Ice loading on podded propeller systems: calibration and notes

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LM-2004-05

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B. Quinton

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SUMMARY

Recent increase in arctic shipping has lead to the increased use of podded propulsors in ice conditions. There is a lack of understanding of how ice loads affect podded propulsors and therefore regulations governing arctic vessels lack the methods to determine design loads caused by ice interaction.

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April 2004

Dr. Ayhan Akinturk
IOT-NRC

Dear Dr. Akinturk,

It was a pleasure to work on this project for you over the past few months. My first workterm at IOT was certainly a valuable learning experience as it afforded ample opportunity to apply what I learned in school, learn new skills, and practice problem solving techniques!

Enclosed is the IOT report you requested. I have made every attempt to include as much information as possible. All my lab notes and hand workings can be found in my binder entitled "Bruce Quinton's Binder – Podded Propellers in Ice – Jan. – May 2004".

If you have any questions concerning this report or any of my work at IOT I would be please to answer them.

I can be reached at (709) 722-0511 at home, or through my school email account bruceq@engr.mun.ca. If you are unable to reach me via any of these methods, you can always find a contact number from my web page: www.engr.mun.ca/~bruceq.

Thank you for the opportunity to work for IOT and for your tutelage.

Sincerely,

Bruce Quinton
Workterm II
Bach. Of Engineering Student
Memorial University of Newfoundland

Summary

This report begins with background information for the lay reader about podded propulsors and this project “Podded Propellers in Ice”. The I talk about calibration of the global, bearing, and blade dynos.

The global dyno was calibrated using two methods, the general method and the linear least squares method. For the general method I performed both a linear and a quadratic calibration, both returning results with high errors. The linear method returned much better results but still not reliable with a high degree of confidence.

I also describe how the calibration loading cases were applied.

For the bearing and blade dynos I describe the “injected cal” calibration and conclude that everything went well for them.

I also talk about the determination of the center of the global dyno and conclude that it is within insignificant error of its assumed position.

In my conclusions I state that I belive we did not get a good calibration for the global dyno due to high deflections in the model and hydraulic rams upon two or more high applied loads in a localized area.

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1 INTRODUCTION

Recent increase in arctic shipping has lead to the increased use of podded propulsors in ice conditions. There is a lack of understanding of how ice loads affect podded propulsors and therefore regulations governing arctic vessels lack the methods to determine design loads caused by ice interaction.

1.1 Objective

The object of the experiment "Azimuthing Podded Propellers in Ice – PJ01959" is to develop a method to predict loads experienced by podded propulsors in ice conditions (this includes loads on the strut, pod stern bearing, propeller shaft, and propeller). This method would then be used to design new arctic shipping codes to govern the design and build of propulsion systems for use in Arctic Climates.

1.2 Azimuthing Podded Propulsors

Azimuthing podded propulsors provide the ability to direct thrust in any direction (360° azimuth), greatly improving the maneuverability of a vessel.

Podded propulsors consist of a pod that contains some sort of engine, propeller shaft, and propeller, and a strut that attaches the pod to the vessel. The engine may be of any sort, but usually is electric, powered by a diesel generator housed in the hull of the vessel. The pod and strut rotate 360° about the z-axis (vertical axis) and hence, are sometimes called "Z Drives".

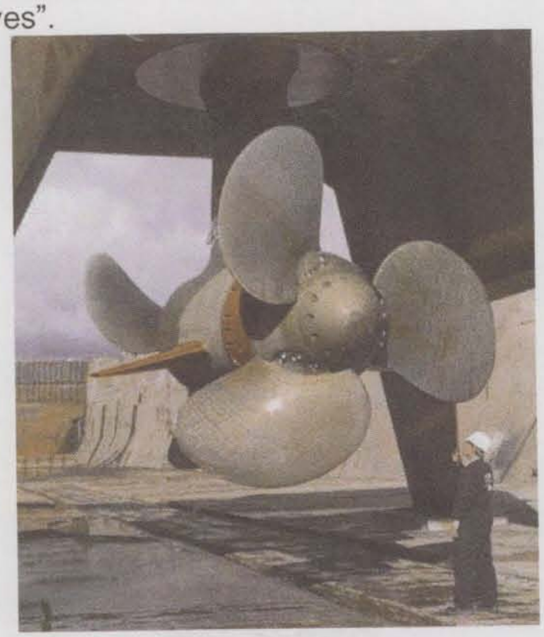


Figure 1. Siemens-Schottel SSP 10 Propulsor.

http://www.marinelog.com/DOCS/PRINT/mmipods3.html

1.3 Ice Tank

The ice tank at IOT is the largest in the world measuring 90m in length by 12m in width by 3m deep. It has a 15m preparation area that can be separated from the rest of the tank during the freezing process, and it has a melt pit. Models ranging from 2m-12m in length or from 0.5m-4m in diameter can be moored, self-propelled, or towed via the ice tank carriage. Underwater and regular video is also available.

The ice tank is capable of maintaining temperatures from -30°C to +15°C, and can grow ice at 3.0 mm/hr at -25°C to a thickness of 150mm. The ice used is EGADS CD model ice, which stands for Ethylene Glycol Aliphatic Detergent Sugar Corrected Density. This ice has a fine grain columnar structure and has a flexural strength of 10 – 120 kPa.

The ice tank carriage is manned and temperature/humidity controlled and is driven with a four wheeled synchronous motor drive capable of 0.0002 – 4.0 m/s. The carriage houses the data acquisition equipment that is capable of using one or more IOtech DagBoards, each with 256 channel capability at 100 kHz aggregate with 16-bit resolution. The test frame attached to the carriage is adjustable on the sway and heave axis.

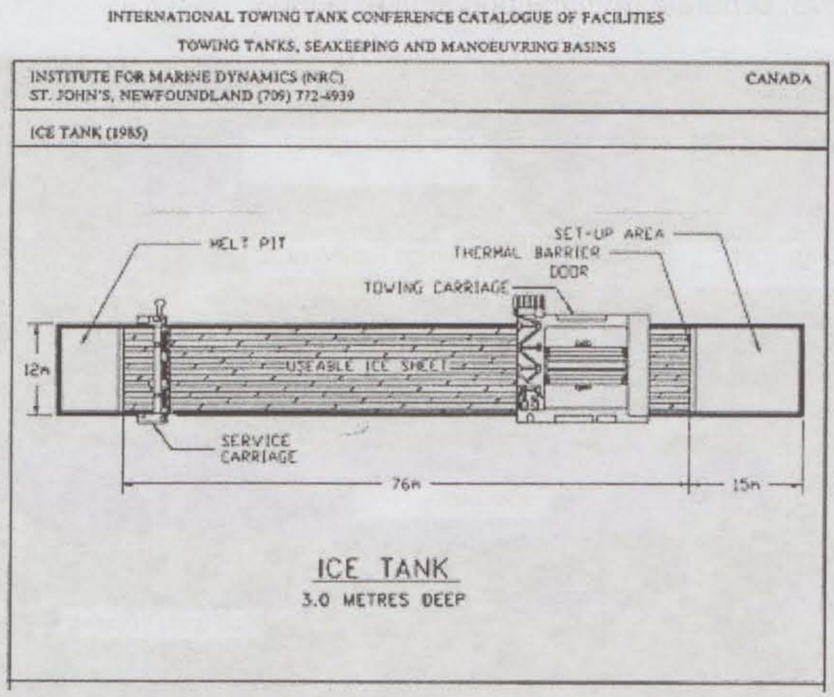


Figure 2. Ice Tank Schematic.

http://iot-ito.nrc-cnrc.gc.ca/photos/icetank_diagram1.jpg

1.4 The Test Apparatus

The experimental model consists of a propeller and propeller shaft encased in a pod, a strut attached to the pod, and a "false stern" which is made to represent the bottom stern of a vessel. The false stern is not physically attached to the rest of the apparatus; there is no direct interaction between the false stern and the pod/strut (i.e. forces exclusive to the false stern will not be felt in the pod/strut). It is present to simulate the real world situation of the vessel hull coupled with the pod/strut. Any interaction as a result of the false stern is due to the action of ice/water as it interacts with the false stern/pod/strut as a system.

The propeller is 0.30m in diameter and has four detachable blades. It is similar to an "R-Class" vessel's propeller. The pod is 0.95m long and has a 0.17m diameter. The strut has an elliptical cross section that is 0.45m wide on the long axis (which is the surge (x) axis).

The pod/strut assembly is rigidly attached to the ice tank carriage rails via a mount that houses the "global dyno", which measures the global forces that act on the entire pod/strut system. The false stern is also attached to the ice tank carriage rails, but as mentioned above, separate from the pod/strut assembly.

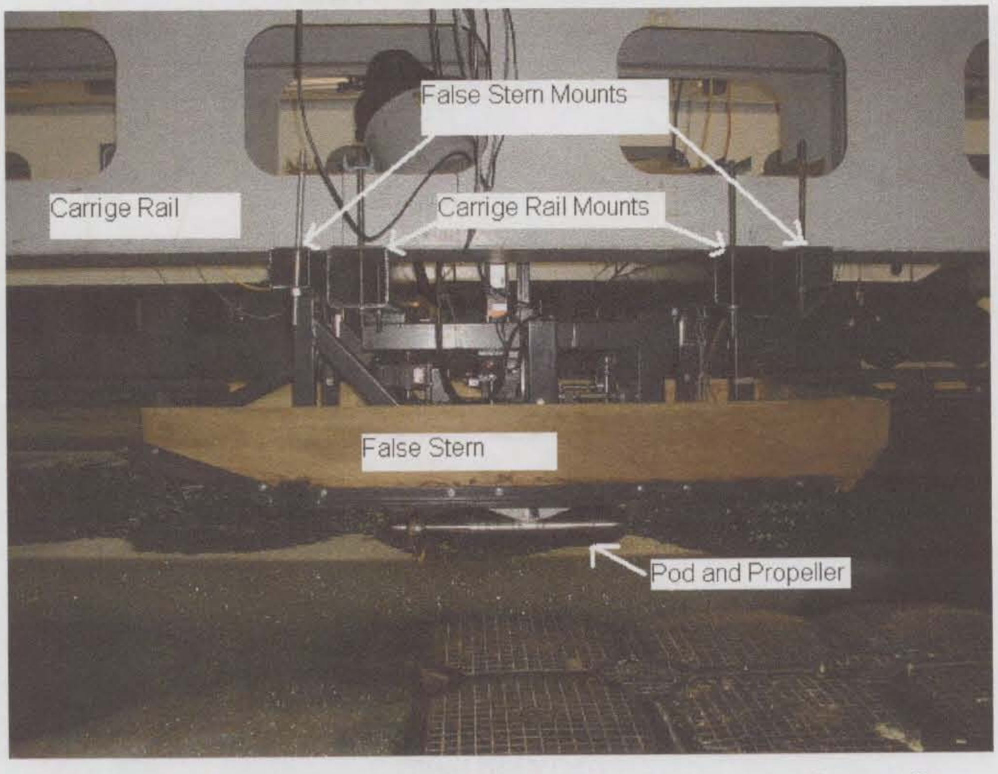


Figure 3. Test apparatus mounted on the ice tank carriage rails.

Blade forces are measured using a specially designed six-component "Blade Dynamometer". Shaft forces are measured using two six-component dynamometers (Forward Dynamometer and Aft Dynamometer) and a torque meter.

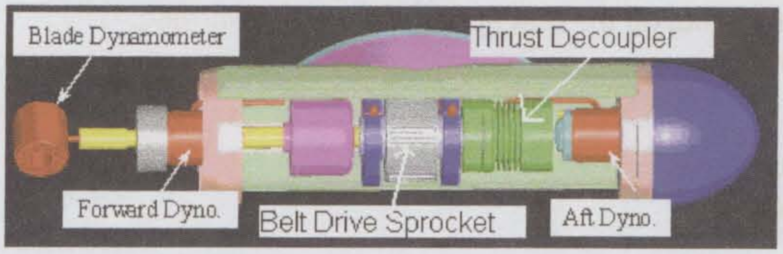


Figure 4. Drawing of the pod showing the location of the Aft, Forward, and Blade Dynamometers.

2 CALIBRATION

Calibration of the instruments used to record data during the test runs is of the utmost importance to ensure that accurate data is being collected. To reduce error as much as possible, all instruments on the test apparatus were calibrated.

These include:

The Global Dyno
The Forward Dyno
The Aft Dyno
The Blade Dyno

2.1 The Global Dyno

The global dyno is a six-component (load cell) system. In the Cartesian coordinate system, it has two load cells in *x* (GFx1 and GFx2), one load cell in *y* (GFy), and three load cells in *z* (GFz1, GFz2, and GFz3). The three *z*-load cells measure total force in *z* (when their sum is taken), roll, and pitch. The two *x*-load cells measure total force in *x* (when their sum is taken) and yaw. The *y*-load cell measures total force in *y*. Each load cell is capable of measuring a uniaxial force up to ±8907 kN. All load cells are attached to the "dyno plate", which connects the load cells to the rest of the podded propulsor.

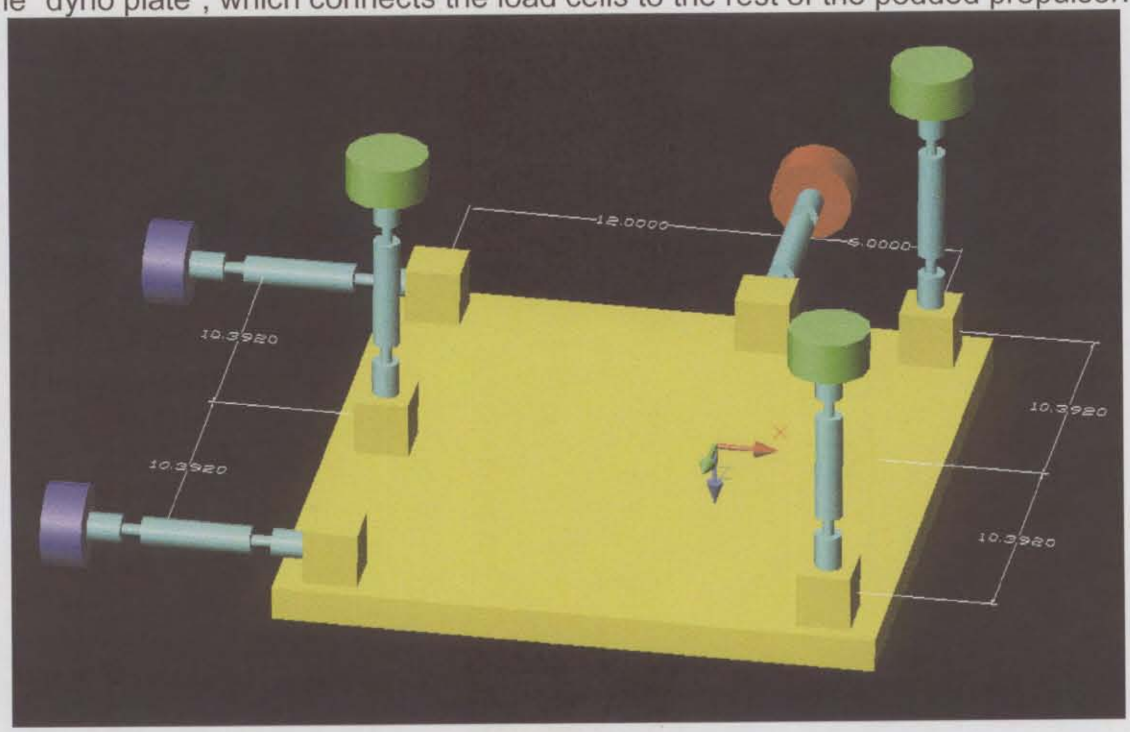


Figure 5. Positions of the global dyno load cells ("GX1, GX2,...") with respect to the dyno "plate" (yellow).

