MEASUREMENT OF HYDRODYNAMIC FORCES AND MOMENTS AND FLOW FIELD MAPPING OF A MODEL IN CONING MOTION

by

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Submitted to the Departments of Ocean Engineering and Mechanical Engineering
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Abstract

A method of captive model testing using an axisymmetric marine vehicle model in steady
motion with constant roll and yaw rates has been used experimentally to obtain functional
relationships between certain motion parameters and the resultant hydrodynamic forces and
moments on the body. Specifically, cross coupling terms in roll rate and yaw rate have been
investigated for non-planar cross-flow. An instrumented slender body of revolution with
length/diameter of 9.5 was tested at Reynolds number of about 5 million, based on length.
The tests were conducted at free stream velocity of 25 ft/s for coning angles between zero
and -20° in 2° increments, at rotation rates of up to 200 rpm in 12.5 rpm increments in both
rotational directions. The character of force and moment terms varying with rotation rate
and coning angle was determined. The results may be translated to functional relationships
between the hydrodynamic coefficients and the angular velocities in roll and yaw. The data
showed a transition in the forms of the sway force and the pitch moment after the coning
angle exceeded -10°, due to body lift in the cross flow.

A method for measuring the velocity field about the model using laser doppler velocimetry
has been developed. The flow field was mapped for two model coning angles at one moderate
rotation rate. The flow field representation portrays perturbations in cross flow velocity at
five sections in a body-fixed reference frame. This method is useful in understanding the
vortex mechanisms at work to influence body forces and moments. The data showed
formation of asymmetric body vortices after the coning angle exceeded -10°.

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Nomenclature

\( A \) Frontal area of hull = \( \pi d^2/4 \) (in feet\(^2\))

\( B \) Model buoyant force

BMC Balance moment center (0.895 inches aft of the COR, on the \( x \) axis)

CB Center of buoyancy of the model

CG Center of mass of the model

COR Center of rotation, the reference point for all measured and calculated forces and moments, located 11.31 inches aft of the model bow, on the \( x \) axis

\( d \) Hull maximum diameter = 2.695 inches

\( g \) Gravitational acceleration = 32.18 ft/sec\(^2\)

\( K,M,N \) Hydrodynamic moments about the \( x \), \( y \) and \( z \) body axes, respectively

\( K',M',N' \) Dimensionless moment coefficients corresponding to \( K,M, \) and \( N \)

\( L_a \) Length aft of parallel midbody

\( L_f \) Length forward of parallel midbody

\( L_{pmh} \) Length of parallel midbody

\( l_l \) Hull length = 23.5 inches

\( l_s \) Hull length in feet

---

**Figure 1:** Body Axes and Related Forces and Moments

LDV Laser Doppler Velocimeter

\( m \) Model mass

\( p,q,r \) Angular velocity components about the \( x \), \( y \) and \( z \) body axes, respectively

rpm Rotation rate in revolutions per minute

\( u,v,w \) Velocity components along the \( x \), \( y \) and \( z \) body axes, respectively

\( u_u,v_w,w_z \) Velocity components along the \( x \), \( y \), and \( z \) tunnel axes, respectively
Figure 2: Body-Fixed and Tunnel-Fixed Coordinates [1]

- $U_\infty$: Tunnel free stream velocity
- $W$: Model weight = $mg$
- $x, y, z$: Right-handed, rectangular body-fixed axes with origin at the COR and positive directions of $x$ toward the bow, $y$ to starboard, and $z$ down through the keel
- $x_0, y_0, z_0$: Right-handed, rectangular tunnel-fixed axes with origin at the COR and positive directions of $x_0$ colinear with the tunnel longitudinal centerline, directed into the free stream, $y_0$ to starboard in the horizontal plane, and $z_0$ vertically down
- $X, Y, Z$: Hydrodynamic forces along the $x, y$ and $z$ body axes, respectively
- $X', Y', Z'$: Dimensionless moment coefficients corresponding to $X, Y$, and $Z$
- $\alpha_c$: Coning angle, measured from the $x_0$ axis to the $x$ axis
- $\nu$: Kinematic viscosity of fresh water = $0.9733 \times 10^{-5}$ ft$^2$/sec
- $\rho$: Density of fresh water at 77°F = 1.9348 slugs/ft$^3$
- $\phi, \theta, \psi$: Roll, pitch and yaw angles about the $x, y$ and $z$ body axes
- $\phi_\omega$: Roll angle about tunnel-fixed $x_\omega$ axis
- $\omega$: Model rotation rate about $x_\omega$ axis = $d\phi_\omega/dt = 2\pi$ rpm/60
- $\omega'$: Model rotation vector in tunnel-fixed axes = $\omega\hat{i}_{x_\omega}$
- Dimensionless rotation rate = $\omega'/U_\infty$
Chapter 1

Introduction

This research program is an effort to improve understanding of the hydrodynamic effects of flow about a submersible marine vehicle in a complex motion which may be described as non-planar with respect to the free stream. Experiments are conducted to determine the relationships between a combination of roll and yaw rates and the hydrodynamic forces and moments experienced by the vehicle. These relationships may be quantified and used to improve the performance of computer-based vehicle motion predictors.

Measurement of the flow velocity at points around the vehicle may provide insight to understand the processes which result in the perceived forces. A method of measuring the perturbation velocities about a vehicle in steady non-planar motion is presented. This introductory chapter will describe the basic nature of the problems to be solved and the methods available for solution.

1.1 Captive Model Testing

Naval architects historically have depended on scale model testing to prove the feasibility of hull designs by experimentally measuring the dynamic performance of the model in water. In recent years, computer based models have been used for motion prediction. Computer synthesis of a hull design is generally cheaper and much faster than physical model building, and on-line testing gives the designer more rapid feedback of performance.
The accuracy of analytical models which use series expansions of generalized equations of motion depend on the validity of the coefficients used to weight the series terms and the degree of expansion included in the series. The coefficients are usually derived from empirical data taken in captive model tests and full-scale experiments. The level of detail in higher order terms included in the expanded equations of motion is determined by the synthesis model designer and is usually limited by the availability of empirical data which would validate the weighting coefficients of the higher order terms.

A typical problem of developing coefficients may be examined to illustrate a motivation for this research. The forces and moments experienced by a marine vehicle in six degrees of freedom may be expressed as a set of nonlinear differential equations. Taking as a zero condition the instantaneous surge velocity \( u(t) \) with all other velocity components zero, the forces are:

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = f(u, v, w, p, q, r) = \frac{1}{2} \rho A U^2 f'(Re, v', w', p', q', r')
\]

where

\[
Re = \frac{UL}{v}
\]

is the Reynolds number.

Using the notation of reference [2] to abbreviate partial differentiation, the method of Taylor series expansion for these analytic equations gives

\[
\begin{bmatrix}
X' \\
Y' \\
Z'
\end{bmatrix} = \sum_{i=0}^{\infty} \frac{1}{i!} \left( v' \frac{\partial}{\partial v'} + w' \frac{\partial}{\partial w'} + p' \frac{\partial}{\partial p'} + q' \frac{\partial}{\partial q'} + r' \frac{\partial}{\partial r'} \right)^i f'(Re, v', w', p', q', r')
\]

As noted in reference [3] the inclusion of series terms beyond third order does not improve accuracy significantly. Abkowitz has shown that the symmetry of ship geometries about
the \(xz\) plane requires that \(X', Z'\) and \(M'\) are even functions of \(v', p'\) and \(r'\), and \(Y', K'\) and \(N'\) are odd functions of \(v', p'\) and \(r'\) [4]. This reduces the terms in equations (2) to a more manageable number, but the experimental determination of coefficients is not trivial.

Traditional experimental methods of measuring model response to various flows have relied on straight towing or rotating arm test facilities. The motions produced with these types of equipment are limited in that the roll component of angular velocity is zero, and the cross-flow velocities are restricted to parallel planes along the ship length. Terms in the equations of motion which require experimentation which controls roll rate and the construction of nonplanar cross flows are significant in modelling many types of vehicle dynamics. A facility which provides for control of these variables is the Coning Motion device at MIT’s Marine Hydrodynamics Laboratory.

1.2 General Motion of Coning

With the advance of vehicle performance level requirements the demand for motion predictors to take account of so called "higher order effects" and coupling terms has increased. An example of a significant dynamic motion effect which was not included in rudimentary systems of equations is the coupling of yaw rate and pitch rate which causes a finned body in an ordered flat turn to pitch and experience a change in depth.

The captive model test method described here as coning motion was first investigated for aircraft in the 1920's by aeronautical engineers using a combination of roll and yaw rates to generate a steady motion of the vehicle in a direction which was never coplanar with the flow. The locus of model axis motion is a cone oriented with its longitudinal axis parallel to the free stream. The motion may be described as "coning motion" and is portrayed in Figure 3 below.
Figure 3: General Motion of "Coning"

In this figure, the constant angular displacement of the model from the free stream axis is the coning angle $\alpha_c$ and the driving motion is the rotation $\omega$ about the direction of the free stream. Thus for $\alpha_c = 0$, the model motion is purely a steady roll ($\phi_o = \phi$). The rotation may be decomposed as a combination of roll rate and yaw rate as

$$p = \omega \cos \alpha_c$$
$$r = \omega \sin \alpha_c$$

Other "coning motion" degrees of freedom have been considered in aircraft tests in aerodynamic facilities. These include variations of the sideslip angle and the displacement between the model's center of rotation and the rotational axis of the system. In this hydrodynamic test those parameters are held to zero. The facility could be modified to account for the added complexity, but given the cross-section constraint in the tunnel, a shorter model (and thus lower Reynolds number) would be required for adding an axis offset.
The facility developed in previous work on this project by Johnson is the first implementation of a coning motion experiment for marine vehicles in water [1]. This thesis describes the first program to gather data using the apparatus over the full range of its operation.
Chapter 2

Test Apparatus for Force and Moment Measures

This chapter provides a description of equipment and systems used in experiments which measured hydrodynamic loads on the model. The development of the Coning Motion Apparatus used at MIT's Marine Hydrodynamic Laboratory is described in detail in reference [1]. This thesis presents the first comprehensive test program conducted using the Coning Motion system.

2.1 Model

The model used for force and moment measurements is an instrumented version of the standard \( (l/d = 9.5) \) body of revolution used in previous studies at MIT and elsewhere [5, 6, 7, 8]. Figure 4 and Table 1 provide gross model characteristics. A detailed discussion of the internally mounted 6-component balance in this model may be found in reference [1]. The internal model arrangement is shown in Figure 5.

![Figure 4: Model Dimensions [1]]
Table 1: Instrumented Model Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length / Diameter</td>
<td>9.5 inches</td>
</tr>
<tr>
<td>Length</td>
<td>23.50 inches</td>
</tr>
<tr>
<td>Diameter</td>
<td>2.695 inches</td>
</tr>
<tr>
<td>Weight</td>
<td>10.45 lbs</td>
</tr>
<tr>
<td>Buoyancy</td>
<td>3.23 lbs</td>
</tr>
<tr>
<td>Parallel Midbody (as a % of L)</td>
<td>39.6 %</td>
</tr>
<tr>
<td>Length Forward</td>
<td>4.85 inches</td>
</tr>
<tr>
<td>Length Aft</td>
<td>10.25 inches</td>
</tr>
</tbody>
</table>

Figure 5: Model Internal Arrangement [1]

2.2 Facility

2.2.1 Tunnel

Testing was performed in the MIT Marine Hydrodynamic Laboratory’s variable pressure water tunnel. The tunnel has a square cross-section test area with 20 inch sides. Limits on the model coning angle ($\alpha_{\text{max}} = \pm 20^\circ$) are based on physical interference with the tunnel wall. The tunnel generates flows of over 30 feet per second.
2.2.2 Rotating Mechanism

The coning motion rotating mechanism is installed through the downstream end of the water tunnel. A belt-driven axle penetrates the tunnel at the aft wall through the flow-turning vanes, and is aligned parallel with the flow and colinear with the central axis of the test section. A 2 horsepower stepping motor drives the axle through a changeable sheave for different speed ranges. The forward end of the driven axle is supported at the downstream end of the tunnel test section by a bearing inside a streamlined housing which bolts into the tunnel walls.

The model is mounted on a "sting" which is set into the adjustable sector piece at the forward end of the driven axle. Figure 5 shows the model (without appendage) mounted with the sector at a coning angle of -20°. The coning angle is adjusted between test runs by removing four machine screws, sliding the sector/sting/model assembly to a new \( \alpha_c \), and reinstalling the screws through the new hole alignment.

![Figure 6: Model in Coning Motion Apparatus](image)

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In Figure 6, the model longitudinal axis is $x$, and the system rotates about the tunnel/flow axis $x_0$. The angular displacement between $x$ and $x_0$ is the coning angle $\alpha_c$.

### 2.3 Data Acquisition System

The data acquisition system is built around an IBM PC XT computer which obtains data from the model instruments, a tunnel pressure sensor, and a 12 bit shaft encoder. The pressure sensor produces a signal proportional to free stream fluid velocity, and the encoder provides shaft angular position indication. The encoder output is also used to determine shaft rotation rate. Figure 7 is a schematic view of the principal components of the data acquisition system and their interconnections.

![Data Acquisition System Diagram]

Figure 7: Data Acquisition Systems [1]

The model instrument signals are routed via a set of slip rings through signal conditioners to the analog-to-digital (A/D) converter board in the PC XT. Several encoder channels are fed to the PC XT, as is the differential pressure signal for tunnel velocity. The program logic which controls dynamic load testing makes use of the encoder signals to determine a reference position in shaft rotation, and then to key the data taking cycle of the
A/D board. A complete listing of Fortran code used in the experiments is included in Appendix D. Most of the force and moment software was developed directly from Johnson's preceding work to demonstrate the apparatus.
Chapter 3

Procedures for Force and Moment Measures

The steps involved in the force and moment measurement experiments are described in this chapter. A method of organizing the large number of repetitive experiments for efficient accomplishment by a team of four is presented. The tests may be characterized by the state of the model and the type of data being collected. The tests conducted at zero rotational speed to measure weight and buoyancy are referred to as static tests. The rotational experiments are dynamic tests: either inertial tests if conducted in air, or hydrodynamic tests if conducted in water.

Calibration of the Daytronix 9170 and 9140 signal conditioners used to amplify and convert the tunnel differential pressure sensor and encoder rotation rate signals was conducted daily, or after a long break during the day. The calibration coefficients were saved for pairing with the tests by date (to allow for post-processing of the load data).

3.1 Static Tests

The goal in this experiment is to isolate flow-related hydrodynamic effects; therefore an accounting must be made of the model's weight, buoyancy and inertia effects. For each coning angle, a zero rotation rate measurement of forces and moments was made in air at 32 evenly spaced intervals around one revolution (i.e., every 11.25°). A similar measure was made with the tunnel filled with water. For each case, an averaged set of "zeros" was determined by averaging the load outputs for each instrument over one revolution. Both the raw data and the averaged values were saved.
The zeros files were used later by the dynamic testing software to reduce the raw loads by the effect of gravity or gravity plus buoyancy, where appropriate. Inertia effects were determined during dynamic tests without water around the model.

3.2 Dynamic Testing

Dynamic tests were conducted by first measuring the inertial loads sensed by the model in the absence of water, then subtracting those, as well as the static components of weight and buoyancy, from the results measured in water to yield loads due solely to hydrodynamic effects.

