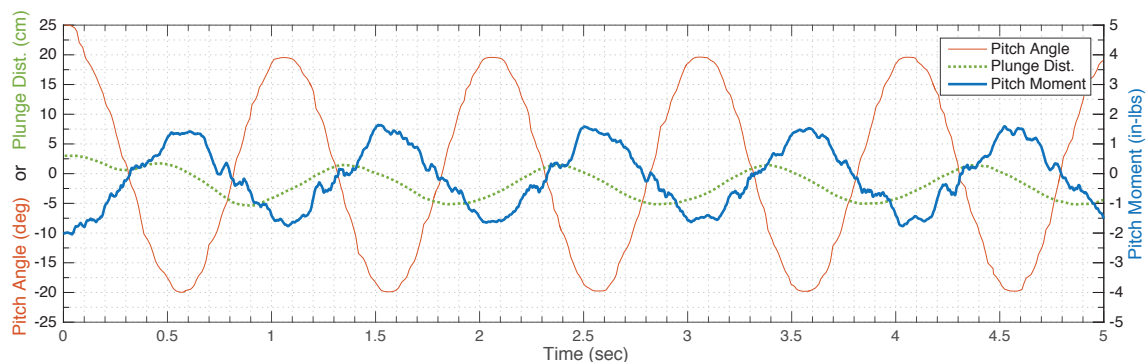


Figure 72. Pitch Angle & Plunge Dist. to Pitch Moment, 1 Hz/ $\pm 20^\circ$ oscillation - 60 mph

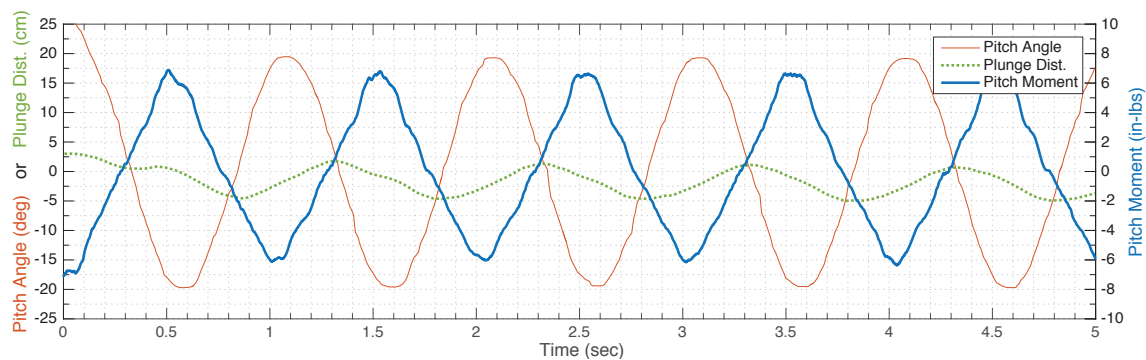


Figure 73. Pitch Angle & Plunge Dist. to Pitch Moment, 1 Hz/ $\pm 20^\circ$ oscillation - 120 mph

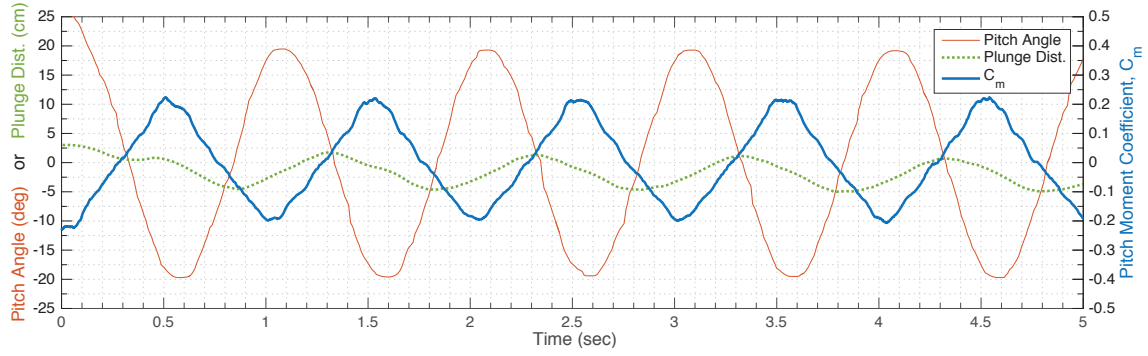


Figure 74. Pitch Angle & Plunge Dist. to Pitch Moment Coeff., 1 Hz/ $\pm 20^\circ$ oscillation - 120 mph

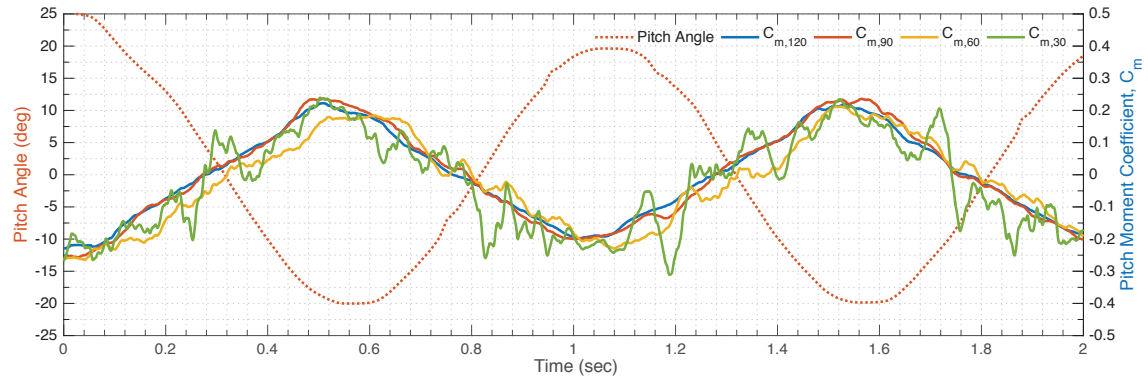


Figure 75. Pitch Angle & Plunge Dist. to Pitch Moment Coefficient for 30, 60, 90, and 120 mph Cases

Finally, as with the pitch-only tests, the roll moment results are presented to show that errors exist in the experimental setup. Similarly to the pitch-only tests, the roll moments could be caused by an un-level wing, flow disturbances from the model support sting, or flow disturbances from the open MTA access port in the side of the wind tunnel.

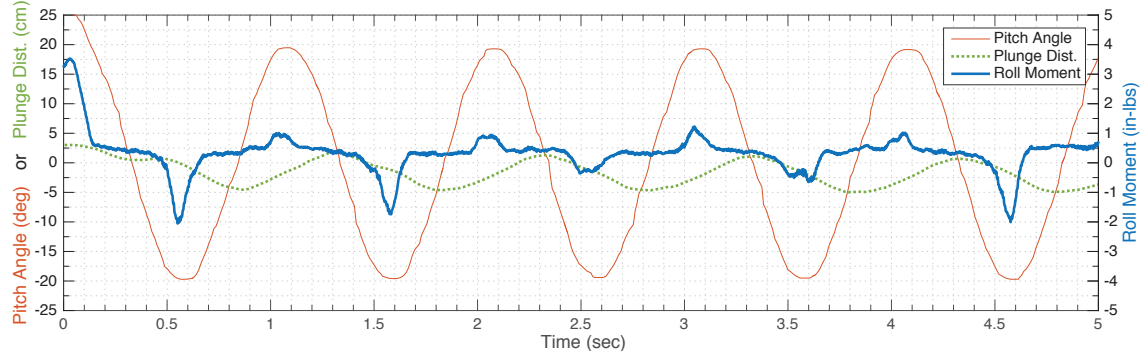


Figure 76. Pitch Angle & Plunge Dist. to Roll Moment, 1 Hz/ $\pm 20^\circ$ oscillation - 120 mph

4.5 Results Summary

The analysis of the preceding results yielded important conclusions from the data collected. Static performance of the Nano25 force transducer proved to be ideal, except for consistent differences in the angle-of-attack when compared to the AFIT-3 balance results. Software upgrades to the MTA significantly improved the repeatability of dynamic motions, which was verified with the comparison of IMU pitch angles with the MTA encoder output angles and trajectory input angles. The angle comparison also revealed that data packets were occasionally dropping due to problems with the data collection rates.

Lastly, the performance of the MTA along with the Nano25 for dynamic motions yielded expected results. Lift, drag, and pitch moment coefficients were within expectations for all pitch oscillation test cases and the 120-mph pitch-plunge oscillation test case. The lift and pitch moment coefficient results, especially at higher flow speeds, revealed flow separation regions at higher angles-of-attack as well as flow reattachment regions along with hysteresis.

V. Conclusions and Recommendations

The primary focus of this research was the development of a data acquisition system suitable for a variety of dynamic wind tunnel tests. This was an important step toward reliably and efficiently performing complex testing with the Motion Test Apparatus and AFIT Low-Speed Wind Tunnel combined system. The following sections discuss the significance of this research with regard to the overall goal. Additionally, recommendations for future research, including the next steps forward from the current state of the system are discussed.

5.1 Performance of the Data Acquisition System

Assessing the performance of the hardware and software components of the data acquisition (DAQ) system is important to determine the need for future modifications and upgrades. In all aspects of this research, including the development of the LabVIEW code and executing actual wind tunnel tests, the majority of the DAQ hardware performed reliably and consistently, especially NI hardware.

Hardware components used for this research not associated with NI hardware specifically revealed potential concerns in reliability. The Nano25 power source and signal converter box provided by the manufacturer detected a significant amount of equipment noise, especially when positioned close to the wind tunnel to allow the Nano25 to be mounted correctly. A reliable noise reduction technique was not established for this problem, however, during many occasions, a majority of the noise was diminished by unsystematically adjusting the cable interface to the signal converter box by loosening or tightening the cable connector. The level of noise reduction was not precisely measured, but was most likely a 60-80% reduction. An additional method used for reducing signal noise was the implementation of a LabVIEW soft-

ware filter to process data, with overall good results. Regardless of these issues, useful data from all sensors was consistently collected.

Since the DAQ hardware consists of mostly fixed components with limited layout flexibility, the development of LabVIEW software provided a significant level of adaptability for research. Furthermore, the LabVIEW Real-Time module made available many additional tools for developing and operating advanced time-accurate programs. Various methods were used within the LabVIEW code to acquire the correct signals. Overall, the LabVIEW code was capable of acquiring data from multiple sensors, simultaneously, at more than sufficient data rates. The next section discusses how well the sensors integrated with the LabVIEW code.

5.2 Integration of Sensors, Current and Future

The integration and operation of the force transducer, IMU, and each pressure transducer with the DAQ system was one of the most important tasks of this research. With the code running reliably, static and dynamic wind tunnel tests were accomplished to obtain results that revealed expected aerodynamic phenomena.

Each sensor required a different level of effort to properly integrate it into the system. The Nano25 and pressure transducer codes required the manipulation of analog voltage signals and calibration data specific to each sensor. The Nano25 calibration data was used to calculate the forces and torques using methods formulated by the manufacturer and the pressure transducers each had a specific sensitivity value which was used to manually create calibration results. The calibration data is the primary difference between each sensor so adding additional sensors to the system is simplified and requires only the incorporation of each respective calibration into the LabVIEW program. The data acquisition rate limits for the Nano25 and pressure transducers are extremely high because the signals originate as raw voltages, so there is significant

flexibility in programming a desired data output rate.

Regarding the comparison of coefficient data for the full range of test cases, it was shown that at speeds from 60 mph to 120 mph, the coefficient data had matching trends and similar peak values. Furthermore, the curves exhibited minimal noise because the peak magnitude of forces, 2 – 7 lbf for lift forces and 3 – 9 in-lbf for pitch moments, were closer to the maximum sensing ranges of the Nano25, 25 lbf and 25 in-lbf, respectively. The 30 mph case, due to the lower magnitudes of forces and torques, exhibited greater signal noise which limited analysis. Overall, as the wind speed was increased, the data signals became significantly more clear.

The IMU LabVIEW code was significantly more problematic to work with because it was originally written by the manufacturer for an older model of IMU, the 3DM-GX3[®]-25. It contains an extensive library of internal code which required modification to properly communicate with the newer 3DM-GX4-15[™] IMU. The difficulty with the code was understanding how it communicated with the IMU and determining which settings had to be modified to ensure compatibility. The current iteration of the IMU LabVIEW code still needs updated and modified to completely enable operation of all features of the IMU, rather than solely the Euler angles and accelerometer values. This can be completed by modifying the moderate priority timed loops within the host VI to enable additional features of the 3DM-GX4-15[™], such as data estimation by the Adaptive Kalman Filter.

Overall, the LabVIEW code performed well for this first iteration of the DAQ system. Later modifications and additions to the code are encouraged to streamline and improve the process. Additionally, more sensors could be supported with this code such as a second IMU or an array of pressure transducers.

With the exception of complete data synchronization with a common time, the research objectives were met. This included the establishment and testing of the DAQ

system hardware and LabVIEW software to ensure that all sensors could be sampled simultaneously. The completion of this objective allowed dynamic wind tunnel tests to be performed using the Nano25 force transducer for collecting aerodynamic force and moment measurements and the 3DM-GX4-15TM IMU for tracking the dynamic MTA motion.

Complete data synchronization can be achieved by programming the DAQ system hardware to reference a common clock or trigger. A voltage trigger can be installed between the MTA computer and the DAQ system hardware which can be referenced within the LabVIEW code. This trigger would allow the LabVIEW code to begin collecting data signals at the same time that the MTA begins the commanded trajectory, synchronizing the MTA with each sensor.

5.3 MTA Upgrades and Performance

Based on the research performed by Lancaster [20], ideal operation of the MTA required closed-loop control of each joint to ensure dynamic motions could be performed the same for every test. Upgrades to the MTA software by Dr. Patrick Rowe, the primary software developer for the MTA, resulted in a large step toward meeting this requirement. The main issue remaining is to achieve precise and repeatable dynamic motions using all six MTA joints. The next tests to investigate these issues, which relate to the topics discussed in this thesis, are store separation motions.

The applied software upgrades enabled closed-loop control of each MTA joint, however, significant errors still existed for certain types of motions, such as linear and radial store separation motions. The existing difficulty with performing these more advanced dynamic motions is the relatively small motions required compared to the massive links of the MTA. The two largest motors, used for the torso yaw and shoulder pitch joints, are designed for much larger motions than the motions currently

being tested. Store separation motions, both linear and radial, were tested after the MTA software was upgraded to determine the degree of improvement that the closed-loop control supplied. The end result of these tests did not fulfill requirements for using these motions experimentally, thus was the reason for postponing store separation dynamic testing in this research. Future research will address this difficulty by attempting to use a fewer number of the MTA joints to perform the same or similar motions.

5.4 Recommendations for Future Research

The primary recommendation for future research originates from goals not achieved with this research, specifically the installation of a common trigger or implementation of a common clock to ensure time synchronicity in all results. This is particularly important for dynamic wind tunnel testing because multiple components with different control systems are operating simultaneously. When all components are synchronized, time-accurate results become more reliable.

The extensive capabilities of the software resulted in a majority of this research effort spent developing the LabVIEW program. However, the current program is only the first iteration so further development and modification is recommended to enhance the performance of the program and to incorporate the preceding recommendation of integrating a software or hardware trigger.

The last recommendation relates to the NACA 0012 wind tunnel model used for this research and the magnitude of forces and moments it generated. From the results, lift forces and pitch moments at flow velocities from 60 mph to 120 mph and drag forces for the 120 mph test case were of sufficient magnitudes to analyze. However, lower flow velocities did not generate sufficient magnitudes to overcome signal noise, especially for determining drag forces. A recommended solution to this is to use a

wind tunnel model with greater surface area which would be capable of generating greater magnitudes of forces and moments up to the maximum sensing ranges of each axis of the Nano25 force transducer.

These recommended research objectives will expand the capabilities of the Motion Test Apparatus and data acquisition system for performing increasingly complex dynamic wind tunnel tests in future research. Starting next with store separation testing, then expanding to other complex dynamic motions, the system has great potential for furthering flexible weapon research.

Appendix A. Additional Experimental Data

This appendix contains additional experimental data not included in Chapter IV, including power spectrum data and analysis from the resonance test of the small weapons bay, additional IMU results, and additional dynamic wind tunnel testing results.

Power Spectrum Analysis from Resonance Test of Small Weapons Bay

In preparation for future store separation testing, a power spectrum analysis was performed in an attempt to track the pressure resonance of flow inside the small weapons bay. The purpose of this test was to determine whether the resonance could be used to guide the timing of separating a store. With the pressure transducer positioned in the aft internal surface of the bay, data was collected in increments of 20 mph from 0 mph to 120 mph. In all tests performed, no resonance was detected relating to the flow. In Figure 77, the spikes were determined to be resonant frequencies caused by surrounding equipment, likely the wind tunnel motor, because the spikes occurred at the same frequency for all wind speeds. However, the signals did show a noticeable difference for each wind speed.

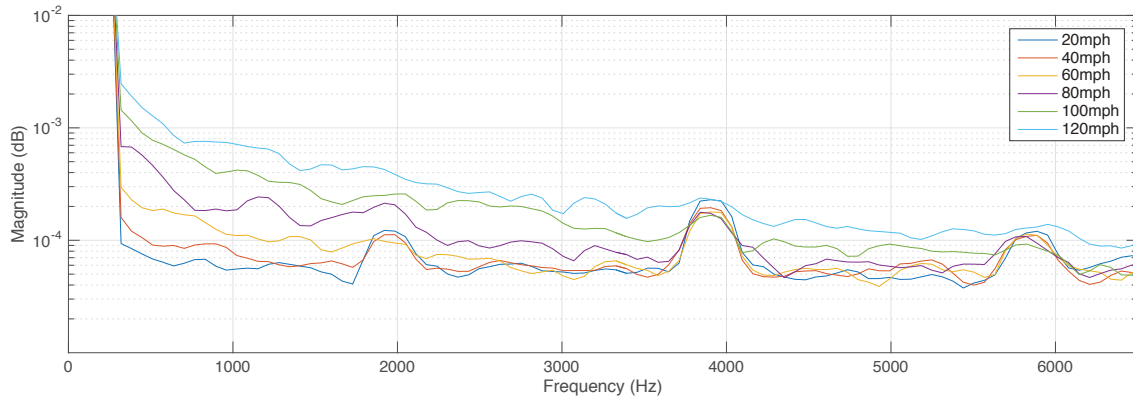


Figure 77. Power Spectrum Results for Partial Range of Frequencies

Because the data collected for this test was inconclusive, an investigation was completed to determine the range of cavity resonance expected. Ideally, this would be performed prior to completing the test. Figure 78 is a plot of Strouhal frequencies as a function of Mach number. For the results at 120 mph, a Mach number of about 0.16, the Strouhal number is expected to be around 1.0 to 2.0 based on the data. Equation 35 calculates the expected cavity resonance frequency to be between 176 Hz to 352 Hz, where St is the Strouhal number, f is the frequency in Hz, L is the cavity length in feet (1 ft in this case), and U_∞ is the flow speed in ft/s.