The load cells are used to analyze the reaction (forces and moments) of the system (podded propulsor) to a load (**P**) applied to any body attached to the "dyno plate".

Application of a load to a load cell causes that load cell to produce a voltage. This voltage varies linearly with applied load; therefore any voltage produced by the load cell can be converted into a force if the calibration equation is known.

2.1.1 Individual load cell calibration

The calibration equation:

$F = CR + C_0$; where F is the force acting on the load cell, C is the linear calibration slope, R is the voltage output of the load cell, and C_0 is the intercept. (1)

can be easily determined for an individual load cell. To find the calibration equation, known loads are applied to the load cell and the output voltages are recorded. Forces (y-axis) and voltages (x-axis) are then plotted and a linear least squares fit is found for the data points. The slope of this line is C and the intercept (i.e. R=0 V) is C_0.

An important note is that it is not sufficient to calibrate a load cell in tension alone, if that load cell is going to be used to measure tension and compression, or just compression loads (and vice versa). This is due to a non-linearity around zero volts that is inherent in most load cells.

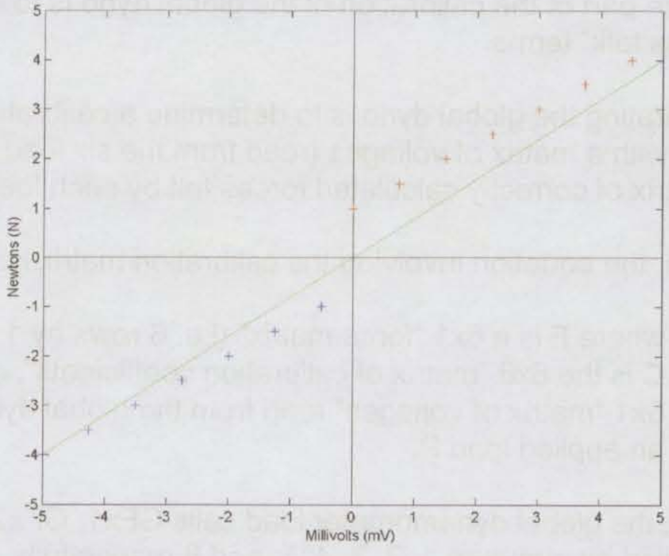


Figure 6. Exaggerated example of non-linear load cell output around zero volts.

(Blue = compression, Red = tension, and Green = linear least squares fit (slope line of which is C)).

If just tension is used for calibration purposes, then forces computed from the compression voltages will have large error (and vice versa).

2.1.2 Calibration of the global dynamometer

As mentioned above, the global dyno is a system of six load cells all physically attached to a rigid "dyno plate". In an ideal situation, the individual calibration equations could be applied to their respective load cells to determine the reaction of the system due to a load **P** applied to the "dyno plate" (or a rigid body rigidly attached to it) – See Appendix C-1 for a spreadsheet of applied loading cases. In practice, this is not the case; linear and quadratic "cross talk" terms are introduced into the calibration equations. Linear "cross talk" terms arise from inaccuracies in fabrication and quadratic "cross talk" terms arise from deflections caused by applied loads (which increase as the applied load increases). "Cross talk" occurs when a load cell experiences a percentage of the load that another (other) load cell(s) is supposed to experience. For example if I apply 10 N in *x* on the dyno plate at $x \neq 0$ meters, the sum of the two *x*-load cells should be 10 N (i.e. GFx1=20 N and GFx2=-10 N), but with the introduction of "cross talk", the sum may be 15 N (i.e. GFx1=25 N and GFx2=-10N) even though I only applied 10 N. This is because GFx1 is experiencing some of the load that GFx2 is supposed to experience exclusively (i.e. "cross talk").

The global dyno was designed with minimization of "cross talk" between components in mind. It is very difficult to eliminate "cross talk" altogether, but it can be reduced to negligible terms. One part of the calibration of the global dyno is to determine the extent of these "cross talk" terms.

The purpose of calibrating the global dyno is to determine a calibration matrix which, when pre-multiplied with a matrix of voltages (read from the six load cells upon applied load), will give a matrix of correctly calculated forces felt by each load cell.

For linear calibration, the equation involving the calibration matrix is:

$F = CV$ where **F** is a 6x1 "force matrix" (i.e. 6 rows by 1 column), **C** is the 6x6 "matrix of calibration coefficients", and **V** is a 6x1 "matrix of voltages" read from the global dyno due to an applied load **P**. (2a)

Note: For simplicity, the global dynamometer load cells GFx1, GFx2, GFy, GFz1, GFz2, and GFz3 will be called by numbers 1, 2, 3, 4, 5, and 6 respectfully. For example, $\mathbf{R_1}$ will be the voltage produced by GFx1 and $\mathbf{F_5}$ will be the force felt by GFz2.

The matrix of voltages is a column matrix that consists the voltage output from each of the six load cells, due to a static applied load (**P**). Matrix row number corresponds with load cell number, for example row 3 corresponds to GFy.

The calibration matrix is a square matrix and consists of six rows and six columns. Again, row number corresponds with load cell number. The coefficient that has row number and column number equal to each other is the slope coefficient for that load

cell, for example $C_{5.5}$ is the slope coefficient for GFz2. The other coefficients in that row account for linear "cross talk" terms.
The force matrix is a column matrix composed of values calculated from the output voltages of the load cells. Like the matrix of voltages, the row number corresponds to load cell number.

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \end{bmatrix} = \begin{bmatrix} C_{1.1} & C_{1.2} & C_{1.3} & C_{1.4} & C_{1.5} & C_{1.6} \\ C_{2.1} & C_{2.2} & C_{2.3} & C_{2.4} & C_{2.5} & C_{2.6} \\ C_{3.1} & C_{3.2} & C_{3.3} & C_{3.4} & C_{3.5} & C_{3.6} \\ C_{4.1} & C_{4.2} & C_{4.3} & C_{4.4} & C_{4.5} & C_{4.6} \\ C_{5.1} & C_{5.2} & C_{5.3} & C_{5.4} & C_{5.5} & C_{5.6} \\ C_{6.1} & C_{6.2} & C_{6.3} & C_{6.4} & C_{6.5} & C_{6.6} \end{bmatrix} \bullet \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \\ R_6 \end{bmatrix} \tag{2b}$$

Figure 7. Example of a calibration equation for a six-component configuration.

The values for $C_{j,k}$, where j=k, represent the Newtons/Volt slope terms for each load cell; the values where $j \neq k$ represent the linear cross talk terms. The values F_j and R_j are force and voltage.

To determine the calibration matrix, the global dyno was placed in a jig that allowed the application of positive and negative loads in the x and y directions (**P_x** and **P_y** respectfully) and positive loads only in the z direction (**P_z**) (a restriction we had to live with). **P_x** and **P_y** loads were applied with hydraulic rams, while **P_z** loads were applied with dead weights. **P_x** loads were applied up to 5000 N, **P_y** loads were applied up to 1000 N and **P_z** loads were applied up to 1961.6 N (200 kg).

To allow the controlled application of load (**P**), the strut and pod were replaced with a "replacement strut" and one of two testing apparatus – an L-shaped or an I-shaped beam. The "replacement strut" and beams were equipped with threaded boltholes at known locations that allowed the rigid attachment of the hydraulic rams or a weight hook (*z* direction).

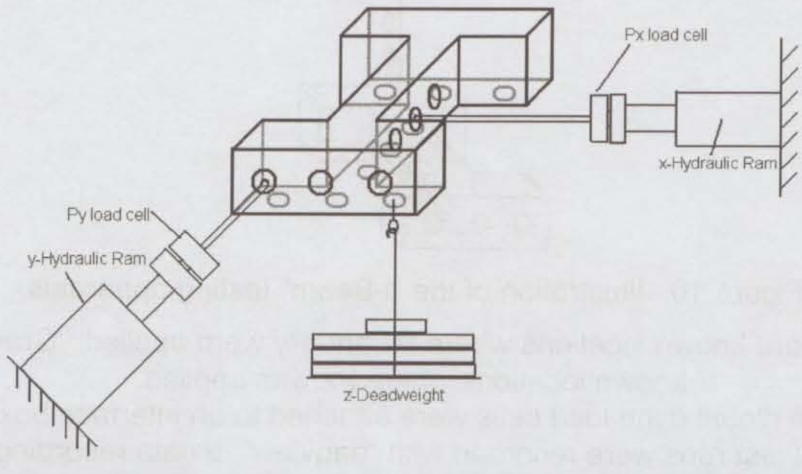


Figure 8. Illustration of calibration jig attached to I-beam test apparatus.

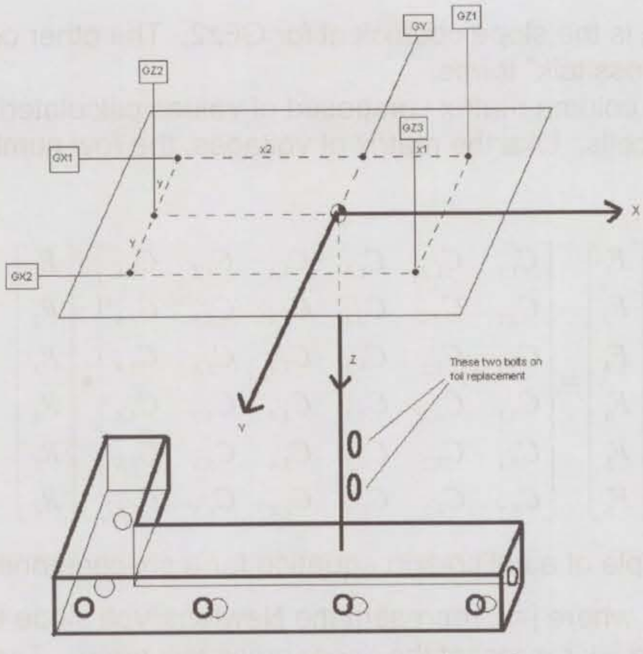


Figure 9. Illustration of the “L-Beam” testing apparatus.

Black circles are known locations where Px and Py were applied. Gray circles are known locations where Pz was applied.

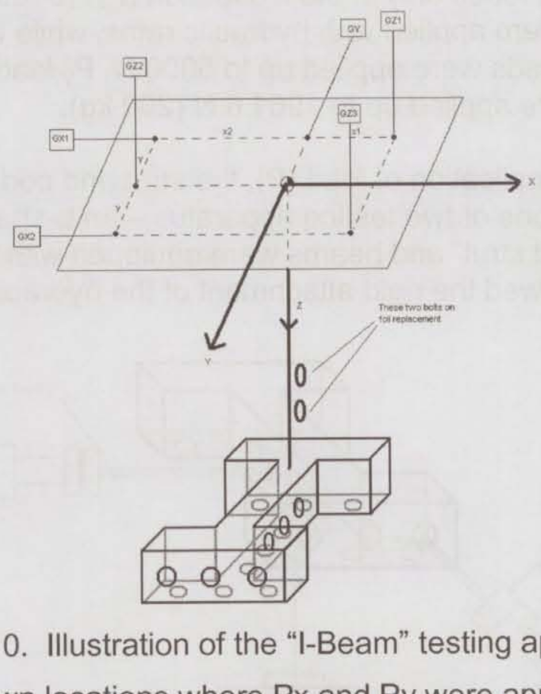


Figure 10. Illustration of the “I-Beam” testing apparatus.

Black circles are known locations where Px and Py were applied. Gray circles are known locations where Pz was applied.

The output of the global dyno load cells were attached to an interface box on a personal computer and all test runs were recorded with “daqview”, a data recording program that runs in a “Windows” environment. Also, there was a load cell on each hydraulic ram that measured their respective applied loads (**P**$_x$ and **P**$_y$). These load cells were also interfaced with the computer and recorded during the trial run.

In order to find the calibration matrix, both the **F** and **V** matrices must be known. The force matrix can be determined from applied load (**P**) through the use of statics. First an origin was taken at the center of the global dyno (See Appendix B-1). This allowed the measurement of the locations of the point of application of the applied loads (**P**$_x$, **P**$_y$, and **P**$_z$), and the locations of each load cell axis (i.e. line of action of the force measured by each load cell). The point of application, magnitude, and direction of each load (**P**$_x$, **P**$_y$, and **P**$_z$), the locations of each load cell axis, and the assumption that the test apparatus is a rigid body allows the determination of the force matrix. A Matlab script written by Dale Duffy and checked (See Appendix F-1) and modified by myself (converted Imperial units to SI) called "ForceFinderMetric.m", was used to determine the force matrix (**F**).

Even though both the **F** and **V** matrices are known for one test case (i.e. applied load (**P**)), this is not sufficient for the determination of the matrix of calibration coefficients because a single load cannot cause enough effects. Various calibration methods require different numbers of varied test cases, but the minimum number required for a linear calibration is six, and the minimum number required for a quadratic calibration is twenty-seven.

Next I will highlight the various methods used in the global dyno calibration.

2.1.2.1 general method

This method consists of applying a specific number of independent loading cases to the global dyno, for a particular type of calibration (linear or quadratic). Each loading case consists of applying a load (**P**) to the global dyno at a constant location in a constant direction with varying magnitudes. Reactions of the six components are recorded at various magnitudes. Six independent loading cases are required for a linear calibration and twenty-seven independent loading cases are required for a quadratic calibration.

Let each load cell be represented by the subscript j and let each loading case be represented by the subscript k.

Set

$$a_{j,k} = \left(\frac{\partial R_{j,k}}{\partial P_k}\right)_{P=0} \quad \text{where } \mathbf{a_{j,k}} \text{ is the slope of a plot of } \mathbf{R_{j,k}} \text{ vs. } \mathbf{P_k} \text{ at } \mathbf{P_k}=0. \qquad (3)$$

and

$$f_{j,k} = \frac{\partial F_{j,k}}{\partial P_k} = \frac{F_{j,k}}{P_k} \quad \text{where } \mathbf{f_{j,k}} \text{ is the slope of the line of } \mathbf{F_{j,k}} \text{ vs. } \mathbf{P_k}. \qquad (4)$$

then

$$\begin{bmatrix} C_{1.1} & C_{1.2} & C_{1.3} & C_{1.4} & C_{1.5} & C_{1.6} \\ C_{2.1} & C_{2.2} & C_{2.3} & C_{2.4} & C_{2.5} & C_{2.6} \\ C_{3.1} & C_{3.2} & C_{3.3} & C_{3.4} & C_{3.5} & C_{3.6} \\ C_{4.1} & C_{4.2} & C_{4.3} & C_{4.4} & C_{4.5} & C_{4.6} \\ C_{5.1} & C_{5.2} & C_{5.3} & C_{5.4} & C_{5.5} & C_{5.6} \\ C_{6.1} & C_{6.2} & C_{6.3} & C_{6.4} & C_{6.5} & C_{6.6} \end{bmatrix} = \begin{bmatrix} f_{1.1} & f_{1.2} & f_{1.3} & f_{1.4} & f_{1.5} & f_{1.6} \\ f_{2.1} & f_{2.2} & f_{2.3} & f_{2.4} & f_{2.5} & f_{2.6} \\ f_{3.1} & f_{3.2} & f_{3.3} & f_{3.4} & f_{3.5} & f_{3.6} \\ f_{4.1} & f_{4.2} & f_{4.3} & f_{4.4} & f_{4.5} & f_{4.6} \\ f_{5.1} & f_{5.2} & f_{5.3} & f_{5.4} & f_{5.5} & f_{5.6} \\ f_{6.1} & f_{6.2} & f_{6.3} & f_{6.4} & f_{6.5} & f_{6.6} \end{bmatrix} \bullet \begin{bmatrix} a_{1.1} & a_{1.2} & a_{1.3} & a_{1.4} & a_{1.5} & a_{1.6} \\ a_{2.1} & a_{2.2} & a_{2.3} & a_{2.4} & a_{2.5} & a_{2.6} \\ a_{3.1} & a_{3.2} & a_{3.3} & a_{3.4} & a_{3.5} & a_{3.6} \\ a_{4.1} & a_{4.2} & a_{4.3} & a_{4.4} & a_{4.5} & a_{4.6} \\ a_{5.1} & a_{5.2} & a_{5.3} & a_{5.4} & a_{5.5} & a_{5.6} \\ a_{6.1} & a_{6.2} & a_{6.3} & a_{6.4} & a_{6.5} & a_{6.6} \end{bmatrix}^{-1} \qquad (5)$$

Please see the "\Plots of a\" directory on the CD-ROM for plots of $\mathbf{a_{j,k}}$.
Please see the "\Plots of f\" directory on the CD-ROM for plots of $\mathbf{f_{j,k}}$.