The measurement of inertial loads was essentially identical to testing in water, except the tunnel facility was drained during the tests. The data gathering software stored results of the tests in files labeled with a first letter "I". These inertia load files were called later by the hydrodynamic test software, and their force and moment component values were subtracted from the associated measurements made in water.

Hydrodynamic tests involved the following basic procedure (items parenthesized are omitted for in-air tests):

• Set the coning angle (and fill the tunnel with water)
• (Set water tunnel flow rate to 25 ft/sec)
• Turn the model drive motor on to the desired rotation rate
• Run the program "DC" which requires responses to calls for
  - the calibration coefficients file
  - the static loads file for this coning angle
• The following data files will be produced during the several minutes required to run DC:
  - Raw data file containing all instrument values measured during the ten full rotations about the tunnel axis
  - Summed and averaged list of instrument values
  - Net of appropriate "zero" values
- Final loads measured in pounds of force and inch-pounds of moment after converting net "counts" data to dimensional values

For high rotation rate tests (>125 rpm), a different sheave was used on the motor drive shaft and a special hydrofoil was attached to the sector portion of the coning motion apparatus. The combined effect was to reduce the load on the motor so that the full range of rotation rates could be achieved. The foil's location nearly a foot downstream of the model ensured negligible foil effect on the test. With the foil installed and the motor shut down, a tunnel flow of 25 ft/sec would autorotate the model/sector assembly at about 125 rpm.

3.3 Test Program

The test program for measurement of forces and moments was conducted by a team of four. The test schedule was coordinated within a Program Matrix (see Table 2 below) which described an ordered method of accomplishment. The order was based on optimizing test conduct time by reducing the number of cycles of filling and draining the tunnel facility. Each number in the matrix represents the chronological order of a pair of tests (one in each rotational direction). The tests labeled "In Air" are inertial tests and those labeled "In Water" are the corresponding hydrodynamic load tests. Late in the program, as time remaining became a consideration, a decision was made to reduce the number of remaining tests by foregoing certain matrix elements. Identification of those tests was based on maintaining an equal distribution of data in both rotational directions, and ensuring even coverage through the entire range of coning angles.

The team followed a detailed procedure checklist to maintain a standard and formal laboratory routine. The checklist covered calibration, static testing, dynamic testing, model
Table 2: Test Program Matrix
Test Order as a Function of Rotation Rate and Angle of Attack

<table>
<thead>
<tr>
<th>Rotation Rate (rpm)</th>
<th>TESTS IN AIR - Coning Angle α,</th>
<th>TESTS IN WATER AT 25 FT/SEC - Coning Angle α,</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0'</td>
<td>2'</td>
</tr>
<tr>
<td>0.0</td>
<td>341</td>
<td>307</td>
</tr>
<tr>
<td>12.5</td>
<td>342</td>
<td>308</td>
</tr>
<tr>
<td>25.0</td>
<td>343</td>
<td>309</td>
</tr>
<tr>
<td>37.5</td>
<td>344</td>
<td>310</td>
</tr>
<tr>
<td>50.0</td>
<td>345</td>
<td>311</td>
</tr>
<tr>
<td>62.5</td>
<td>346</td>
<td>312</td>
</tr>
<tr>
<td>75.0</td>
<td>347</td>
<td>313</td>
</tr>
<tr>
<td>87.5</td>
<td>348</td>
<td>314</td>
</tr>
<tr>
<td>100.0</td>
<td>349</td>
<td>315</td>
</tr>
<tr>
<td>112.5</td>
<td>350</td>
<td>316</td>
</tr>
<tr>
<td>125.0</td>
<td>351</td>
<td>317</td>
</tr>
</tbody>
</table>

Add Wing and Large Sheave

<table>
<thead>
<tr>
<th>Rotation Rate (rpm)</th>
<th>TESTS IN AIR - Coning Angle α,</th>
<th>TESTS IN WATER AT 25 FT/SEC - Coning Angle α,</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0'</td>
<td>2'</td>
</tr>
<tr>
<td>137.5</td>
<td>363</td>
<td>322</td>
</tr>
<tr>
<td>150.0</td>
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<td>320</td>
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<tr>
<td>162.5</td>
<td>365</td>
<td>321</td>
</tr>
<tr>
<td>175.0</td>
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<td>322</td>
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<td>187.5</td>
<td>367</td>
<td>323</td>
</tr>
<tr>
<td>200.0</td>
<td>368</td>
<td>324</td>
</tr>
</tbody>
</table>

Add Wing and Large Sheave

<table>
<thead>
<tr>
<th>Rotation Rate (rpm)</th>
<th>TESTS IN AIR - Coning Angle α,</th>
<th>TESTS IN WATER AT 25 FT/SEC - Coning Angle α,</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0'</td>
<td>2'</td>
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<td>361</td>
<td>327</td>
</tr>
<tr>
<td>125.0</td>
<td>362</td>
<td>328</td>
</tr>
</tbody>
</table>

Add Wing and Large Sheave
and tunnel set-up between tests, and recording of data onto serialized portable storage media (360 KB floppy disks). A record book was kept with a data sheet for each $\alpha_c$ and $\omega$ combination.
Chapter 4

Test Results: Forces and Moments

This chapter presents the results obtained from hydrodynamic load experiments, and describes the methods used to obtain dimensionless parameter values from the summarized raw data.

4.1 Data Reduction

The hydrodynamic load files (one for each combination of coning angle and rotation rate) representing forces and moments in dimensions of pounds force and inch-pounds of moment were compiled for summarizing in dimensional and non-dimensional form. Forces, moments and rotational frequency were converted to dimensionless coefficient form by the following relationships:

\[
Y' = \frac{Y}{\frac{1}{2}\rho A l V^2}, \quad M' = \frac{M}{\frac{1}{2}\rho A l V^2}, \quad \omega' = \frac{\omega}{V}
\]

The resulting coefficients are generalized for length, maximum diameter and free stream velocity, but are characteristic of the particular slender body form of this model. The results show variation of these coefficients with coning angle and rotation rate.

4.2 Results

The force and moment measurement results may be illustrated concisely by Figures 8, 9, 10 and 11. These surfaces represent the strength of dimensionless forces and moments with respect to coning angle and dimensionless rotational frequency.
Figure 8: Sway Force Coefficient, $Y'$

Figure 9: Heave Force Coefficient, $Z'$
The next sets of graphs examine the data from two orthogonal perspectives. Variation of tangential and normal forces with rotation rate and coning angle are given in Figures 12 and
13. Figures 14 and 15 show variation of the related moments with the same parameters. These figures cover the range of coning angles from -10° to -20°. The results for smaller coning angles follow similar trends, and are presented in Appendix B.

Figure 12: Sway Force, Y' vs. ω′
For Various Coning Angles

Figure 13: Heave Force, \( Z' \) vs. \( \omega' \)

Figure 14: Pitch Moment, \( M' \) vs. \( \omega' \)
Figure 15: Yaw Moment, $N'$ vs. $\omega'$

An orthogonal presentation of data (forces and moments versus coning angle) is given in figures 16, 17, 18 and 19 for a range of positive rotation rates. The results for opposite rotational direction are essentially identical, except for the asymmetry of odd functions.
Figure 16: Sway Force, $Y'$ vs. $\alpha_w$

Figure 17: Heave Force, $Z'$ vs. $\alpha_w$
Figure 18: Pitch Moment, $M'$ vs. $\alpha$

Figure 19: Yaw Moment, $N'$ vs. $\alpha$
The summarized test data are presented in detail in tabular form and as graphical images for each coning angle in Appendix B.

In comparison with data obtained using the same equipment in April 1989, the test data seem consistent and repeatable. Figures 20 and 21 show the correlation at a coning angle used by Johnson in the proof of concept work ($\alpha_c = -14^\circ$).

**Figure 20: Comparison of Force Data**

**Figure 21: Comparison of Moment Data**
4.3 Interpretation

The data seem to group into two regions of behavior with respect to the coning angle. For angles more negative than -10°, the pitch moment ($M'$) is highly dependent upon rotation rate. However, for coning angles between 0 and -10° the shape of the $M'$ surface is independent of $\omega'$. Similarly, the sway force ($Y'$) passes through a saddle at about -10°, at which point the nature of the surface changes direction, passing through zero again at about $\alpha_s = -15^\circ$. The following sections describe a method of visualizing the flow near the model. The force and moment data lead to the conclusion that something transitional occurs near $\alpha_s = -10^\circ$, and indeed it will be shown that the body-shed vortices first become visible over the model length after $\alpha_s = -10^\circ$.

Relationships between the experimental parameters $\alpha_s$ and $\omega$ and the measured hydrodynamic forces and moments do not tell the entire story of flow-induced motion response for the vehicle. The process described above has built an empirical body of evidence to derive dependencies. Translation of those relationships to a more practical basis of hydrodynamic performance as a function of roll rate and yaw rate sets the data up for inclusion into a larger group of experiments on more conventional captive model test facilities such as towing tank and radial arm tests. The experiments described herein lead to derivation of the partial derivatives with respect to angular velocities $\rho$ and $r$.

Understanding the flow mechanisms which cause the resultant hydrodynamic forces is essential to advancement of the state of the art in hull design. The remainder of this report develops a method of measuring the velocity field near the maneuvering vehicle so that numerical and graphical techniques may be used to evaluate and visualize the flow character. The nonplanar motion of the vehicle in coning motion is the steady action of a vehicle rolling during a flat turn from an initial condition of steady forward velocity. The component of flow across the vehicle induces vorticity in a manner analogous to flow over a cylinder. For sufficient cross flow, the body sheds two vortices from the separation points into the
surrounding flow. The longitudinal velocity carries the vorticity along the body, interacting with the locally shed vorticity distribution along the remaining length. The roll component of vehicle motion complicates analysis of the process and gives rise to other coupling because it leads to asymmetry of the vortices shed from the body. The two dimensional analogy of a rotating bluff body would result in a lift force and drag. The flow visualizations are expected to demonstrate the distribution of vorticity. Given the predicted transition near \( \alpha_c = -10^\circ \), the flow should be significantly different for experiments at coning angles above and below \(-10^\circ\).
Chapter 5

Description of Test Apparatus for Flow Mapping

5.1 Model

The model used in flow mapping has the same basic geometry of the instrumented model. It is constructed without any sensor devices. It has the capacity to accept a fin appendage or a blanking plug in a receptacle located about eight inches aft of the bow. A special sting shaft was built to mate this model to the sector described earlier. The new sting had a slightly larger diameter at the end in the model, and a smooth transition to the diameter acceptable at the sector. If deflection of the shaft/model due to the effects of flow and rotation were to be considered, this distinction from the instrumented phase of testing may possibly be significant.

5.2 Laser Doppler Velocimeter

All of the laser doppler velocimetry equipment used herein is indigenous to the MIT Marine Hydrodynamic Laboratory. The system is based on a laser device which produces three separate and independently polarized beam pairs out of a prism (blue, green and violet). Two of the beam pairs are used in this project, and the third set is available for future work in three-component velocity measures. A very complete description of general systems and concepts used in laser doppler anemometry is found in reference [9]. Coney describes the MIT installation in reference [10].
Back-scattered light from particles suspended in the tunnel flow is collected by a photo-multiplier in each channel. The doppler shift in frequency of the scattered light compared to a reference beam is proportional to the velocity of the particle in the direction orthogonal to the polarization of the measuring laser beams. With two beam pairs, two of the three velocity components can be measured with respect to a coordinate system fixed in the laser/tunnel space. In this case, the measured velocities are the streamwise component $u_\infty$ and the vertical component $w_\infty$. The table on which the laser system is mounted allows controlled translation in the three directions corresponding to the $(x_0,y_0,z_0)$ reference system. Computer controlled positioning of the table is used to automate the process of sampling a distribution of locations in the tunnel.

Figure 22 provides a diagram of the LDV equipment and laser beam schematic for one beam.

![Figure 22: LDV Equipment Arrangement](image-url)
5.3 Data Acquisition Systems

The data acquisition system for LDV experiments is based on an IBM compatible personal computer built by Everex which runs at 20 MHz using an Intel 80386 microprocessor. The PC operates software written by the author and by laboratory engineers to control the movement of the LDV through a controller which drives three independent stepping motors. The software provides closed-loop feedback control of LDV position referenced to magnetic position sensors. The same digital encoder described in chapter 2 is used to read angular position of the model about the spin axis, and its output is converted to a rotation rate display using a frequency counter. Figure 23 illustrates the data acquisition system schematically.

![Data Acquisition System Diagram]

Figure 23: LDV Data Acquisition System

The PC surveys the output of the LDV system’s Intelligent Flow Analyzers (IFAs) and matches velocity pairs with the angular position output of the encoder. Values are stored in data bins corresponding to angle (each is 2° wide, centered on even degrees). After collection of 4000 velocity/angle pairings, the LDV moves on to the next sample point in the water tunnel test section according to the operator’s instructions.
Chapter 6
Test Procedures for Flow Mapping

This chapter will present methods of obtaining and evaluating velocity data from the field surrounding the rotating body in coning motion.

6.1 Geometry of Laser Mapping

The goal in measuring flow velocities is to produce a view of perturbation velocities around the model cross-section at various longitudinal locations. The visualization of cross flow velocities at sections provides a step toward understanding the character and magnitude of vorticity shed due to the steady nonplanar cross flow of coning motion. The action of the resulting vortex sheets working along the hull and on each other accounts for complex nonlinear behavior in forces and moments.

In this work, the five stations in the tunnel where cross-sections were mapped were chosen to correspond to stations mapped in a series of static experiments conducted at MIT by Shields in 1988 [7]. The model used by Shields was the same model used in this project.

The laser doppler velocimeter (LDV) focuses its beams on a point in tunnel-fixed coordinates and takes data during the model's rotation. The set of data taken over a revolution forms a trajectory in body-fixed coordinate space. The shape of that trajectory must be determined to apply the data properly.
6.1.1 Transformation of Coordinates

The transformation of coordinates from stationary tunnel-fixed space to the rotating body-fixed reference frame may be described in the context of a rotation matrix. This matrix combines the independent effects of the model taking on a coning angle and moving to a rotational position with respect to the tunnel-fixed system. Derivation of the transformation for steady coning motion is given in Appendix A. Equations which relate the two frames of reference are:

\[ x = x_o \cos \alpha_c + y_o \sin \alpha_c \sin \phi_o - z_o \sin \alpha_c \cos \phi_o \]  
\[ y = y_o \cos \phi_o + z_o \sin \phi_o \]  
\[ z = x_o \sin \alpha_c - y_o \cos \alpha_c \sin \phi_o + z_o \cos \alpha_c \cos \phi_o \]

Using this transformation, the path traced in body-fixed space by a tunnel-fixed sample point may be determined by parameterizing \( \phi_o \), rotation. Given a coning angle and position in the tunnel \((x_o, y_o, z_o)\), body rotation through one revolution translates to a sample point trajectory in \((x, y, z)\) which lies in a plane orthogonal to a line rotated \( \alpha_c \) from \( x \) in pitch. The trajectory is circular in that plane with radius \( \sqrt{y_o^2 + z_o^2} \). The trajectory origin (center of the circle) is displaced from the \( x \) axis by \( x_o \sin \alpha_c \). Figure 24 depicts this general path with respect to the model.