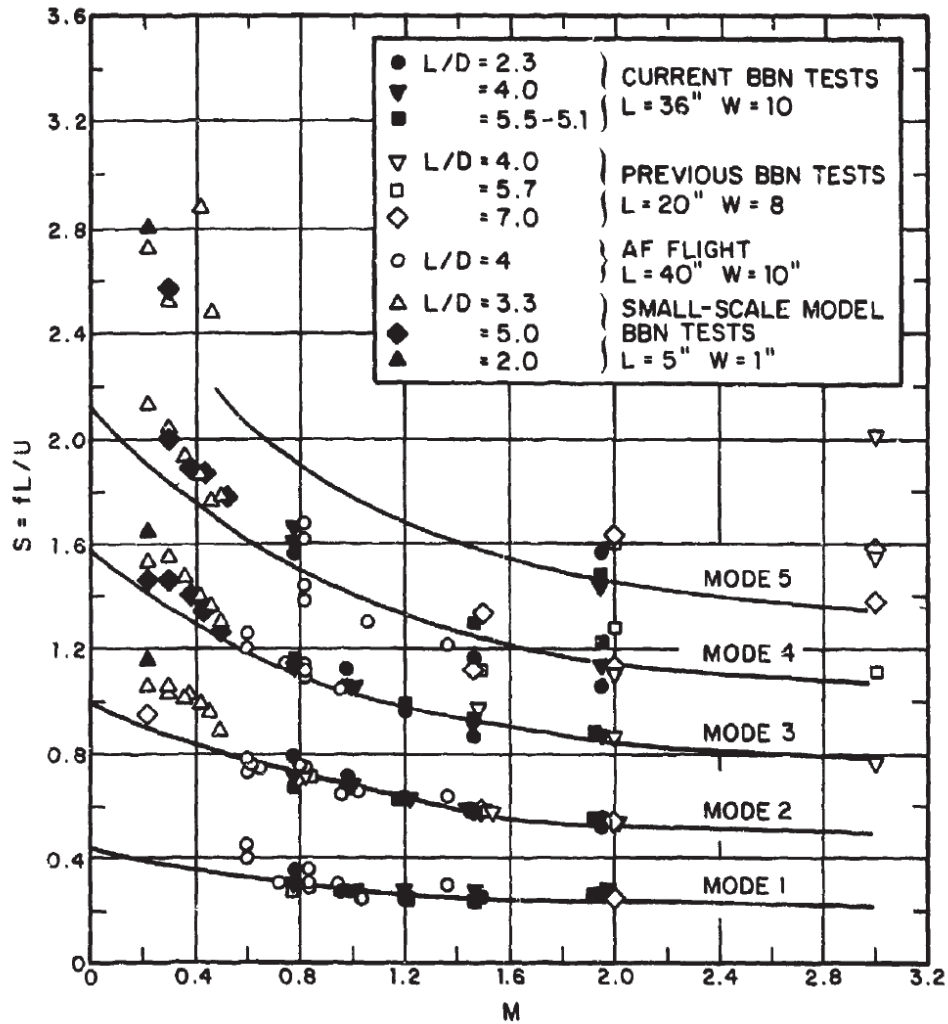


Figure 78. Strouhal frequencies of cavity modes as function of Mach number [16].

$$St = \frac{fL}{U_\infty} \approx 1.0 - 2.0 \Rightarrow f = 176 \text{ Hz} - 352 \text{ Hz} \quad (35)$$

This frequency range is much lower than the range shown in Figure 77, so the power spectrum test should be performed again to record data within the calculated frequency range. However, it is expected the test would again yield inconclusive results because of the low Mach number the wind tunnel is capable of producing.

Additional IMU Comparison Results

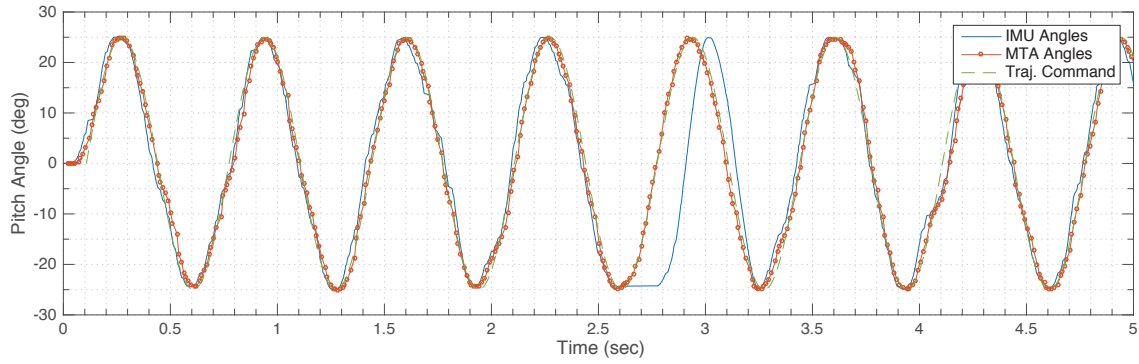


Figure 79. IMU Pitch Angle to MTA Encoder Pitch Angle, 1.5 Hz/ $\pm 25^\circ$ oscillation - 30 mph

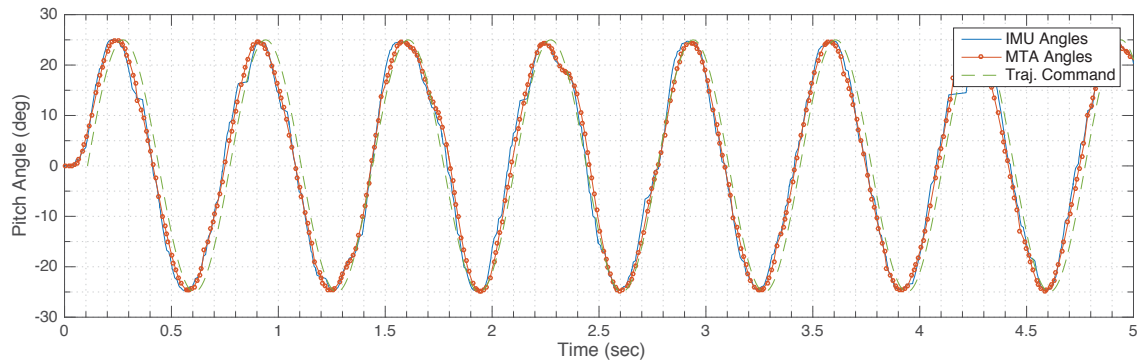


Figure 80. IMU Pitch Angle to MTA Encoder Pitch Angle, 1.5 Hz/ $\pm 25^\circ$ oscillation - 90 mph

Additional Pitch Oscillation Data

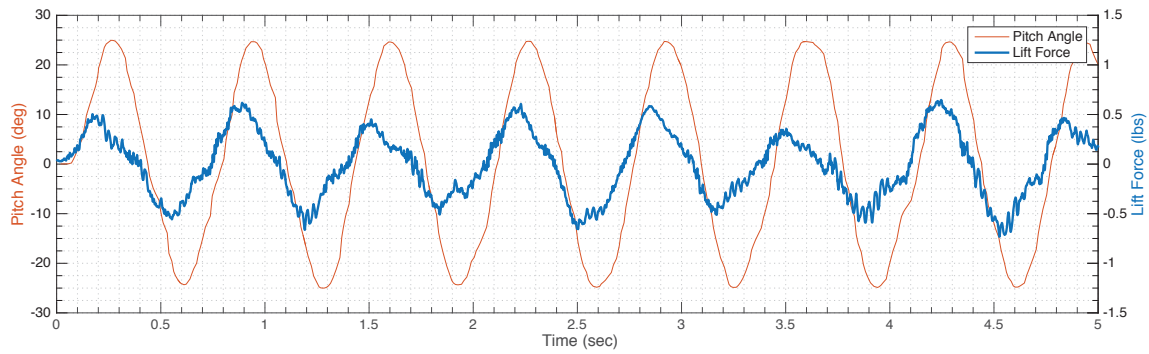


Figure 81. Pitch Angle to Lift Force, 1.5 Hz/ $\pm 25^\circ$ oscillation - 30 mph

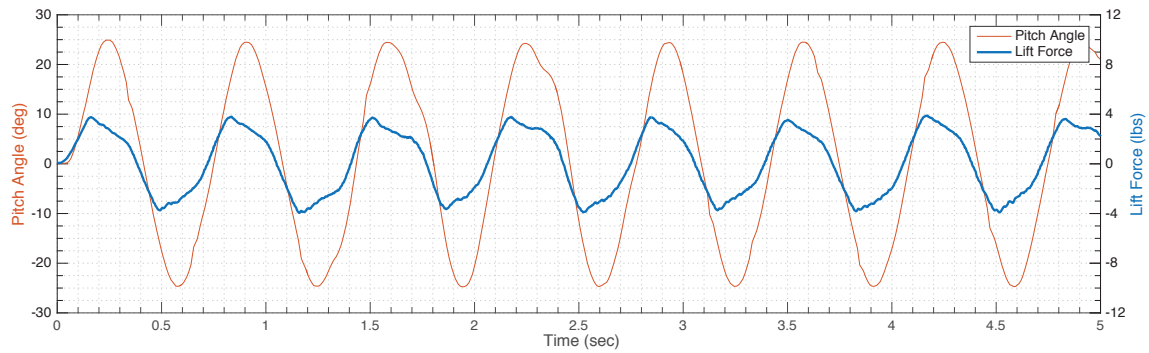


Figure 82. Pitch Angle to Lift Force, 1.5 Hz/ $\pm 25^\circ$ oscillation - 90 mph

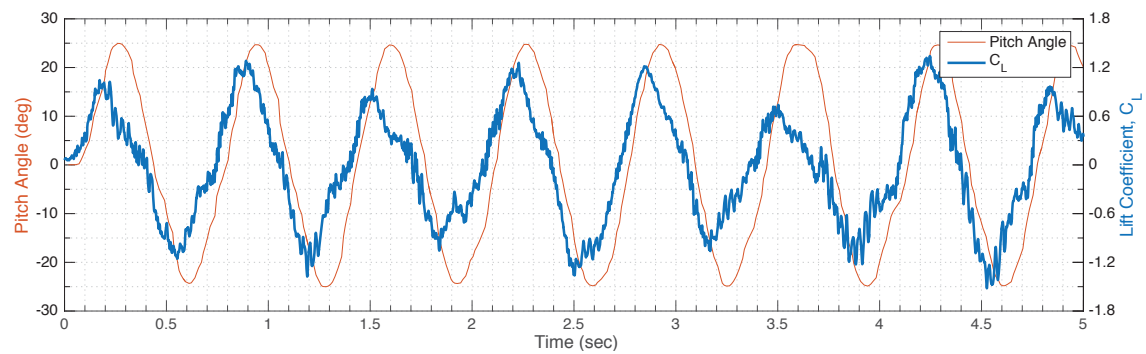


Figure 83. Pitch Angle to Lift Coefficient, 1.5 Hz/ $\pm 25^\circ$ oscillation - 30 mph

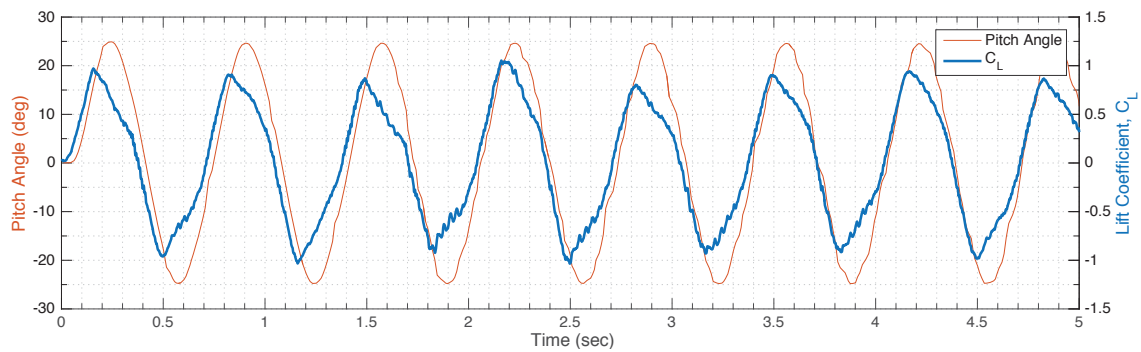


Figure 84. Pitch Angle to Lift Coefficient, 1.5 Hz/ $\pm 25^\circ$ oscillation - 60 mph

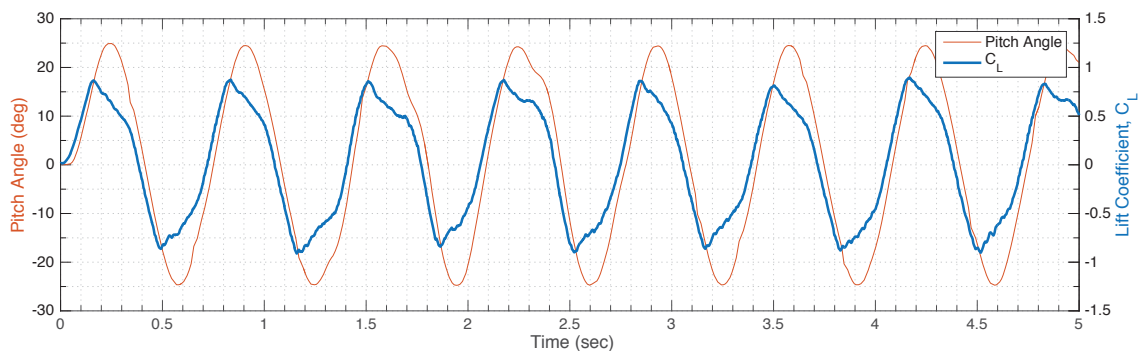


Figure 85. Pitch Angle to Lift Coefficient, 1.5 Hz/ $\pm 25^\circ$ oscillation - 90 mph

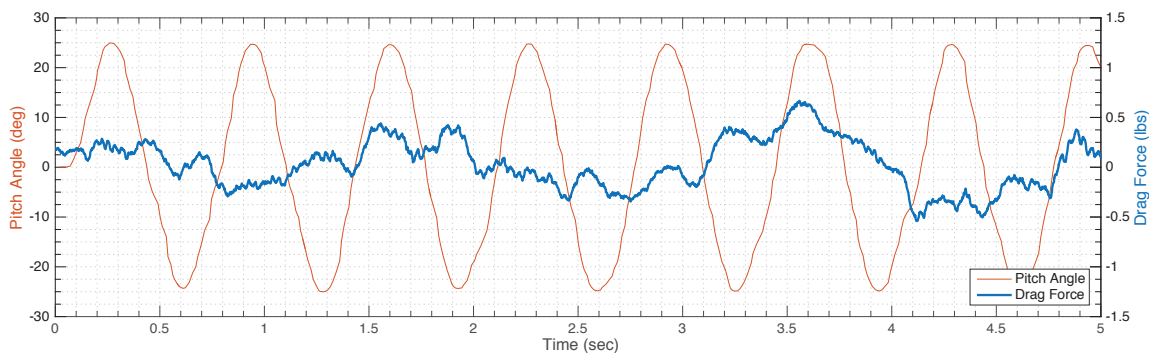


Figure 86. Pitch Angle to Drag Force, 1.5 Hz/ $\pm 25^\circ$ oscillation - 30 mph

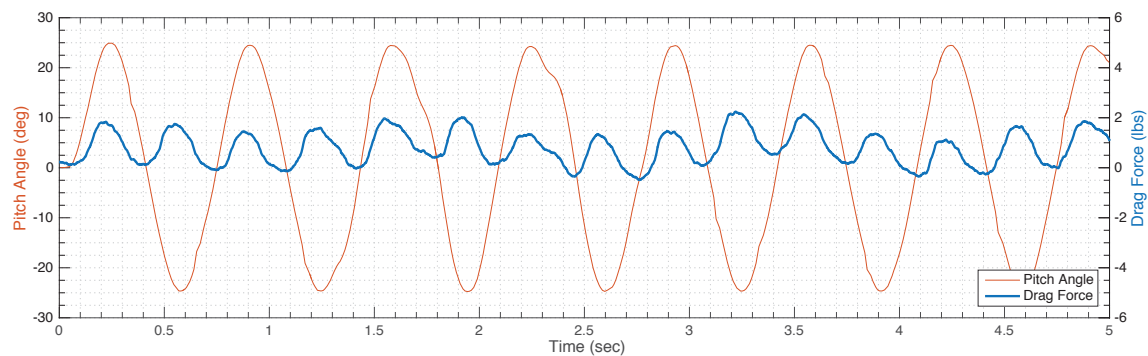


Figure 87. Pitch Angle to Drag Force, 1.5 Hz/ $\pm 25^\circ$ oscillation - 90 mph

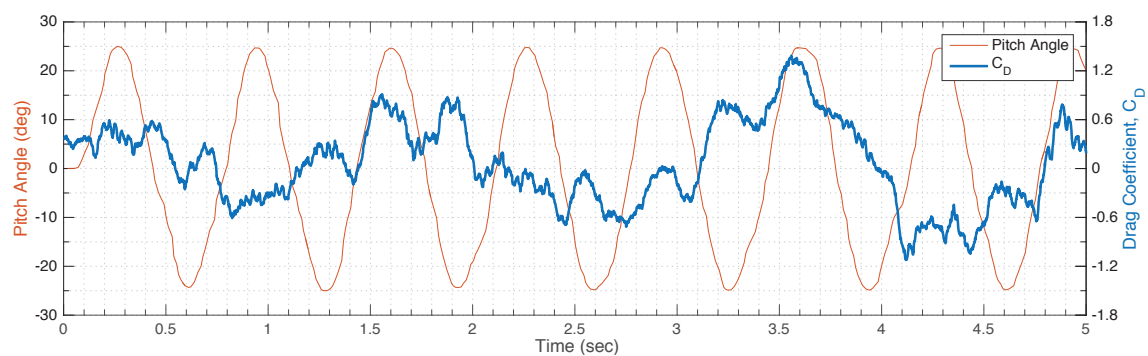


Figure 88. Pitch Angle to Drag Coefficient, 1.5 Hz/ $\pm 25^\circ$ oscillation - 30 mph