When it is difficult or expensive to perform a large number of independent loading cases, the general method is ideal; however, when a large number of independent loading cases are possible, a "linear least squares method" will provide more accurate results.

2.1.2.2 linear least squares method

This method theorizes that if enough varied loads are applied in varied directions, then an accurate estimate of the calibration matrix can be obtained using an optimized linear least squares fit. In other words, if the test apparatus can be loaded with enough independent loading cases to cover the expected use of the model during actual testing, then an accurate calibration matrix can be derived.

Let the number of trial runs to be used in determining the calibration matrix be represented by the subscript m.

The algorithm used to obtain the linear least squares Calibration Matrix is:

$$\underset{6,6}{C} = \underset{6,m}{F} \cdot \underset{m,6}{V^T} \cdot \left[\underset{6,m}{V} \cdot \underset{m,6}{V^T} \right]^{-1} \tag{6a}$$

and in expanded form:

$$\begin{bmatrix} C_{1,1} & \cdots & C_{1,6} \\ C_{2,1} & \cdots & C_{2,6} \\ C_{3,1} & \cdots & C_{3,6} \\ C_{4,1} & \cdots & C_{4,6} \\ C_{5,1} & \cdots & C_{5,6} \\ C_{6,1} & \cdots & C_{6,6} \end{bmatrix} = \begin{bmatrix} F_{1,1} & \cdots & F_{1,m} \\ F_{2,1} & \cdots & F_{2,m} \\ F_{3,1} & \cdots & F_{3,m} \\ F_{4,1} & \cdots & F_{4,m} \\ F_{5,1} & \cdots & F_{5,m} \\ F_{6,1} & \cdots & F_{6,m} \end{bmatrix} \bullet \begin{bmatrix} R_{1,1} & \cdots & R_{1,m} \\ R_{2,1} & \cdots & R_{2,m} \\ R_{3,1} & \cdots & R_{3,m} \\ R_{4,1} & \cdots & R_{4,m} \\ R_{5,1} & \cdots & R_{5,m} \\ R_{6,1} & \cdots & R_{6,m} \end{bmatrix}^T \bullet \left[\begin{bmatrix} R_{1,1} & \cdots & R_{1,m} \\ R_{2,1} & \cdots & R_{2,m} \\ R_{3,1} & \cdots & R_{3,m} \\ R_{4,1} & \cdots & R_{4,m} \\ R_{5,1} & \cdots & R_{5,m} \\ R_{6,1} & \cdots & R_{6,m} \end{bmatrix} \bullet \begin{bmatrix} R_{1,1} & \cdots & R_{1,m} \\ R_{2,1} & \cdots & R_{2,m} \\ R_{3,1} & \cdots & R_{3,m} \\ R_{4,1} & \cdots & R_{4,m} \\ R_{5,1} & \cdots & R_{5,m} \\ R_{6,1} & \cdots & R_{6,m} \end{bmatrix}^T \right]^{-1} \tag{6b}$$

I have completed three calibration matrices using this method: C1, C2, and C3.

C1 only takes into account loading cases that were similar in magnitude to loads experienced in 2003 ice tests.

C2 is similar to C1 but the maximum loading limits have been raised to incorporate more loading cases.

C3 includes all usable loading cases.

Please see Appendix Afor plots of results of the three calibration matrices.
Please see Appendix E for the Matlab scripts used for the linear least squares method.

2.2 The Forward, Aft, and Blade Dynos

The bearing dynamometers (Forward Dyno and Aft Dyno) and blade dynamometers are one-piece units; not comprised of *n* number of load cells like the global dyno. They are manufactured by AMTI and capable of measuring motions is six degrees of freedom: up to 2224 N in *x* and *y*, up to 4448 N in *z*, and up to 56.5 Nm rotation about all three axes.

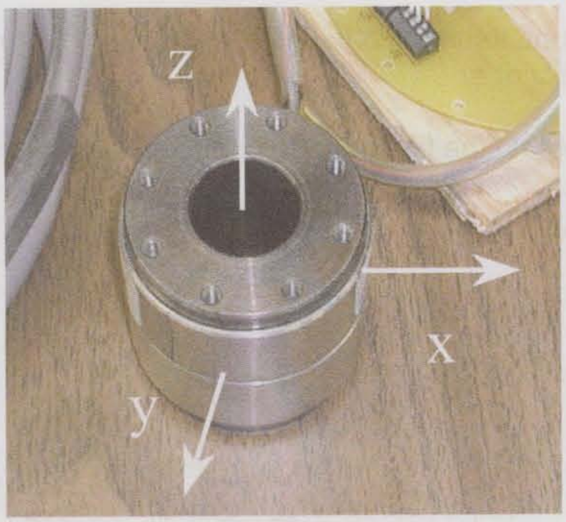


Figure 11. AMTI Dynamometer capable of measuring motions in six degrees of freedom.

2.2.1 Calibration of the Forward, Aft, and Blade Dynamometers

These dynamometers are single units, and therefore the extensive manner in which the global dyno was calibrated does not apply here. Each dynamometer has six channels: Fx, Fy, Fz, Mx, My, and Mz; where Fx is force along the *x*-axis, and My is moment about the *y*-axis. The dynamometers were calibrated at AMTI - using a 7.5 Vdc reference voltage - before they were shipped to us and we know the calibration equations. The same 7.5 volt reference is supplied to the dynamometers when they are in use, but they only output around ± 0.5 volts. The data acquisition system is designed to handle ± 10 volts; therefore to get maximum resolution, the output of each dynamometer has to be amplified.

This calibration does not actually involve recalibration of the dynamometers, but calibration of the amplified signal from each dynamometer channel so that the values recorded are the same as they would be if each dynamometer channel was not amplified. To accomplish this a universal voltage source is attached to the data acquisition system in place of the a dynamometer, and specially selected voltages are "injected" into the data acquisition system based on the cal factor (calibration slope) for each channel of the dynamometer that it is replacing. For example, if the cal factor for a particular dynamometer channel is 2 mv/N + 0 Newtons (offset), then with the application of uniaxial force of 200 N (corresponding to that channel's alignment) the dyno should output 0.4 volts (i.e. $0.002V/N \times 200N = 0.4V$). If the signal from the dynamometer is amplified by 10, then the data acquisition system sees the output signal as 4 volts. We know that this 4 volts represents 100 N, therefore we can determine a new cal factor from the least square fit of at least five data points (force vs. voltage).

Each channel of each dynamometer is calibrated in this manner.

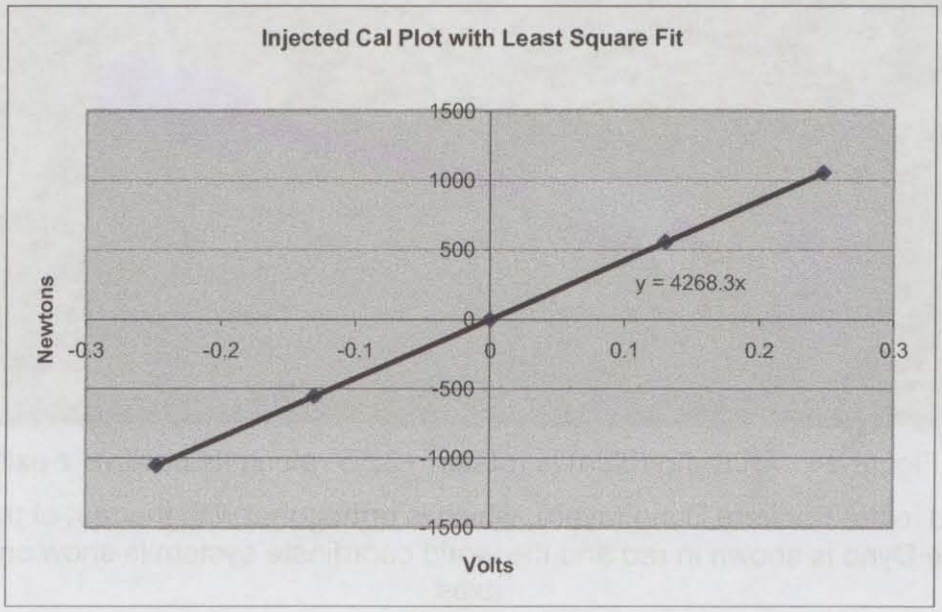


Figure 12. Injected Cal Plot with Least Squares fit.

2.2.2 Notes on Bearing and Blade Dynos

A mistake was made during fabrication of the Aft Dyno mount inside the pod; when the Aft Dyno is in place, it is rotated 22.5° along its positive *z*-axis away from the Forward Dyno (which is orthogonal with the rest of the system). This must be taken into account when analyzing the Aft Dyno data and comparing it with data acquired from the other dynamometers.

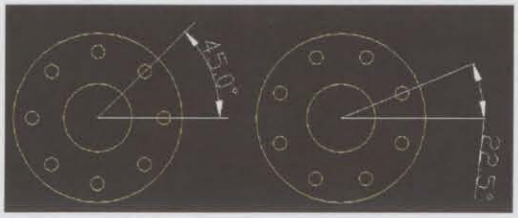


Figure 13. Illustration of Aft Dyno mount rotation.

The mount on the right is the correct mount in order for the dynamometer to be orthogonal with the rest of the system. The mount on the left represents the orientation of the Aft Dyno mount, which is incorrect.

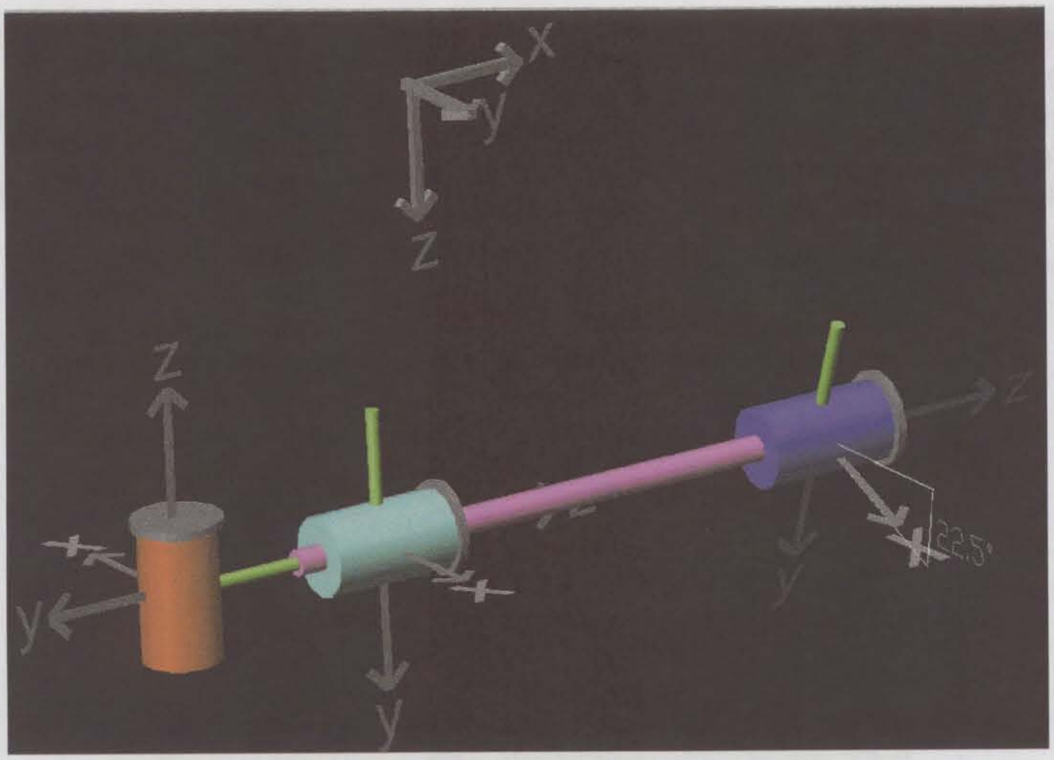


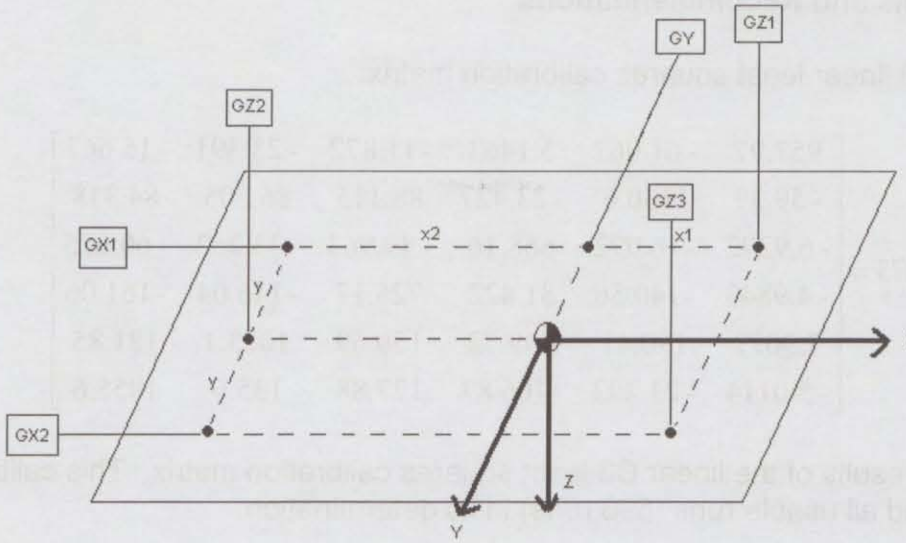
Figure 14. Aft Dyno (blue) is rotated +22.5° along its positive *z*-axis

compared to the Forward Dyno (cyan), which is orthogonal with the rest of the system. The Blade Dyno is shown in red and the world coordinate system is show on top in 3D axes.

3 Examining the center of the Global Dyno

It was required to verify that the assumed center of the global dyno was infact, the actual physical center. This information was required to ensure that the global dyno was reacting as we assumed it would.

The center of the global dyno refers to the point that, if acted upon by any force, no moment is produced. Theoretically, this point is 1/2 way between the 2 x-dynamometers, 2/3 of the way from z2 dynamometer to z1 and z3 dynamometers, and on the line of action of the y dynamometer.



Due to fact that the placements of the dynamometers are, by nature, not perfect; the need to examine whether the position of the center of the global dyno is within experimental error of its assumed position, or not, is necessary.

To accomplish this, special test cases were performed and analyzed using Matlab.

The Global Dyno Center of Gravity was found to be at (X,Y,Z) = (0.000586, 0.0013, -.0040) meters from the assumed center of global dyno.

Please see Appendix B for a complete description of how the center of the global dyno was found.