A series of laser sample points at a constant coning angle and \( x_o \) will fill the inclined plane with data points in circles of various diameters. This implies that for one location in space and one full rotation of the model in roll, a system which gathers velocities paired with roll angle may obtain several hundred data points at different locations in \((x,y,z)\) space. By careful planning, the LDV data taking locations may be selected so that the velocities with respect to the body are measured optimally (i.e., without unnecessary redundancy).
A useful presentation of this velocity data is a view of perturbation velocities in the body-fixed $yz$ plane. The component of free stream velocity in the $yz$ plane is the cross flow, $U_\infty \sin \alpha$. Perturbation velocities are determined by subtracting the magnitude $U_\infty \sin \alpha$ from the LDV measured vertical velocity in the $yz$ plane.

For a fixed $x$, series of tunnel cross section velocity measurements, the data vary in $x$ location by $z \sin \alpha$. Therefore, near the body $x = x_o$ and at the tunnel walls $|x - x_o| = 10 \sin \alpha$, inches. Since the change in the $u$ component of velocity changes so little with $x$, especially with increasing distance from the body, data are presented as if measured at fixed $x$. This assumption may be corrected by either changing the portrayal of perturbation velocities to the inclined plane of sample trajectories, or by taking data at very large numbers of points in the tunnel (i.e., at a tight distribution of $x$, so that a "slice" through the data is actually at a single value of $x$). The first solution complicates the visualization (because the views are not parallel to ship sections), and the second implies prohibitively large experiments for this developmental stage of the process.
The LDV system measures two velocity components with respect to the tunnel, \( u \), and \( w \). As discussed in Appendix A, the relationship between velocities relative to the body and tunnel referenced velocities is expressed by

\[
\begin{pmatrix}
\nu \\
\nu \\
\nu 
\end{pmatrix} = 
\begin{bmatrix}
\cos \alpha_c & \sin \alpha_c \sin \phi_c & -\sin \alpha_c \cos \phi_c \\
0 & \cos \phi_c & \sin \phi_c \\
\sin \alpha_c & -\cos \alpha_c \sin \phi_c & \cos \alpha_c \cos \phi_c 
\end{bmatrix} 
\begin{pmatrix}
u \\
\nu \\
\nu 
\end{pmatrix}
\]

The velocities \( u, \nu \) and \( w \) are not fully determined by \( u_0, v_0, \alpha_c \) and \( \phi_o \) except for certain values of \( \phi_o \). In the case where \( \phi_o = 0^\circ \) or \( 180^\circ \),

\[
u = u_0 \cos \alpha_c + w_0 \sin \alpha_c
\]

and \( \nu \) is undetermined. When \( \phi_o = 90^\circ \) or \( 270^\circ \),

\[v = \pm w_0\]

and \( u \) and \( w \) are undetermined. These equations can be used to find \( u \) and \( w \) for two different points in \((x, y, z)\) when \( \phi_o = 0^\circ \) and \( 180^\circ \). We can find the \( \nu \) velocity component for those points by moving to a spot in \((x_o, y_o, z_o)\) which is \( 90^\circ \) rotated in \( y_o z_o \) from the original spot and using the measured velocity data for \( \phi_o = 90^\circ \) and \( 270^\circ \). By moving the LDV focus to two different spots and using data corresponding to a total of four roll positions, complete sets of velocities relative to the body \((u, \nu, w)\) are obtained while measuring only \( u_o \) and \( \nu_o \).

This idea that every point in \((x, y, z)\) can be evaluated completely by measuring only two components with the LDV while keeping track of roll about \( x_o \) is the basis for the logic employed in this part of the experiment. It can be shown that if we take data at a series of points along \( y_o = 0 \) then the combination of \((u_o, w_o, \phi_o)\) represents velocity normal to the trajectory in \( yz \) which was described above. Similarly, data taken along \( z_o = 0 \) and shifted in roll phase as \((u_o, w_o, \phi_o - 90^\circ)\) represents velocity tangent to the trajectory in \( yz \). As long as the sample intervals on each leg correspond to the other, the points will map one-to-one
in \((x,y,z)\). Furthermore, because each sample point in \((x_o,y_o,z_o)\) correlates to a complete trajectory \(u(x,y,z)\), we need only take data along the lines described in one quarter space of the tunnel (at a chosen \(x_o\)) as \(z < 0\) and \(y < 0\). The points in \((x,y,z)\) which result from this scheme are distributed evenly along circles inclined from \(yz\) by \(\alpha_c\) and concentric about \((x_o \cos \alpha_o, 0, x_o \sin \alpha_o)\).

6.1.2 Laser Relocation Instructions

A Fortran program to develop the sequence of sample points along the \(y_o\) and \(z_o\) axes was used to create the Laser Movement file according to data density parameters entered by the user. The \(u_o, w_o\) velocity data collected over a range of roll angles at each of these points in the \(y_o z_o\) half plane will map into complete velocity description in \((u,v,w)\) at points distributed throughout the \(yz\) plane.

6.2 Data Gathering Process

The velocity data gathering software uses subroutines developed in the MIT Marine Hydrodynamics Laboratory to move the LDV focus to each point in the Laser Movement file of coordinates, and to measure \(u_o\) and \(w_o\) and pair the velocities with \(\phi_o\). Velocity measurements are grouped into bins corresponding to roll angles. Each of the 180 bins is two degrees wide and centered on even angles. At each location, the velocity measurement loops until 4000 data points are received and distributed within the bins. The computer may be configured to pause and provide the user with graphs representing the distribution of numbers of data points, magnitudes of velocities with respect to \(\phi_o\), and a summary of standard deviation from the mean within each bin. The user is afforded the choice of proceeding to the next point or lingering to gain more data in 4000 point increments. During development, the value of 4000 points was chosen to minimize the variance in number of
points within each bin, ensuring comparable statistical consistency over the full range of rotation angle positions. When a location is completed, the values written to the output file are the average velocities in each bin for $u_o$ and $w_o$. The standard deviation within each bin was about 0.7 ft/sec in the $u_o$ component (mean near 25 ft/sec), and about 0.3 ft/sec in the $w_o$ component (mean near 0 ft/sec). The LDV is then repositioned to the next grid coordinates, and the process continues.

The end product in this raw data gathering phase is a file which lists $u_o$, $w_o$ and $\varphi_o$ for 180 even values of $\varphi_o$ at each of the sample points along the negative tunnel-fixed axes. The data from this file will be transformed in the data reduction phase to describe completely the velocity in the body-fixed system at hundreds of unique points in $(x,y,z)$. Those velocities may be represented further graphically, or used in numerical calculation of vortex strength distributions. An example of the output in each of its forms is included in Appendix C.
Chapter 7

Test Results: Flow Field Mapping

7.1 Data Reduction

The data are translated from $u_o$, $w_o$, and $\phi_o$ pairings at the LDV sample locations to $u$, $v$, and $w$ at points in body-fixed space by employing equations presented in Appendix A. Equations (5), (6) and (7) of section 6.1.1 provide spatial translation for the $y_o=0$ data, and a check for $z_o=0$ data evaluated at $\phi_o=-90^\circ$. Equation (30) of Appendix A relates the velocity components between systems and is repeated here:

$$
\begin{bmatrix}
    u \\
    v \\
    w
\end{bmatrix}
= 
\begin{bmatrix}
    \cos \alpha_c & -\sin \alpha_c \cos \phi_o & -\sin \alpha_c \sin \phi_o \\
    0 & \sin \phi_o & -\cos \phi_o \\
    \sin \alpha_c & \cos \alpha_c \cos \phi_o & \cos \alpha_c \sin \phi_o
\end{bmatrix}
\begin{bmatrix}
    u_o \\
    w'(\phi_o=0, \phi_o) \\
    w'(\phi_o=0, \phi_o=-90^\circ)
\end{bmatrix}
$$

Cross flow components are changed to perturbation velocities by subtracting the ambient cross flow from the vertical direction relative to the body:

$$
v' = v \tag{13}$$

$$
w' = w - U_w \sin \alpha_c \tag{14}$$

The resulting data file for the body-fixed coordinate system has three velocity components ($u,v,w$) related to each point ($x,y,z$) on the various trajectories described previously. A final Fortran program to generate graphical images of cross flow in a $yz$ section takes this body-fixed data as input. The output is a file written in Adobe PostScript which will drive most laser printers. The format of the image is a distribution of vectors whose lengths and directions correspond to the measured perturbation velocities in the sectional plane. A summary copy of a sample PostScript file is included in Appendix C.
7.2 Results

The LDV testing for this report was conducted to demonstrate feasibility of the technique for future work which may cover the wide, multidimensional spectrum of operating points which are possible in the MIT Coning Motion Apparatus. The test data reported in chapter 4 showed that heave force and pitch moment were much less dependent on rotation rate when coning angle was less than $-10^\circ$. It seemed likely that formation of vorticity shed from the body was occurring near that coning angle (for constant free stream tunnel flow) so the LDV experiments included one angle below the breakpoint, $-8^\circ$. The first LDV experiment was done at the extreme coning angle, $-20^\circ$ at a mid-range rotation rate of 75 rpm. As in the force and moment experiments, the tunnel velocity was maintained at 25 feet per second.

The next several pages provide cross-sectional views, in body-fixed coordinates, of the net perturbation velocities projected onto the plane of the body cross-section. Each view is for data at a specific longitudinal tunnel position relative to the center of rotation, measured in millimeters. The first three positions are for $\alpha_c=-20^\circ$, and at increasing distances aft of the COR. The first shows formation of two unequal body vortices. The next two demonstrate the shedding path into the surrounding fluid of the vortices as they are convected astern. In the second two views, however, a "shadow zone" obscures the starboard vortex. This shadow is a result of the body's obstruction of the LDV's laser beams during part of each rotation. A solution to the shadow problem is presented in the concluding chapter. Finally, the fourth view demonstrates the predicted lack of shed body vorticity at $\alpha_c=-8^\circ$ due to the relatively small ambient cross flow.
Cross Flow Velocities
Coning Angle = -20 degrees, 75 rpm, at Xo = -83.6

Figure 25: Perturbation Velocities at Section 3, $\alpha_c$=-20°
Cross Flow Velocities
Coning Angle = -20 degrees, 75 rpm, at Xo = -169.9

Figure 26: Perturbation Velocities at Section 4, $\alpha = -20^\circ$
Cross Flow Velocities
Coning Angle = -20 degrees, 75 rpm, at \( X_0 = -258.8 \)

Figure 27: Perturbation Velocities at Section 5, \( \alpha = -20^\circ \)
Cross Flow Velocities
Coning Angle = -8 degrees, 75 rpm, at Xo = -83.6

Figure 28: Perturbation Velocities at Section 3, $\alpha = -8^\circ$
Chapter 8

Conclusions and Recommendations

8.1 Conclusions

The goal in the coefficient measurement part of this project was the acquisition of a comprehensive set of force and moment data over a full range of coning angles and rotation rates. The goal was achieved by filling a matrix of over 350 experiments at different combinations of $\alpha$ and $\omega'$.

The development of a method of flow visualization from a body-fixed perspective during steady coning motion was the second major goal of this work. The method was developed and demonstrated at two coning angles and one moderate rotation rate for five sections in the tunnel. A problem with partial data obscuration in regions where the model blocks the laser from its focal point was discovered at large coning angles and furthest longitudinal distances from the center of rotation. These "shadow zones", in the worst case, may obscure the important data associated with the body shed vorticity off one side of the model (see Figures 26 and 27 in chapter 7). A solution to the shadow problem is put forward in the next section.

The surfaces in $(\alpha, \omega')$ space which define the dimensionless force and moment coefficients may be transformed using the relationship between $\alpha$, and $\omega'$ to describe the angular rotation rates experienced by the body given by equations (3). Partial derivatives with respect to roll rate and yaw rate may be measured from these transformed surfaces to yield some of the coefficients in series form equations of motion. The coupled nature of roll and yaw rates in coning motion provides a unique method of determining these...
coefficients which is not offered by other conventional captive model test techniques. Actual
surface fitting of this data and correlation with other sources (such as developmental
analytical models) will be accomplished by the research sponsor.

8.1.1 Stability

For this report, a simplified analysis was conducted for positive rotation rates so that the
dependence of forces and moments on roll rate and yaw rate could be determined in a
linear model. The dimensionless data was transformed to correspond to the angular velocity
variables of roll rate and yaw rate. By fitting the data to a fourth order polynomial using a
least squares method, the partial derivatives at each operating point was evaluated.

The relationship between the measured forces and moments and the angular velocities
(which describe the state of the system in the context of this set of experiments) may be
represented by a nonlinear system matrix as

\[
\begin{bmatrix}
X' \\
Y' \\
Z'
\end{bmatrix} =
\begin{bmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
a_{31} & a_{32} & a_{33}
\end{bmatrix}
\begin{bmatrix}
p' \\
q' \\
r'
\end{bmatrix}
\]

\[
\begin{bmatrix}
K' \\
M' \\
N'
\end{bmatrix} =
\begin{bmatrix}
b_{11} & b_{12} & b_{13} \\
b_{21} & b_{22} & b_{23} \\
b_{31} & b_{32} & b_{33}
\end{bmatrix}
\begin{bmatrix}
p' \\
q' \\
r'
\end{bmatrix}
\]

(15)

where the matrix coefficients are a function of the imposed velocity vector. An approximate
method for assessing the stability of the hydrodynamic force and moment coefficients near
the selected operating points is to evaluate the eigenvalues of a linearized form of the
equations which describe the motion of small perturbations about a steady operating
condition. These are the linearized form of equations (15) above. The components of the
system matrices in a linearized problem become the first order partial differentials. The
terms in \( p \) and \( r \) were found from the polynomial fit of the data. Since the coning motion
evaluated here uses an unappended body of revolution, the terms describing dependence on
pitch rate may be assumed to be symmetric with the yaw rate terms. For this case then, the
eigenvalues of the linearized systems of \((X,Y,Z)\) and \((K,M,N)\) were approximated over the
ranges in \(p\) and \(r\) used in the experiments.

The partial differentials of \(X\) and \(K\) with respect to \(p\) and \(r\) are very nearly zero when
compared with the magnitude of \(\frac{\partial Z}{\partial p}\) and \(\frac{\partial N}{\partial r}\). Also \(\frac{\partial Z}{\partial p}\) and \(\frac{\partial N}{\partial p}\) are small compared to the dominant
term, so the two corresponding eigenvalues are real and nearly equal to zero. The other
eigenvalue, which determines the nature of the unsteady response, is also real and is nearly
equal to the term \(Z, = \frac{\partial Z}{\partial p}\) in the \((X,Y,Z)\) system (and \(N, = \frac{\partial N}{\partial r}\) in the \((K,M,N)\) system). Therefore,
wherever \(Z,\) has positive real part the system is not asymptotically stable in heave force for
nonzero yaw rate. And similarly, for positive real parts in \(N,\) the system is not stable in yaw
moment.

Using the simplified linearized conclusions above and the results of a polynomial
curve fit, the derivatives were calculated over the range of \(p\) and \(r\). The curve fitting algorithm
may be somewhat suspect because the coupled nature of the coning motion when projected
into \((p,r)\) space does not provide an evenly distributed set of data points. However, over
most of the range of interest the error between equation and measured data was generally
less than 10\% and usually less than 3\%. The derived partial slopes are as follows:

\[ Z, \leq 0 \text{ everywhere except along } r = 0 \]
\[ N, \geq 0 \text{ throughout the range in } (p,r) \]

This rough analysis indicates that the heave force is asymptotically stable and the yaw
moment is unstable for variation in the coupled angular velocities \(p\) and \(r\). The interesting
observations would come with more refined knowledge of the nonlinear dependences, but
this "back of the envelope" look at stability may be a first step in evaluating the trends
observed for sensitivity and maneuvering character.
8.1.2 Transition After $\alpha_c = -10^\circ$

In the results presented in chapter 4, a transition in the nature of the nonlinear dependence on $\alpha_c$ and $\omega'$ was seen at a coning angle between $-8^\circ$ and $-10^\circ$. Figure 18 is particularly indicative of the occurrence of some distinct change in the character of the pitch moment coefficient $M'$ near $\alpha_c = -10^\circ$. In this case, $M'$ is independent of $\omega'$ for $\alpha_c$ less negative than $-10^\circ$, but varies dramatically with $\omega'$ after $-10^\circ$. A possible explanation for the variation is the development of significant vorticity shed into the free stream by the body. Also, from Figure 16, the sway force coefficient $Y'$ changes the sign of its slope with respect to coning angle at about the same point. The effect is to generate a positive sway force for coning angles beyond $-15^\circ$, where it had been negative between 0 and $-15^\circ$.