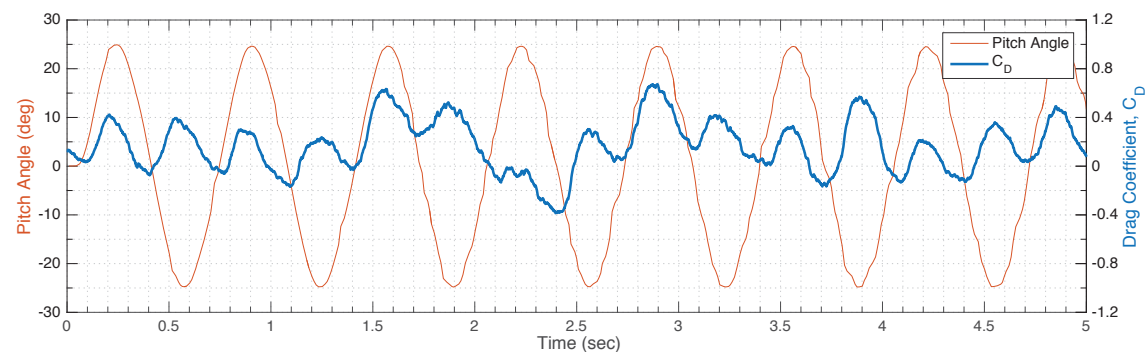


Figure 89. Pitch Angle to Drag Coefficient, 1.5 Hz/ $\pm 25^\circ$ oscillation - 60 mph

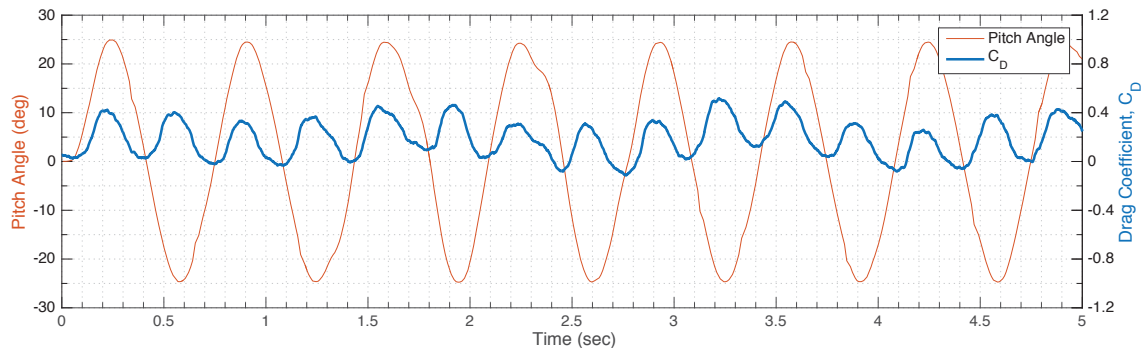


Figure 90. Pitch Angle to Drag Coefficient, 1.5 Hz/ $\pm 25^\circ$ oscillation - 90 mph

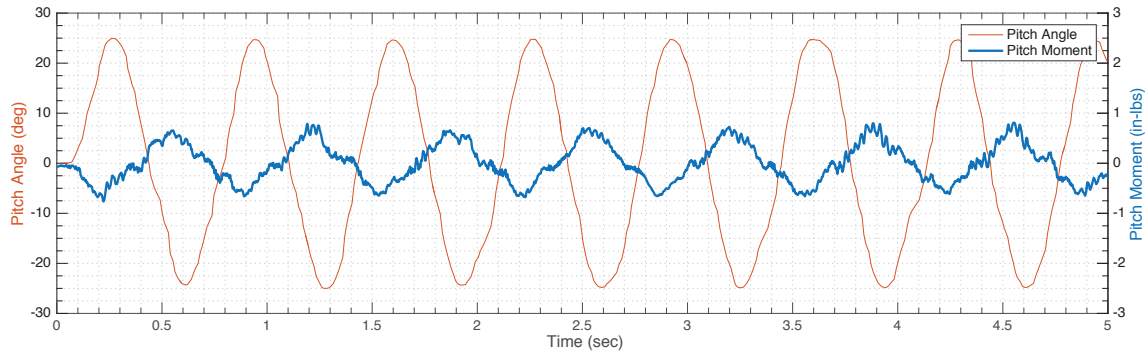


Figure 91. Pitch Angle to Pitch Moment, 1.5 Hz/ $\pm 25^\circ$ oscillation - 30 mph

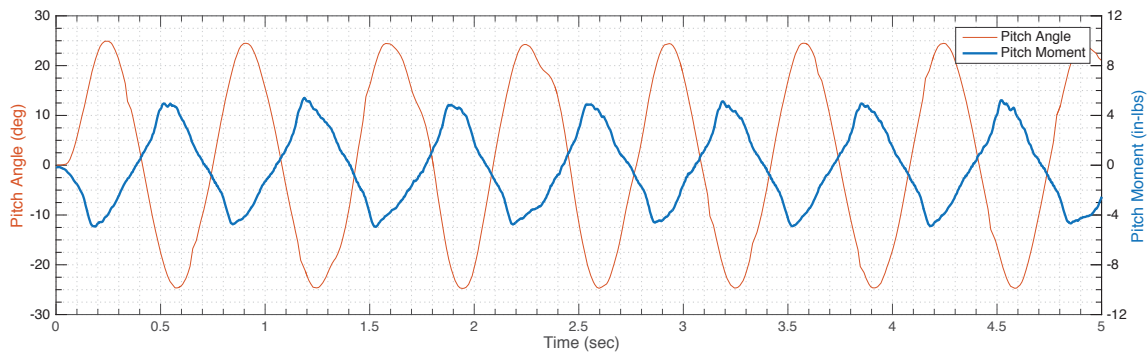


Figure 92. Pitch Angle to Pitch Moment, 1.5 Hz/ $\pm 25^\circ$ oscillation - 90 mph

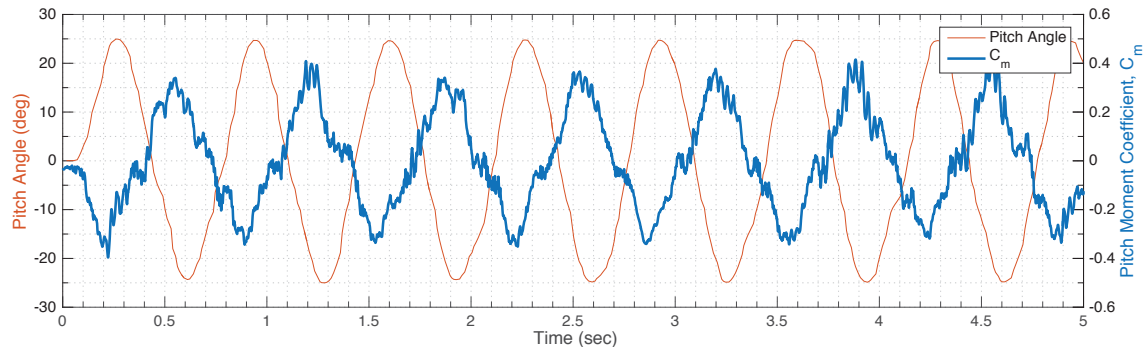


Figure 93. Pitch Angle to Pitch Moment Coefficient, 1.5 Hz/ $\pm 25^\circ$ oscillation - 30 mph

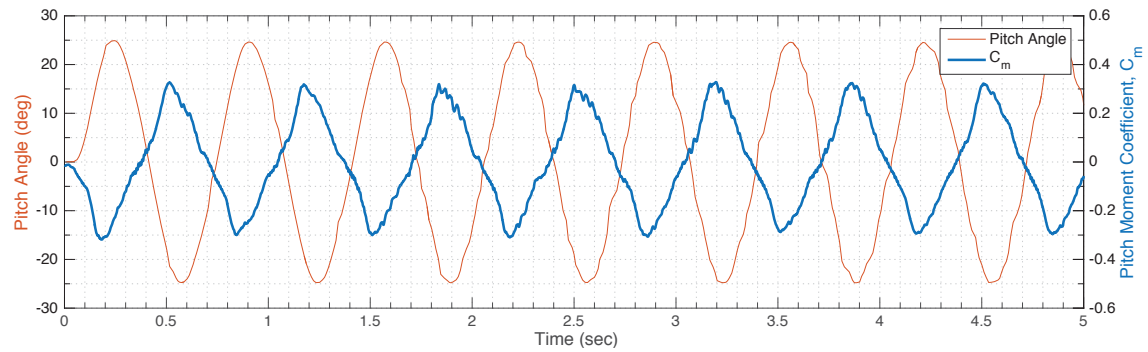


Figure 94. Pitch Angle to Pitch Moment Coefficient, 1.5 Hz/ $\pm 25^\circ$ oscillation - 60 mph

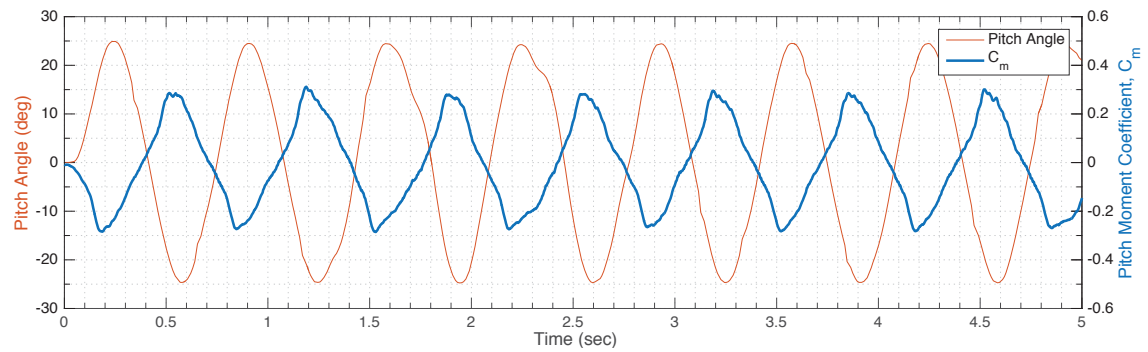


Figure 95. Pitch Angle to Pitch Moment Coefficient, 1.5 Hz/ $\pm 25^\circ$ oscillation - 90 mph

Additional Pitch-Plunge Oscillation Data

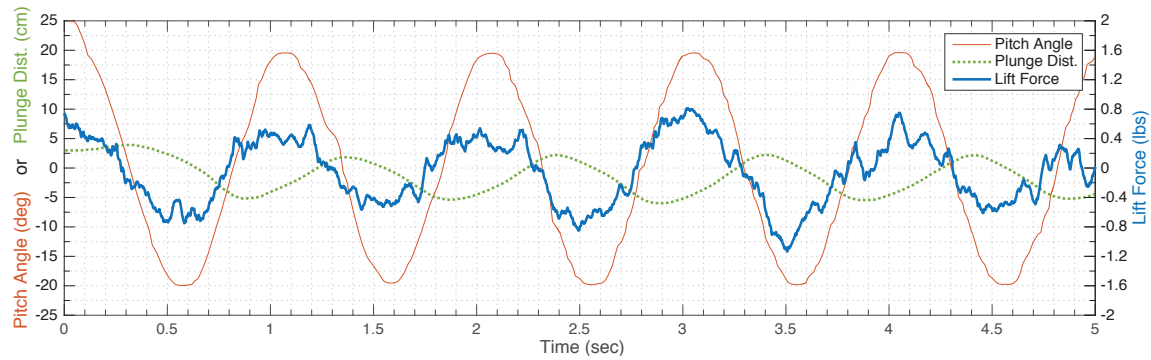


Figure 96. Pitch Angle & Plunge Dist. to Lift Force, 1 Hz/ $\pm 20^\circ$ oscillation - 30 mph

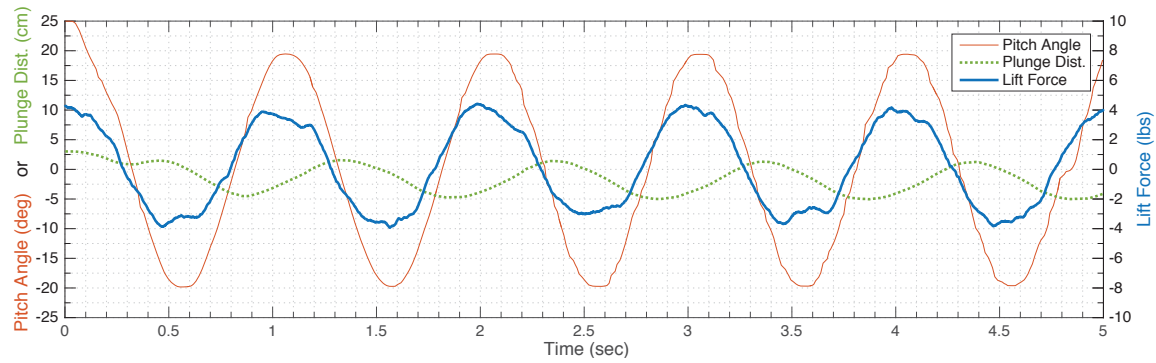


Figure 97. Pitch Angle & Plunge Dist. to Lift Force, 1 Hz/ $\pm 20^\circ$ oscillation - 90 mph

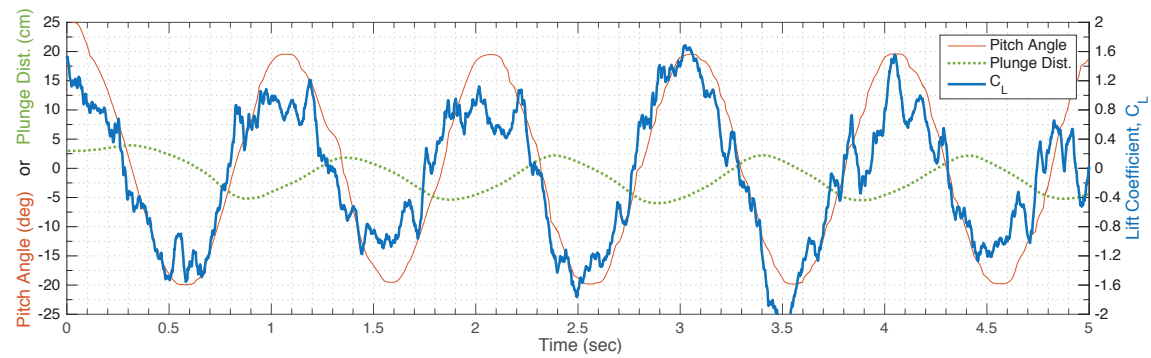


Figure 98. Pitch Angle & Plunge Dist. to Lift Coefficient, 1 Hz/ $\pm 20^\circ$ oscillation - 30 mph

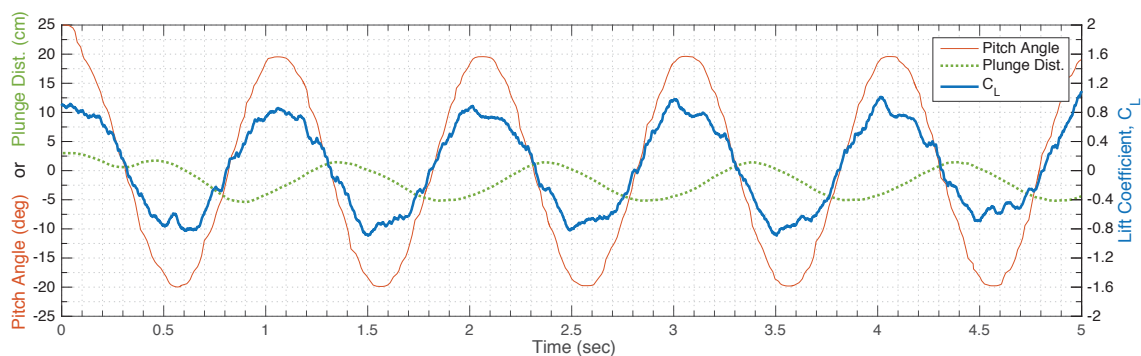


Figure 99. Pitch Angle & Plunge Dist. to Lift Coefficient, 1 Hz/ $\pm 20^\circ$ oscillation - 60 mph

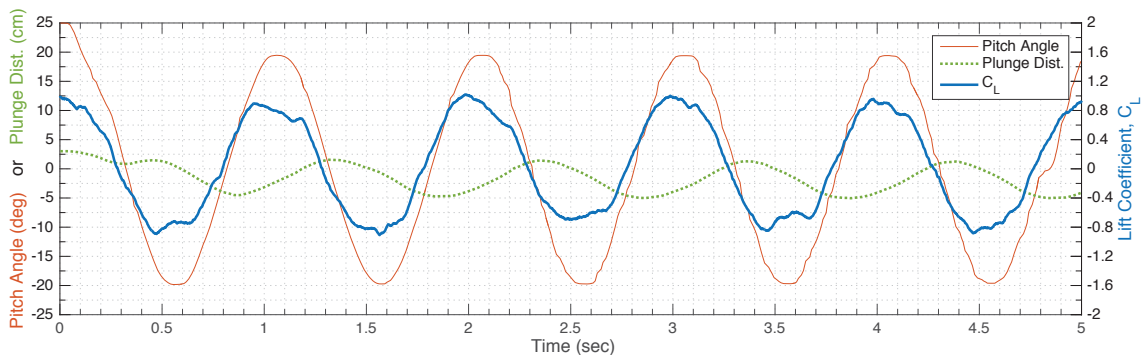


Figure 100. Pitch Angle & Plunge Dist. to Lift Coefficient, 1 Hz/ $\pm 20^\circ$ oscillation - 90 mph

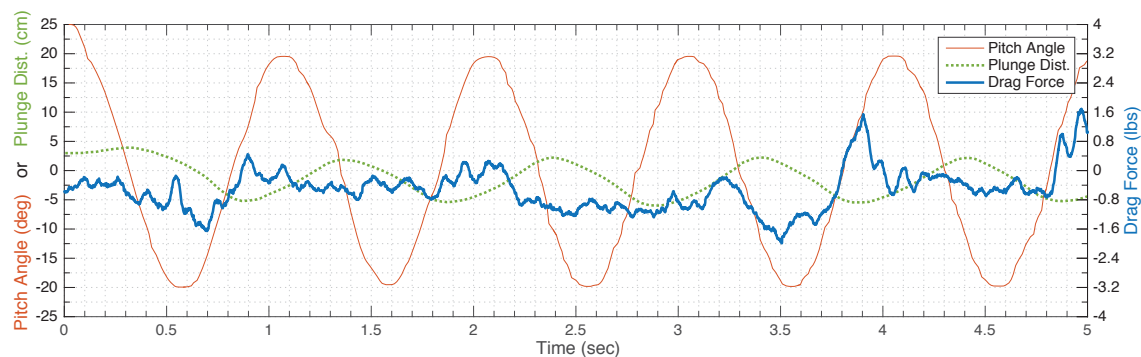


Figure 101. Pitch Angle & Plunge Dist. to Drag Force, 1 Hz/ $\pm 20^\circ$ oscillation - 30 mph