4 Problems Encountered

Here is a list of some of the problems we encountered:

- Unable to apply a negative $\mathbf{P_z}$ load.
- Tare values not constant, especially for $\mathbf{P_y}$.
- Some tare values were not done.
- Some $\mathbf{P_x}$ and $\mathbf{P_y}$ applied loads varied in magnitude over the course of the run recording, also noticeable oscillations.
- During the initial few seconds of some trial runs, the amplitude of the applied load ($\mathbf{P_x}$ and/or $\mathbf{P_y}$) was large then faded away to a constant level (while the mean value remained constant). This suggests that recording was started before the system had reached equilibrium.
- Application of large applied loads in two or more directions caused severe deflections in the flexlinks and caused the hydraulic rams to swivel at their mounts (which the mounts allowed them to do). **This was a major problem.**

5 Conclusions and Recommendations

Here is the C3 linear least squares calibration matrix:

$$\underset{6,6}{C3} = \begin{bmatrix} 957.97 & -61.067 & 5.1463 & -11.872 & -23.391 & -15.667 \\ -59.39 & 1130.6 & -23.427 & 88.115 & 86.605 & 84.318 \\ -6.9292 & -16.092 & 668.16 & -49.963 & -33.252 & -60.075 \\ -4.9843 & -140.56 & 81.422 & 725.17 & -146.04 & -161.06 \\ 7.9077 & 190.41 & -49.72 & 150.69 & 1023.1 & 121.85 \\ -5.0114 & -21.292 & -106.87 & 177.88 & 135.6 & 1055.6 \end{bmatrix}$$

Here are the results of the linear C3 least squares calibration matrix. This calibration matrix included all usable runs (596 runs) in its determination.

C3 (calculations performed on runs used in the matrixes determination)
Percentage of Runs within 200 N error of calculated F values

Load cell	Percentage
GFx1	0.99
GFx2	0.89
GFy	1
GFz1	0.98
GFz2	0.86
GFz3	0.77

Here is the individual load cell cals (C4 matrix):

$$\underset{6,6}{C4} = \begin{bmatrix} 919.72 & 0 & 0 & 0 & 0 & 0 \\ 0 & 917.32 & 0 & 0 & 0 & 0 \\ 0 & 0 & 645.35 & 0 & 0 & 0 \\ 0 & 0 & 0 & 921.37 & 0 & 0 \\ 0 & 0 & 0 & 0 & 913.87 & 0 \\ 0 & 0 & 0 & 0 & 0 & 920.22 \end{bmatrix}$$

and the intercepts:

$$\underset{6,1}{C4_0} = \begin{bmatrix} -18.419 \\ -29.337 \\ 5.3285 \\ 26.332 \\ -62.662 \\ 27.218 \end{bmatrix}$$

Here are the results of the C4 matrix when used to determine forces from voltages for the same runs used in C3.

C4
Percentage of Runs within 200 N error of calculated F values

Load cell	Percentage
GFx1	0.99
GFx2	0.71
GFy	0.99
GFz1	0.99
GFz2	0.55
GFz3	0.65

The C3 matrix has better results, proving that there is cross talk happening within the global dyno.

Load cells GFx1 and Gfy have reliable calibrations either using C3 or C4, while the others generally have better results (at least against the calibration runs) using C3.

I believe that during the calibration loading cases, the deflections in the model and hydraulics caused when two or more large loads were applied in close proximity to eachother, were sever enough to upset the calibration process.

I recommend that neither the C3 nor the C4 matrices be trusted with a high degree of confidence.

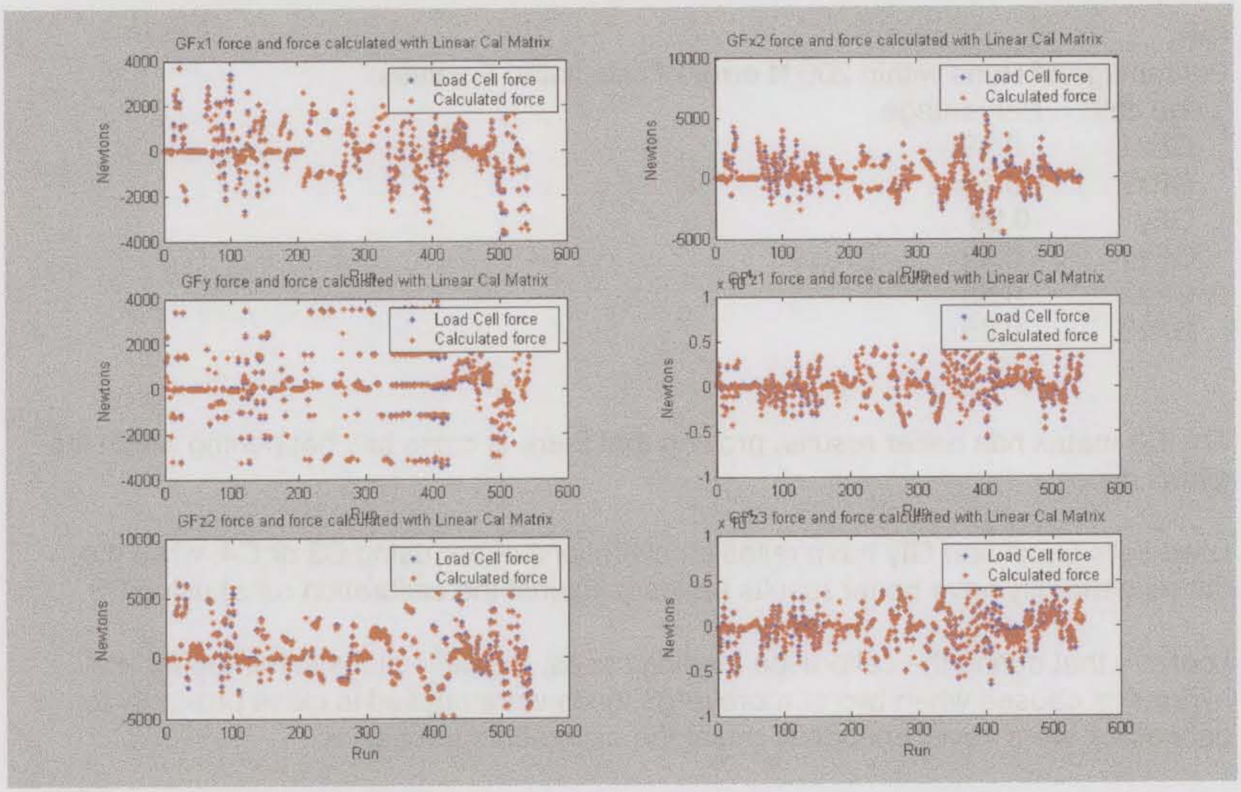
With regards to the bearing and blade dynos, and the center of global dyno calculations, I believe they are reliable and trustworthy.

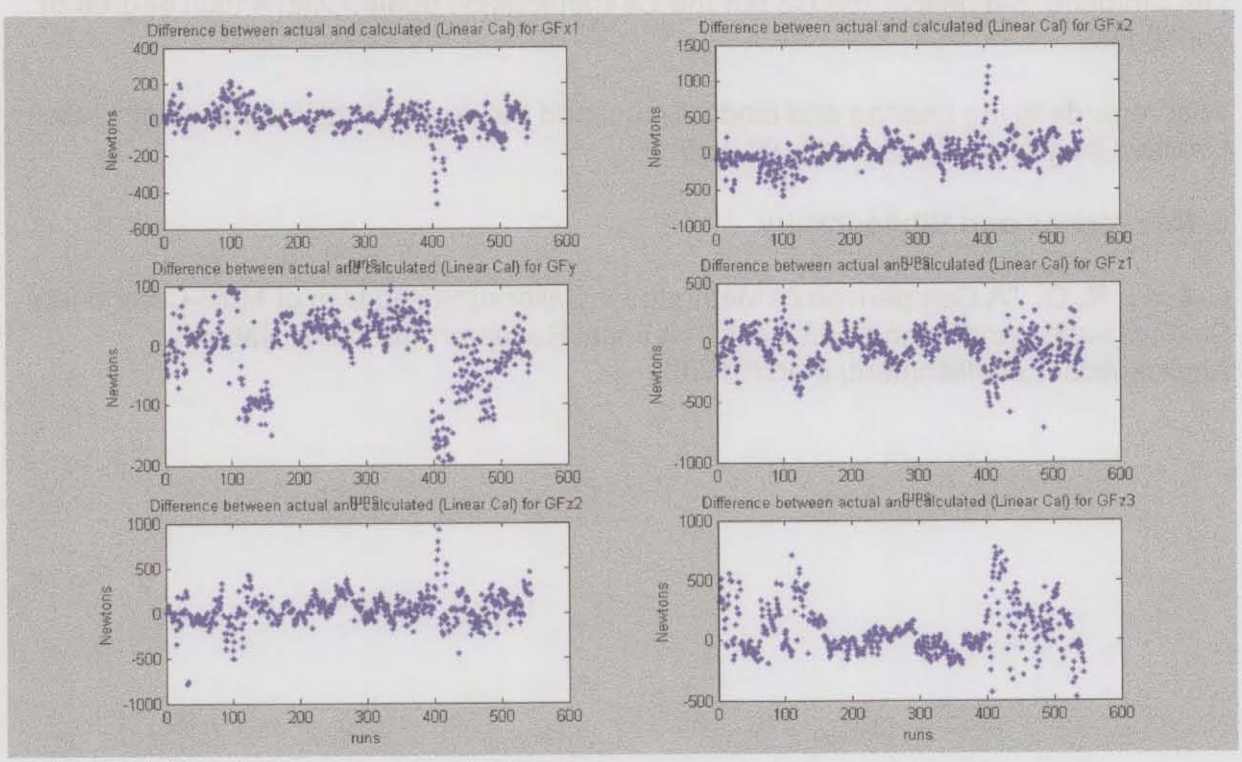
6 References and Bibliography

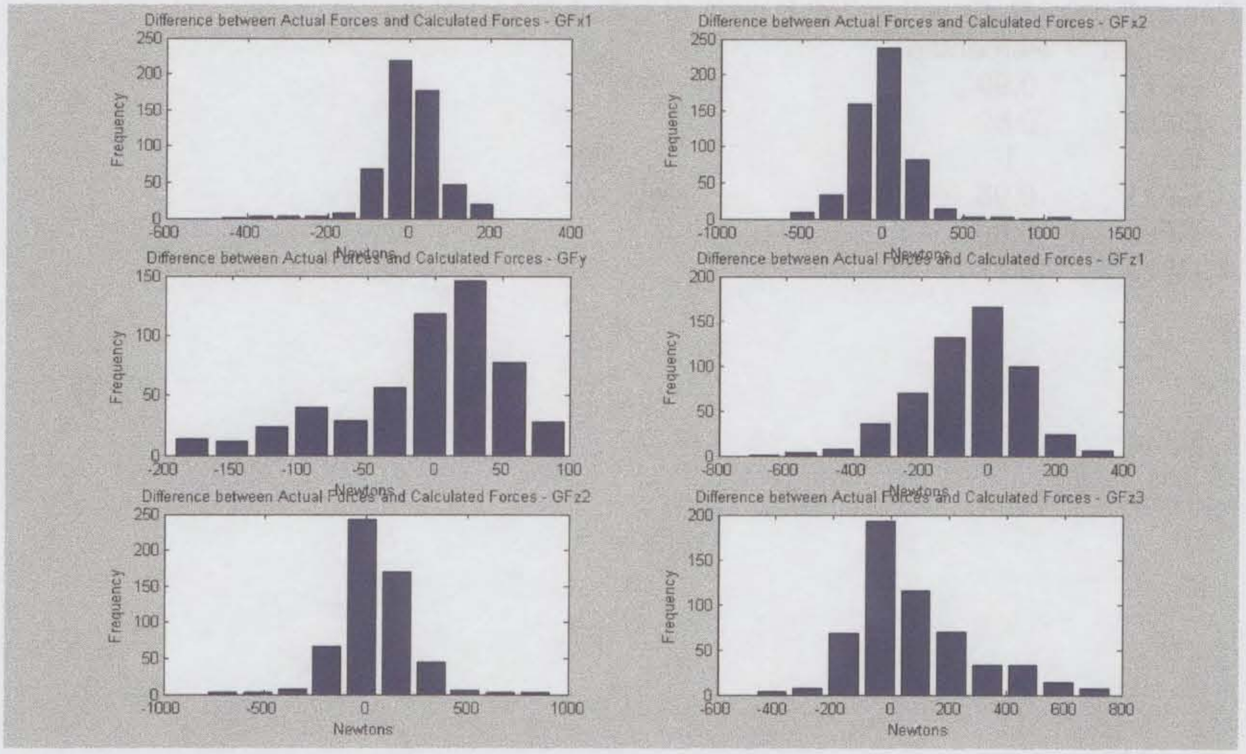
Galway, R. D., "A Comparison of Methods for Calibration and Use of Multi-Component Strain Gauge Wind Tunnel Balances", National Research Council – National Aeronautical Establishment, March 1980.