If the formation of body shed vorticity is considered as the superposition of a distribution of two dimensional cross-flow vorticies shed from the bluff hull and transported longitudinally by the component of stream velocity parallel to the hull axis, then the formation of the expected pair of vortex sheets should occur at some particular velocity associated with a transitional Reynolds number. The component of stream velocity orthogonal to the body axis is $U \cdot \sin \alpha_c$, so for constant tunnel flow rate the change in section velocity is due to variation in $\alpha_c$. In the demonstration of flow visualization, the LDV data show formation of strong body shed vortices at $\alpha_c = -20^\circ$ and no vortex sheets at $\alpha_c = -8^\circ$. Additional tests have shown the first formation of this vortex shedding at about $\alpha_c = -10^\circ$. Also, note that because nonzero roll rate acts to oppose development of one vorticity direction and adds to the other, we should expect the strengths and locations of the two shed vortex sheets to be asymmetric. As the views of perturbation velocities demonstrate, this was confirmed by experiment.

The sway force component of positive $Y''$ which develops after $\alpha_c = -10^\circ$ corresponds to the lift generated by the cross flow over the rolling hull (analogous to flow about a cylinder with circulation). For coning angles smaller than $-10^\circ$ the sway force coefficient is negative.
due to the resultant of the lengthwise distribution of viscous drag from negative yawing. That seems to be consistent given that the wetted surface area of the model aft of the center of rotation is greater than the surface area forward of the COR. In other words, for coning angles between 0 and -10° the sway force is mainly the expected drag due to yaw. For coning angles exceeding about -10° the addition of (opposing) lift due to roll rate and cross flow must be considered, and the vorticity shed from the body is visible in a perturbation velocity graphic. This lift force dominates the yaw drag after about \( \alpha_r = -15 \)°. Figure 16 (and 51) shows this for the case of positive roll and negative yaw rates, and Figure 52 demonstrates the same trend for negative roll and positive yaw rates.

8.2 Recommendations

The method of flow visualization presented here is feasible, but for large coning angles and greater distances from the model’s center of rotation the problem of data obscuration can prevent complete characterization of important elements of the flow such as a body vortex. The problem arises because while the laser focal point is located inside the "cone" of the body rotation there may be some time when the model obscures the laser beams by passing between the laser source and the intended focus. The efficient use of all data gathered during the model’s rotation allows for a minimum number of assigned LDV focal positions. However, when a particular position is blocked over a range of rotation angle, the result is seen in the graphical output as zero velocity in either the radial or tangential component of vectors. The missing component data form a "shadow" near the model. An example of this shadow effect is found if one looks for the starboard body-shed vortex in Figures 26 and 27.

A solution for the shadow problem is achievable at the cost of adding several more LDV focal positions to the grid file and performing some overlaying of data within the post-processing software. The same information that one gathers by taking data along the
negative $y$, and $z$, axes may be obtained by looking at analogous positions on the positive legs of those axes and shifting the data by a phase difference in $\varphi$. By recognizing which points may be obscured during rotation, the experimenter may add the necessary duplicative points to "fill in the shadow" with valid, nonzero velocity measurements. The process of matching zero values with the repeat data may be undertaken in the program which transforms tunnel-fixed data to the body-fixed system. This is a reasonably simple series of comparisons and sorts which recognize inappropriate zero velocities and rewrite a value which corresponds to the same position in body-fixed space. The first effort to implement this solution is proceeding today at MIT's Marine Hydrodynamic Laboratory.

Further steps in this experimental program will naturally include using the laser doppler velocimetry techniques developed here to map the near-body flow over a range of parameters including coning angles, rotation rates and perhaps for varying tunnel velocities. The model may have a fin appendage added and, with slight modifications to the sting shaft, the model roll angle with respect to the rotating system may be changed from 0° to 90°. The addition of an appendage and change in roll angle would allow dynamic versions of the sort of flow experiments conducted at static positions by Shields in 1987 [7]. It is expected that coupling of the appendage-shed vorticity would be significant in its effect on body reactions.

The force and moment measurements conducted here will likely be expanded to include experiments with a fully instrumented fin appendage. Again, model roll angle might be varied to increase the number of experimental parameters.

Numerical analysis of flow velocity data may provide more quantitative insight into the complex vortical mechanisms working over the model length to influence ship motions. Such work might include determining the strength distribution of the vortices in three dimensions. Closer spacing of the sample sections would probably be required to obtain
sufficient detail. Comparison of these experiments with the patterns predicted by leading edge analytical tools would be useful in validating the computational methods of predicting vehicle motions.
References


Appendix A

Coordinate Transformations in Rotating Systems

A.1 Positions

The problem of mapping data taken in a water tunnel/laser table based reference frame during model rotation to locations in a model fixed reference frame was solved by considering the superposition of independent motions to develop a rotation matrix, [C], which describes the following relationship

\[
\begin{pmatrix}
x \\
y \\
z
\end{pmatrix} = [C(\alpha, \phi)] \cdot 
\begin{pmatrix}
x_o \\
y_o \\
z_o
\end{pmatrix}
\] (16)

The coning motion may be constructed from a starting point where the tunnel and body coordinates are coincident by adding two independent motions. The first is to pitch the body to a coning angle \(\alpha_c\) without roll. The second movement, which will be parameterized in time as a continuous steady motion, is to roll the \((x,y,z)\) frame to an angle \(\phi_o\) about the tunnel's \(x_o\) axis. Each movement may be represented by a separate rotation matrix as

\[
\begin{pmatrix}
x_{\alpha_c} \\
y_{\alpha_c} \\
z_{\alpha_c}
\end{pmatrix} = [C_{\alpha_c}] \cdot 
\begin{pmatrix}
x_o \\
y_o \\
z_o
\end{pmatrix}
\]

and

\[
\begin{pmatrix}
x_{\phi_o} \\
y_{\phi_o} \\
z_{\phi_o}
\end{pmatrix} = [C_{\phi_o}] \cdot 
\begin{pmatrix}
x_o \\
y_o \\
z_o
\end{pmatrix}
\] (17)

Superposition of the two motions is given by series multiplication of the rotation matrices, so that
\[
\begin{pmatrix}
 x \\
 y \\
 z 
\end{pmatrix} = [C(\alpha_0, \phi_o)]
\begin{pmatrix}
 x_o \\
 y_o \\
 z_o 
\end{pmatrix} = [C_\alpha][C_\phi]
\begin{pmatrix}
 x_o \\
 y_o \\
 z_o 
\end{pmatrix}
\]

(18)

A general matrix \([C_\theta]\) which relates a coordinate system \((x', y', z')\) to a base coordinate system \((x, y, z)\) by a rotation of \(\theta\) about an arbitrary axis \(\overline{u_\theta}\) is given by reference [11].

\[
[C_\theta] = \cos \theta \begin{bmatrix}
 1 & 0 & 0 \\
 0 & 1 & 0 \\
 0 & 0 & 1 
\end{bmatrix} + (1 - \cos \theta) \begin{bmatrix}
 l^2 & lm & ln \\
 lm & m^2 & mn \\
 ln & mn & n^2 
\end{bmatrix} + \sin \theta \begin{bmatrix}
 0 & n & -m \\
 -n & 0 & l \\
 m & -l & 0 
\end{bmatrix}
\]

(19)

where

\[
l = \overline{u_x} \cdot \overline{u_\theta} \quad m = \overline{u_y} \cdot \overline{u_\theta} \quad n = \overline{u_z} \cdot \overline{u_\theta}
\]

(20)

For the case of pitching to a coning angle \(\alpha_c, \overline{u_\alpha} = \overline{u_y}\) so

\[
l_\alpha = \overline{u_x} \cdot \overline{u_y} = 0 \quad m_\alpha = \overline{u_y} \cdot \overline{u_y} = 1 \quad n_\alpha = \overline{u_z} \cdot \overline{u_\alpha} = 0
\]

(21)

thus

\[
[C_{\alpha_c}] = \begin{bmatrix}
 \cos \alpha_c & 0 & -\sin \alpha_c \\
 0 & 1 & 0 \\
 \sin \alpha_c & 0 & \cos \alpha_c 
\end{bmatrix}
\]

(22)

Similarly,

\[
[C_{\phi_o}] = \begin{bmatrix}
 1 & 0 & 0 \\
 0 & \cos \phi_o & \sin \phi_o \\
 0 & -\sin \phi_o & \cos \phi_o 
\end{bmatrix}
\]

(23)

The product of these two provides the solution

\[
[C(\alpha_c, \phi_o)] = \begin{bmatrix}
 \cos \alpha_c & 0 & -\sin \alpha_c \\
 0 & \cos \phi_o & \sin \phi_o \\
 \sin \alpha_c & 0 & \cos \alpha_c 
\end{bmatrix} \begin{bmatrix}
 1 & 0 & 0 \\
 0 & \cos \phi_o & \sin \phi_o \\
 0 & -\sin \phi_o & \cos \phi_o 
\end{bmatrix}
\]

(24)

\[
[C(\alpha_c, \phi_o)] = \begin{bmatrix}
 \cos \alpha_c & \sin \alpha_c \sin \phi_o & -\sin \alpha_c \cos \phi_o \\
 0 & \cos \phi_o & \sin \phi_o \\
 \sin \alpha_c & -\cos \alpha_c \sin \phi_o & \cos \alpha_c \cos \phi_o 
\end{bmatrix}
\]

(25)

This matrix leads to the equations of Chapter 6.1.1 from

\[
\begin{pmatrix}
 x \\
 y \\
 z 
\end{pmatrix} = \begin{bmatrix}
 \cos \alpha_c & \sin \alpha_c \sin \phi_o & -\sin \alpha_c \cos \phi_o \\
 0 & \cos \phi_o & \sin \phi_o \\
 \sin \alpha_c & -\cos \alpha_c \sin \phi_o & \cos \alpha_c \cos \phi_o 
\end{bmatrix} \begin{pmatrix}
 x_o \\
 y_o \\
 z_o 
\end{pmatrix}
\]

(26)
Finally, a transformation from a known tunnel coordinate position \((x_0, y_0, z_0)\) to a body fixed coordinate position \((x, y, z)\) may be made through simple equations which depend upon coning angle and roll position \((\alpha_c, \phi_o)\). To reverse the transformation (i.e., from body fixed to tunnel fixed), the inverse of the rotation matrix may be used as

\[
\begin{pmatrix}
x_o \\
y_o \\
z_o
\end{pmatrix} = [C(\alpha_c, \phi_o)]^{-1}
\begin{pmatrix}
x \\
y \\
z
\end{pmatrix}
\] (27)

Since the matrix \([C(\alpha_c, \phi_o)]\) is orthogonal, its inverse is equivalent to its transpose. Therefore the transformation of coordinates may be given by the following table, which allows coordinate translation in either direction:

Table 3: Coordinate Transformations

<table>
<thead>
<tr>
<th></th>
<th>(x_o)</th>
<th>(y_o)</th>
<th>(z_o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x)</td>
<td>(\cos \alpha_c)</td>
<td>(\sin \alpha_c \sin \phi_o)</td>
<td>(-\sin \alpha_c \cos \phi_o)</td>
</tr>
<tr>
<td>(y)</td>
<td>0</td>
<td>(\cos \phi_o)</td>
<td>(\sin \phi_o)</td>
</tr>
<tr>
<td>(z)</td>
<td>(\sin \alpha_c)</td>
<td>(-\cos \alpha_c \sin \phi_o)</td>
<td>(\cos \alpha_c \cos \phi_o)</td>
</tr>
</tbody>
</table>

A.2 Velocities

Particle velocities \((u, v, w)\) may be represented by vector positions in \((x, y, z)\), so the translation of velocity vectors follows the same method described above for positions. The result is that

\[
\begin{pmatrix}
u \\
v \\
w
\end{pmatrix} =
\begin{bmatrix}
\cos \alpha_c & \sin \alpha_c \sin \phi_o & -\sin \alpha_c \cos \phi_o \\
0 & \cos \phi_o & \sin \phi_o \\
\sin \alpha_c & -\cos \alpha_c \sin \phi_o & \cos \alpha_c \cos \phi_o
\end{bmatrix}
\begin{pmatrix}
u_o \\
v_o \\
w_o
\end{pmatrix}
\] (28)

Since the LDV equipment measures two of the three tunnel fixed velocities \((u_o, w_o)\), but not \(v_o\), the body velocities \(u, v,\) and \(w\) are not obviously fully determined for most values of \(\phi_o\). This is the subject of some discussion in Chapter 6.
Let us first consider the simplified case of \( \alpha_c = 0 \). Then vertical velocity data gathered along the LDV axis where \( y_c = 0 \) and \( z_c < 0 \) may be described as normal to the trajectory in \((x, y, z)\). Similarly, vertical velocity data taken along \( z_c = 0 \) for \( y_c < 0 \) represents velocity tangent to the same trajectory at locations along the trajectory shifted by \(-90^\circ\). For this zero coning angle case the body fixed velocities can be found from the streamwise, normal and tangential velocities by:

\[
\begin{align*}
\begin{pmatrix}
U \\
0 \\
W
\end{pmatrix} &=
\begin{bmatrix}
1 & 0 & 0 \\
0 & \sin \phi_c & -\cos \phi_c \\
0 & \cos \phi_c & \sin \phi_c
\end{bmatrix}
\begin{pmatrix}
U_o \\
W_{o(1_c=0,\phi_o=0)} \\
W_{o(1_z=0,\phi_o=90^\circ)}
\end{pmatrix}
\end{align*}
\]

This use of orthogonal data taking legs in the water tunnel coupled with the rotation of the body allows simple movement of the LDV while mapping the entire space around the model. The general case of nonzero coning angle may be determined by multiplying the square matrix in equation (29) by the direction cosines matrix for coning, \([C_a]\) of equation (22). The resulting transformation of \((U_o, W_o, \alpha_c, \phi_o)\) data to \((U, V, W)\) is:

\[
\begin{align*}
\begin{pmatrix}
U \\
V \\
W
\end{pmatrix} &=
\begin{bmatrix}
\cos \alpha_c & -\sin \alpha_c \cos \phi_c & -\sin \alpha_c \sin \phi_c \\
0 & \sin \phi_c & -\cos \phi_c \\
\sin \alpha_c & \cos \alpha_c \cos \phi_c & \cos \alpha_c \sin \phi_c
\end{bmatrix}
\begin{pmatrix}
U_o \\
W_{o(1_c=0,\phi_o=0)} \\
W_{o(1_z=0,\phi_o=90^\circ)}
\end{pmatrix}
\end{align*}
\]

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Appendix B

Test Data: Forces and Moments

Data presented herein include:

- Plots of $Y'$ and $Z'$ versus $\omega'$ at each $\alpha_c$
- Plots of $M'$ and $N'$ versus $\omega'$ at each $\alpha_c$
- Plots of $Y'$, $Z'$, $M'$, and $N'$ versus $\alpha_c$ for various rotation rates, both positive and negative
- Tabulated dimensionless force and moment coefficients for a range of $\omega'$ at each $0^\circ \leq \alpha_c \leq -20^\circ$
- Identical data in units of pounds force and inch-pounds of moment for a range of rpm over the same coning angles
M' and N' vs w'
Coning Angle = -20 degrees
$Y'$ and $Z'$ vs $w'$

Coning Angle = -18 degrees
M' and N' vs w'
Coning Angle = -18 degrees
Coning Angle = -16 degrees

Non-Dimensional Force ($Y' = \frac{Y}{(0.5 \rho U)}$) vs Non-Dimensional Rotation Rate ($w' = \frac{w}{U}$)
M' and N' vs w'

Coning Angle = -16 degrees

Non-Dimensional Rotation Rate (w' = w/U)

Non-Dimensional Moment (M' = M/N/\sqrt{\beta})
Non-Dimensional Force \((Y' = Y/(\gamma' \cdot \text{Spau})\))

Y' and Z' vs \(w'\)

Coning Angle = -14 degrees

Non-Dimensional Rotation Rate \((w' = w/U)\)
$Y'$ and $Z'$ vs $w'$

Coning Angle = -12 degrees

Non-Dimensional Force ($Y' = Y/\omega_{pAU}$)

Non-Dimensional Rotation Rate ($w' = w/\omega$)

- $Y'$
- $Z'$
$Y'$ and $Z'$ vs $w'$
Coning Angle = -10 degrees
$M'$ and $N'$ vs $w'$

Coning Angle = -10 degrees

Non-Dimensional Moment ($M' = M/(\rho U^2)$) vs Non-Dimensional Rotation Rate ($w' = w/l$)
\( Y' \) and \( Z' \) vs \( w' \)

Coning Angle = -8 degrees

Non-Dimensional Force (\( Y' = Y/(0.5pAU) \))

Non-Dimensional Rotation Rate (\( w' = w/U \))

\(-0.3\) \(-0.2\) \(-0.1\) 0 0.1 0.2 0.3

\(-2\) \(-1.5\) \(-1\) \(-0.5\) 0 0.5 1 1.5 2
M' and N' vs w'
Coning Angle = -8 degrees
Y' and Z' vs w'
Coning Angle = -6 degrees
M' and N' vs w'  
Coning Angle = -6 degrees
Y' and Z' vs w'
Coning Angle = -4 degrees
Non-Dimensional Moment ($M' = M/(.5\rho U^2)$)

Non-Dimensional Rotation Rate ($w' = wl/U$)

$M'$ and $N'$ vs $w'$

Coning Angle = -4 degrees
Y' and Z' vs w'
Coning Angle = -2 degrees

Non-Dimensional Force (Y' = Y/(.5pAUU))

Non-Dimensional Rotation Rate (w' = wI/U)

Y' • Z'
$M'$ and $N'$ vs $w'$

Coning Angle = -2 degrees

Non-Dimensional Moment ($M' = M/(0.5pAlU)$)

Non-Dimensional Rotation Rate ($v' = wl/U$)

$M'$, $N'$
Non-Dimensionalized Force ($Y' = Y/\rho AU$)

Combing Angle = 0 degrees

$Y'$ and $Z'$ vs $W'$

Non-Dimensional Rotation Rate ($W' = w/\Omega$)
$M'$ and $N'$ vs $w'$

Coning Angle = 0 degrees

Non-Dimensional Moment ($M' = M / (c \cdot p \cdot A \cdot U)$)

Non-Dimensional Rotation Rate ($w' = w / U$)

- $M'$
- $N'$
Y' vs Coning Angle

for various positive rotation rates

Non-Dimensional Force ($Y' = Y/(5.5AUU)$)

Coning Angle (degrees)

- 62.5 rpm
- 87.5 rpm
- 112.5 rpm
- 137.5 rpm
- 162.5 rpm
- 187.5 rpm
$Y'$ vs Coning Angle
for various negative rotation rates

Non-Dimensional Force ($Y' = Y/(\lambda pA_U)$)

Coning Angle (degrees)

-75 rpm -100 rpm -125 rpm
-150 rpm -175 rpm -200 rpm
Z' vs Coning Angle
for various positive rotation rates

Non-Dimensional Force ($Z' = Z/(.5 pAUU)$)

Coning Angle (degrees)

- 62.5 rpm
- 87.5 rpm
- 112.5 rpm
- 137.5 rpm
- 162.5 rpm
- 187.5 rpm
Z’ vs Coning Angle
for various negative rotation rates

Non-Dimensional Force (Z’ = Z/(5pAUU))

Coning Angle (degrees)

-75 rpm  -100 rpm  -125 rpm
-150 rpm  -175 rpm  -200 rpm
M' vs Coning Angle
for various positive rotation rates

Non-Dimensional Moment (M' = M/(.5pAU))

Coning Angle (degrees)

- 62.5 rpm
- 87.5 rpm
- 112.5 rpm
- 137.5 rpm
- 162.5 rpm
- 187.5 rpm
Non-Dimensional Moment (M' = M/M_p)

M' vs Coning Angle for various negative rotation rates
N’ vs Coning Angle
for various positive rotation rates

Non-Dimensional Moment (N’ = N/(.5\rho\lambda u'))

Coning Angle (degrees)

- 62.5 rpm  - 87.5 rpm  - 112.5 rpm
- 137.5 rpm  - 162.5 rpm  - 187.5 rpm
N' vs Coning Angle
for various negative rotation rates

Non-Dimensional Moment (N' = N/(0.5pAU))

Coning Angle (degrees)

-75 rpm
-100 rpm
-125 rpm
-150 rpm
-175 rpm
-200 rpm
### Dimensional Load Data For Forward Rotation at Coning Angle = -20 degrees

<table>
<thead>
<tr>
<th>Z</th>
<th>M</th>
<th>Y</th>
<th>N</th>
<th>K</th>
<th>X</th>
<th>Vel</th>
<th>rpm</th>
</tr>
</thead>
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### Dimensional Load Data For Reverse Rotation at Coning Angle = -20 degrees

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<th>M</th>
<th>Y</th>
<th>N</th>
<th>K</th>
<th>X</th>
<th>Vel</th>
<th>rpm</th>
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### Non-Dimensional Load Data For Forward Rotation at Coning Angle = -20 degrees

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<th>$Y'$</th>
<th>$N'$</th>
<th>$K'$</th>
<th>$X'$</th>
<th>Vel</th>
<th>rpm'</th>
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### Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -20 degrees

<table>
<thead>
<tr>
<th>$Z'$</th>
<th>$M'$</th>
<th>$Y'$</th>
<th>$N'$</th>
<th>$K'$</th>
<th>$X'$</th>
<th>Vel</th>
<th>rpm'</th>
</tr>
</thead>
<tbody>
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### Dimensional Load Data For Forward Rotation at Coning Angle = -18 degrees

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<th>N</th>
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<th>Vel</th>
<th>rpm</th>
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### Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -18 degrees

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### Non-Dimensional Load Data For Forward Rotation at Coning Angle = -16 degrees

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### Non-Dimensional Load Data For Forward Rotation at Coning Angle = -14 degrees

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Dimensional Load Data For Reverse Rotation at Coning Angle = -12 degrees

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### Dimensional Load Data For Reverse Rotation at Coning Angle = -8 degrees

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**Dimensional Load Data For Reverse Rotation at Coning Angle = -4 degrees**

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### Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -4 degrees

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### Dimensional Load Data For Forward Rotation at Coning Angle = -2 degrees

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### Dimensional Load Data For Reverse Rotation at Coning Angle = -2 degrees

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Non-Dimensional Load Data For Forward Rotation a' Coning Angle = -2 degrees

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Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -2 degrees

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### Dimensional Load Data For Reverse Rotation at Coning Angle = 0 degrees

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### Non-Dimensional Load Data For Reverse Rotation at Coning Angle = 0 degrees

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Appendix C

Test Data: Flow Field Mapping

The data included in this Appendix is a sample (for $\alpha_o=-20^\circ$) of the output for:

- The data gathering in LDV/Tunnel Space
- The translation into Body Space
- The PostScript output file which drives a graphics device

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<td>-100.958</td>
<td>-123.348</td>
<td>-33.049</td>
<td>0.150</td>
<td>0.826</td>
<td>0.413</td>
</tr>
<tr>
<td>-99.472</td>
<td>-125.562</td>
<td>-28.966</td>
<td>0.131</td>
<td>0.785</td>
<td>0.360</td>
</tr>
<tr>
<td>-97.960</td>
<td>-127.622</td>
<td>-24.813</td>
<td>0.115</td>
<td>0.758</td>
<td>0.317</td>
</tr>
<tr>
<td>-96.425</td>
<td>-129.528</td>
<td>-20.595</td>
<td>0.129</td>
<td>0.936</td>
<td>0.356</td>
</tr>
<tr>
<td>-94.866</td>
<td>-131.275</td>
<td>-16.317</td>
<td>0.111</td>
<td>0.804</td>
<td>0.306</td>
</tr>
<tr>
<td>-93.291</td>
<td>-132.863</td>
<td>-11.985</td>
<td>0.091</td>
<td>0.817</td>
<td>0.249</td>
</tr>
<tr>
<td>-91.696</td>
<td>-134.288</td>
<td>-7.603</td>
<td>0.074</td>
<td>0.757</td>
<td>0.204</td>
</tr>
<tr>
<td>-90.085</td>
<td>-135.550</td>
<td>-3.177</td>
<td>0.075</td>
<td>0.880</td>
<td>0.206</td>
</tr>
<tr>
<td>-88.460</td>
<td>-136.647</td>
<td>1.288</td>
<td>0.063</td>
<td>0.860</td>
<td>0.172</td>
</tr>
<tr>
<td>-86.823</td>
<td>-137.578</td>
<td>5.786</td>
<td>0.057</td>
<td>0.953</td>
<td>0.158</td>
</tr>
<tr>
<td>-85.176</td>
<td>-138.340</td>
<td>10.311</td>
<td>0.047</td>
<td>0.980</td>
<td>0.129</td>
</tr>
<tr>
<td>-83.521</td>
<td>-139.935</td>
<td>14.850</td>
<td>0.033</td>
<td>0.931</td>
<td>0.092</td>
</tr>
</tbody>
</table>
This is an abbreviated version of a PostScript file which is the output of VECTORS:

%%BeginProlog

%&!PS-Adobe-1.0
%&BBox: 0 0 612 792
%&Title: 75520.ps
%&Pages: 1
%&DocumentFont: Helvetica
%&EndComments
/m [moveto] def
/l [lineto] def
/s [stroke] def
/q [fill] def
/n [newpath] def
/arrow [newpath
0 0 moveto
1 0 lineto
1 moveto
0.75 0.10 lineto
1 moveto
0.75 -0.10 lineto
] def
0.072 setlinewidth
2 setlinejoin
/Helvetica findfont
9 scalefont setfont
%&EndProlog
%&Page: 1 1
306.306 translate
1 1 1.1339 1.1339 scale
gsave
2.000 2.000 scale
0 88.515 translate
gsave
n .392 setlinewidth
.000 42.751 translate
-5.398 rotate
.255 .255 scale
arrow s
grestore
gsave
n .494 setlinewidth
-4.875 42.671 translate
-41.399 rotate
.203 .203 scale
arrow s
grestore
gsave
n .542 setlinewidth
-9.745 42.432 translate
260.334 rotate
.185 .185 scale
arrow s
grestore
gsave
n .376 setlinewidth
-14.616 42.032 translate
186.607 rotate
.266 .266 scale
arrow s
grestore
gsave
n .72 setlinewidth
/Helvetica findfont 9 scalefont setfont
n
-203.2 -203.2 m
-203.2 203.2 l
203.2 203.2 1 s
1 -1 scale
n
-210. 200 m
-203. 200 1 s
n
-235. 200. m (-11 ) show
n -210. 180. m
-203. 180. 1s
n -235. 180. m ( -1 ) show
n -210. 160. m
-203. 160. 1s
n
..........n
n 200. -210. m
200. -203. 1 s
n 190. -220. m (100 ) show
n /Helvetica findfont 12 scalefont setfont
-20 -240 m
(Y \rin mm)) show
n /Helvetica findfont 16 scalefont setfont
-70 260 m
(Cross Flow Velocities) show
n /Helvetica findfont 10 scalefont setfont
-115 245. m
(Coning Angle = 20 degrees. 75 rpm, at Xn = -258.8) show
n /Helvetica findfont 12 scalefont setfont
-240.0 m
90 rotate
(Z \rin mm)) show
greendraw showpage
%7 Trailer
%7 EOF
Appendix D
Computer Programs

The following programs were written in Microsoft FORTRAN and compiled for use on an IBM PC XT, AT or PS/2.

This program takes tunnel coordinates in mm from a data file, converts to vessel table coordinates, positions the laser at those coordinates and measures the velocity there for 1000 counts and writes the data to an output file which records velocity and rotational position.

Program subvel

$DEBUG:
character*1 stop
integer alpha
integer*2 speed,base=x
real rpm
dimension x(100), y(100), phi(100)
character*20 infile,outfile

Setup all devices
abase=x*84
call setup(baserite)
call set

call setup

write*, '(t) Enter the input data file = :'
read*, infile
write*, '(t) Enter the output data file = :'
read*, outfile
open(infile=file=status='old')
open(outfile=file=status='old')
call getunit(base,1,infile)
call getunit(base,2,outfile)
call getunit(alpha,1)
read(infile,alpha,rpm)
write*, 'SET THE ABOVE VALUES THEN HIT RETURN'
write*(alpha, rpm, mom, xday, xhr)
call read1(alpha)
pause