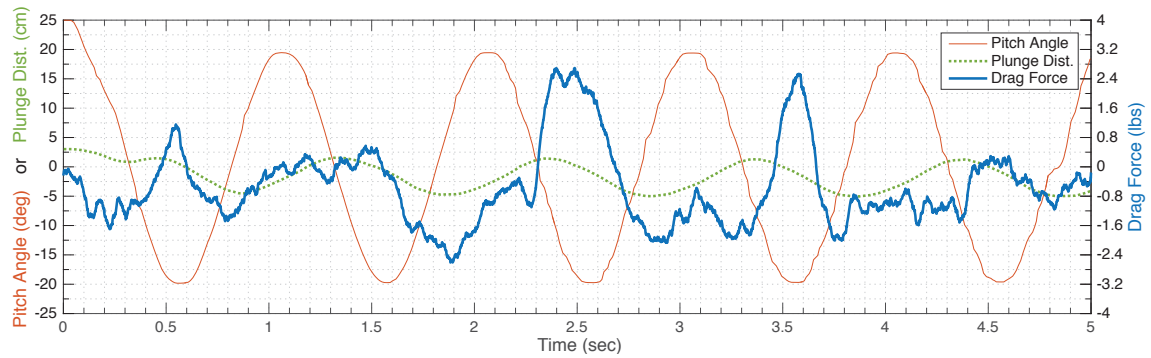


Figure 102. Pitch Angle & Plunge Dist. to Drag Force, 1 Hz/ $\pm 20^\circ$ oscillation - 90 mph

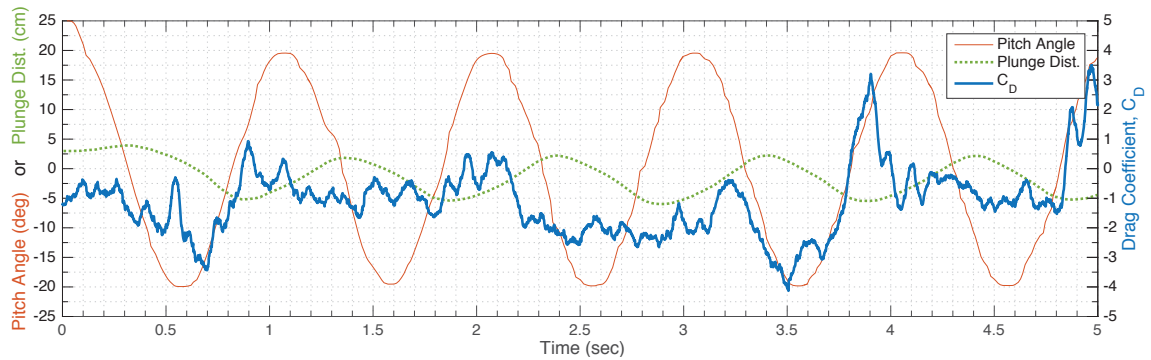


Figure 103. Pitch Angle & Plunge Dist. to Drag Coefficient, 1 Hz/ $\pm 20^\circ$ oscillation - 30 mph

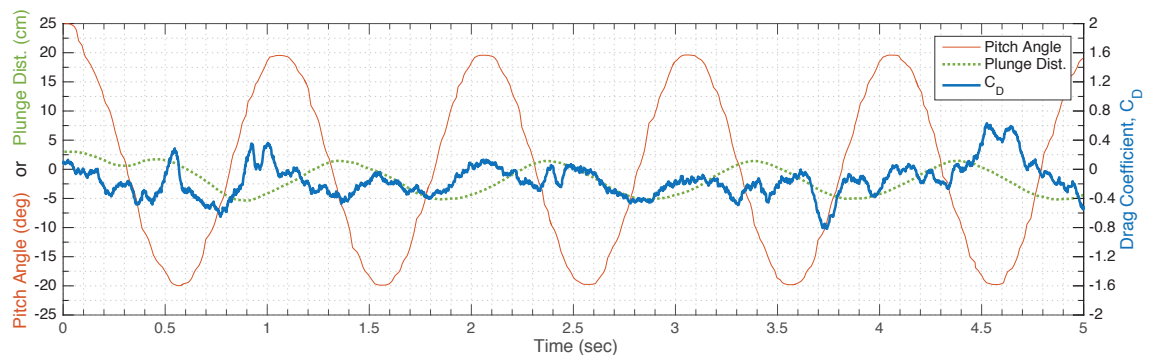


Figure 104. Pitch Angle & Plunge Dist. to Drag Coefficient, 1 Hz/ $\pm 20^\circ$ oscillation - 60 mph

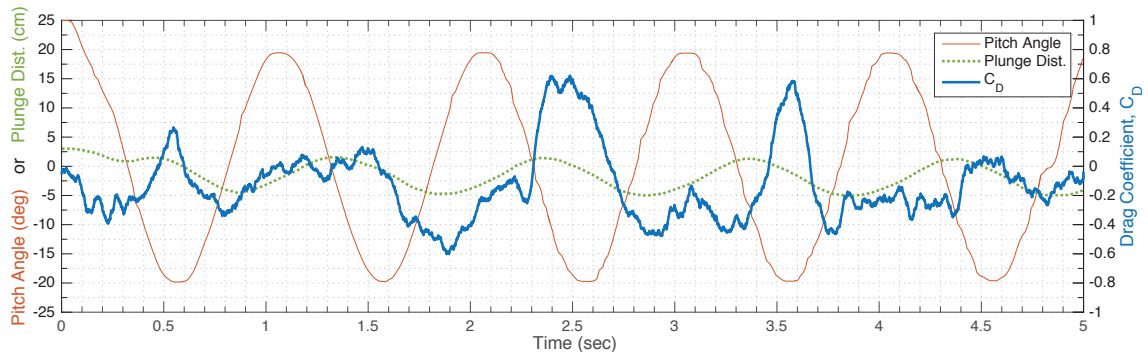


Figure 105. Pitch Angle & Plunge Dist. to Drag Coefficient, 1 Hz/ $\pm 20^\circ$ oscillation - 90 mph

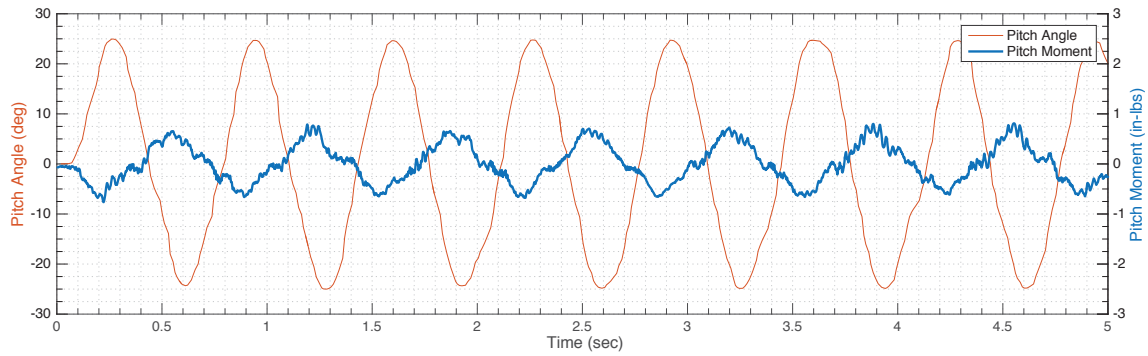


Figure 106. Pitch Angle & Plunge Dist. to Pitch Moment, 1 Hz/ $\pm 20^\circ$ oscillation - 30 mph

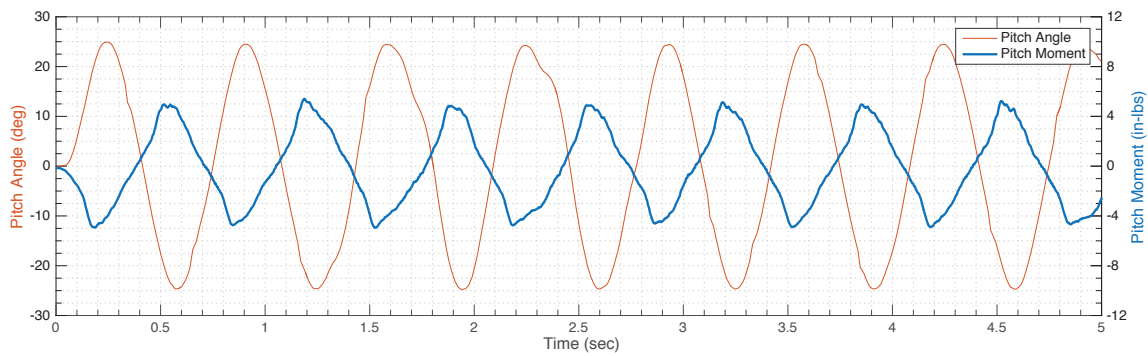


Figure 107. Pitch Angle & Plunge Dist. to Pitch Moment, 1 Hz/ $\pm 20^\circ$ oscillation - 90 mph

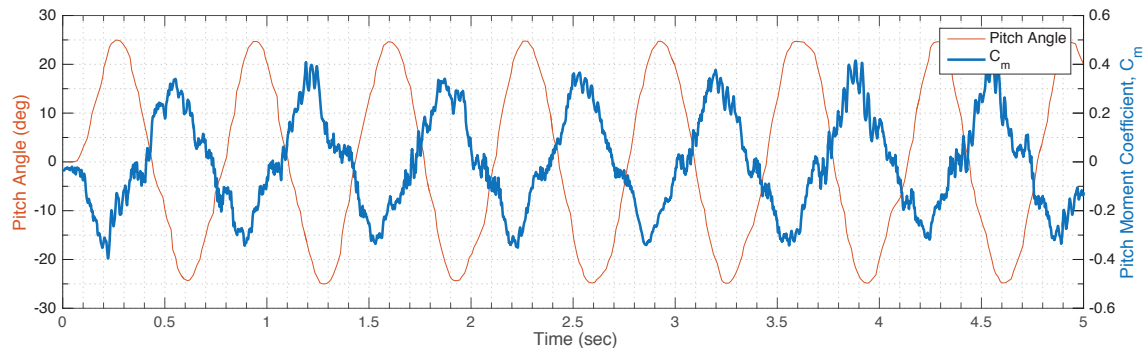


Figure 108. Pitch Angle & Plunge Dist. to Pitch Moment Coeff., 1 Hz/ $\pm 20^\circ$ oscillation - 30 mph

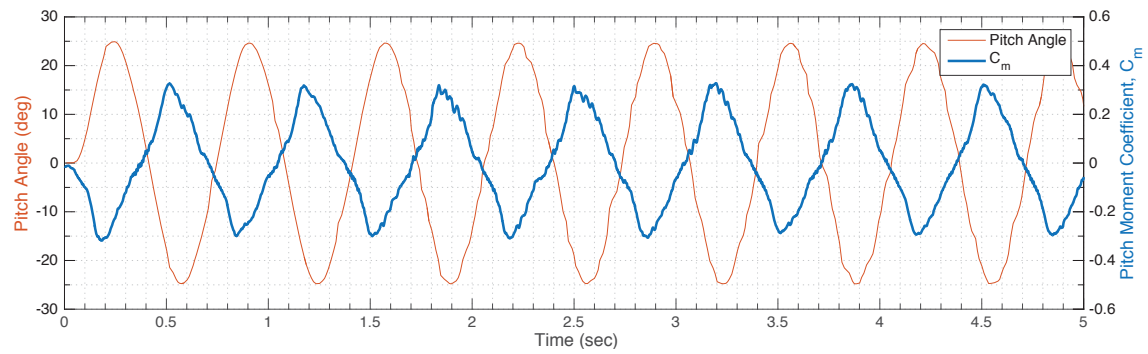


Figure 109. Pitch Angle & Plunge Dist. to Pitch Moment Coeff., 1 Hz/ $\pm 20^\circ$ oscillation - 60 mph

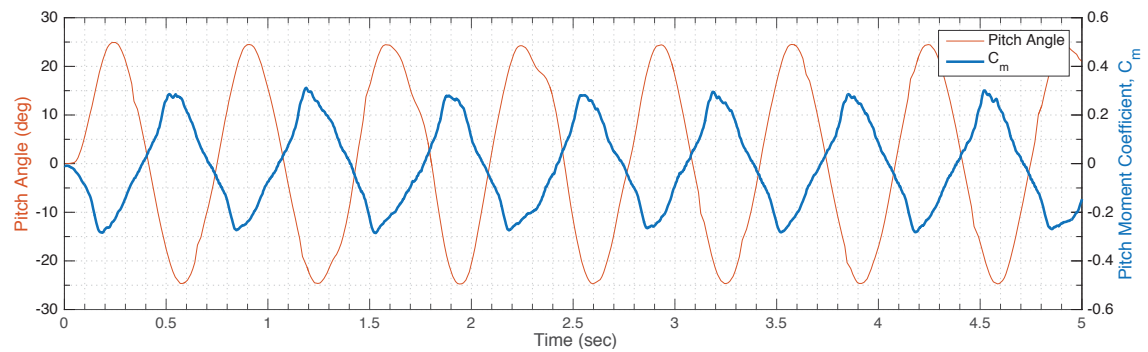


Figure 110. Pitch Angle & Plunge Dist. to Pitch Moment Coeff., 1 Hz/ $\pm 20^\circ$ oscillation - 90 mph

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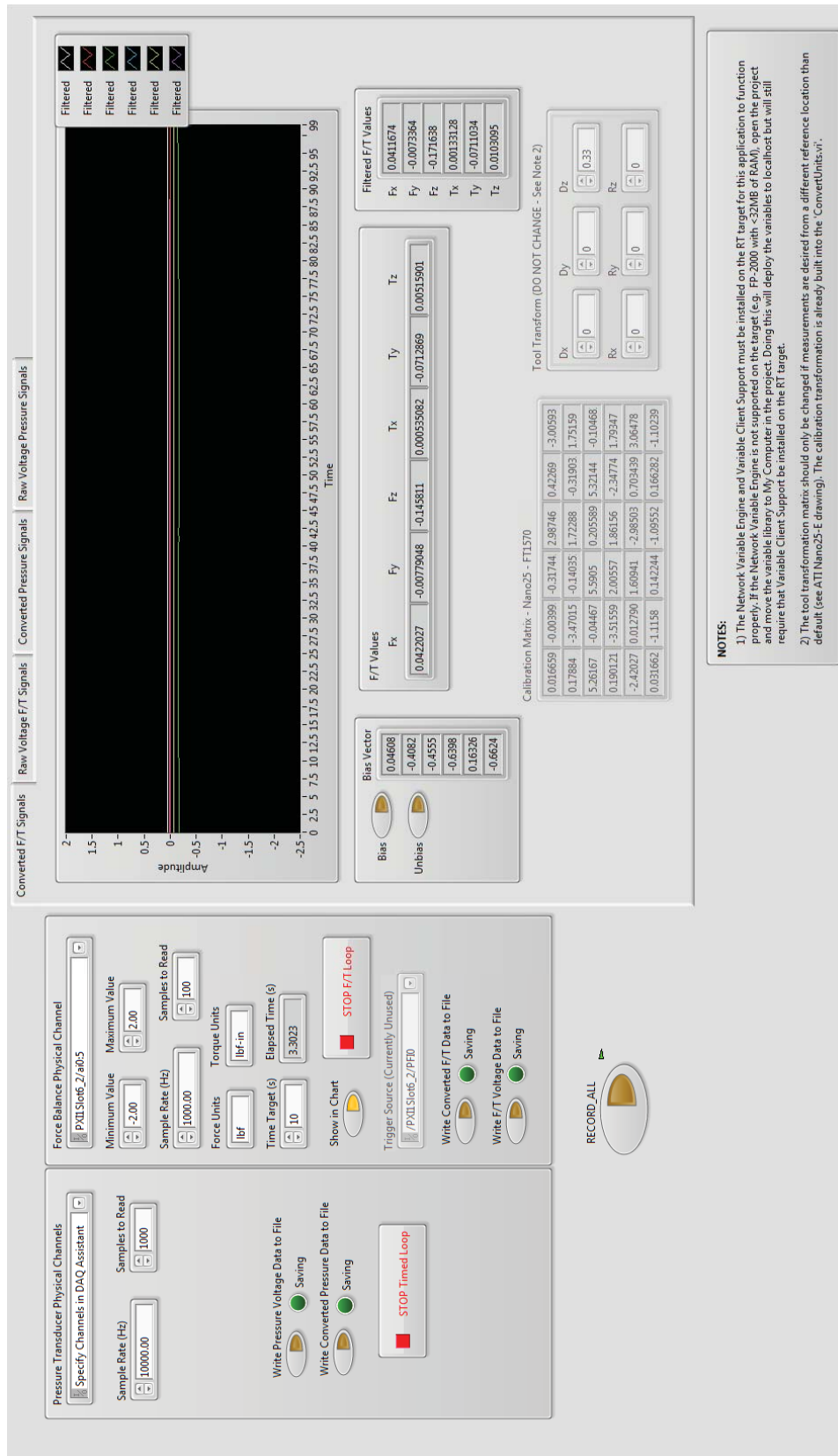