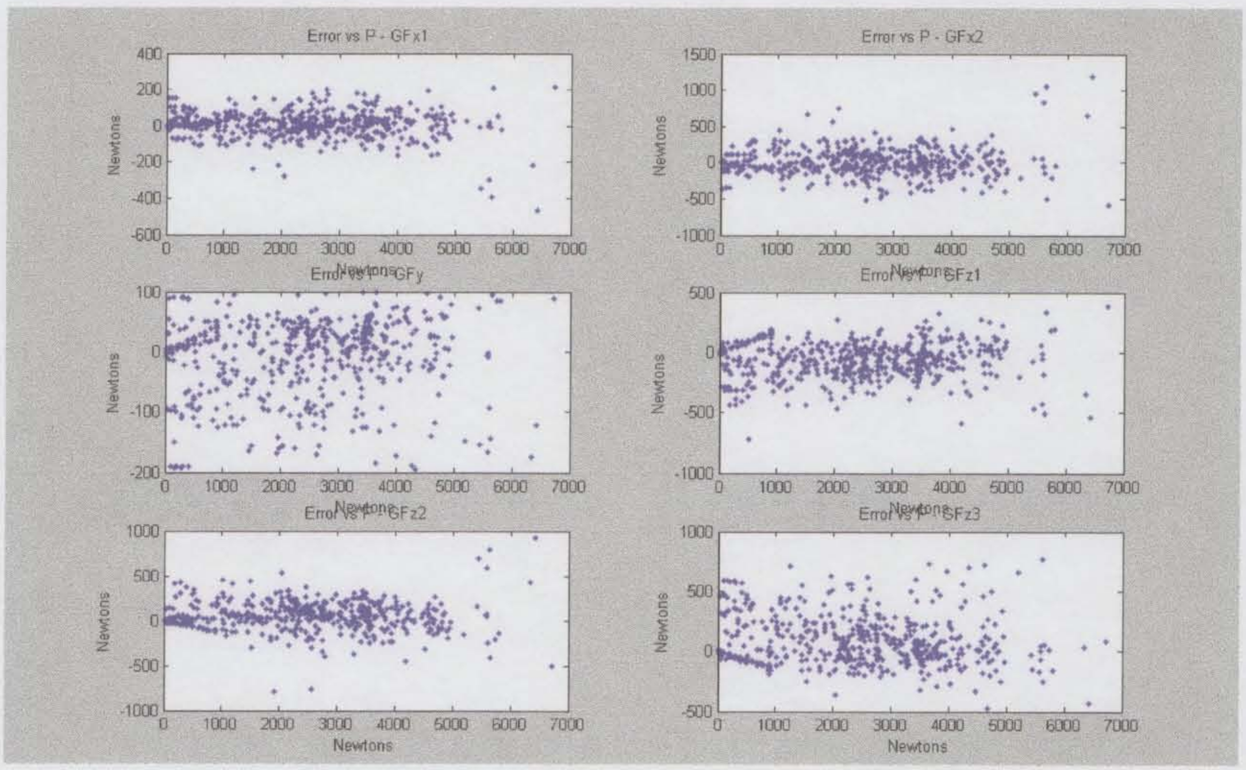
Appendix A

A-1 Results of C3 Linear Least Squares Global Dyno Calibration Matrix





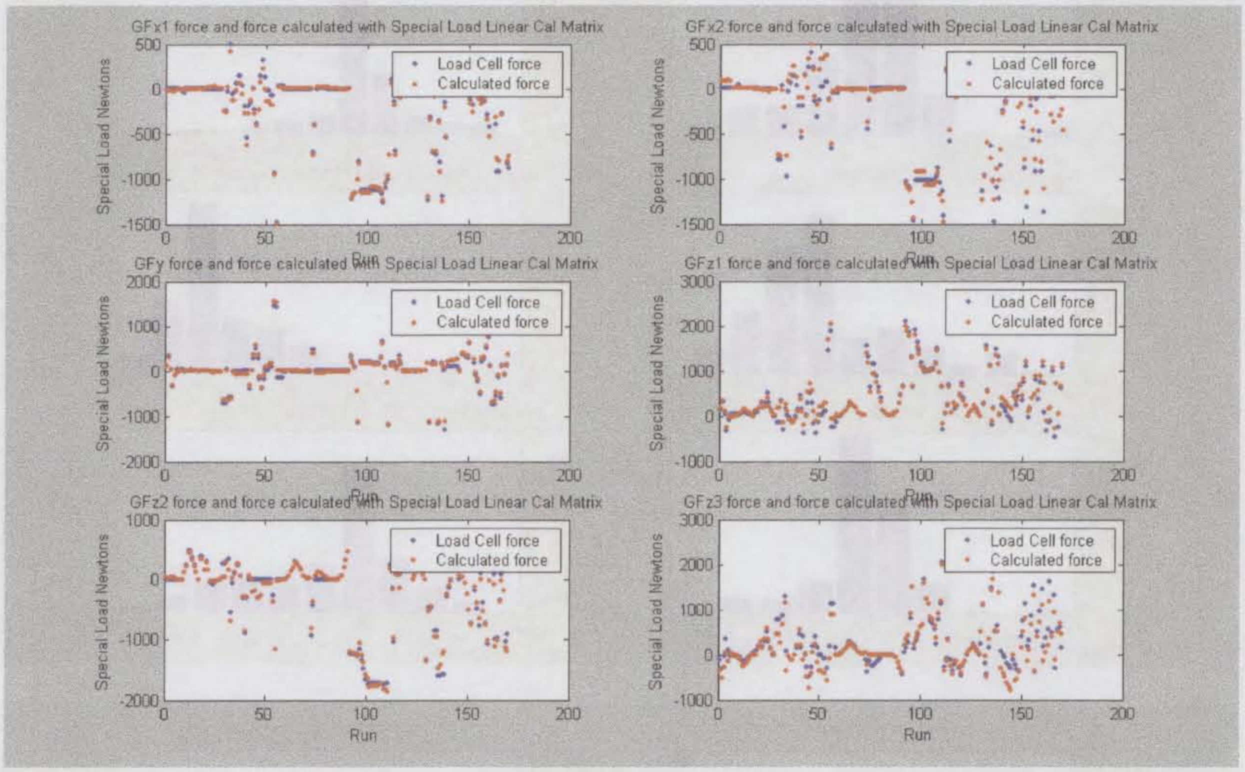

Difference between Actual Forces and Calculated Forces - GFx1
Difference between Actual Forces and Calculated Forces - GFx2
Difference between Actual Forces and Calculated Forces - GFy
Difference between Actual Forces and Calculated Forces - GFz1
Difference between Actual Forces and Calculated Forces - GFz2
Difference between Actual Forces and Calculated Forces - GFz3
Frequency
Newtons

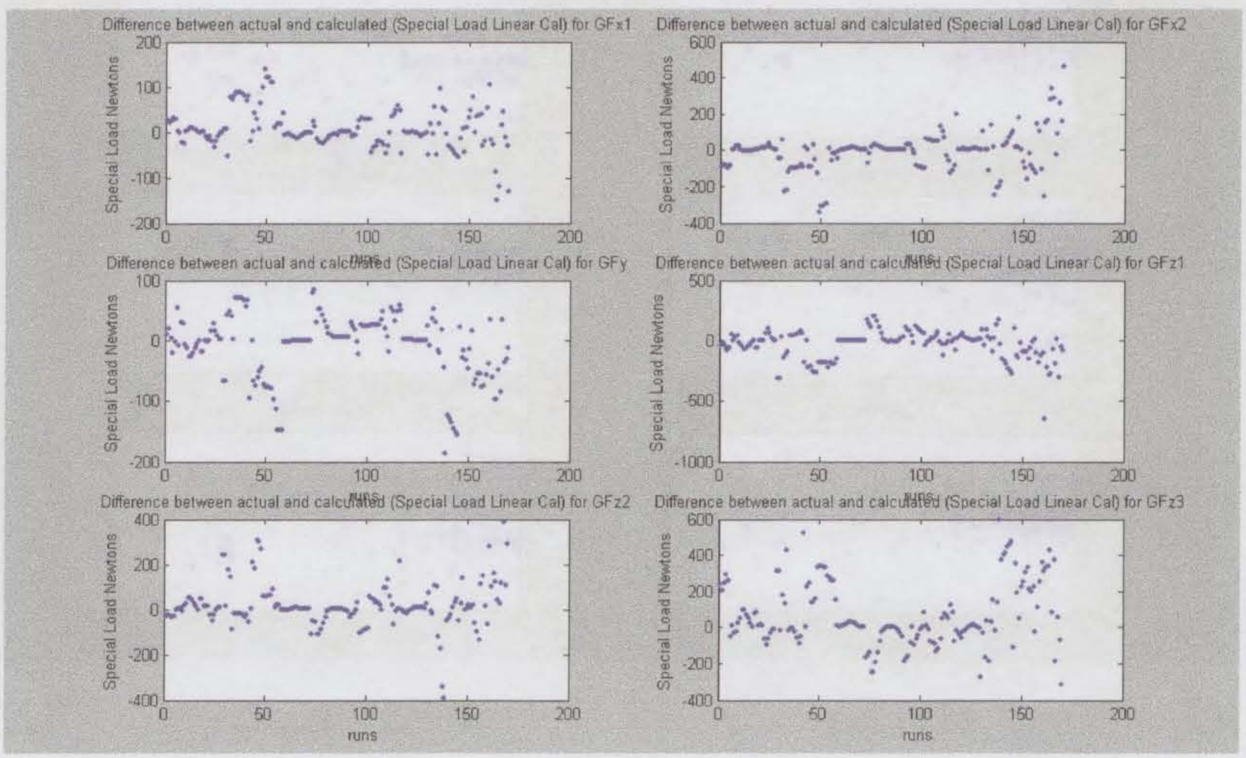

Error vs P - GFx1
Error vs P - GFx2
Error vs P - GFy
Error vs P - GFz1
Error vs P - GFz2
Error vs P - GFz3
Newtons
Newtons

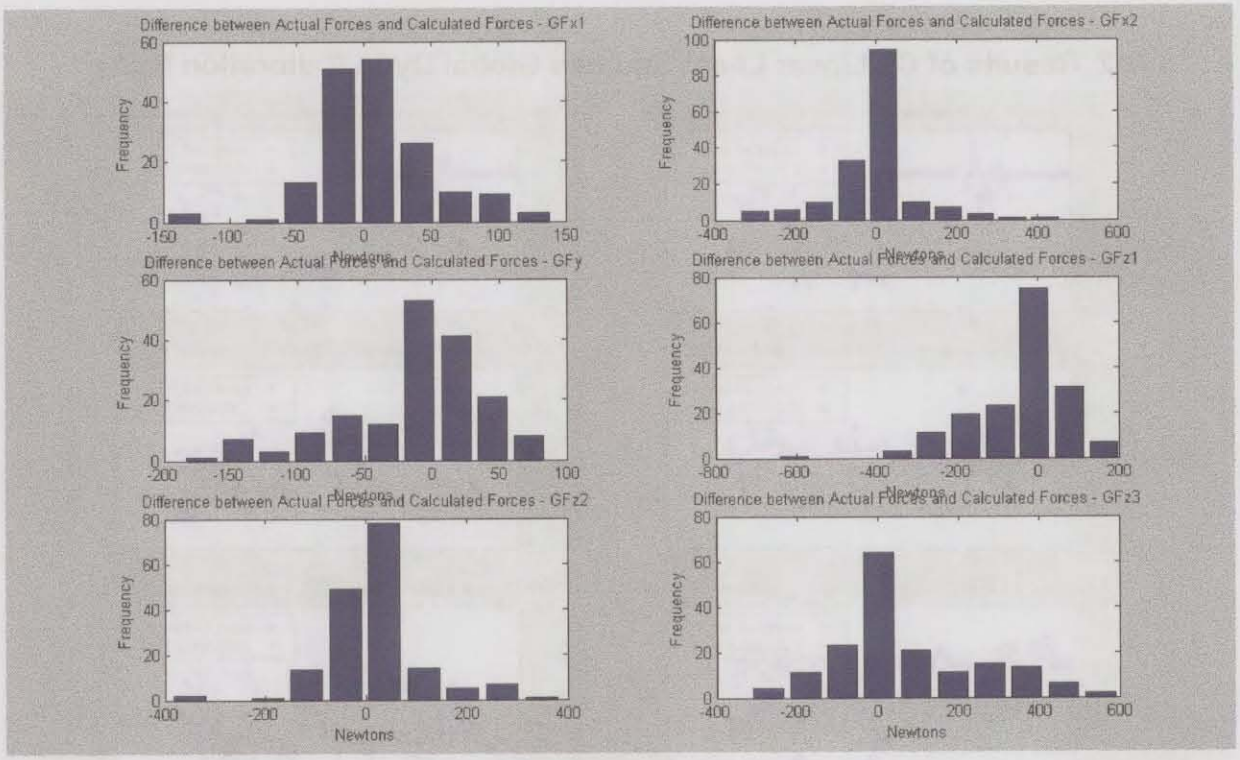
Percentage of Runs within 200 N error of calculated F values

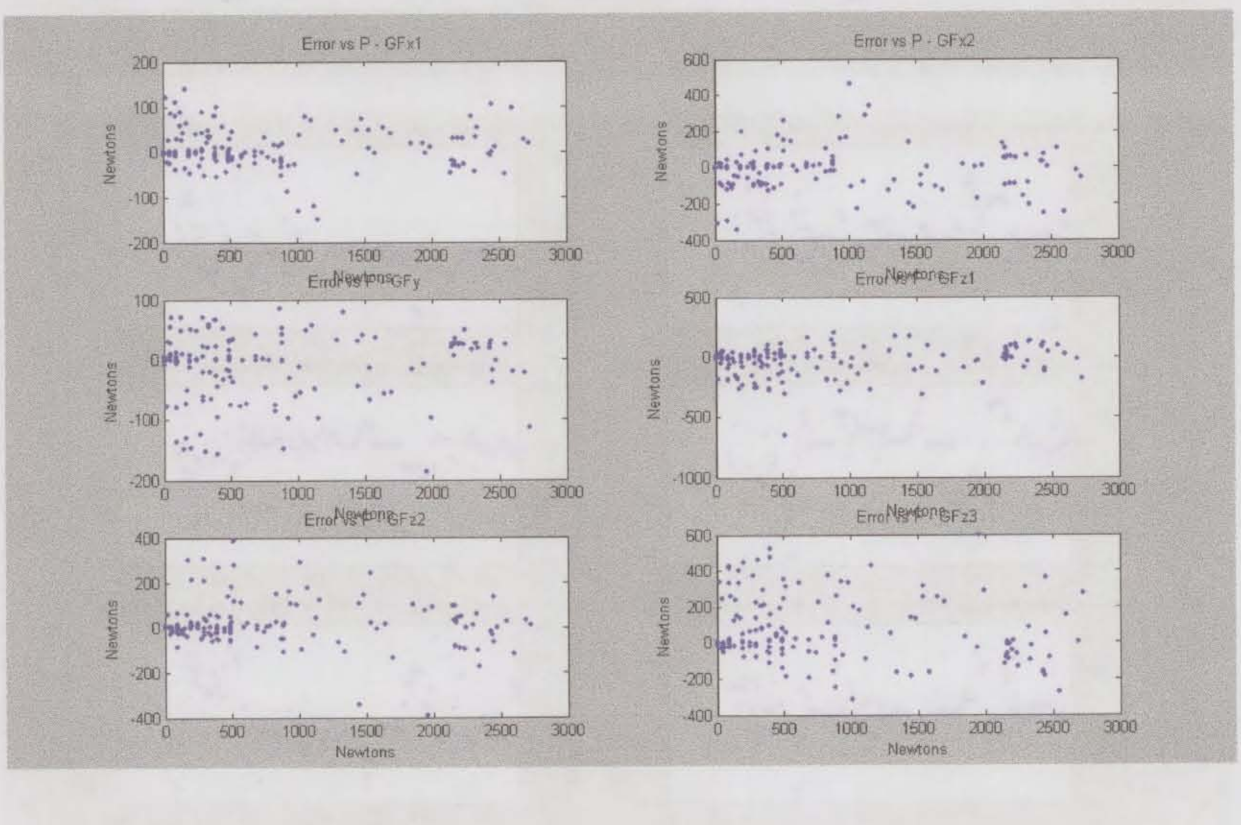
Load cell	Percentage
GFx1	0.99
GFx2	0.89
GFy	1
GFz1	0.98
GFz2	0.86
GFz3	0.77

A-2 Results of C1 Linear Least Squares Global Dyno Calibration Matrix





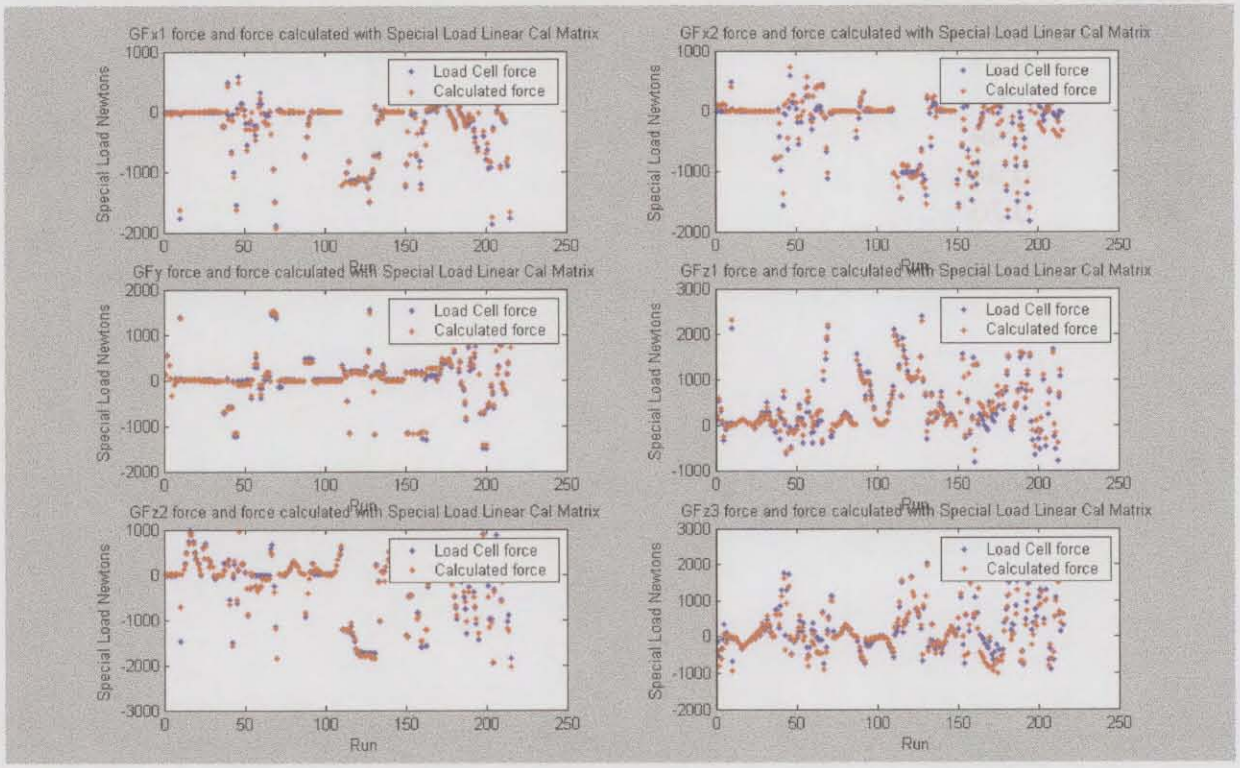

Difference between Actual Forces and Calculated Forces - GFx1
Difference between Actual Forces and Calculated Forces - GFx2
Difference between Actual Forces and Calculated Forces - GFy
Difference between Actual Forces and Calculated Forces - GFz1
Difference between Actual Forces and Calculated Forces - GFz2
Difference between Actual Forces and Calculated Forces - GFz3
Frequency
Newtons