Set refraction value to account for Y correction
snell=1/1.3456

Move the LDV table to each sample point and measure velocities
and rotation angle (phi). Write the data to the output file.
npos = 1
continue
read 1,*,end=1000) x0, y0, z0
write( *, 5005) npos
y0 = y0*snell
call submove(x0,y0,z0)
y0 = y0/snell

write position header to output file
write(3,5001) npos, x0, y0, z0

c get the data at this point
  call get_data(vx, vz, phi, bin)

write the data out
do 1002 j = 1, nbin
  reverse the IFA sign convention to correspond to SNAME
  vx(j) = -1.*vx(j)
  vz(j) = -1.*vz(j)
write(3,5003) phi(j), vx(j), vz(j)
1002 continue
npos = npos + 1
continue

goto 900

1003 continue
4999 format(' Alpha = ',A,' RPM = ',F,7,2)
5000 format(' Alpha = ',A, ' deg', 'F-6.1', 'rpm test on ',F,12.2,12.2)
  ' ',F,14.4, ' at ',F,12,12,2)
5001 format(' Posit ',F,5,3x,F,9,3x,F,9,3x,F,9,3x)
5003 format(3F,10.3)
5004 format(A,2x,A,4)
5005 format ' Moving LDV to position number ',I4)
6000 continue
  close(1)
  close(3)
end
This program takes the measured velocities and roll angles for each position and converts the velocities and locations to a body fixed coordinate system. The velocities are given as perturbations from the ambient free stream flow.

```
program perturb

Declarations
character*80 header
character*20 invel, outvel
character*8 date
character*4 time
integer*2 alpha, qbin, q34bin

dimension phi(70,180), u(70,180), w(70,180)
dimension x(70,180), y(70,180), z(70,180)
pi = acos(-1.)

Find input and output file names
write(5,'(a)')
write(5,'(a)') 'Type the INPUT velocity data filename ==>
read*(a) invel
open(unit=1, file=invel, status=old)
write(3,5006) alpha, rpm, date, time
write(3,5002)
nbin=180

Read sample points from input data file

rpts=0
1100 continue
npts=npts+1
read(1,5001) alpha, rpm, date, time
write(3,5006) alpha, rpm, date, time
write(3,5002)
nbin=180
1200 continue

Find all the positions in body space (x,y,z)
do 1225 k=1,npts
dc 1225 m=1,nbin
x(k,m)=x0(k)*cos(alpha*pi/180)+sin(alpha*pi/180)*
  (y0(k)*sin(phi(k,m))*pi/180)-z0(k)*cos(phi(k,m))*pi/180)
  +z0(k)*sin(phi(k,m))*pi/180)
y(k,m)=y0(k)*cos(phi(k,m))*pi/180)-z0(k)*sin(phi(k,m))*pi/180)
z(k,m)=x0(k)*sin(alpha*pi/180)-cos(alpha*pi/180)*
  (y0(k)*sin(phi(k,m))*pi/180)-z0(k)*cos(phi(k,m))*pi/180))
1225 continue
```
continue

htps=npts/2
qbin=nbin/4
q34bin=3*nbin/4

do 1350 k=1,htps
  do 1325 m=1,qbin
    u(k,m)=-1*sin(alpha*pi/180)*
      (w0(k,m)*cos(phi(k,m)*pi/180)+
       w(k+hpts+m+q34bin)*sin(phi(k,m)*pi/180))
    v(k,m)=w0(k,m)*sin(phi(k,m)*pi/180)-
      w(k+hpts+m+q34bin)*cos(phi(k,m)*pi/180)+
    w0(k,m)*cos(alpha*pi/180)+
      w(k+hpts+m+q34bin)*sin(phi(k,m)*pi/180))
  continue
  continue
  do 1450 i=1,htps
    do 1400 j=1,nbin
      write(3,5005) x(i,j),y(i,j),z(i,j),u(i,j),v(i,j),w(i,j)
  continue
1400 continue

continue

1500 continue

5000 format(A8,2x,A4)
5001 format(3x,13.5x,F6.1,13x'A10,4x,A4)
5002 format(8x,'X',11x,'Y',11x,'Z',11x,'U',11x,'V',11x,'W')
5003 format(7x,15.3x,F9.3,3x,F9.3,3x,F9.3)
5004 format(3F10.3)
5005 format(6F12.3)
5006 format('Coning Angle = ',A3,' at ',F5.1,' rpm on ',A10,' at ',A4)
  close(unit=1)
  close(unit=3)

6000 continue

end
program vectors

This program will generate the PostScript file to produce perturbation vectors in the body-fixed section on a laser printer

integer alpha, num, nspace, hdata, rpm, q34data
treal x0
character*20 indata, outps

pi = acos(-1.)
write(*, '(a)') Enter the INPUT data file name ==>
read*(a) indata
open(3, file=indata, status= 'old')
write*(a) Enter the output PostScript file name ==>
read*(a) outps
open(5, file=outps, status='new')
write*(a) Enter the number of lines of data ==>
read*(a) indata
write*(a) Enter the coning angle ==>
read*(a) alpha
write*(a) Enter the rotation rate in rpm ==>
read*(a) rpm
write*(a) Enter Xo ==>
read*(a) x0
write*(a) Enter scale factor ==>
read*(a) sfac

This establishes the requires PostScript header material

write(5, '(a)') '%%BeginProlog'
write(5, '(a)') '%%BoundingBox: 0 0 612 792'
write(5, '(a)') '%%Title: .outps'
write(5, '(a)') '%%Pages: 1'
write(5, '(a)') '%%DocumentFonts: Helvetica'
write(5, '(a)') '%%EndComments'
write(5, '(a)') '/m (moveto) def'
write(5, '(a)') '/l (lineto) def'
write(5, '(a)') '/s (stroke) def'
write(5, '(a)') '/f (fill) def'
write(5, '(a)') '/n (newpath) def'
write(5, '(a)') '/arrow (newpath) def'
write(5, '(a)') '0 0 moveto'
write(5, '(a)') 10 lineto'
write(5, '(a)') 1.0 moveto'
write(5, '(a)') 0.75 0.10 lineto'
write(5, '(a)') 1.0 moveto'
write(5, '(a)') 0.75 0.10 lineto}
edf
write(5, '(a)') '0.072 setlinewidth'
write(5, '(a)') '2 setlinejoin'
write(5, '(a)') '/Helvetica findfont'
write(5, '(a)') 9 scalefont setfont'
write(5, '(a)') '%%EndProlog'
write(5, '(a)') '/%Page: 1 1'
write(5, '(a)') 306 396 translate'
write(5, '(a)') 1.1339 -1.1339 scale'
write(5, '(a)') 'gsave
shift=(1.*a*sin(alpha*pi/180.))
write(5, '(a)') sfac,sfac,sfac,sfac, 'scale'
write(5, '(a)') '0 ,shift, translate'
write(5, '(a)') 'gsave

This reads thru the velocity data files and produces the individual vectors

read(3, '(a)') header
read(3, '(a)') header

125
hdata=ndata/2
q34data=3*ndata/2

do 100 j=1,ndata
  read(3,5000) x,y,z,u,v,w
  veclen=sqrt(v**2+w**2)
  if ((v.eq.0.)and.(w.eq.0.)) then
    vecang=0.
    veclen=0.
  elseif ((v.eq.0.)and.(w.gt.0.)) then
    vecang=90.
  elseif ((v.gt.0.)and.(w.eq.0.)) then
    vecang=0.
  elseif ((v.lt.0.)and.(w.eq.0.)) then
    vecang=180.
  elseif ((v.gt.0.)and.(w.ne.0.)) then
    vecang=(atan(w/v))*180./pi
  elseif ((v.lt.0.)and.(w.ne.0.)) then
    vecang=180.+((atan(w/v))*180./pi
  endif
  if (veclen.ne.0) then
    width=0.1/veclen
  else
    width=0.1
  endif
  if ((j.lt.hdata).or.((j.lt.q34data).and.(mod(j,3).eq.0))
    .or.(mod(j,6).eq.0)) then
    write(5,'(a)')'n'
    write(5,'(F9.3.a 13)') width,' setlinewidth'
    write(5,'(2F9.3,a10)') y,z,' translate'
    write(5,'(F9.3,a13)') veclen,' rotate'
    write(5,'(2F9.3,a6)') veclen, veclen,' scale'
    write(5,'(a)')'arrow s'
    write(5,'(a)')'gsave'
  endif
  continue
  c
  This draws the hull cross-section
  write(5,'(a)')'n'
  write(5,'(a)')'0 0 34.2265 0 360 arc s'
  c
  This establishes the coordinate axes
  write(5,'(a)')'grestore'
  write(5,'(a)')'grestore'
  write(5,'(a)')'n'
  write(5,'(a)')'0.72 setlinewidth'
  write(5,'/H-eulvetica findfont 9 scalefont setfont'
  write(5,'(a)')'n'
  write(5,'(2F9.3,a10)') -203.2,-203.2 m'
  write(5,'(2F9.3,a10)') 203.2 203.2 l'
  write(5,'(2F9.3,a10)') 203.2 203.2 l'
  write(5,'(a)')'n'
  write(5,'(a)')'0.72 setlinewidth'
  write(5,'(a)')'n'
  write(5,'(a)')'1 -1 scale'
  do 250 k=1,2
    fixed=-k*.2
  do 200 m=1,21
    if (k.eq.1) then
      chars=-2 35.
      space=(m-1)*20
      num=-1*space/a fac-shift
      write(5,'(a)')'n'
      write(5,5002) num,'m'
      write(5,5003) tic,space,' 1 s'
    else
      write(5,'(a)')'n'
      write(5,'(a)')'char',space,' m',(m,.num,.' show'
      elseif (k.eq.2) then
        chars=-2 35.
        space=(m-11)*20
      endif
      write(5,5002) space, fixed, ' m'
      write(5,5003) space, tic, ' 1 s'
    endif
    if (k.eq.2) then
      chars=-2 35.
      space=(m-11)*20
      num=-1*space/a fac-shift
      write(5,'(a)')'n'
      write(5,5002) fixed,space,' m'
      write(5,5003) space, tic, ' 1 s'
    endif
  do 200 m=1,21
  do 250 k=1,2
  continue
  c
  This draws the tic marks and labels them
  write(5,'(a)')'n'
  write(5,5002) fixed,space,' m'
  write(5,5003) space, tic, ' 1 s'
write(5,'(a)') 'n'
space=space-10.
write(5,5004) space,chars,' m ('.'space,'') show'
endif
200 continue
250 continue
c This labels the axes
write(5,'(a)') 'n'
write(5,'(a)')/Helvetica findfont 12 scalefont setfont'
write(5,'(a)') '-20 -240 m'
write(5,'(a)')(Y \,\,\,\, mm) show'
write(5,'(a)') 'n'
write(5,'(a)')/Helvetica findfont 16 scalefont setfont'
write(5,'(a)') '-70 260 m'
write(5,'(a)')(Cross Flow Velocities) show'
write(5,'(a)') 'n'
write(5,'(a)')/Helvetica findfont 10 scalefont setfont'
write(5,'(a)') '-115 245, m'
write(5,5005)(Coning Angle = ',alpha,' degrees, ',rpm,
' rpm, at Xo = ',xo,) show'
write(5,'(a)') 'n'
write(5,'(a)')/Helvetica findfont 12 scalefont setfont'
write(5,'(a)') '-240 0 m'
write(5,'(a)')(Z \,\,\,\, mm) show'
write(5,'(a)') restore'
write(5,'(a)') showpage'
write(5,'(a)') "%%Trailer'
write(5,'(a)') "%%EOF'
1000 continue
5000 format(6F12.3)
5002 format(2F7.0,A2)
5003 format(2F7.0,A6)
5004 format(2F7.0,A4,14,A8)
5005 format(16.13,A10,14,A14,F6.1,A6)
close(3)
close(5)
end
program DC

--- PROGRAM DC.FOR ---

Version: 1.3

Date: August 1989

Purpose: Main driver program that links with the following programs: Davlab, Common, DCDave and Calibr.For. This program is to obtain readings from the balance, store them (ac and dc), and convert the steady state components to forces and moments. Program for ROTATING measurements, DC forces and moments.

Programmers: Tom Eccles, Dave Johnson and Glenn McKee

Language: Microsoft Fortran 4.1

Variables:

fdata(i): Raw MIT counts array filled with counts from all a/d channels. ('full' data)

pdata(i): Raw MIT counts array with 6 preferred channels of a/d channels. Array values are later corrected for zeros and Convair/MIT counts. This array is then multiplied by a(i,j) for the balance loads. ('preferred' data)

loads(i): Array with balance loads. loads(i) comes from the matrix multiplication of pdata(i) and a(i,j).

zerot(i): Row array with averaged counts for all a/d channels. This array is read by the subroutine 'filter' to convert to the preferred 6 channels and put into zerot(i).

a(i,j): Coefficient matrix \( B \). From \( L = [B|R] \)

Files:

main: Raw MIT counts file with data from all a/d channels

Ratio: file of Convair R-cal/MIT R-cal readings for the 6 preferred channels.

M2XIT.DAT: Balance coefficients for Roll bridge 2 and Axial bridge 1, referenced to C of Rot.

Data Conventions Used in This Code

IndexReadings() Loads()

1Normal Force 1Normal Force at center

2Normal Force 2Pitch Moment at center

3Side Force 3Side Force at center

4Side Force 4Yaw Moment at center

5Selected Roll Bridge Roll Moment at center

6Selected Axial Bridge Axial Force at center

(The zerot() and ratios() vectors use the same conventions as the pdata())

real pdata(6), loads(6), zerot(6), ratios(6), fdata(9)
real zerot(9), dpc, rpmc, dp, rpmk, loads(6)
character*3 tcase, zcase
character*11 zname, iname, iname, iname, iname, iname, iname, iname, iname, iname
character*80 id, header, header, header, header
character ans
common /dcase/ rho, zero, full, tt
common /rpm/ rpm, rpm, rpm, rpm, rpm
common /revsect/ revsect

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c ----- open files
  open (unit=10, file = 'ratio', status = 'old')
  write (*,*)
  write (*,*) ' *** PROGRAM DC.FOR *** '
  write (*,*)

cdb --- Debug commands for reading in Convair test case. This is to
cdb check the data reduction algorithm ......
cdb
goto 52
  write (*,*) ' Note: Zeros for this program are stored in the '
  write (*,*) ' file aawww.CTS. The program zero should be '
  write (*,*) ' run first to get the proper DAILY zeros. '
  write (*,*) ' Input the zero (cts) filename (I/HFaa.CTS): '
  read (*,1) zname
  zname
  write (*,*)
  write (*,*) 'Zeroes read in successfully! '
  goto 100
52 continue

c ----- Read in zeros from file zname
  open (unit=2, file = zname . status = 'old')
  read (2, ' (a80)') header
  read (2,' (a50)') id
  read (unit=2, fmt = 2, err = 51) zcase, (zerot(i), i = 1,9)
  write (*,*) 'Zeros read in successfully! '
  goto 100
51 continue

c ----- Debug command
  goto 52
  write (*,*) zerot(1),zerot(9)
  goto 52
51 write (*,*) ' Error in reading zero file '
  goto 100
52 continue

c ----- Read in ratios from file of preferred channels (file "RATIO")
  read (unit=10, fmt = 6, err = 55) (ratios(i), i=1,6)
  write (*,*) ' Ratios read in successfully'

c ----- Debug command
  goto 56
  write (*,*) ratios(1),ratios(6)
  goto 56
55 write (*,*) ' Error in reading in ratios'
  goto 100
56 continue

cdb --- Debug for reading in Convair test case ....
cdb
goto 57

c ----- Call filter subroutine for producing zeros(i)
  call filtz (zerot.zeros())
  write (*,*) 'Coefficient Data has been read'
  call setzero( zeros)
  write (*,*) ' Original signal levels at calibration ...
  call setrcal( ratios)

cdb --- Debug for reading in Convair test case ......
cdb
goto 58

c ----- Offer option of either taking data or processing a previous
  run's data .......
c
  write (*,*) ' Do you wish to take new data or process '
  write (*,*) ' old data ? (N/O): '
  read (*, fmt=9) ans
  if ((ans eq. 'N').or.(ans eq. 'n')) then

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c ----- Calibrate or read from an old calibration file?
write (*,*)
write (*, (a:*)) 'Calibrate? (y/n):'
read (*,9) ans
if (ans.eq. 'n').or.(ans .eq. 'N')) then
write (*,*)
write (*, (a:*)) 'Input old cal file (date.CAL): '
read (*,1) calibr
open(unit=5, file=calibr,status='old')
read (5, (a80')) heac
read (5, (a80')) id
read (5,15) rho.zero.full.tt,rvz,rvcal
close (unit=5)
goto 80
endif
c ----- Call calibration routines ....
call dpcal
call rpmcal
c ------ write result of recent calibration to file Calibr.
write (*,*)
write (*, (a:*)) 'Input new calibration file (date.CAL): '
read (*,1) calibr
write (*, (a80')) heac
write (5, (a80')) headc
read (5,15) rho.zero.full.tt,rvz,rvcal
close(unit=5)
80 write (*,*)
c ----- write # of revolutions, nrev:
write (*,*)
write (*, (a:*)) 'Input # of revolutions, nrev:'
c ----- write tcase (3 max):
write (*,*)
write (*, (a:*)) 'Type in tcase(3 max):'
read (*, (a3)) tcase
nsect = 32
nrev = 10
c ------- Go to data taking subroutine
Call takedata (fdata.dpcrpmc,tcase.header)
write (*,*) 'takedata finished'
write (*,*)
c --------- debug command
cdb pause
goto 62
eendif
cdb --- Debug for reading in Convair test case or for inputing
previous run file ....
continue
write (*,*)
write (*, (a:*)) 'Input OLD net counts file (f or Hdaawww.NET): '
read (*,1) marne
write (*,*)
open(unit=9, file = marne, status = 'old')
read(9, (a80')) header
read(9, (a80')) id
read (unit=9,fmt=I 8,err=-61)
tcase.(fdata(i), i=1,9),dpc,rpmc
write (*,*) 'Previous counts ....'
write (*,*) fdata(1), rpmc
c ----- Read in old calibration file........
write (*,*)
write (*, (a:*)) 'Input old calibration file (date.CAL): '
read (*,1) calibr
open(unit=5, file=calibr,status='old')
read (5, (a80')) heac
read (5, (a80')) id
read (5,15) rho.zero.full.tt,rvz,rvcal
close (unit=5)
cdb do 60 j = 1,6
cdb zeros(j) = 0.0
cdb60 continue
goto 62
61 write (*,*) 'Error in reading Previous counts ....'
goto 10x
62 continue
I

---

---

---

... adjust the values by removing the zeros and compensating ....