Figure 111. Nano25 Converted F/T Signals Page - Front Panel

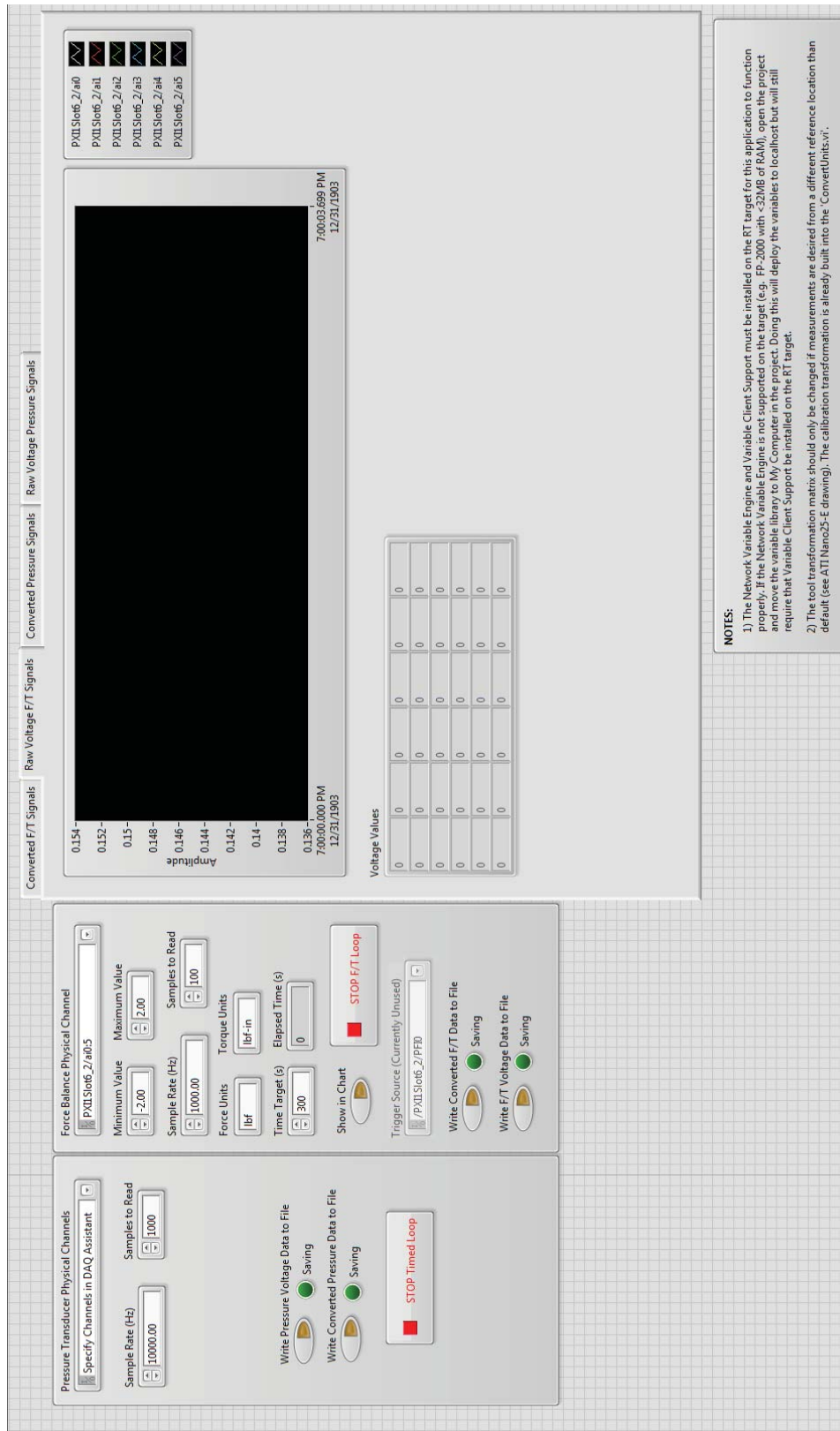


Figure 112. Nano25 Raw Voltage Signals Page - Front Panel

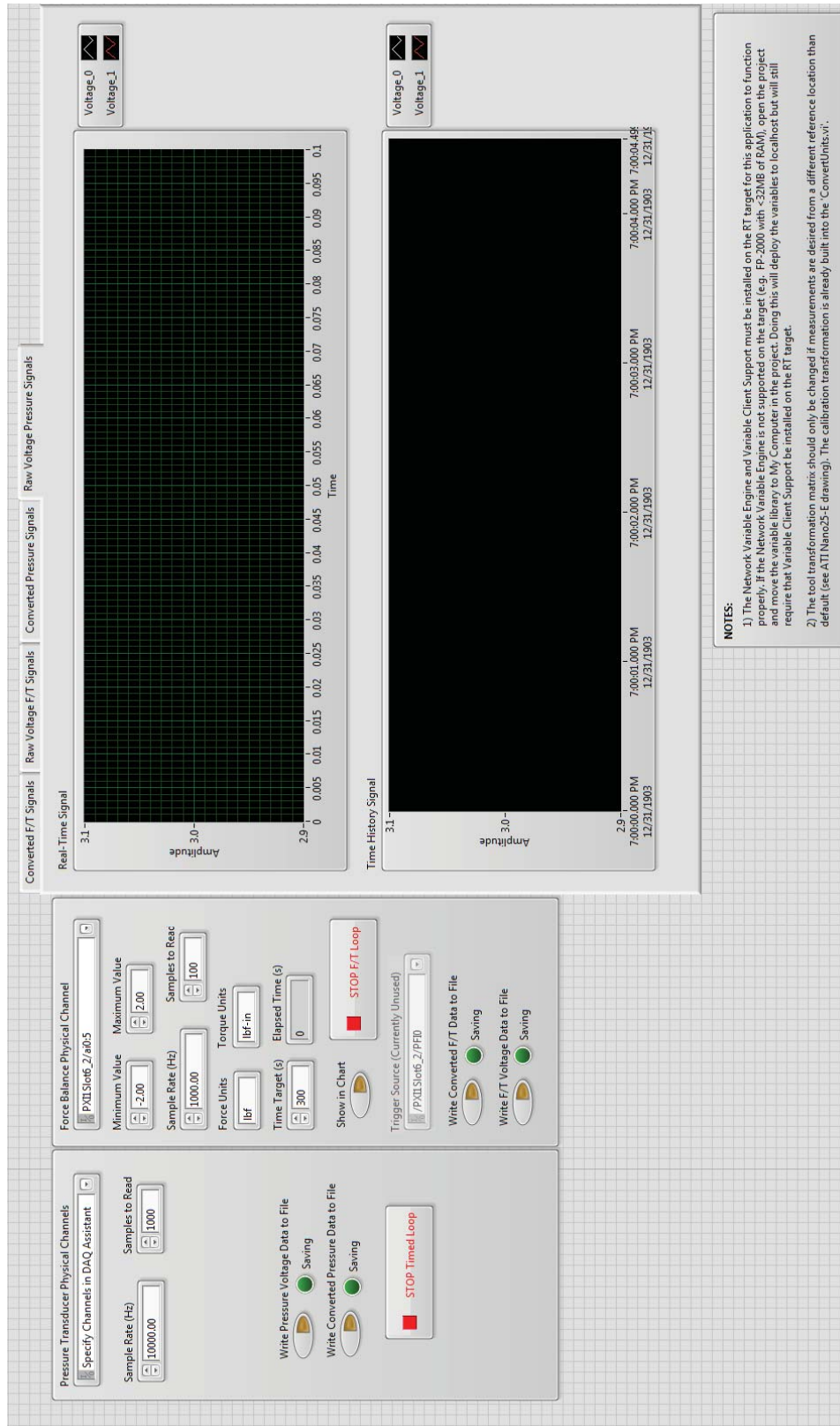


Figure 113. Pressure transducer Raw Voltage Signals Page - Front Panel

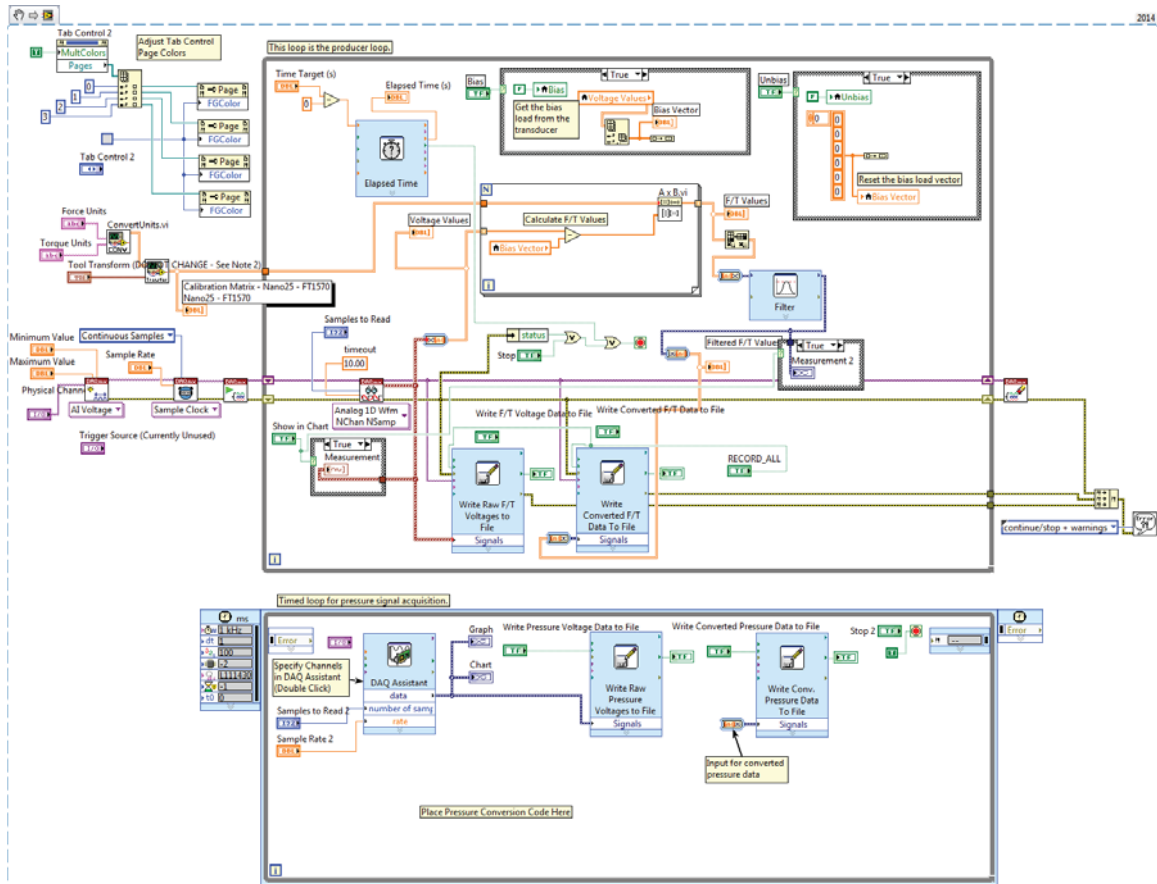


Figure 114. Nano25 F/T Transducer and Pressure Transducer Data Acquisition - Block Diagram

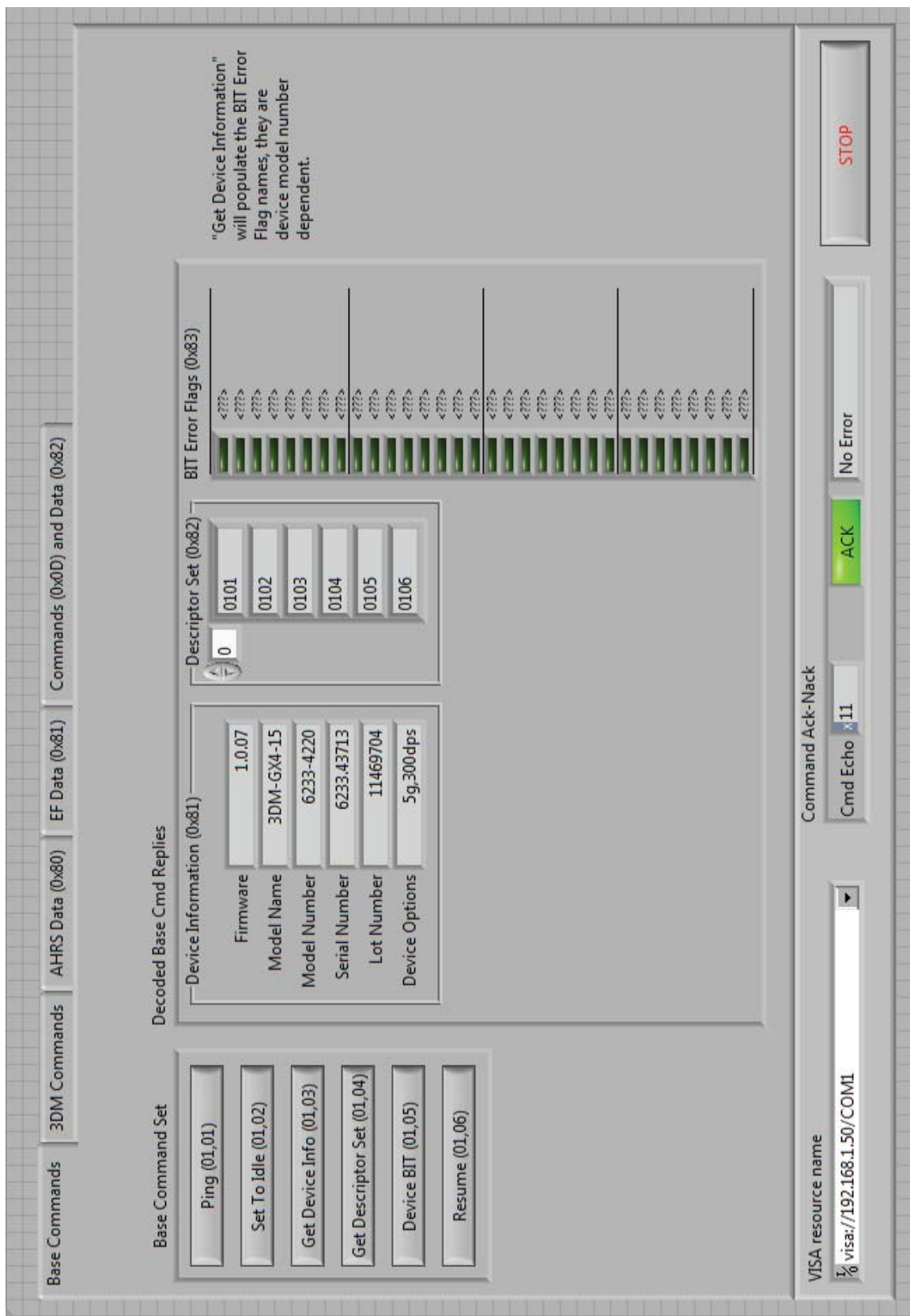


Figure 116. IMU Base Command Page - Front Panel

Base Commands

3DM Commands

AHRS Data (0x80)

EF Data (0x81)

Commands (0x0D) and Data (0x82)

GX4 Device Selector

AHRS

Function Selector

Apply

Set Data Msg Format

Select the desired data stream to set up using "GX4 Device Selector" at the far left. Set "Function Selector" at the left to "Apply". Select the desired data elements and rates in the appropriate array using the drop-down lists. Click "Set Data Msg Format" button.

Available AHRS Message Formats

0

Descriptor

Scaled Accel Vector

Rate (0x)

A

Descriptor

Euler Angles

Rate (0x)

C

Descriptor

<Click to Select>

Rate (0x)

0

Descriptor

<Click to Select>

Rate (0x)

0

0

Descriptor

<Click to Select>

Rate (0x)

4

Descriptor

<Click to Select>

Rate (0x)

0

Descriptor

<Click to Select>

Rate (0x)

0

Descriptor

<Click to Select>

Rate (0x)

0

0

Descriptor

<Click to Select>

Rate (0x)

A

Descriptor

<Click to Select>

Rate (0x)

0

Descriptor

<Click to Select>

Rate (0x)

0

Descriptor

<Click to Select>

Rate (0x)

0

Enable/Disable

Disable

Continuous Stream (0C,11)

Set the "Enable/Disable" switch at the far left. Select the device stream to control using "GX3 Device Selector" above. Set "Function Selector" above to "Apply". Click "Continuous Stream" button.