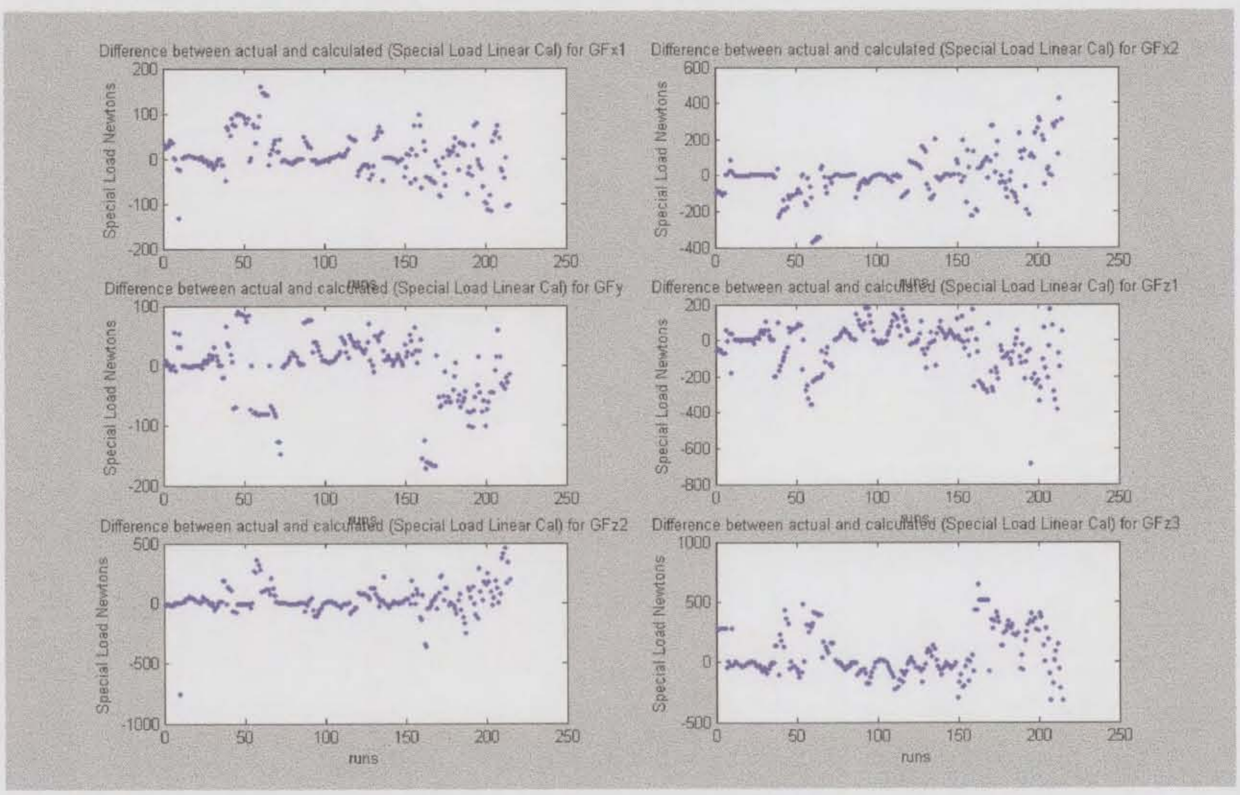

Error vs P - GFx1
Error vs P - GFx2
Error vs P - GFy
Error vs P - GFz1
Error vs P - GFz2
Error vs P - GFz3
Newtons

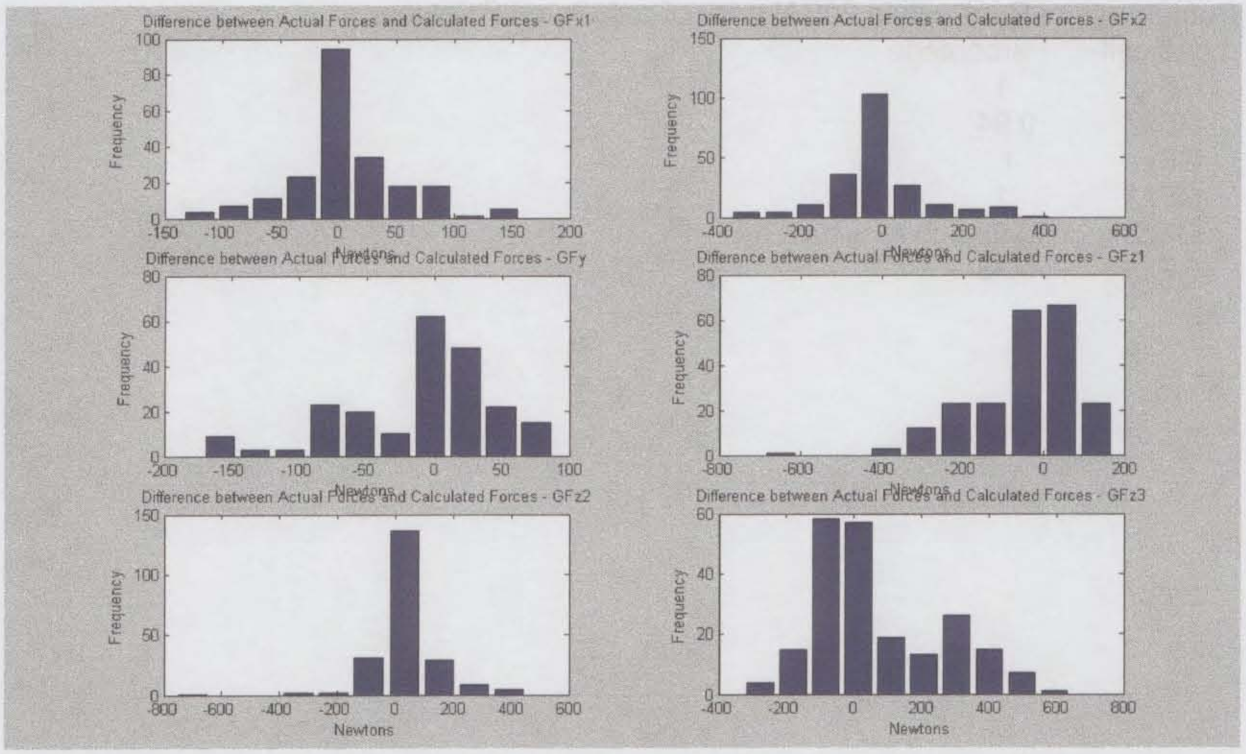
Percentage of Runs within 200 N error of calculated F values

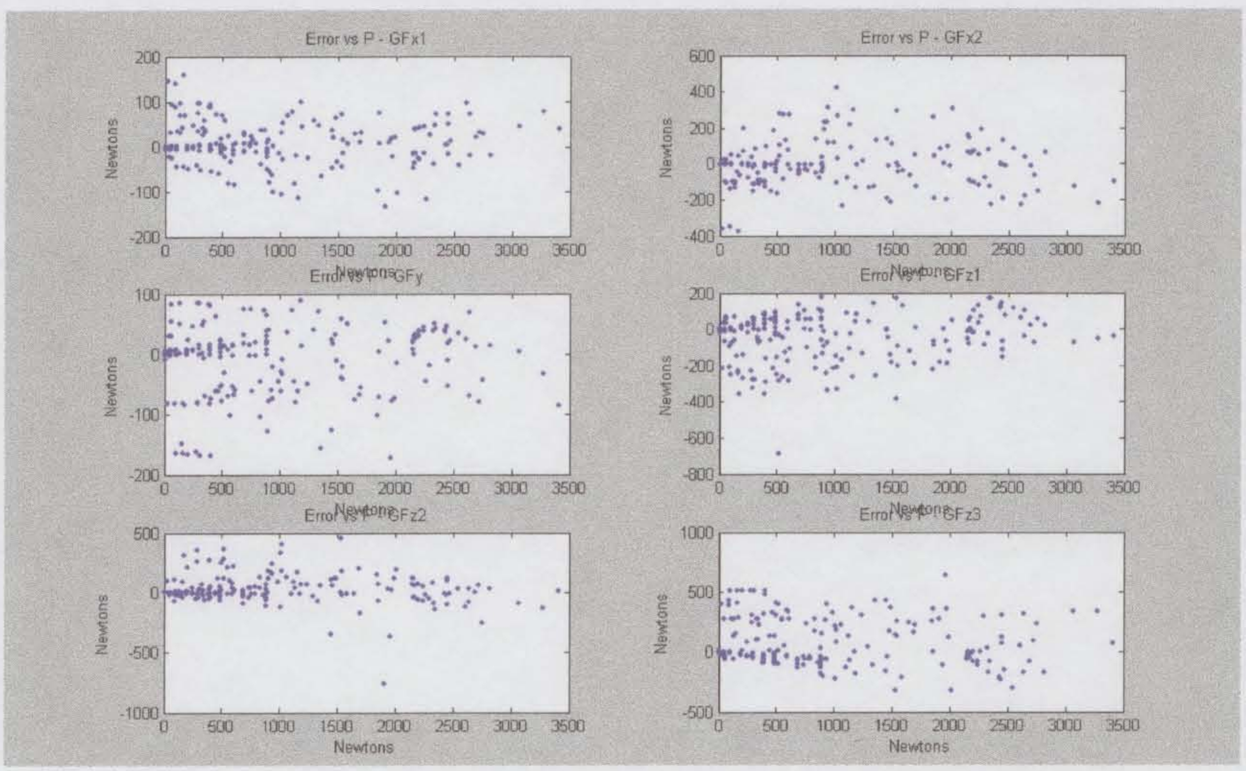
Load cell	Percentage
GFx1	1
GFx2	0.97
GFy	1
GFz1	0.99
GFz2	0.94
GFz3	0.76

A-3 Results of C2 Linear Least Squares Global Dyno Calibration Matrix





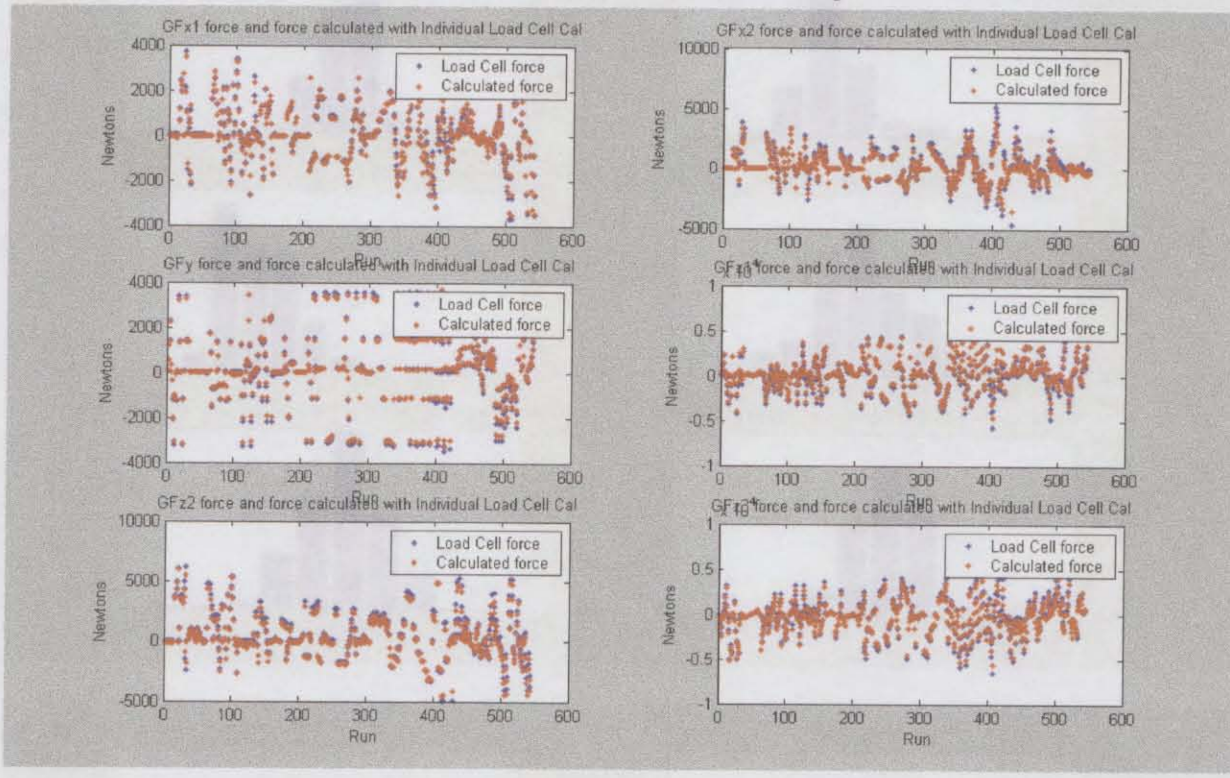

Difference between Actual Forces and Calculated Forces - GFx1
Difference between Actual Forces and Calculated Forces - GFx2
Difference between Actual Forces and Calculated Forces - GFy
Difference between Actual Forces and Calculated Forces - GFz1
Difference between Actual Forces and Calculated Forces - GFz2
Difference between Actual Forces and Calculated Forces - GFz3
Frequency
Newtons