---

---

..--

---

---

----

---

---

...

... for the ratio of the signal level ...

call doadjust(pdata)

call doload(pdata, loads, ierr)

if (ierr .ne. 0) then
write(6,12) tcase
endif
continue

20 continue

--- Convert dpc and rpmc counts to velocity and rpm...
call rpmvel(dpcrpmcdp,rpma)

--- Write loads to screen
write(*,*), (loads(i), i=1,6), dp, rpma
write(*,') Input Inertial LOADS file (ldaaww.LOD):'
read(M, al) iname
open(unit=6, file=iname, status='old')
read(6,') tcase,(loads(i), i=1,6)
close(unit=6)

c ---- Do Load subtraction .......
do 85 i=1,6
loads(i)=loads(i)-iloads(i)
85 continue endif

c ----- Write loads to file Iname......
write(*,'(A1)'), 'Input load output filename (l or Hdaaww.LOD):'
read(*,1) iname
write(*,')
open(unit=7, file = iname, status = 'new')
c ----- Write header for load file . . . . .
read(*,'(A80)') header
write(7,') header
write(7,') tcase, (loads(i), i=1,6), dp, rpma

c ---- Write loads to screen again.........
write(*,') Final loads for this run...
write(*,')
write(*,')
write(*,')
write(*,')
write(*,')
write(*,')
write(*,')
write(*,')
write(*,')
read(*, fmt =9, err = 90) ans
m=m+1
if ((ans .EQ. 'y') .or. (ans .EQ. 'Y')) goto 70

c ----- Format Statements ..............................
  1 format(A11)
  2 format(A3, 9F7.1)
  3 format(i2)
  6 format(6F8.4)
  7 format(A3, 6F9.4,2F9.2)
  9 format(A11)
 10 format('TC', '4X', 'Z', '8X', 'M', '8X', 'Y', '8X', 'N', '8X', 'K',
    '8X', 'X', '8X', 'VEL', '6X', 'RPM')
 12 format('Convergence problem on point ', 'A10')
 15 format(6F9.5)
 16 format(a3, 6F9.4)
 17 format(3x, 'Rho', '6x', 'Zero', '5x', 'Full', '6x', 'Tr', '6x', 'Rvz',
    '6x', 'Rvcal')
 18 format(a3, 'F7.1')

100 continue
end

$DEBUG

** -------------------------- PROGRAM DCDAVE.FOR --------------------------

** -------------------------- PROGRAM DCDAVE.FOR --------------------------

** Version: 1.3

** Note: Full Revolution Version. Therefore nrev=10 max!

** Date: 29 March 1989

** Purpose: To provide the collection of subroutines necessary
for rotating data taking and DC processing. This
program is for linking with the main driver program
DC.FOR.

** Programmer: Tom Eccles and Dave Johnson

** Language: Microsoft Fortran 4.1

** Subroutines:

** TAKEDATA: Primary rotary data collection subroutine

** FILTER: Reduces readings to the preferred 6
channels for later processing

** FILTZ: Reduces zero readings to 6 preferred
channels for later processing

** RPMVEL: Converts dp and rpm counts to actual
  tunnel velocity and model rpm

SUBROUTINE TAKEDATA(fdata, dpc, rpmc, tcase, header)

** Arrays:  fdata(i,j): Averaged (over nsamp) raw MIT counts
for all 9 a/d channels of balance data.

  iarray(i): Row array filled by EACH mcbatod call

tarray(i): Temporary array with rows of iarray
  and columns of nrev*nsect samples

  higarray(i,j): Summed counts array that is divided
  by nsamp and written to tareas(j)

dpc(i): Raw MIT counts read from dpcell

  rpmc(i): Raw MIT counts read from daytronix chan C

132
c ----- Files: RCxxxx.xxx: Raw data file in MIT counts.

c

c ----- Dimensions set for max of 32 sectors/rev x 10 revs = 96 data pts and max of 11 channels sampled at 3 samples/channel ....
  integer*2 array(33), array(320,33), nval, n, nsamp
  integer*2 nchan, echan, k
  real rdata(320,9), bdata(320,11), frpmc(320), fdpc(320)
  real rpmc, dpc, rpm, dp, num(132,11), fdata(9)
  character*11 name, rsum, tsum
  character*80 header
  character*3 tcase

  common /revsect/ nrev, nsect

  nchan = 11
  echan = 10

c ----- Set clock set for 1kHz
  call mbopen
  call setclock(.001,0)

c ----- Input data counts filename and # of samples to be taken at each data point ....
  write (*,*) ' Format for Raw Counts File is Idawww.RAW '
  write (*,*) ' or Hdaawww.RAW where d is either F or R for '
  write (*,*) ' rotation direction, aa is coning angle, ' 
  write (*,*) ' and www is rotation rate in rpm. '
  write (*,*)
  write (*, '(A)') ' Input Raw Output Filename (I/Hdaawww.RAW):'
  read (*, 5) name
  open (unit= 1, file = name)

  write (*,*)

  c ----- Write (*,*) ' Before entering # of samples per data point, '
  c ----- write (*,*) ' remember that for any high speed data taking, '
  c ----- write (*,*) ' nsamp should not be > 1. '
  c ----- write (*,*)
  c ----- write (*,*) ' Input # of samples for each data point: '
  c ----- read (*, 6) nsamp
  nsamp = 1
  write (*,*)
  pause 'Press any key to start data taking .......

c ----- The following logic is based on inputs to the digital input ports #0 and #1 being 32(0) and 1/rev(K) pulses respectively.
  The elaborate if-then statements ensure that the data taking actually starts at 0 degrees and counts for nrev revolutions.

c ----- Initialize counters ....
  n = 0
  m = 0
  k = 0
  call dina(nval)

  c ----- If the following expression is true, then K is low....
  100 if (nval .le. 1) goto 200
  call dina(nval)
  goto 100

c ----- If the following expression is true, then K is high and thus the model is at 0 degrees. Now start counting 32 times for 1 revolution and then start taking data on 33rd count.......
  200 call dina(nval)
  250 if (nval .ge. 2) goto 290
  call dina(nval)
  goto 250

  c ----- Start counting 32 times off J trigger
  290 call dina(nval)
  300 if ((mod(nval,2)).eq. 1) goto 400
  call dina(nval)
  goto 300

  400 n = n + 1
  if (n .eq. 32) goto 500

  c ----- Look for J low....
  450 if ((mod(nval,2)).eq. 0) goto 290
  call dina(nval)
  goto 450

133
c ----- Look for J low before taking data ....
500 if ((mod(nval,2)) .EQ. 0) goto 600
   call dina(nval)
goto 500

500 c ----- Look for J high to trigger data taking. This ensures start at
600 c 0 degrees ....
650 if ((mod(nval,2)) .EQ. 1) goto 700
   call dina(nval)
goto 650

500 c ----- Now at 0 degrees, begin taking data .......
700 call mcbatod(0,echan, Insamp, iarray)
m = m+1

700 c ----- Throw temporary data into tarray to prevent overwrite of data ....
do 750 i = 1, (nsamp*nchan)
tarray(i) = iarray(i)
750 continue

700 c ----- Exit condition: exit loop after nrev revs of data taking (10 max)
900 if (m .EQ. (nrev*nsect)) goto 755

700 c ----- Look for J low. if J is low, go up to top of loop and look for
751 c J high again. This prevents multiple triggers off the same
761 pulse, especially important for slow rpm runs .......
751 if ((mod(nval,2)) .EQ. 0) goto 650
   call dina(nval)
goto 751

700 c ----- Done taking data, now put into proper arrays and store in file....
755 write(*,*)
755 write(*,*), 'Done taking data ....' 
755 write(*,*)

755 c ----- Fill array bigarray(i,j) with zeroes ....
do 760 i = 1, (nrev*nsect)
do 760 j = 1, (nchan)
bigarray(i,j) = 0.0 
760 continue

755 c ----- Place sum of nsamp number of data points in each storage bin ....
do 780 i = 1, (nrev*nsect)
do 780 j = 1, (nchan)
bigarray(i,j) = bigarray(i,j) + tarray(i, (j+(nchan*k))
780 continue

755 c ----- Next, divide the samples by nsamp and put in arrays rfdata(i,j),
dfpc(i) and frpmc(i)
do 790 i = 1, (nrev*nsect)
do 790 j = 1, nsamp
rfdata(i,j) = bigarray(i,j)/nsamp
790 continue

755 c ----- Finally, put data values into the data file name ....
write(*,*)
write(*,*), 'Type in file Header .......
read(*,') (a80)') header
write(1,') (a80)') header
write(1,14)
write(*,*), 'Processing Raw Data .......
write(1,15) (rfdata(i,j), j = 1,9), dfpc(i), frpmc(i)
795 continue

755 c ---------------- DATA HANDLING -----------------------

755 c ----- Sum up nrev points into 1 rev of data and put into file ...
c 755 Fill sum, rfdata, dfpc, and rpmc with zeros ....
do 82 i = 1, 11
do 82 j = 1, nsamp
   sum(i,j) = 0.0
82 continue

134
do 81 i = 1,9
   fdata(i)=0.0
81 continue
   dpc = 0.0
   rpmc = 0.0

*----- First do balance counts ....
   k = 0
83 do 85 j = 1,9
5    sum(1,j) = sum(1,j) + fdata(j+1)*nsect*k
57    k = k + 1
587     if (k .eq. nev) goto 86
85 continue
86 continue

*----- Now do dp and rpm measurements ..... 
   k = 0
89 continue
   do 90 j = 1,nsect
5    sum(1,j) = sum(1,j) + fdata(j+1)*nsect*k
90 continue
   k = k + 1
   if (k .eq. nev) goto 91
95 continue

*----- Divide by nev for averaged values over 1 revolution ...
91 do 105 i = 1,11
5 sums(i) = sums(i) + sum(1,j)
95 continue

*----- Now sum up over remaining revolution for averaged counts ..... 
   do 95 j = 1,11
95 sums(i) = 0.0
   do 95 j = 1,nsect
5   sums(i) = sums(i) + sum(1,j)
95 continue

*----- Again, do dp and rpm ..... 
   dpc = dpc + sum(1,j)
105 continue

*----- Divide by nsect ..... 
   rpmc = rpmc + sum(1,j)
120 continue

*----- Write sum 1 and fdata, dpc, rpmc, to files ...
   write (*,*) write (*,*) write (*,*)
135 write (*,*) write (*,*) write (*,*)
   read(*,1) num
   write (*,*) write (*,*) write (*,*)
   write (*,*) write (*,*) write (*,*)
   open unit = 15, file = num, status = 'new'
   open unit = 16, file = num, status = 'new'
   write (15,') (a80) header
   write (16,') header
   write (15,')
   write (16,')
   write (16,')
   open unit = 15, file = num, status = 'new'
   open unit = 16, file = num, status = 'new'
   write (15,') write (16,')
   write (15,')
   write (16,')
135 continue

*----- FORMAT statements ...............
1 format(a11)
5 format(a11)
6 format(a2)
7 format(a11,2f7.1)
10 format('T','P','R','R','R','R','R','R','R','R','R','R','R',
5 'R','R','R','R','R','R','R','R','R','R',
14 format(a6.1),a2,2f7.1)
15 format(1f7.1)
135
```fortran
1000 continue
   close (unit = 1)
   return
end

c ***************************************************************
subroutine filtz(zerot, zeros)
c --------------- SUBROUTINE FILTZ -------------------------------
   real zerot(9), zeros(6)
   do 30 i = 1, 4
       zeros(i) = zerot(i)
30    continue
       zeros(5) = zeros(6)
       zeros(6) = zeros(7)
   return
end

c ***************************************************************
subroutine filter(fdata, pdata)
c -------------- SUBROUTINE FILTER -------------------------------
c c Date- 16 Feb 1989
C c Purpose- Filter subroutine to take all channels of data and read
C c in the 6 preferred channels for processing by Mainist.
C c c Variables:
C c fdata(i) = array with all channels of data (11)
C c pdata(i) = array with 6 preferred channels of
C c balance data.
C c c---------------------------------------------------------------
   real pdata(6), fdata(9)
   c ----- debug command
cdb   write (*,*) 'Have reached subroutine filter'
   cdb   pause
   c ----- Do test reading conversion
   do 10 i = 1, 4
       pdata(i) = fdata(i)
10    continue
   c ----- debug command
cdb   write (*,*) 'First 4 points read in successfully'
       pdata(5) = fdata(6)
       pdata(6) = fdata(7)
   return
end

c ***************************************************************
subroutine rpmvel(dpc, rpmc, dp, rpma)
c --------------- SUBROUTINE RPMVEL -------------------------------
c c Purpose- To convert dpcell and rpm readings to actual
C c velocities and rpm's.
C c c---------------------------------------------------------------
   real dpc, rpmc, dp, rpma
   common dpcell/rho, zero, full, tt
   common rpm/rv, z, zval
   c ----- Convert dp counts to voltages and convert to ft/sec
   c using 409.6 counts/volt and Lisa's function dp speed ....
       dpc = dpc(409.6)
       dp = dp(409.6)
   c ----- Convert rpm counts to rpm's
       rpmc = rpmc(409.6)
       rpma = rpma(409.6)
   return
end
```
program davlafb.for

subroutine doload(pdata, loads, ierr)

real pdata(6), loads(6)
integer ierr

*** The subroutine takes the readings corrected for zeros and ***
and scaling, and then converts them to equivalent loads
using a linear 6th order fit determined by the Davidson
Laboratory MCB program.

common /convair/ a(6,6)

... there is no possible error in this case ...
ierr = 0

... do the matrix multiplication ...
do 20 i = 1, 6
    loads(i) = 0.0
    do 10 j = 1, 6
        loads(i) = loads(i) + a(i,j) * pdata(j)
 10 continue
 20 continue

... done, so return ...
return
end

subroutine intcoef(runit, item)

integer runit, item

*** Subroutine to obtain the necessary information from a file ***
and to store it for later use of the conversion routines.