VISA resource name

visa://192.168.1.50/COM1

Command Ack-Nack

Cmd Echo 11

ACK

No Error

STOP

Figure 117. IMU 3DM Commands Page - Front Panel

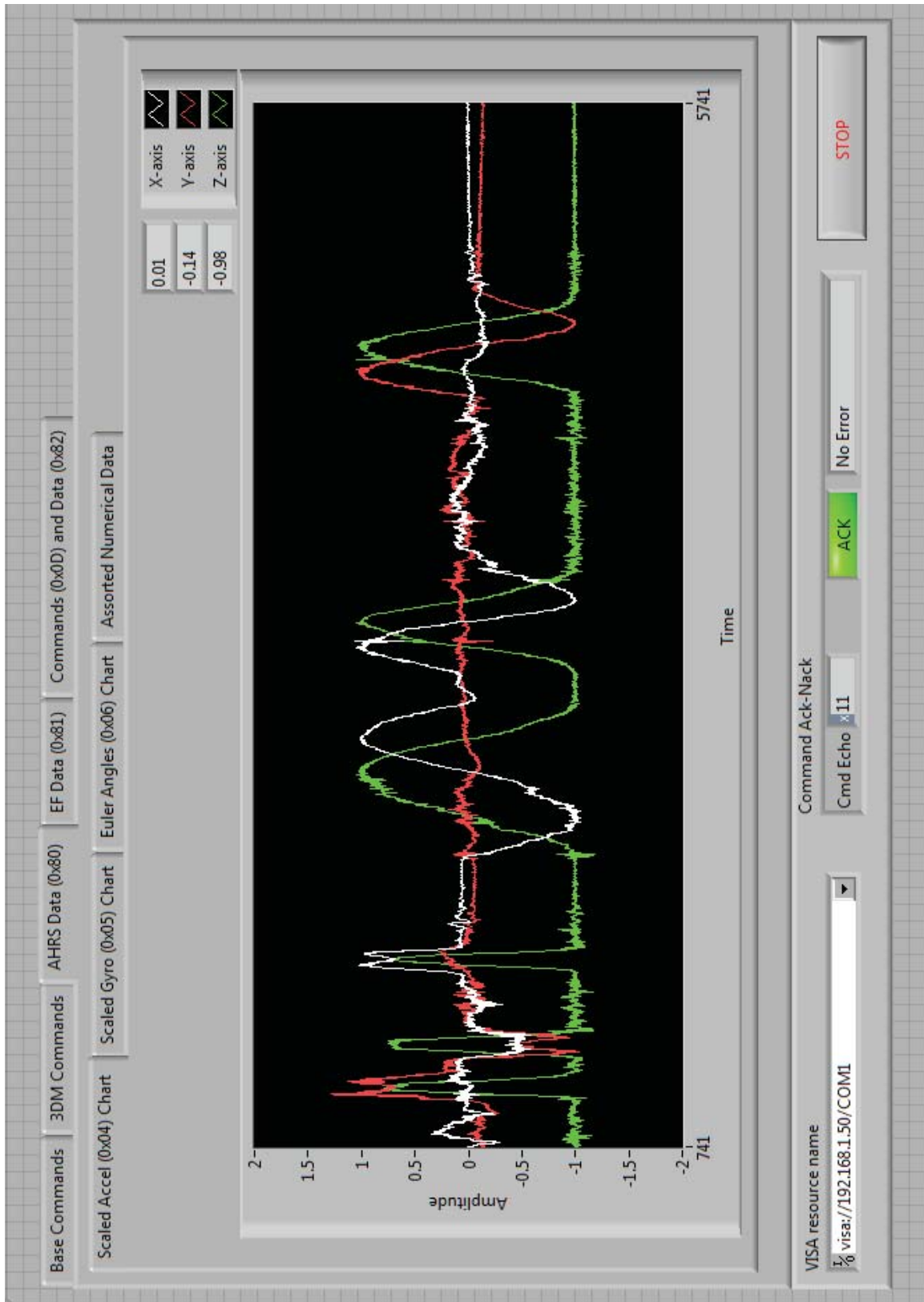


Figure 118. IMU AHRS Data Page, Scaled Accelerometer Signals - Front Panel

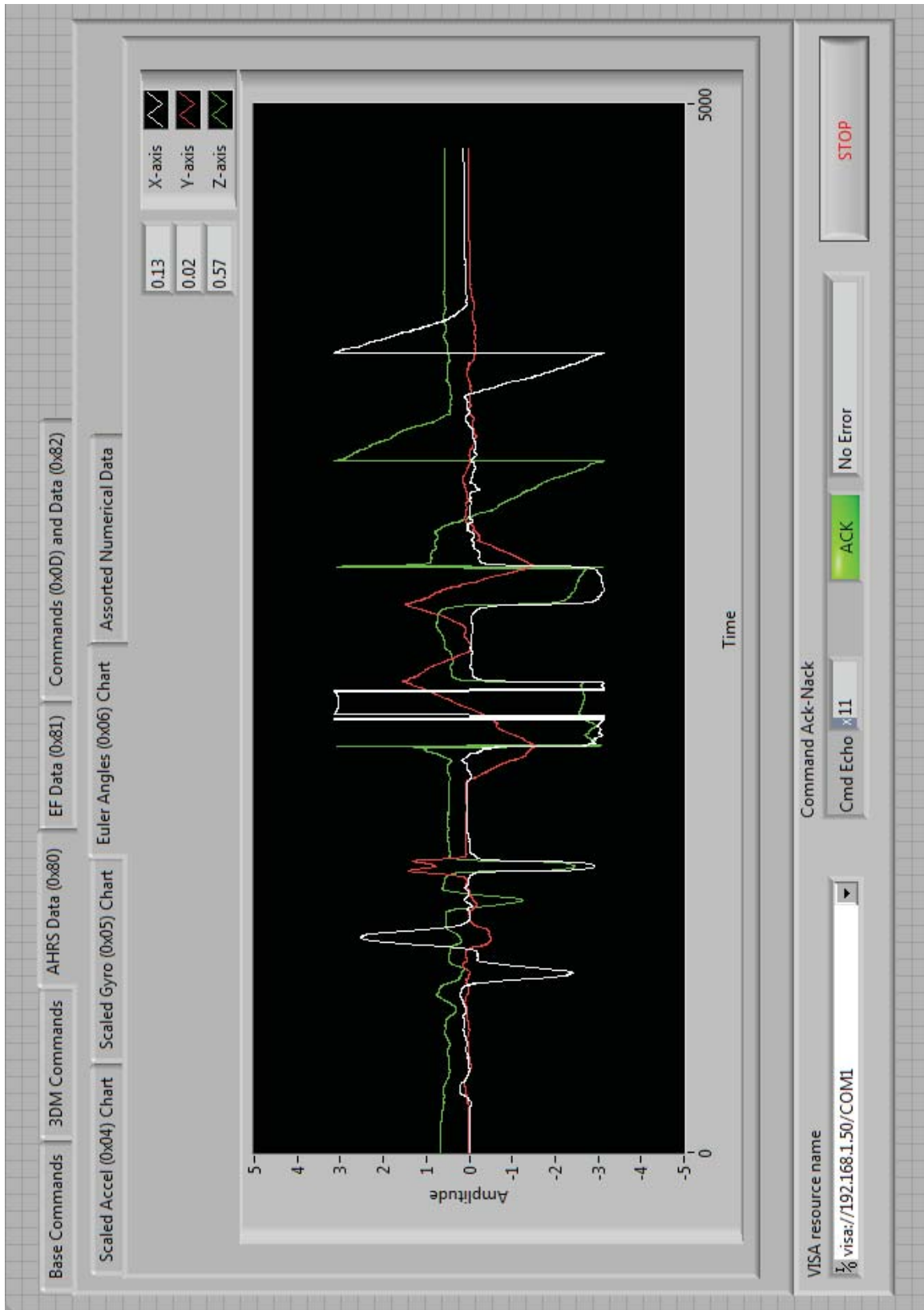


Figure 119. IMU AHRS Data Page, Euler Angle Signals - Front Panel

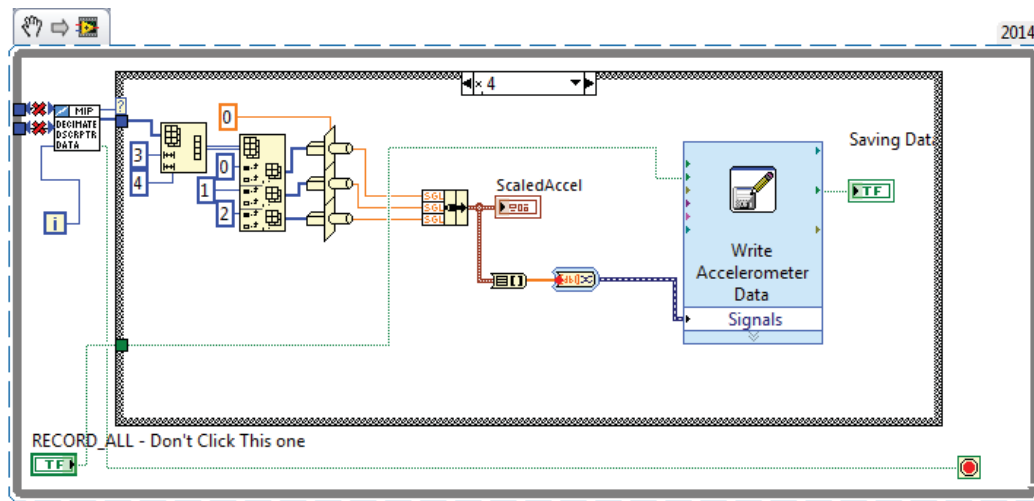


Figure 121. IMU AHRS Data Loop Detail, Scaled Accelerometer Data

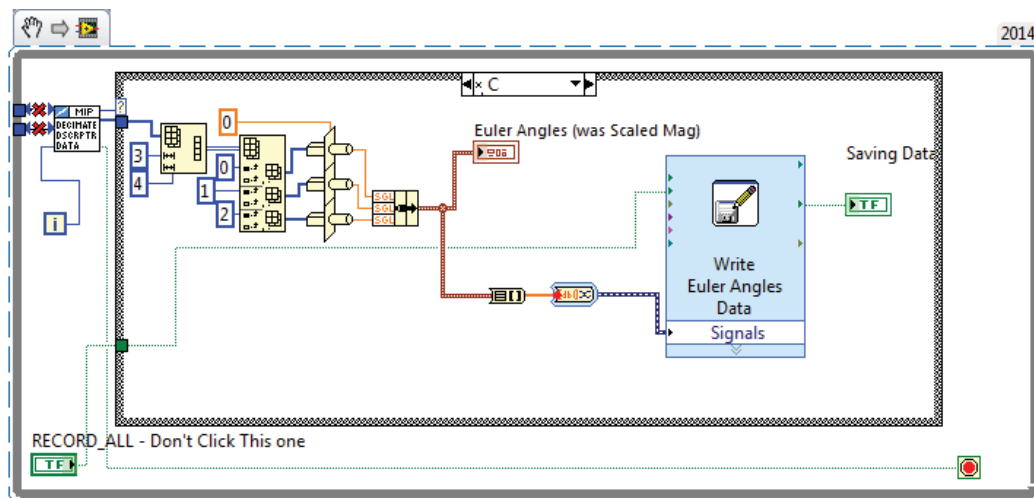


Figure 122. IMU AHRS Data Loop Detail, Euler Angles Data

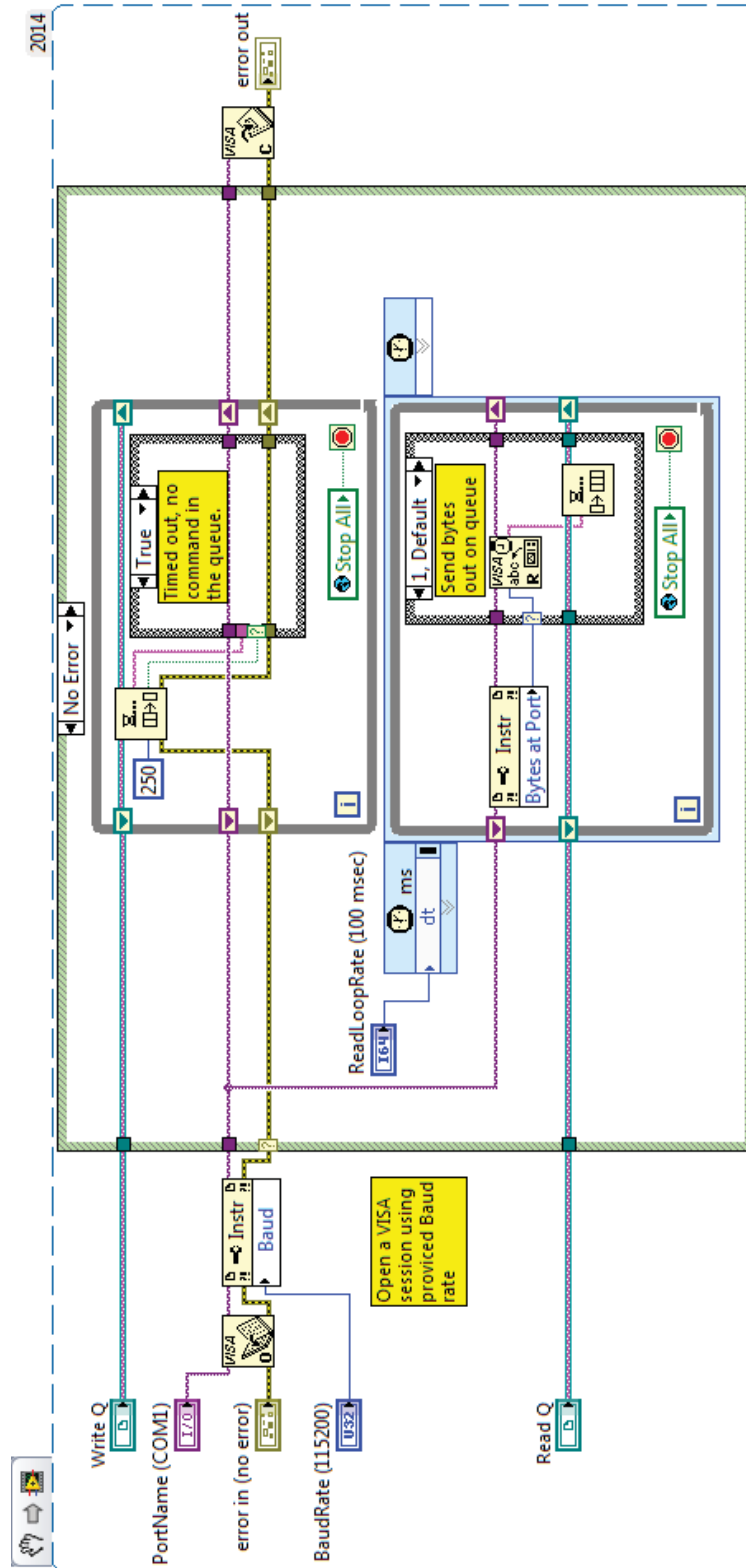


Figure 123. IMU COM Port Interface Settings VI

```

% 2dLt James Sellers, AFIT/ENY, Feb. 2, 2016
clear; close all; clc
format long
set(0,'DefaultFigureWindowStyle','normal')
%#ok<*NBRAK>

% Load all Test Data:
load EncoderData.mat           % Loads MTA Encoder Data (Pitch & Pitch-Plunge)
load IMUData.mat               % Loads IMU Data, Accelerations & Euler Angles (Pitch only)
load Nano25Data.mat            % Loads FT Data from Nano25 (Pitch & Pitch-Plunge)
load tare_correction.mat        % Loads tare correction data for pitch-plunge data
load EA.mat                    % Loads Euler Angle Data from IMU
load Traj.mat                   % Loads trajectory file

% Correct Time Column (Enter output rate used):
% -----
Rate = 1000;      % Output Rate, Hz
% -----
Pitch0(:,1) = (0:1/Rate:(length(Pitch0)-1)/Rate)';
Pitch30(:,1) = (0:1/Rate:(length(Pitch30)-1)/Rate)';
Pitch60(:,1) = (0:1/Rate:(length(Pitch60)-1)/Rate)';
Pitch90(:,1) = (0:1/Rate:(length(Pitch90)-1)/Rate)';
Pitch120(:,1) = (0:1/Rate:(length(Pitch120)-1)/Rate)';
PitchPlunge0(:,1) = (0:1/Rate:(length(PitchPlunge0)-1)/Rate)';
PitchPlunge30(:,1) = (0:1/Rate:(length(PitchPlunge30)-1)/Rate)';
PitchPlunge60(:,1) = (0:1/Rate:(length(PitchPlunge60)-1)/Rate)';
PitchPlunge90(:,1) = (0:1/Rate:(length(PitchPlunge90)-1)/Rate)';
PitchPlunge120(:,1) = (0:1/Rate:(length(PitchPlunge120)-1)/Rate)';
tare_cor0(:,1) = (0:1/Rate:(length(tare_cor0)-1)/Rate)';
tare_cor30(:,1) = (0:1/Rate:(length(tare_cor30)-1)/Rate)';
tare_cor60(:,1) = (0:1/Rate:(length(tare_cor60)-1)/Rate)';
tare_cor90(:,1) = (0:1/Rate:(length(tare_cor90)-1)/Rate)';
tare_cor120(:,1) = (0:1/Rate:(length(tare_cor120)-1)/Rate)';

% Tare correction mean (tcm) for pitch-plunge correction:
tcm0 = mean(tare_cor0(:,2:7));
tcm30 = mean(tare_cor30(:,2:7));
tcm60 = mean(tare_cor60(:,2:7));
tcm90 = mean(tare_cor90(:,2:7));
tcm120 = mean(tare_cor120(:,2:7));
tcm0(:,3) = -tcm0(:,3);
tcm30(:,3) = -tcm30(:,3);
tcm60(:,3) = -tcm60(:,3);
tcm90(:,3) = -tcm90(:,3);
tcm120(:,3) = -tcm120(:,3);

% Correct Pitch-Plunge tare error (offset correction):
% columns 2-7 = columns 1-6 for tcm
PitchPlunge0(:,2:7) = PitchPlunge0(:,2:7) + ones(length(PitchPlunge0),1)*tcm0(1:6);
PitchPlunge30(:,2:7) = PitchPlunge30(:,2:7) + ones(length(PitchPlunge30),1)*tcm30(1:6);
PitchPlunge60(:,2:7) = PitchPlunge60(:,2:7) + ones(length(PitchPlunge60),1)*tcm60(1:6);
PitchPlunge90(:,2:7) = PitchPlunge90(:,2:7) + ones(length(PitchPlunge90),1)*tcm90(1:6);
PitchPlunge120(:,2:7) = PitchPlunge120(:,2:7) + ones(length(PitchPlunge120),1)*tcm120(1:6);

% Preliminary Plots for cropping code, COMMENT OUT WHEN VALUES ARE UPDATED:
% -----
% figure; plot(Pitch0(:,1),Pitch0(:,6));    title('WR Pitch - 0mph')
% figure; plot(Pitch30(:,1),Pitch30(:,6)); title('WR Pitch - 30mph')
% figure; plot(Pitch60(:,1),Pitch60(:,6)); title('WR Pitch - 60mph')
% figure; plot(Pitch90(:,1),Pitch90(:,6)); title('WR Pitch - 90mph')
% figure; plot(Pitch120(:,1),Pitch120(:,6));title('WR Pitch - 120mph')

```

```

% figure; plot(PitchPlunge0(:,1),PitchPlunge0(:,6)); title('Pitch Plunge - 0mph')
% figure; plot(PitchPlunge30(:,1),PitchPlunge30(:,6)); title('Pitch Plunge - 30mph')
% figure; plot(PitchPlunge60(:,1),PitchPlunge60(:,6)); title('Pitch Plunge - 60mph')
% figure; plot(PitchPlunge90(:,1),PitchPlunge90(:,6)); title('Pitch Plunge - 90mph')
% figure; plot(PitchPlunge120(:,1),PitchPlunge120(:,6));title('Pitch Plunge - 120mph')
% figure; plot(Euler0(:,1),Euler0(:,3));title('IMU Euler Angles - 0mph')
% figure; plot(Euler30(:,1),Euler30(:,3));title('IMU Euler Angles - 30mph')
% figure; plot(Euler60(:,1),Euler60(:,3));title('IMU Euler Angles - 60mph')
% figure; plot(Euler90(:,1),Euler90(:,3));title('IMU Euler Angles - 90mph')
% figure; plot(Euler120(:,1),Euler120(:,3));title('IMU Euler Angles - 120mph')
% return
% -----/ \-----
%                               /| |\
%                               / | |\
% Leave movement data only:    /  |  \
% Movement start time and end time (seconds):
% -----|
W0st = 10.606;      W0en = 25.723;      % |
W30st = 10.006;    W30en = 25.139;    % |
W60st = 9.591;     W60en = 24.708;    % | (get from plots above)
W90st = 9.224;     W90en = 24.353;    % |
W120st = 9.692;    W120en = 24.786;   % |
P0st = 9.513;      P0en = 24.600;     % |
P30st = 10.060;    P30en = 25.150;    % |
P60st = 8.574;     P60en = 23.670;    % |
P90st = 8.640;     P90en = 23.660;    % |
P120st = 9.066;    P120en = 24.130;   % |
E0st = 10.6316;    E0en = 25.9265;    % |
E30st = 10.0386;   E30en = 25.2184;   % |
E60st = 9.6066;    E60en = 24.8664;   % |
E90st = 9.2025;    E90en = 24.4024;   % |
E120st = 9.7146;   E120en = 24.8434;  % |
% -----|

% Define useful data (cuts off beginning and end):
WRPitch_0a = Pitch0([(W0st*Rate)+1:(W0en)*Rate)+2],:);
WRPitch_30a = Pitch30([(W30st*Rate)+1:(W30en)*Rate)+2],:);
WRPitch_60a = Pitch60([(W60st*Rate)+1:(W60en)*Rate)+2],:);
WRPitch_90a = Pitch90([(W90st*Rate)+1:(W90en)*Rate)+2],:);
WRPitch_120a = Pitch120([(W120st*Rate)+1:(W120en)*Rate)+2],:);
PtchPlng_0a = PitchPlunge0([(P0st*Rate)+1:(P0en)*Rate)+2],:);
PtchPlng_30a = PitchPlunge30([(P30st*Rate)+1:(P30en)*Rate)+2],:);
PtchPlng_60a = PitchPlunge60([(P60st*Rate)+1:(P60en)*Rate)+2],:);
PtchPlng_90a = PitchPlunge90([(P90st*Rate)+1:(P90en)*Rate)+2],:);
PtchPlng_120a = PitchPlunge120([(P120st*Rate)+1:(P120en)*Rate)+2],:);

% Offset data to start at 0 seconds:
WRPitch_0a(:,1) = WRPitch_0a(:,1) - WRPitch_0a(1);
WRPitch_30a(:,1) = WRPitch_30a(:,1) - WRPitch_30a(1);
WRPitch_60a(:,1) = WRPitch_60a(:,1) - WRPitch_60a(1);
WRPitch_90a(:,1) = WRPitch_90a(:,1) - WRPitch_90a(1);
WRPitch_120a(:,1) = WRPitch_120a(:,1) - WRPitch_120a(1);

PtchPlng_0a(:,1) = PtchPlng_0a(:,1) - PtchPlng_0a(1);
PtchPlng_30a(:,1) = PtchPlng_30a(:,1) - PtchPlng_30a(1);
PtchPlng_60a(:,1) = PtchPlng_60a(:,1) - PtchPlng_60a(1);
PtchPlng_90a(:,1) = PtchPlng_90a(:,1) - PtchPlng_90a(1);
PtchPlng_120a(:,1) = PtchPlng_120a(:,1) - PtchPlng_120a(1);

% Adjust Euler Angle Data:
EA0(:,1) = EA0(:,1) - EA0(1);
EA30(:,1) = EA30(:,1) - EA30(1);
EA60(:,1) = EA60(:,1) - EA60(1);
EA90(:,1) = EA90(:,1) - EA90(1);
EA120(:,1) = EA120(:,1) - EA120(1);