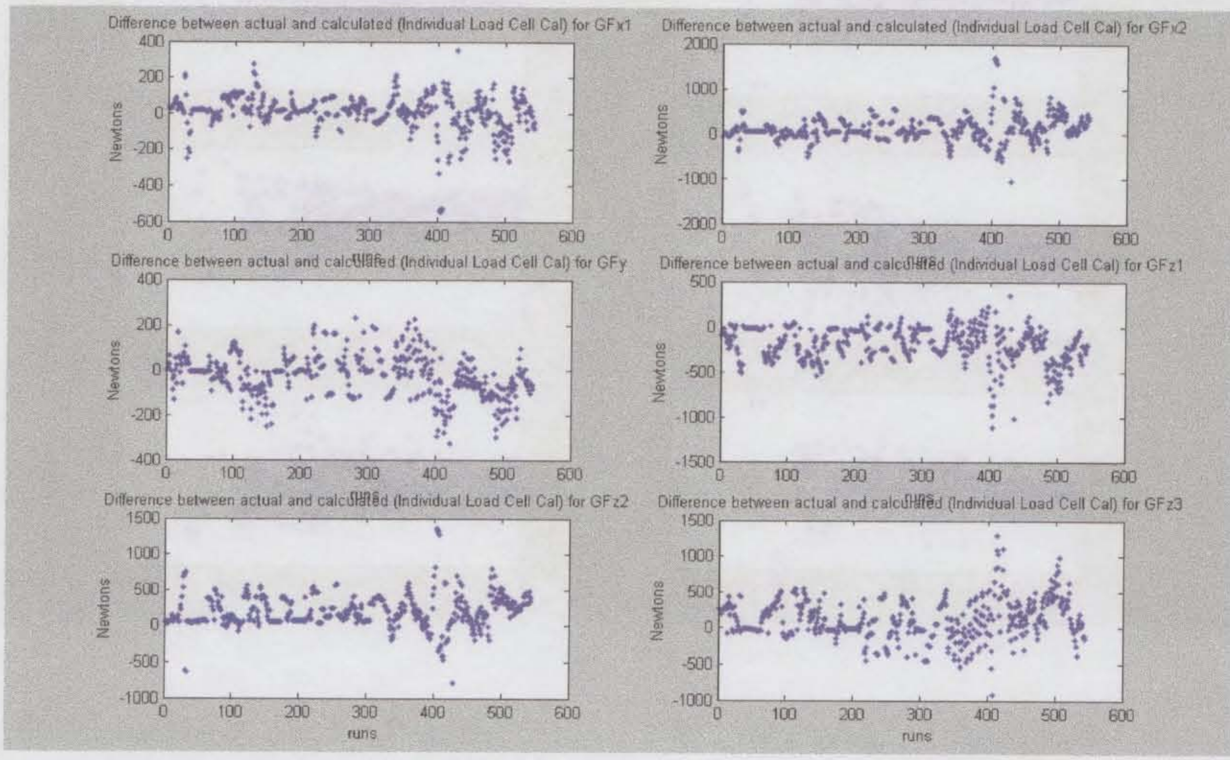

Error vs P - GFx1
Error vs P - GFx2
Error vs P - GFy
Error vs P - GFz1
Error vs P - GFz2
Error vs P - GFz3
Newtons

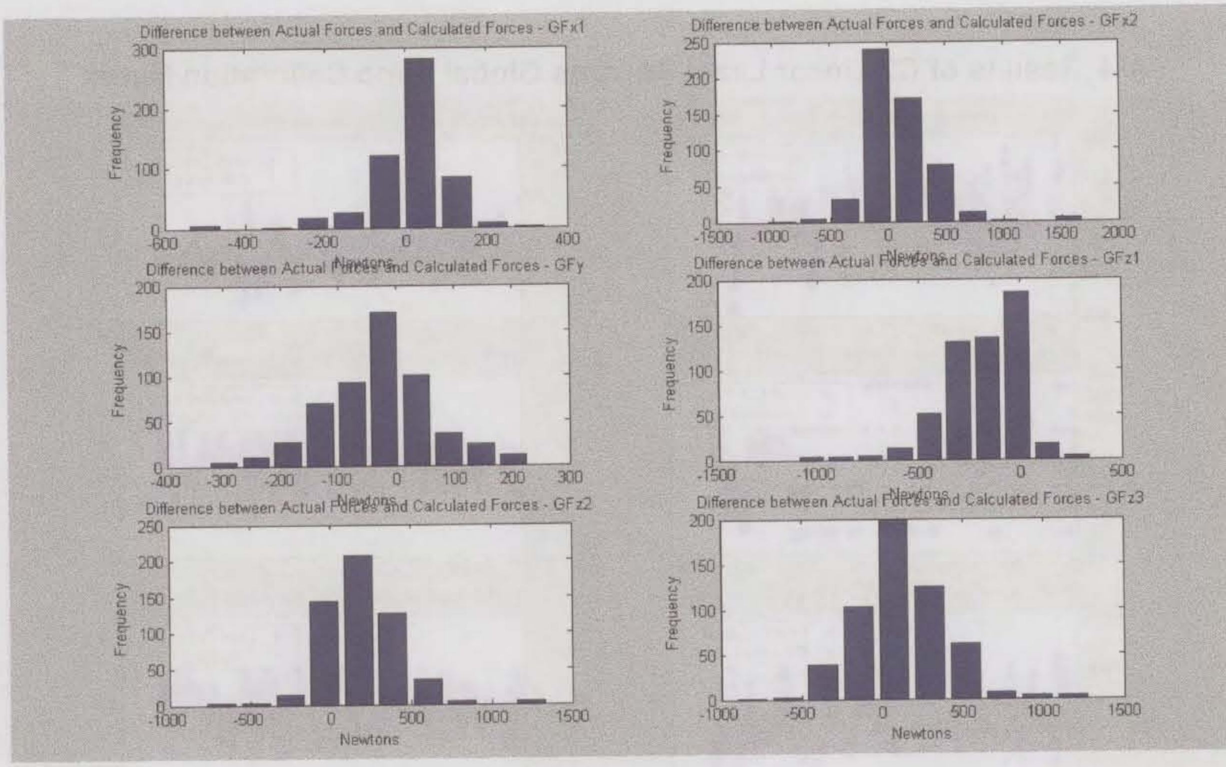
Percentage of Runs within 200 N error of calculated F values

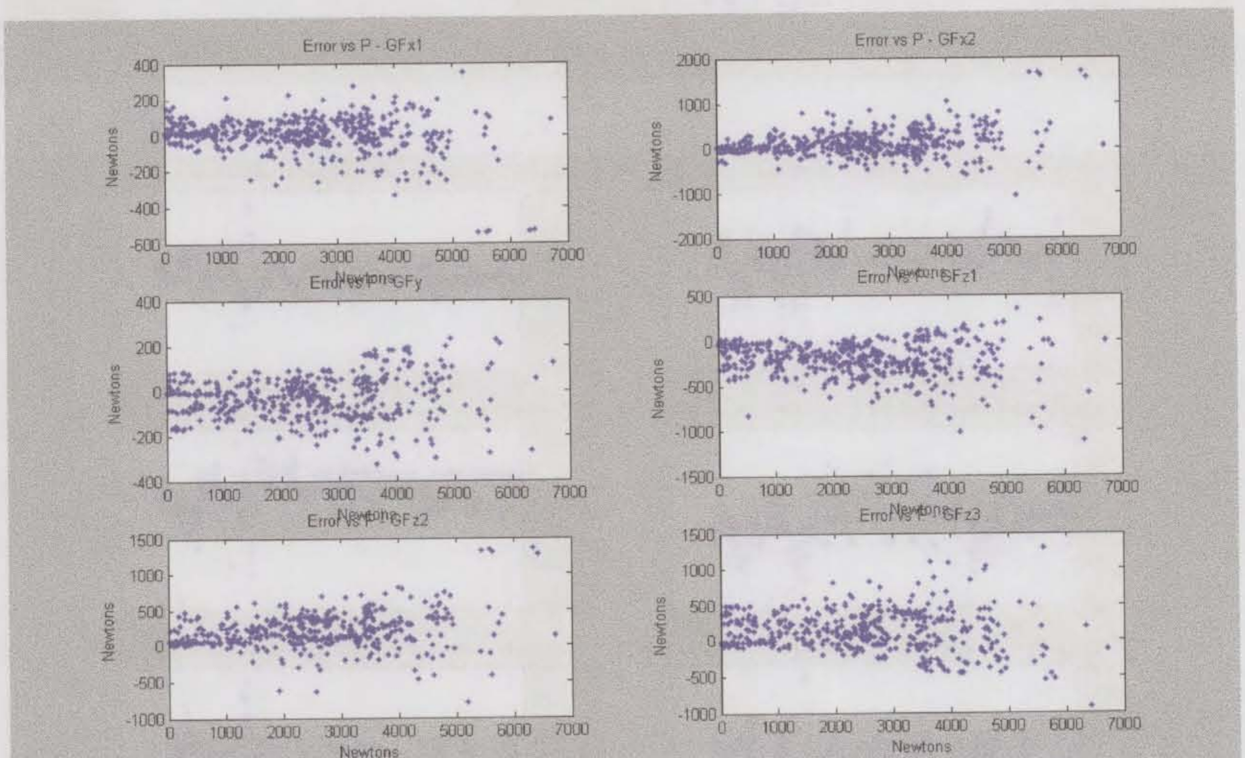
Load cell	Percentage
GFx1	1
GFx2	0.94
GFy	1
GFz1	1
GFz2	0.93
GFz3	0.73

A-4 Results of C2 Linear Least Squares Global Dyno Calibration Matrix






Difference between Actual Forces and Calculated Forces - GFx1
Difference between Actual Forces and Calculated Forces - GFx2
Difference between Actual Forces and Calculated Forces - GFy
Difference between Actual Forces and Calculated Forces - GFz1
Difference between Actual Forces and Calculated Forces - GFz2
Difference between Actual Forces and Calculated Forces - GFz3
Frequency
Newtons


Error vs P - GFx1
Error vs P - GFx2
Error vs P - GFy
Error vs P - GFz1
Error vs P - GFz2
Error vs P - GFz3
Newtons

y-Coordinate

To get the y coordinate of the center of the global dyno, a constant weight was suspended, at known locations, from an L-shaped beam attached to the "foil replacement" strut, which was attached to the base plate of the global dyno. The moment about the x-axis (**Mpx**$_i$), due to the weight (**P**) at position **i,** was then plotted along with the reaction moment (**Mx**$_R$) calculated from the z-load cell readings of the global dyno. If the point where the lines on the graphs cross is sufficiently close to the point (0,0), the center of the dyno is said to be within experimental error of its expected position. The point of intersection was found by obtaining the equations of both lines from a "least squares fit" on each, and setting them equal to each other to solve for y. All moments were calculated with counterclockwise rotation taken as positive.

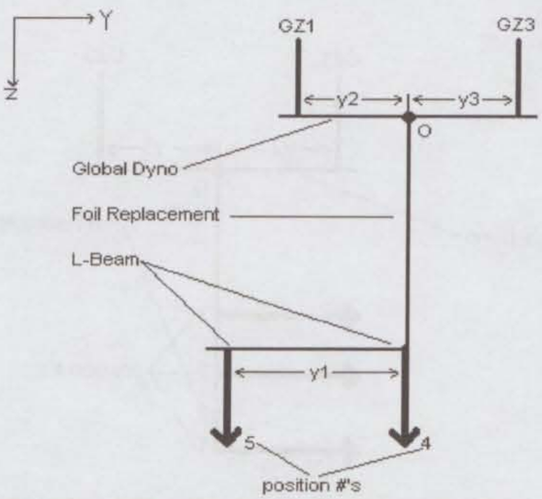


Figure 2. Arrows show the application of weight P

Formulae

Moment about x-axis due to **P** at position **i**:

$$Mpx_i = p \cdot y_i \tag{4}$$

Reaction moment about y-axis:

$$Mx_R = Fz1 \cdot y2 + Fz3 \cdot y3\,; \tag{5}$$

where Fz1, Fz2, Fz3 are the negatives of the load cell forces felt in load cells Gz1, Gz2, and Gz3 respectfully, for a particular position **i**. Negatives because they are the forces felt by the supports, not the free body in question

Sum of the moments:

$$\sum M = Mpx_i + Mx_R = 0 \tag{6}$$

z-Coordinate

To get the z coordinate of the center of the global dyno, a constant weight was suspended, at known locationss, from the foil replacement, which was attached to the base plate of the global dyno. This was possible because the whole global dyno was rotated 90° so that the y-axis was pointed against the force of gravity. The moment about the x-axis (**Mpx$_i$2**), due to the weight (**P**) at position **i,** was then plotted along with the reaction moment (**Mx$_R$2**) calculated from the z-load cell readings of the global dyno. If the point where the lines on the graphs cross is sufficiently close to the point (0,0), the center of the dyno is said to be within experimental error of its expected position. The point of intersection was found by obtaining the equations of both lines from a "least squares fit" on each, and setting them equal to each other to solve for y. All moments were calculated with counterclockwise rotation taken as positive.

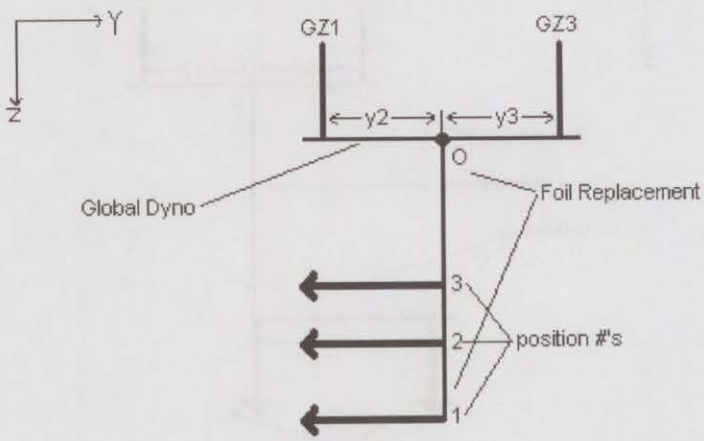


Figure 3. Arrows show the application of weight P

Formulae

Moment about x-axis due to **P** at position **i**:

$$Mpx_i 2 = P \cdot y_i \tag{7}$$

Reaction moment about y-axis:

$$Mx_R 2 = Fz1 \cdot y2 + Fz3 \cdot y3; \tag{8}$$

where Fz1, Fz2, Fz3 are the negatives of the load cell forces felt in load cells Gz1, Gz2, and Gz3 respectfully, for a particular position **i**. Negatives because they are the forces felt by the supports, not the free body in question

Sum of the moments:

$$\sum M = Mpx_i 2 + Mx_R 2 = 0 \tag{9}$$

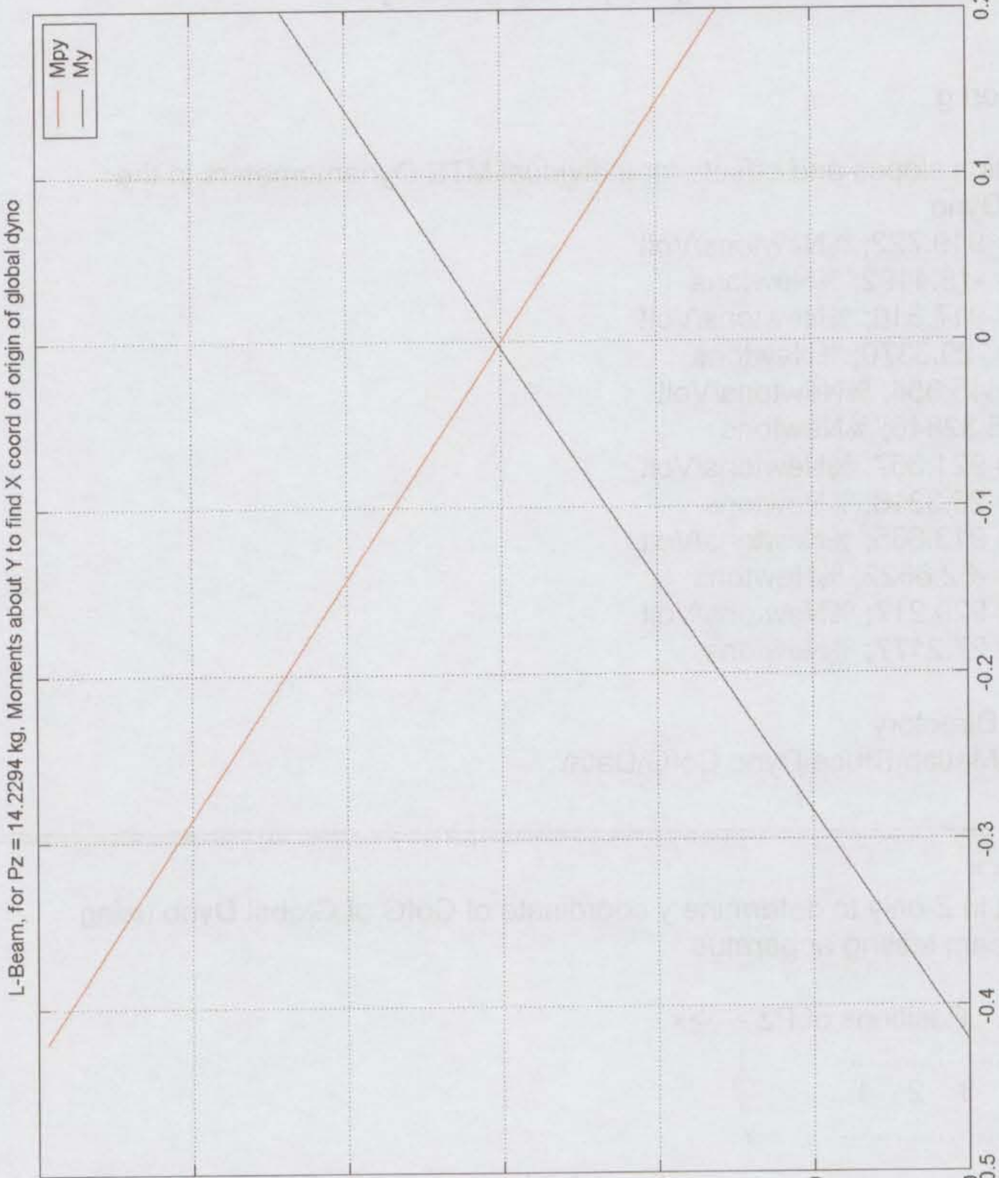


Figure 5. A graph of Mpy_i and My_R vs. X

$$Y_{Mpy} = -139.56x + 0 \quad (1)$$
$$Y_{My} = 142.22x + 0.1653 \quad (2)$$
$$X \text{ coord} = x = 0.00059 \text{ (m)} \quad (1) \text{ in } (2)$$