ITEM: An available FORTRAN unit number for reading the
data file

ITEM # Selection
Roll Bridge  Axial Bridge
1  1  1
2  1  2
3  1  3
4  2  1
5  2  2
6  2  3

character*80 id
character*9 name(6)
common /convair/ a(6,6)
data name/ 'M1X1T.DAT', 'M1X2T.DAT', 'M1X3T.DAT',
'M2X1T.DAT', 'M2X2T.DAT', 'M2X3T.DAT'/

*** attempt to open the data file ***
open unit=runit, file = name(item), status = 'old', err= 70 )

*** insure that zero is the default value ***
do 10 i = 1, 6
    do 10 j = 1, 6
        a(i,j) = 0.0
 10 continue

*** read the contents of the file ***
read(runit,15) id
15 format(a80)
do 20 i = 1, 6
    read(runit,* ,end=25,err=25) ( a(i,j), j = 1, 6 )
 20 continue
goto 30
25 print *, 'ERROR - Trouble reading Coefficient Data'
return
30 continue
write(6,40) id
137
c --- debug commands
c 40 format(1x,a80)
c do 60 i= 1, 6
   write(5,50) i, (a(i,j), j=1,6)
c 50 format(1x,i4,6fi2.6)
c 60 continue

$DEBUG

c -------------------Program CALIBR.FOR-------------------
c ---- This program contains the calibration subroutines for calibrating
c the dpcell and rpm channel.

SUBROUTINE DPCAL

Calibrates the differential pressure cell.
Stores the calibrations "zero", and "full"
in the common block called "dpcell".

After calling DPCAL once in your program,
a special function exists in the MHL library
that you can use to convert voltages from
the Daytronics channel C to velocity. It
is called "dpspeed", and has one calling
parameter, "voltage".

Example:

c call dpcal

c <do an A/D conversion on channel 2 (Daytronics C)>
freestream=dpspeed(voltage)

c etc

You do not have to include the common block in your
main program to make these routines work

Lisa Shields
June 12, 1987

common /dpcell/ rho-zero.full, tt
integer*2 channeligival
character ans, line*70

write(*,*)'Welcome to Dpcal'
write(*,*)
write(*,'(A)')'Please input water temp (deg f) :
read(*,*,err=10) tt
rhow=1.9574-0.0023*tt
100 format(5x,a70)
write(*,*)
write(*,*)
write(*,'(A)')'The dpcell should be connected to the Daytronic channel c' 
write(*,100) line
write(*,*)
write(*,'(A)')'The span and balance should be set such that the digital'
write(*,100) line
write(*,'(A)')'play reads from -820 (zero flow) to +600 (with '
write(*,20) line
write(*,'(A)')'the "cal" button depressed.)'
format(5x,'Welcome to the RPM (Channel B)'.
^ ' calibration routine:'
write(*,20)
write(*,10)
format(5x,'A: Set Zero to read 000')

Subroutine rpmcal
common rpm, rvz, rvcal
integer*2 channel
character ans*1

This subroutine is used to calibrate the Daytronics Channel B, used to record propeller rpm data
write(*,*)
write(*,*)
write(*,10)
write(*,20)
format(5x,'A: Set Zero to read 000')
write(*,30)
format(15x,'B: Push cal button, adjust span to 1500')
write(*)
write(*,*)
pause 'With propeller stopped, take time to do this now!'
write(*)
write(*,*)
write(*,40)
format(1x,'Hit any key while holding down channel B',
'cal button for 5 seconds: ')
read(*,41) ans
format(a)
channel=10
rvcal=average(0.5,channel)
write(*,*)
write(*,*)
write(*,50)
format(1x,'Please release cal button, and hit any',
'key to take rpm zero: ')
read(*,41) ans
rvz=average(0.05,channel)
write(*,*)
write(*,55) rvz,rvcal
format(2x,'Rvz = f7.4,Rvcal = f7.4')
write(*,*)
write(*,*)
write(*,*)
write(*,40)
format(1x,'Do you wish to recalibrate? (y/n): ')
read(*,41) ans
if (ans ne. 'n') goto 5
return
end

subroutine dloadjus( pdata )
real pdata(6)
... remove the zero first ...
pdata(i) = pdata(i) - zero(i)
pdata(i) = pdata(i)*rcal(i)
continue
return
end

subroutine sezero( zeros )
real zeros(6)
... This subroutine takes zero applied load readings and stores them for later use ...
common /convarl/ zero(6), rcal(6)
do 10 i = 1, 6
zero(i) = zero(i)
10 continue
return
end

subroutine setrcal( ratios )
real ratios(6)
... This subroutine takes the current readings, corrects for the readings for zero applied load, and then scales the result back to the levels at which the calibration was done. The returned values should be the bits that would be read at CONVAIR calibration bench.

--- Program COMMON.FOR ---
**This subroutine takes calibration signal ratios and stores them for later use**

```fortran
common /convarl/ zero(6), rcal(6)
do 10 i = 1, 6
   rcal(i) = ratios(i)
10 continue
return
end
```

`$DEBUG`

---

**Program DAVEAST.FOR**

**Subroutine quickrd(fdats, tcase, m)**

---

**Purpose:** To take static (w=0) measurements for combinations of coning angles and roll angles. This subroutine is for doing runs with the static TEST driver Mainst.for.

**Programmer:** Dave Johnson

**Language:** Microsoft Fortran 4.1

**Variables:**
- `iarray`: row array in DMA filled by each MCBATOD call.
- `fdata(i)`: array with averaged counts from all 11 channels.
- `tcase`: Reading.tst! Raw counts file of "averaged" counts from each of the 9 channels.

**Files:**
- `integer*2 iarray(2000), bchan, echan, nsamp, nchan, m`
- `real fdata(16)`
- `character*10 tcase`
- `character*11 maine`

---

**Set clock set for 1kHz**

```fortran
call mcbopen
 call setclock(.001,1)
write (*,*)
write (*, '(A)') 'Type test case : '
read (*, '(A10)') tcase
```

**Following allows the tester to skip this mundane data entry for multiple runs.**

```fortran
if (m .NE. 0) goto 40
```

```fortran
cdb -- write (*,*)
cdb -- write (*, '(A) ') 'Input Starting A/D Channel to Sample: '
cdb -- read (*,5) bchan
   bchan = 0
5 format (12)
cdb -- write (*,*)
cdb -- write (*, '(A) ') 'Input Ending A/D Channel to Sample: '
cdb -- read (*,5) echan
   echan = 8
6 format (14)
cdb -- write (*,*)
cdb -- write (*, '(A) ') 'Input Number of samples (e.g. 100): '
cdb -- read (*,6) nsamp
```

**Type raw counts output file (HFa000.RAW):**

```fortran
read (*,4) maine
```

```fortran
format (A11)
open (unit = 1, file = maine)
```

**Pause **

```fortran
write (*,*)
pause ' Press enter to start data taking '
```

**Take Static Data!!!**

---

141
call MCBATOD (bchan,echan,1,nsamp,iarray)

C ------ calculate number of channels sampled
       nchan= (echan - bchan) + 1
       k=0

C ------ fill fdata(i) with zeros
do 50 i=1,nchan
   fdata(i) = 0.0
50 continue

C ------ read in data to fdata(i)
55 do 60 i=1,nchan
   fdata(i) = fdata(i) + iarray(i+(nchan*k))
60 continue

k=k+1
if (k.EQ.nsamp) goto 71
    goto 55
71 continue

C ------ Next, divide the values in fdata(i) to get averaged values
do 80 i=1,nchan
   fdata(i) = fdata(i)/nsamp
80 continue

C ------ Write fdata(i) to file "reading.tst"
write(1,14)
write(1,15) tcase, (fdata(i), i=1,nchan)
7 format (A10,11F6.0)
14 format (3x,'N1',5x,'N2',5x,'Y1',5x,'Y2',5x,'R1',
     5x,'R2',5x,'X1',5x,'X2',5x,'X3')
15 format (A3,9F7.1)
write (*,*) 'Raw counts from Balance'
write (*,14) tcase, (fdata(i), i=1,nchan)
write (*,*)
return
end

C-----------------------------------------------------------------------------
C-----------------------------------------------------------------------------
C------------------------Subroutine filter-----------------------------------
C----------------------- Date: 16 Feb 1989
C------------ Purpose: Filter subroutine to take all channels of data and read
C---------------------- in the 6 preferred channels for processing by Mainist.
C------------ Variables :
C       fdata(i): array with all channels of data (11)
C       pdata(i): array with 6 preferred channels of
C                 balance data.
C-----------------------------------------------------------------------------

C-------------------subroutine filter(fdata, pdata)
real pdata(6),fdata(16)
C------- debug command
cdb   write (*,*) 'Have reached subroutine filter'
cdb   pause
C------- Do test reading conversion
do 10 i=1,4
   pdata(i) = fdata(i)
10 continue
C------- debug command
cdb   write (*,*) 'First 4 points read in successfully'
pdata(5) = fdata(6)
pdata(6) = fdata(7)

C------- Now do ratio conversion
C       do 20 i=1,4
C       ratio(i) = ratio(i)
20 continue
C       ratio(5) = ratio(6)
C       ratio(6) = ratio(7)
Subroutine Filtz

subroutine filtz(zerot,zeros)
real zerot(16), zeros(6)
do 30 i = 1, 14
   zeros(i) = zerot(i)
30 continue
zeros(5) = zerot(6)
zeros(6) = zerot(7)
return
end

Program MAINAST

program mainast

Program: Dave Johnson and Glenn McKee

Language: Microsoft Fortran 4.1

Variables:

fdata(i): Raw MIT counts array filled with counts from all a/d channels. ("full" data)
pdata(i): Raw MIT counts array with 6 preferred channels of a/d channels. Array values are later corrected for zeros and Convair/MIT counts. This array is then multiplied by a(i,j) for the balance loads. ("preferred" data)
loads(i): Array with balance loads. loads(i) comes from the matrix multiplication of pdata(i) and a(i,j).
zerot(i): Row array with averaged counts for all a/d channels. This array is read by the subroutine "filter" to convert to the preferred 6 channels and put into zero-(i).
ap(i,j): Coefficient matrix [B]. From [L] = [B][R]

Files:
mame: Raw MIT counts file with data from all a/d channels
Ratio: file of Convair R-cal/MIT R-cal readings for the 6 preferred channels.
M2X1.DAT: Balance coefficients for Roll bridge 2 and Axial bridge 1.
Testout: Loads from test runs, uncorrected for zeros.

Data Conventions Used in This Code

IndexReadings(Loads)
1 Normal Force 1 Normal Force at center
2 Normal Force 2 Pitch Moment at center
3 Side Force 1 Side Force at center
4 Side Force 2 Yaw Moment at center
5 Selected Roll Bridge Roll Moment at center
6 Selected Axial Bridge Axial Force at center
(The zeros) and ratios vectors use the same conventions as
c the pdata() 

integer*2 m 
real pdata(6), loads(6), zeros(6), fdata(16) 
real zero(16), angle 
character*10 tcase, zcase 
character*11 fname, tname, name 
character**80 header, id 
character aus 
m=0 
c ----- open files 
open (unit=10, file = 'ratio', status = 'old') 
write (*,*) *** PROGRAM MAINTST.FOR *** 
write (*) 
cdb --- Debug commands for reading in Convair test case. This is to 
check the data reduction algorithm ...... 
cdb goto 52 
write (*,*) ' Note: The program needs the name of the zeros' 
write (*,*) ' file for this coming angle. This should' 
write (*,*) ' be something like HFaa.ZER (not .CTS)' 
write (*) 
write (*, '(A)') ' Input the zero file name (HFaa.ZER): ' 
read (*,*) fname 
1 format(A11) 
write (*) 
c ----- Read in zeros from file fname 
open (unit = 2, file = fname, status = 'old') 
read (2,'(a80)') header 
read (2,'(a80)') id 
read (unit =2, fmt = 2, err = 51) angle, (zerot(i), i = 1,9) 
2 format (F6.2, F9F1.1) 
write (*) 
write (**) 'Zeroes read in successfully!' 
write (**) 
c ----- Debug command 
write (**),zerot(1),zerot(9) 
goto 52 
51 write (**), 'Error in reading zero file' 
goto 100 
52 continue 
c ----- Read in ratios from file of preferred channels (file "RATIO") 
read (unit = 10, fmt = 6, err = 55) (ratios(i), i=1,6) 
6 format (6F8.4) 
write (**) 
write (**), 'Ratios read in successfully' 
c ----- Debug command 
write (**), ratios(1),ratios(6) 
goto 56 
55 write (**), 'Error in reading in ratios' 
goto 100 
56 continue 
cdb --- Debug for reading in Convair test case .... 
cdb goto 57 
c ----- Call filter subroutine for producing zeros(i) 
call filtz (zerot.zeros) 
57 continue 
c **************** Data Reduction Portion *********************** 

c ... assign a vacant FORTRAN unit number ... 
lunit = ? 
c ... use the CONVAIR preferred set of coefficients (R2X1) ... 
item = 4 
call intcoef lunit, item ) 
write (**), 'Coefficient Data has been read ' 
c ... these are the A/D readings without applied external forces 
call setzero zeros )
... these are the ratios of the current signals divided by the original signal levels at calibration ...
call setrcal(ratios)
write(*,*) 'Input the load output file name (HFa00.LOD):'
read(*,1) lname
write(*,*)
oname=7, file = lname, status = 'new')
write(7,10)
format (1X,'TC',3X,'Z',8X,'M',8X,'Y',8X,'N',8X,'K*,8X,'X')
cdb --- Debug for reading in Convair test case ......
cdb --- goto 58
c ----- Go to data taking subroutine
80 Call quickrd(fdata,tcase,m)
write(*,*) 'quickrd done'
c ----- debug command
cdb pause
goto 62
cdb --- Debug for reading in Convair test case ......
58 continue
write(*,*) 'Input PREVIOUS raw counts file: '
read(*,1) lname
write(*,*)
oname=9, file = lname, status = 'old')
read(unit = 9, fmt = 59, err = 61) tcase, (fdata(i), i=1,9)
59 format (a10,9F7.1)
write(*,*) 'Previous counts ....'
write(*,*) 
write(*,*) 
do 60 j=1,6
zeros(j)=0.0
60 continue
goto 62
61 write(*,*) ' Error in reading Previous counts ....'
62 continue
c ----- Call filter subroutine to reduce the readings to the preferred
6 channels (i.e. read in data to pdata(i))
call filter(fdata, pdata)
write(*,*) ' filter done'
c ----- debug command
cdb pause
write(*,*) 'Now Processing Data!!! '
write(*,*)
c ... adjust the values by removing the zeros and compensating ....
c ... for the ratio of the signal level ...
call doadjus(pdata)
call doload(pdata, loads, ierr)
if(ierr ne 0) then
write(6,12) tcase
12 format('Convergence problem on point ',a10)
endif
write(7,7) tcase, (loads(i), i=1,6)
20 continue
c ----- Write loads to screen
write(*,*)
write(*,*) ' Loads for this run...'
write(*,*)
write(*,7) tcase, (loads(i), i=1,6)
7 format (A3,6F9.4)
write(*,*)
write(*,*) 'Would you like another test run? (y/n):'
read(*,fmt =9, err = 90) ans
9 format (A1)
mm=1
if(ans .EQ. 'y') goto 80

145
close(unit = 10)
close(unit = 7)
close(unit = 1)

100  continue
end