```

```

% Subtract out dynamic tare (subtract 0mph data):
WRPitch_0 = WRPitch_0a(1:length(WRPitch_120a),:);
WRPitch_30 = WRPitch_30a(1:length(WRPitch_120a),:) - [zeros(length(WRPitch_120a),1) WRPitch_0(
:,2:7)];
WRPitch_60 = WRPitch_60a(1:length(WRPitch_120a),:) - [zeros(length(WRPitch_120a),1) WRPitch_0(
:,2:7)];
WRPitch_90 = WRPitch_90a(1:length(WRPitch_120a),:) - [zeros(length(WRPitch_120a),1) WRPitch_0(
:,2:7)];
WRPitch_120 = WRPitch_120a - [zeros(length(WRPitch_120a),1) WRPitch_0(:,2:7)];
PtchPlng_0 = PtchPlng_0a(1:length(PtchPlng_90a),:);
PtchPlng_30 = PtchPlng_30a(1:length(PtchPlng_90a),:) - [zeros(length(PtchPlng_90a),1) PtchPlng
_0(:,2:7)];
PtchPlng_60 = PtchPlng_60a(1:length(PtchPlng_90a),:) - [zeros(length(PtchPlng_90a),1) PtchPlng
_0(:,2:7)];
PtchPlng_90 = PtchPlng_90a - [zeros(length(PtchPlng_90a),1) PtchPlng_0(:,2:7)];
PtchPlng_120 = PtchPlng_120a(1:length(PtchPlng_90a),:) - [zeros(length(PtchPlng_90a),1) PtchPl
ng_0(:,2:7)];

% Calculate Lift & Drag forces w.r.t. Pitch Angle:
pa0 = interpft(MTA0(:,5),length(WRPitch_0));
Lift0 = WRPitch_0(:,2).*cosd(pa0) + WRPitch_0(:,4).*sind(pa0);
Drag0 = -(WRPitch_0(:,4).*cosd(pa0) - WRPitch_0(:,2).*sind(pa0));
pa0pl = interpft(MTA0plunge(:,5),length(PtchPlng_0));
Lift0pl = PtchPlng_0(:,2).*cosd(pa0pl) + PtchPlng_0(:,4).*sind(pa0pl);
Drag0pl = -(PtchPlng_0(:,4).*cosd(pa0pl) - PtchPlng_0(:,2).*sind(pa0pl));

pa30 = interpft(MTA30(:,5),length(WRPitch_30));
Lift30 = WRPitch_30(:,2).*cosd(pa30) + WRPitch_30(:,4).*sind(pa30);
Drag30 = -(WRPitch_30(:,4).*cosd(pa30) - WRPitch_30(:,2).*sind(pa30));
pa30pl = interpft(MTA30plunge(:,5),length(PtchPlng_30));
Lift30pl = PtchPlng_30(:,2).*cosd(pa30pl) + PtchPlng_30(:,4).*sind(pa30pl);
Drag30pl = -(PtchPlng_30(:,4).*cosd(pa30pl) - PtchPlng_30(:,2).*sind(pa30pl));

pa60 = interpft(MTA60(:,5),length(WRPitch_60));
Lift60 = WRPitch_60(:,2).*cosd(pa60) + WRPitch_60(:,4).*sind(pa60);
Drag60 = -(WRPitch_60(:,4).*cosd(pa60) - WRPitch_60(:,2).*sind(pa60));
pa60pl = interpft(MTA60plunge(:,5),length(PtchPlng_60));
Lift60pl = PtchPlng_60(:,2).*cosd(pa60pl) + PtchPlng_60(:,4).*sind(pa60pl);
Drag60pl = -(PtchPlng_60(:,4).*cosd(pa60pl) - PtchPlng_60(:,2).*sind(pa60pl));

pa90 = interpft(MTA90(:,5),length(WRPitch_90));
Lift90 = WRPitch_90(:,2).*cosd(pa90) + WRPitch_90(:,4).*sind(pa90);
Drag90 = -(WRPitch_90(:,4).*cosd(pa90) - WRPitch_90(:,2).*sind(pa90));
pa90pl = interpft(MTA90plunge(:,5),length(PtchPlng_90));
Lift90pl = PtchPlng_90(:,2).*cosd(pa90pl) + PtchPlng_90(:,4).*sind(pa90pl);
Drag90pl = -(PtchPlng_90(:,4).*cosd(pa90pl) - PtchPlng_90(:,2).*sind(pa90pl));

pa120 = interpft(MTA120(:,5),length(WRPitch_120));
Lift120 = WRPitch_120(:,2).*cosd(pa120) + WRPitch_120(:,4).*sind(pa120);
Drag120 = -(WRPitch_120(:,4).*cosd(pa120) - WRPitch_120(:,2).*sind(pa120));
pa120pl = interpft(MTA120plunge(:,5),length(PtchPlng_120));
Lift120pl = PtchPlng_120(:,2).*cosd(pa120pl) + PtchPlng_120(:,4).*sind(pa120pl);
Drag120pl = -(PtchPlng_120(:,4).*cosd(pa120pl) - PtchPlng_120(:,2).*sind(pa120pl));

% Room pressure, temperature, and density:
P_room = 28.7991 * 0.4911541; % Psi
T_room = 70.0 + 459.67; % deg R
rho = (P_room * 144)/(1716 * T_room); % slug/ft^3 or lbf-s^2/ft^4

% Dynamic pressure, psi:
q30 = (0.5*rho*((30*(5280/3600))^2))/144;
q60 = (0.5*rho*((60*(5280/3600))^2))/144;
q90 = (0.5*rho*((90*(5280/3600))^2))/144;

```

```

q120 = (0.5*rho*((120*(5280/3600))^2))/144;

% Wing Area and Chord Length:
S = 32.0;    % Wing area, in^2
c = 4.0;    % Chord length, in

% Calculate Lift/Drag/Pitch Moment Coefficients:
% Lift Coefficient, Pitch and Pitch-Plunge:
CL30 = Lift30./(q30*S);
CL60 = Lift60./(q60*S);
CL90 = Lift90./(q90*S);
CL120 = Lift120./(q120*S);
CL30pl = Lift30pl./(q30*S);
CL60pl = Lift60pl./(q60*S);
CL90pl = Lift90pl./(q90*S);
CL120pl = Lift120pl./(q120*S);
% Drag Coefficient, Pitch and Pitch-Plunge:
CD30 = Drag30./(q30*S);
CD60 = Drag60./(q60*S);
CD90 = Drag90./(q90*S);
CD120 = Drag120./(q120*S);
CD30pl = Drag30pl./(q30*S);
CD60pl = Drag60pl./(q60*S);
CD90pl = Drag90pl./(q90*S);
CD120pl = Drag120pl./(q120*S);
% Pitch Moment Coefficient, Pitch and Pitch-Plunge:
Cm30 = WRPitch_30(:,6)./(q30*S*c);
Cm60 = WRPitch_60(:,6)./(q60*S*c);
Cm90 = WRPitch_90(:,6)./(q90*S*c);
Cm120 = WRPitch_120(:,6)./(q120*S*c);
Cm30pl = PtchPlng_30(:,6)./(q30*S*c);
Cm60pl = PtchPlng_60(:,6)./(q60*S*c);
Cm90pl = PtchPlng_90(:,6)./(q90*S*c);
Cm120pl = PtchPlng_120(:,6)./(q120*S*c);
% -----

% Plot Choice UI:
global checked h

PlotChoose
waitfor(h.p)
r = checked;

% Plot chosen plots:
PlotThePlots_v2

```

Published with MATLAB® R2015b

```

% ----- Choose which plots to plot -----
% ----- 2dLt James Sellers, AFIT/ENY, 5 Feb 2016 -----
% -----

function PlotChoose
global h
% Create figure
h.f = figure('units','pixels','position',[300,250,300,600],...
    'toolbar','none','menu','none');
% Create checkboxes
h.c(1) = uicontrol('style','text','units','pixels',...
    'position',[10,575,300,15],'string','Choose Plots to Display vs. Pitch Angle:');

h.c(2) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,550,300,15],'string','Lift - WR Pitch');
h.c(3) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,525,300,15],'string','Drag - WR Pitch');
h.c(4) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,500,300,15],'string','Lift Coefficient (CL) - WR Pitch');
h.c(5) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,475,300,15],'string','Drag Coefficient (CD) - WR Pitch');
h.c(6) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,450,300,15],'string','Pitch Moment - WR Pitch');
h.c(7) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,425,300,15],'string','Pitch Moment Coefficient (Cm) - WR Pitch');
h.c(8) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,400,300,15],'string','Roll Moment - WR Pitch');
h.c(9) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,350,300,15],'string','Lift - Pitch Plunge');
h.c(10) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,325,300,15],'string','Drag - Pitch Plunge');
h.c(11) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,300,300,15],'string','Lift Coefficient (CL) - Pitch Plunge');
h.c(12) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,275,300,15],'string','Drag Coefficient (CD) - Pitch Plunge');
h.c(13) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,250,300,15],'string','Pitch Moment - Pitch Plunge');
h.c(14) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,225,300,15],'string','Pitch Moment Coefficient (Cm) - Pitch Plunge');
h.c(15) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,200,300,15],'string','Roll Moment - Pitch Plunge');
h.c(16) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,150,300,15],'string','Combined Lift Coefficients - Pitch Only');
h.c(17) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,125,300,15],'string','Combined Pitch Moment Coefficients - Pitch-Plunge');
h.c(18) = uicontrol('style','checkbox','units','pixels',...
    'position',[10,75,300,15],'string','IMU vs. Encoder');

% Create OK pushbutton
h.p = uicontrol('style','pushbutton','units','pixels',...
    'position',[40,25,70,30],'string','PLOT',...
    'callback',@p_call);

% Pushbutton callback
function p_call(varargin)
    global checked

    vals = get(h.c,'Value');
    checked = find([vals{:}]);
    if isempty(checked)
        checked = 0;
    end
    close

%     disp(checked)
end
end