B-2 GetCofG.m Code

```
%Program to find the centre of gravity of the global dyno
clear all
clc
format short g

%Calibration slopes and offsets for individual MTS Dynamometers in the
%Global Dyno
Fx1_C1 = 919.722; %Newtons/Volt
Fx1_C0 = -18.4192; %Newtons
Fx2_C1 = 917.316; %Newtons/Volt
Fx2_C0 = -29.3370; %Newtons
Fy_C1 = 645.354; %Newtons/Volt
Fy_C0 = 5.32846; %Newtons
Fz1_C1 = 921.367; %Newtons/Volt
Fz1_C0 = 26.3318; %Newtons
Fz2_C1 = 913.865; %Newtons/Volt
Fz2_C0 = -62.6622; %Newtons
Fz3_C1 = 920.217; %Newtons/Volt
Fz3_C0 = 27.2177; %Newtons

%Source Directory
dir2 = 'G:\Matlab\Bruce\Dyno CofG\Data\';

%==================================================================
=========
%Loading in Z only to determine y coordinate of CofG of Global Dyno using
%the L-Beam testing apparatus
%      .....
%      . 5 .   Positions of Pz ---->x
%      .  .....................      |
%      . 4   3   2   1 .            \|/
%      .........................     y

Pz=90*9.808;    %Weight in Z direction = 90 kg * 9.808 m/s^2

%import tare data
A=importdata(strcat(dir2,'B_calrun0001.mat'));
temp=mean(A);
TareGFz1=temp(8);
TareGFz3=temp(10);
```

```
%import a run for position_5
A=importdata(strcat(dir2,'B_calrun0007.mat'));
temp = mean(A);
Fz1(5)=(temp(8)-TareGFz1) * Fz1_C1 + Fz1_C0;    %Subtract tare voltage and convert
to Newtons
Fz3(5)=(temp(10)-TareGFz3) * Fz3_C1 + Fz3_C0;   %Subtract tare voltage and convert
to Newtons

    %Statics
    Mpx(1) = 0.0254*(-5.906)*Pz;
    Mx(1)  = 0.0254* (-10.392*-Fz1(5) + 10.392*-Fz3(5));

%import a run for position_4
A=importdata(strcat(dir2,'B_calrun0017.mat'));
temp = mean(A);
Fz1(4)=(temp(8)-TareGFz1) * Fz1_C1 + Fz1_C0;    %Subtract tare voltage and convert
to Newtons
Fz3(4)=(temp(10)-TareGFz3) * Fz3_C1 + Fz3_C0;   %Subtract tare voltage and convert
to Newtons

    %Statics
    Mpx(2) = 0;
    Mx(2)  = 0.0254* (-10.392*-Fz1(4) + 10.392*-Fz3(4));

Y=[-0.1500124; 0];   %coordinates of points of application of load Pz

%plot Mpx and Mx on the same graph (Figure 1)
figure(1);
plot(Y,Mpx,'r', Y,Mx,'k');
legend('Mpx','Mx');
title('L-Beam, for Pz = 90kg, Moments about X to find Y coord of origin of global dyno');
grid on;
xlabel('Y (m)'); ylabel('Mx (Nm)');


%==================================================================
=========
%Loading in -Y only to determine z coordinate of CofG of Global Dyno using
%the only the foil replacement
%
% Positions 1 and 2 on the foil replacement
%       ___________
%      /          /
%     /__________/
%        |     ||          -------> x
%        |     ||        /|
```

```
%        |  3   | |___    / |
%        |  2   | |  /          / \|/
%      / |______|/  /    \/  z
%     /___________/      y
%           1


Py= -21.3955*9.808;    %Weight in Y direction = 21.3955 kg * 9.808 m/s^2

%import tare data
A=importdata(strcat(dir2,'cofgz0001.mat'));
temp=mean(A);
TareGFz1=temp(4);
TareGFz3=temp(6);


%import a run for position_1
A=importdata(strcat(dir2,'cofgz0002.mat'));
temp = mean(A);
Fz1(6)=(temp(4)-TareGFz1) * Fz1_C1 + Fz1_C0;    %Subtract tare voltage and convert
to Newtons
Fz3(6)=(temp(6)-TareGFz3) * Fz3_C1 + Fz3_C0;    %Subtract tare voltage and convert
to Newtons

   %Statics
   Mpx2(1) = -0.0254*(13.437 - 0.25 + 3.525)*Py;
   Mx2(1)  = 0.0254* (-10.392*-Fz1(6) + 10.392*-Fz3(6));

%import a run for position_2
A=importdata(strcat(dir2,'cofgz0003.mat'));
temp = mean(A);
Fz1(7)=(temp(4)-TareGFz1) * Fz1_C1 + Fz1_C0;    %Subtract tare voltage and convert
to Newtons
Fz3(7)=(temp(6)-TareGFz3) * Fz3_C1 + Fz3_C0;    %Subtract tare voltage and convert
to Newtons

   %Statics
   Mpx2(2) = -0.0254*(11.031+3.525)*Py;
   Mx2(2)  = 0.0254* (-10.392*-Fz1(7) + 10.392*-Fz3(7));

%import a run for position_3
A=importdata(strcat(dir2,'cofgz0004.mat'));
temp = mean(A);
Fz1(8)=(temp(4)-TareGFz1) * Fz1_C1 + Fz1_C0;    %Subtract tare voltage and convert
to Newtons
```

```
Fz3(8)=(temp(6)-TareGFz3) * Fz3_C1 + Fz3_C0;    %Subtract tare voltage and convert
to Newtons

   %Statics
   Mpx2(3) = -0.0254*(7.094+3.525)*Py;
   Mx2(3)  = 0.0254* (-10.392*-Fz1(8) + 10.392*-Fz3(8));

%coordinates of points of application of force Py
Z=[0.0254*(13.437 - 0.25 + 3.525); 0.0254*(11.031+3.525); 0.0254*(7.094+3.525)];

%plot Mpx2 and Mx2 on the same graph (Figure 2)
figure(2);
plot(Z,Mpx2,'r', Z,Mx2,'k');
legend('Mpx2','Mx2');
title('L-Beam, for Py = -21.3955 kg, Moments about X to find Z coord of origin of global
dyno');
grid on;
xlabel('Z (m)');ylabel('Mx (Nm)');


%=================================================================
=========
%Loading in Z only to determine x coordinate of CofG of Global Dyno using
%the L-Beam testing apparatus
%       .....
%       . 5 .  Positions of Pz       ---->x
%       .  ....................         |
%       . 4   3   2   1 .           \|/
%       .........................        y

%(Dr. Akinturk's Code)

%Calibration slopes and offsets for individual MTS Dynamometers in the
%Global Dyno
C1 = [919.722 917.316 645.354 921.367 913.865 920.217];
C0 = [-18.4192 -29.3370 5.32846 26.3318 -62.6622 27.2177];

WforX= 14.2294*9.808;    %Weight in Z direction = 14.2294 kg * 9.808 m/s^2

X=[-0.4207002 -0.1999996 0 0.1999996];  %coordinates of points of application of force
WforX

fileN(1,:) = strcat(dir2,'cofgx0005.mat');
fileN(2,:) = strcat(dir2,'cofgx0004.mat');
fileN(3,:) = strcat(dir2,'cofgx0003.mat');
fileN(4,:) = strcat(dir2,'cofgx0002.mat');
```

```
fileN(5,:) = strcat(dir2,'cofgx0001.mat');

for j = 1:5
   i = j;
   %import tare data
   A=importdata(fileN(j,:));
   Volts(i,:) = mean(A);
   if i == 1, tare_1 = C1 .* Volts(1,:) + C0; end
   F(i,:) = C1.*Volts(i,:)+C0 - tare_1;
   My(i) = 0.0254* (12*-F(i,5) + -6*(-F(i,4)+-F(i,6)));
end
Mpy = -X .* WforX;

%plot Mpy and My on the same graph (Figure 3)
figure(3);
plot(X,Mpy,'r', X,My(2:5),'k');
legend('Mpy','My');
title('L-Beam, for Pz = 14.2294 kg, Moments about Y to find X coord of origin of global
dyno');
grid on;
xlabel('X (m)');ylabel('My (Nm)');
```

Appendix C

C-1 Location of *x*, *y*, and *z* applied loads, and magnitude of *z* applied load, for each calibration loading case.

Please see "\Pz and Load Coordinates spreadsheets\" CD-ROM directory for this spreadsheet.

Appendix D

D-1 Notes on Procedure for the Derivation of the C3 Linear Least Squares Calibration Matrix for the Global Dyno

The C3 linear least squares calibration matrix takes all usable runs into account.

All steps were performed in the derivation of the calibration matrix were completed using Matlab.

1. Plotted a figure for each test run that contained a plot of the output of each channel vs. time - 8 channels, therefore 8 plots per figure. This was done to allow visual inspection of the quality of the test run. Variations in quality are due to the nature of the setup (e.g. gain of 1 on an old controller produces slow hydraulic ram response time, or other hydraulic rams hooked up to the same pump but not part of this experiment tax the pumps ability to hold a constant pressure). Any runs in which $\mathbf{P_x}$ and $\mathbf{P_y}$ sloped greater than ± 10 N were thrown out. Also any runs in which there was a sudden step up or down in the data, or any other apparent abnormality, were thrown out.
2. Tare runs were plotted, as in 1., and compared with each other to ensure tare integrity.
3. All files that passed the visual inspection in 1. were loaded into Matlab, and their means taken. The mean of each run was then tared with the mean of the tare runs taken during the test run recordings. The tared values for each run (i.e. voltages from global dyno load cells and forces from load cells on X and Y hydraulics (i.e. $\mathbf{P_x}$ and $\mathbf{P_y}$) were then saved in a file called "all_data_12_channels.mat", which could be loaded into any Matlab program at any time. The file was called "all_data_12_channels" because there were actually 12 channels recorded in each data run, but channels 1-4 are useless data. Channels 5-12 held the global dyno load cell outputs (channels 5-10 (in Volts)) and the hydraulic load cell outputs (channel 11 and 12 (in Newtons) for $\mathbf{P_x}$ and $\mathbf{P_y}$ respectfully).
4. The $\mathbf{P_z}$ values for each run, along with the coordinates of $\mathbf{P_x}$, $\mathbf{P_y}$, and $\mathbf{P_z}$ with respect to the center of the global dyno, were entered into a Matlab ".m" file as matrices and saved. This allowed them to be called by any other Matlab program.
5. Retrieved the global dyno load cell output voltages (channels 5-10) from "all_data_12_channels.mat" and saved them as "R.mat". (Matlab program "get_voltages_all.m")
6. Called "Pz_all.m" and "Coords_all.m", and loaded "all_data_12_channels.mat" and "totalruns.mat" in a Matlab program called "get_forces_all.m". This program calls another program called "ForceFinderMetric.m" which inputs the P component loads and their coordinates and returns the forces acting on each global dyno load cell. The resulting forces matrix is then saved as "F.mat"
7. Loaded "F.mat" and "R.mat" and calculated the calibration matrix from them (Matlab program called "LS_linear_all.m"). This program calculates the predicted

force values from actual voltages using the calibration matrix, and compares them with actual forces.

8. Wrote a program to give percentage of calculated forces that were within 2% error of actual values ("number_less_than_200.m"), which is called by "LS_linear_all.m".
9. Wrote a program to return the confidence interval, an error histogram, and error vs. load plot for calculated forces ("get_statistics.m"), which is called by "LS_linear_all.m".

Appendix E

Please see the "*.m" files on the CD-ROM "\Global Dyno Calibration\" for software coding. They were much to large to include in this document and they are much easier to understand in a text editor such as the Matlab text editor in which they were written.

Appendix F

F-1 ForceFinderMetric.m

```
% Function to determine the forces acting on each dyno resulting from a global
% force on the foil replacement

function F=ForceFinder(P,C)

% R is a vector with the components of the resultant load P (on the foil replacement)
% C is the point of application of the resultant load (i.e. line of action of P)

% Coordinates of load cells in meters - 3 Load cells in Z, 1 in Y, and 2 in X
        % Load cells for z-axis (have the same z coordinate)
        Xz1=0.1524;
        Yz1=-0.2639568;
        Xz2=-0.3048;
        Yz2=0;
        Xz3=0.1524;
        Yz3=0.2639568;

        % Load cells for x-axis (have the same x and z coordinates)
        Yx1=-0.2639568;
        Yx2=0.2639568;
        Zx=0;

        % Load cells for y-axis
        Xy=0;
        Zy=0;


% System of equations
R=[P(1) 0   0;
   0  P(2) 0;
   0   0  P(3)];

for i=1:3
% The following matrix has been check and is OK
   A=[ 1    1  0  0  0    0;
      0    0  1  0  0    0;
      0    0  0  1  1    1;
      0    0 -Zy Yz1  0   Yz3;
      Zx          Zx  0 -Xz1 -Xz2 -Xz3;
     -Yx1 -Yx2 0   0   0    0];
```

```
    b=[-R(i,1); -R(i,2); -R(i,3); -(R(i,3)*C(i,2)-R(i,2)*C(i,3)); -(R(i,1)*C(i,3)-R(i,3)*C(i,1)); -
(R(i,2)*C(i,1)-R(i,1)*C(i,2))];

    Forces(:,i)=A\b;

    %Returns a vector containing Fx1,Fx2,Fy,Fz1,Fz2,Fz3
end

F=Forces(:,1)+Forces(:,2)+Forces(:,3);
```

Appendix G

Bearing and Blade Dyno "injected cal" spreadsheets.

Please see CD-ROM "\Forward, Aft, Blade Dyno Injected Cal Sheets\" for the bearing and blade dyno "injected cal" spreadsheets.