```

Contents

■ ----- Pitch-Plunge Plots: -----

```
% ----- Plot/Save Results based on selections -----
% ----- 2dLt James Sellers, AFIT/ENY, 5 Feb 2016 -----
% -----
set(0,'DefaultFigureWindowStyle','docked') % Show all plots in editor
% -----

% ----- WR Pitch Only Plots: -----
if ismember(2, r)

figure(1)
[ax,k1,k2] = plotyy(MTA0(:,1),MTA0(:,5),WRPitch_0(:,1),Lift0);
k2.LineWidth = 2;
k1.Color = [0.8500 0.3250 0.0980];
k2.Color = [0 0.4470 0.7410];
grid minor
title(['\fontsize{12} Pitch Angle vs. Lift Force - 0 mph'],'interpreter','tex')
legend({'Pitch Angle','Lift Force'],'FontSize',12)
xlabel(['\fontsize{14} Time (sec)'],'interpreter','tex')
ylabel(ax(1),(['\fontsize{14} {\color{rgb}{0.8500 0.3250 0.0980}Pitch Angle (deg)}'],'interpreter','tex'))
set(ax(1),'YColor','k')
ylabel(ax(2),(['\fontsize{14} {\color{rgb}{0 0.4470 0.7410}Lift Force (lbs)}'],'interpreter','tex'))
set(ax(2),'YColor','k','FontSize',12)
set(gca,'XMinorTick','on','YMinorTick','on','FontSize',12)

figure(2)
[ax,k1,k2] = plotyy(MTA30(:,1),MTA30(:,5),WRPitch_30(:,1),Lift30);
k2.LineWidth = 2;
k1.Color = [0.8500 0.3250 0.0980];
k2.Color = [0 0.4470 0.7410];
grid minor
title(['\fontsize{12} Pitch Angle vs. Lift Force - 30 mph'],'interpreter','tex')
legend({'Pitch Angle','Lift Force'],'FontSize',12)
xlabel(['\fontsize{14} Time (sec)'],'interpreter','tex')
ylabel(ax(1),(['\fontsize{14} {\color{rgb}{0.8500 0.3250 0.0980}Pitch Angle (deg)}'],'interpreter','tex'))
set(ax(1),'YColor','k')
ylabel(ax(2),(['\fontsize{14} {\color{rgb}{0 0.4470 0.7410}Lift Force (lbs)}'],'interpreter','tex'))
set(ax(2),'YColor','k','FontSize',12)
set(gca,'XMinorTick','on','YMinorTick','on','FontSize',12)

figure(3)
[ax,k1,k2] = plotyy(MTA60(:,1),MTA60(:,5),WRPitch_60(:,1),Lift60);
k2.LineWidth = 2;
k1.Color = [0.8500 0.3250 0.0980];
k2.Color = [0 0.4470 0.7410];
grid minor
title(['\fontsize{12} Pitch Angle vs. Lift Force - 60 mph'],'interpreter','tex')
legend({'Pitch Angle','Lift Force'],'FontSize',12)

xlabel(['\fontsize{14} Time (sec)'],'interpreter','tex')
ylabel(ax(1),(['\fontsize{14} {\color{rgb}{0.8500 0.3250 0.0980}Pitch Angle (deg)}'],'interpreter','tex'))
set(ax(1),'YColor','k')
ylabel(ax(2),(['\fontsize{14} {\color{rgb}{0 0.4470 0.7410}Lift Force (lbs)}'],'interpreter','tex'))
set(ax(2),'YColor','k','FontSize',12)
set(gca,'XMinorTick','on','YMinorTick','on','FontSize',12)
```

```

set(gca,'XMinorTick','on','YMinorTick','on','FontSize',12)

figure(30)
[ax,k1,k2] = plotyy(MTA30plunge(:,1),MTA30plunge(:,5),PtchPlng_30(:,1),Lift30pl);
k2.LineWidth = 2;
k1.Color = [0.8500 0.3250 0.0980];
k2.Color = [0 0.4470 0.7410]; hold on
plot(MTA30plunge(:,1),(-MTA30plunge(:,4)*100)-179.3,'LineWidth',2,'Color',[0.4660 0.6740 0.188
0],'LineStyle',':')
grid minor
title('\fontsize{12} Pitch Angle, Lift Force, Plunge Distance - 30 mph'),'interpreter','tex')
legend({'Pitch Angle','Plunge Dist.','Lift Force'},'FontSize',12)
xlabel('\fontsize{14} Time (sec)'),'interpreter','tex')
ylabel(ax(1),['\fontsize{14} {\color{rgb}{0.8500 0.3250 0.0980}Pitch Angle (deg) ',...
'\color{black} or ', '\color{rgb}{0.4660 0.6740 0.1880}Plunge Dist. (cm) '],'interp
reter','tex')
set(ax(1),'YColor','k')
ylabel(ax(2),['\fontsize{14} {\color{rgb}{0 0.4470 0.7410}Lift Force (lbs) '],'interpreter','
tex')
set(ax(2),'YColor','k','FontSize',12)
set(gca,'XMinorTick','on','YMinorTick','on','FontSize',12)

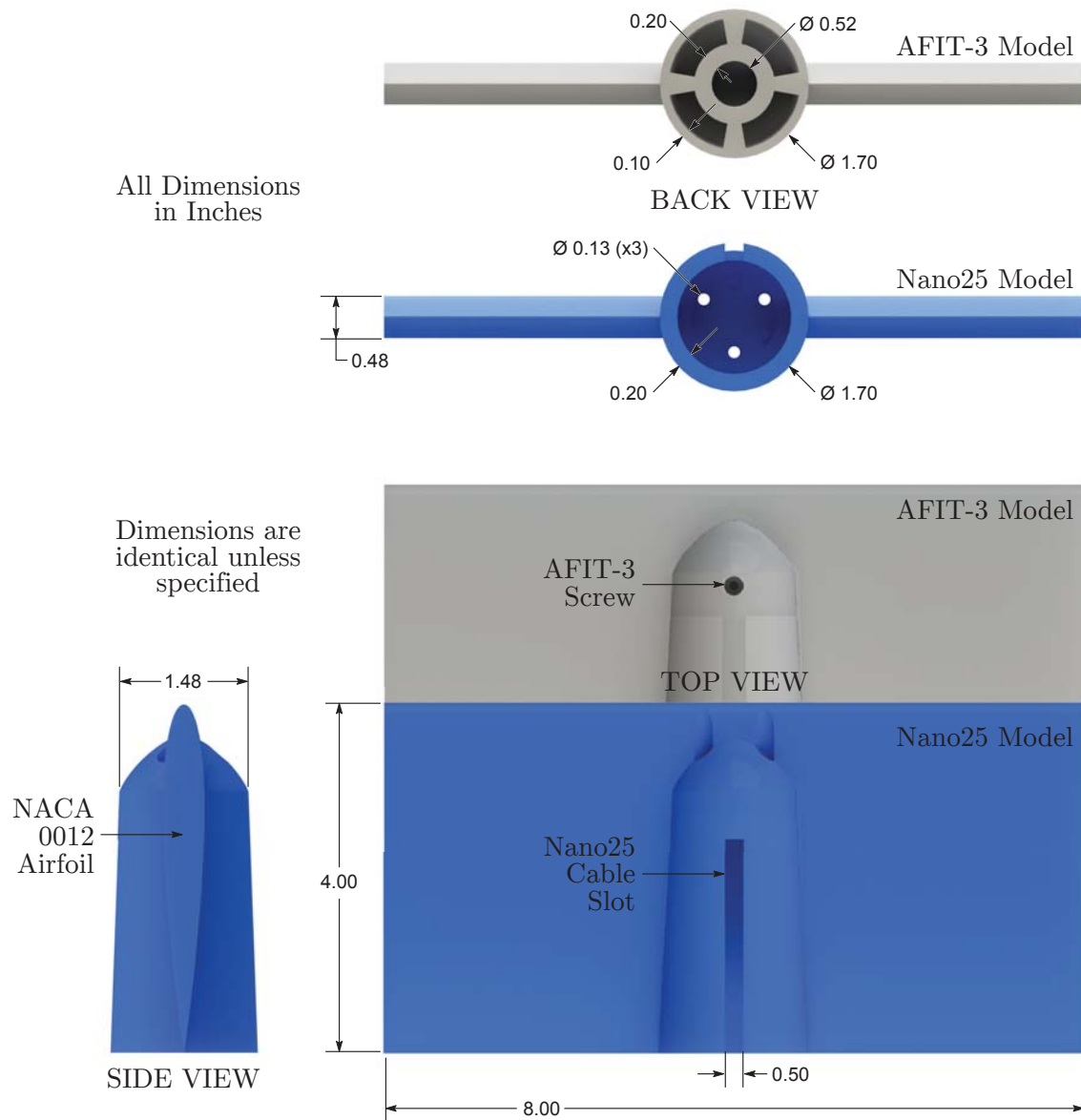
figure(31)
[ax,k1,k2] = plotyy(MTA60plunge(:,1),MTA60plunge(:,5),PtchPlng_60(:,1),Lift60pl);
k2.LineWidth = 2;
k1.Color = [0.8500 0.3250 0.0980];
k2.Color = [0 0.4470 0.7410]; hold on
plot(MTA60plunge(:,1),(-MTA60plunge(:,4)*100)-179.3,'LineWidth',2,'Color',[0.4660 0.6740 0.188
0],'LineStyle',':')
grid minor
title('\fontsize{12} Pitch Angle, Lift Force, Plunge Distance - 60 mph'),'interpreter','tex')
legend({'Pitch Angle','Plunge Dist.','Lift Force'},'FontSize',12)
xlabel('\fontsize{14} Time (sec)'),'interpreter','tex')
ylabel(ax(1),['\fontsize{14} {\color{rgb}{0.8500 0.3250 0.0980}Pitch Angle (deg) ',...
'\color{black} or ', '\color{rgb}{0.4660 0.6740 0.1880}Plunge Dist. (cm) '],'interp
reter','tex')
set(ax(1),'YColor','k')
ylabel(ax(2),['\fontsize{14} {\color{rgb}{0 0.4470 0.7410}Lift Force (lbs) '],'interpreter','
tex')
set(ax(2),'YColor','k','FontSize',12)
set(gca,'XMinorTick','on','YMinorTick','on','FontSize',12)

figure(32)
[ax,k1,k2] = plotyy(MTA90plunge(:,1),MTA90plunge(:,5),PtchPlng_90(:,1),Lift90pl);
k2.LineWidth = 2;
k1.Color = [0.8500 0.3250 0.0980];
k2.Color = [0 0.4470 0.7410]; hold on
plot(MTA90plunge(:,1),(-MTA90plunge(:,4)*100)-179.3,'LineWidth',2,'Color',[0.4660 0.6740 0.188
0],'LineStyle',':')
grid minor
title('\fontsize{12} Pitch Angle, Lift Force, Plunge Distance - 90 mph'),'interpreter','tex')
legend({'Pitch Angle','Plunge Dist.','Lift Force'},'FontSize',12)
xlabel('\fontsize{14} Time (sec)'),'interpreter','tex')
ylabel(ax(1),['\fontsize{14} {\color{rgb}{0.8500 0.3250 0.0980}Pitch Angle (deg) ',...
'\color{black} or ', '\color{rgb}{0.4660 0.6740 0.1880}Plunge Dist. (cm) '],'interp
reter','tex')
set(ax(1),'YColor','k')

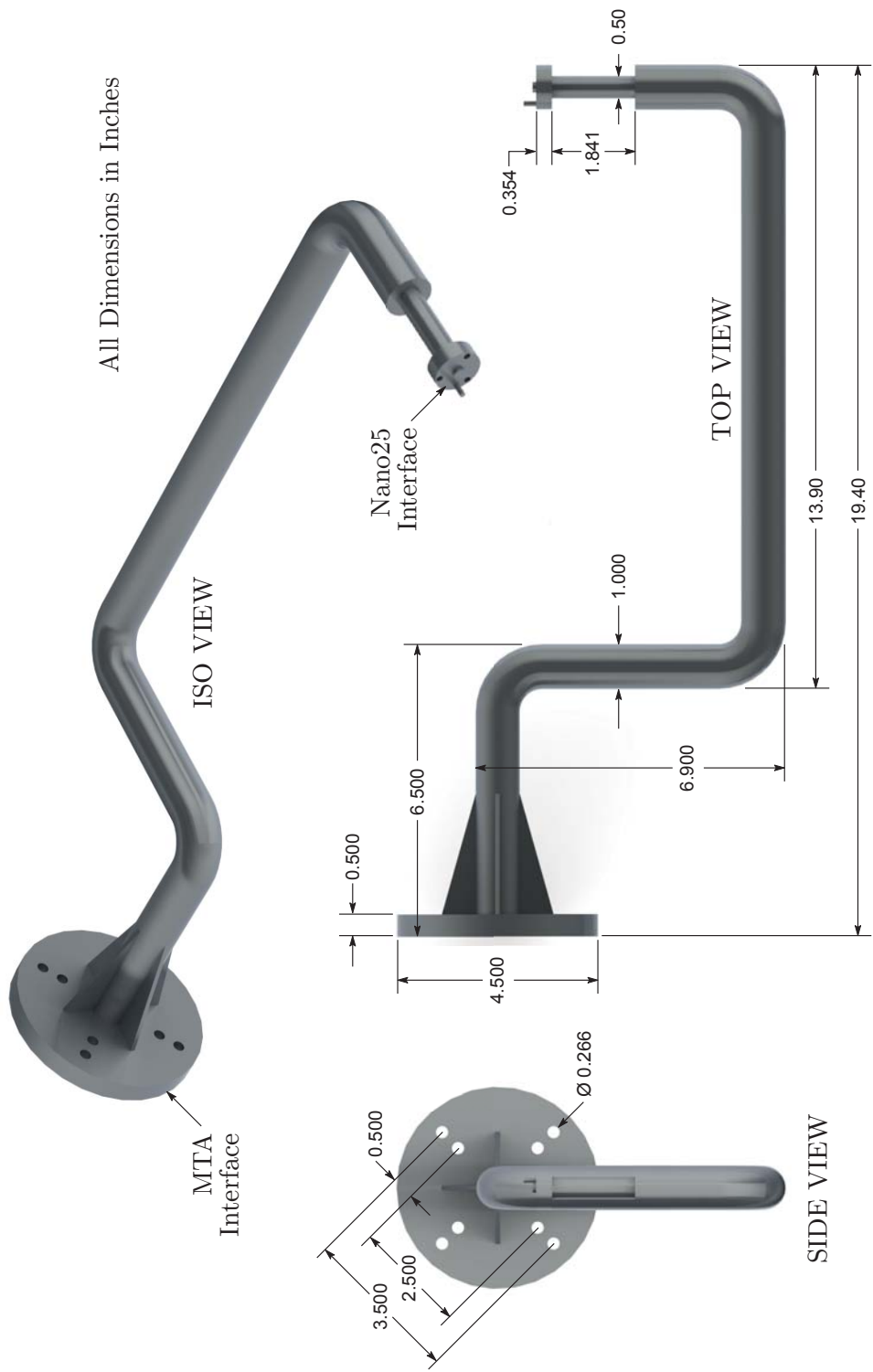
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Appendix C. Drawings of Wind Tunnel Models and Sensors

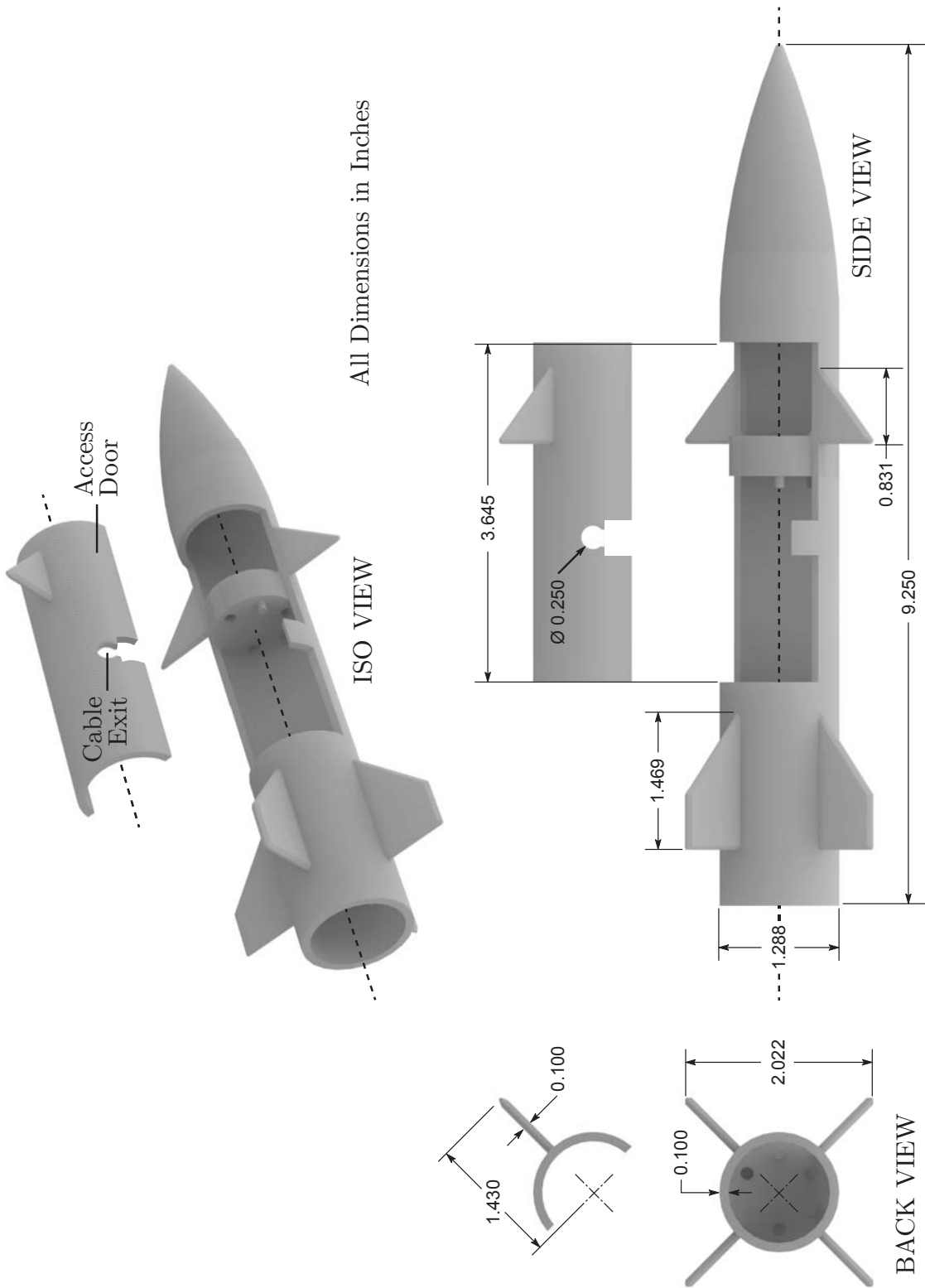
NACA 0012 Wing Model - Nano25 & AFIT-3 Balance Versions



Model Support Sting



Store Separation Missile Model



Mounting Side

Dimensions: $\phi 6.060 \pm 2.1$, $\phi 6.035 \pm 2.1$, $\phi 5.3$, 29.6 , 4.294 ± 0.025 , 9.208 ± 0.025 , 4.8 , 21.6 , $\phi 25$.

Labels: Mounting Adapter, Sensing Reference Frame Origin, Tool Adapter, Sensing Reference Frame Origin, $3 \times M3-0.5 \pm 7.0$ Equally Spaced Customer Interface (See Note 3), $\phi 3$ Slip Fit ± 7.0 Customer Interface, B.C. $\phi 20.32$.

Side View

Dimensions: 15.240 ± 0.025 , 10.160 ± 0.025 , 8.799 ± 0.025 .

Labels: Tool Adapter, Sensing Reference Frame Origin, $2 \times \phi 3$ Slip Fit ± 3.3 Customer Interface, B.C. $\phi 20.32$.

Tool Side

Labels: Sensing Reference Frame Origin, $3 \times M3-0.5 \pm 3.5$ Equally Spaced Customer Interface (See Note 5), B.C. $\phi 20.32$.

Isometric View

Notes:

- Mounting and Tool Adapter made of Stainless Steel. Transducer made of hardened Stainless Steel.
- WARNING: DO NOT LOOSEN OR REMOVE INTERFACE PLATES OR CABLE DUE TO POTENTIAL DAMAGE.
- DO NOT EXCEED INTERFACE DEPTH. MAY CAUSE DAMAGE.
- Standard connector (not shown) has a 17mm diameter and is 67.5mm long.

3DM-GX4-15TM IMU Mounting Specifications [4]

6. Sensor Installation

6.1 Sensor Mounting

The 3DM-GX4-15™ sensor housing is rated for indoor use only, unless used inside a protective enclosure.

The sensor has two mounting tabs with holes for fastening. There are two additional holes used for precise alignment with 2mm dowel pins. One of the holes is slotted to allow for relaxed pin positioning accuracy. The sensor can be mounted in any orientation, as required for the application ([see Sensor Reference Frames on page 26](#)). The axes are labeled on the face of the sensor for reference, and the sensor measurement origin is shown in the sensor dimensional drawing ([see Reference Diagrams on page 55](#)).

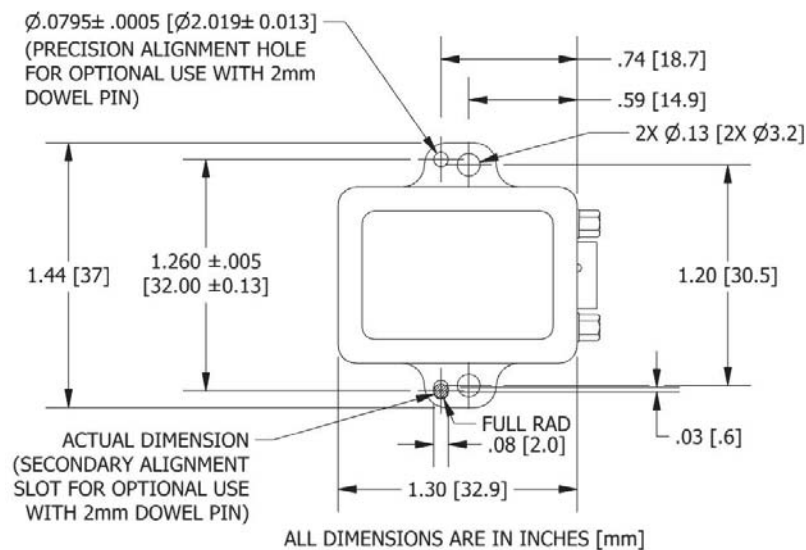


Figure 23 - Mounting the Sensor

3DM-GX4-15™ IMU Additional Dimensions [4]

13. Addendum

13.1 Reference Diagrams

The diagrams in this section are to intended to aid in product installation and troubleshooting. For more information contact LORD MicroStrain® Technical Support ([see Technical Support on page 46](#)).

13.1.1 Sensor Dimensions and Origin

This diagram describes the sensor physical specification including the measurement point of origin.

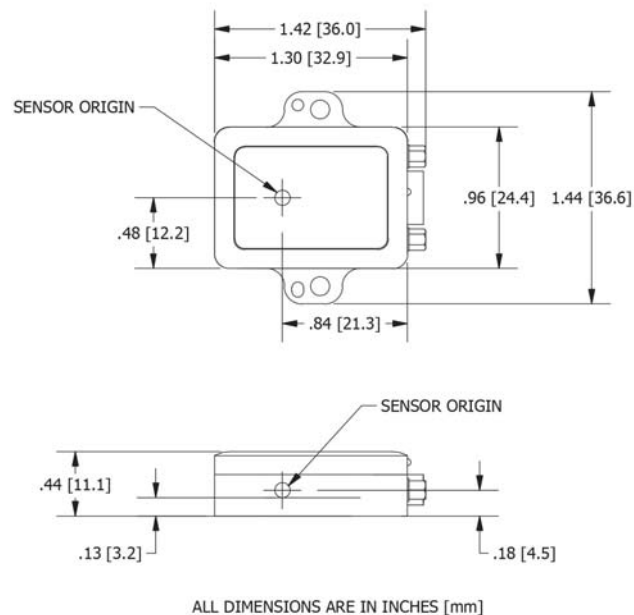


Figure 29 - 3DM-GX4™ Sensor Origin

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14. ABSTRACT Continuing the development of the 6-DOF Motion Test Apparatus (MTA) for performing dynamic wind tunnel tests revealed the importance of a capable data acquisition (DAQ) system for collecting and analyzing data. Assembling and testing the DAQ system in conjunction with the MTA, AFIT Low-Speed Wind Tunnel, and a selection of high-performance sensors was the primary focus of this research. Specifically, acquiring time-accurate aerodynamic force and moment measurements on a variety of test models was of high importance. The complete DAQ hardware and software system was employed in both static and dynamic wind tunnel tests to collect the aerodynamic forces and moments acting on a NACA 0012 wing model. Dynamic testing involved pitch oscillation motions, as well as pitch-plunge oscillation motions. Static tests yielded results that matched traditional sting mounted wind tunnel tests, despite minor angle-of-attack differences. Dynamic measurements of the lift, drag, and pitch moment coefficients were within expectations for the pitch oscillation tests and the highest flow velocity case of the pitch-plunge oscillation test.						
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