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and Calibration of

STATICS OF CAVITATION TUNNEL DYNAMOMETER

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SUMMARY

This report is intended as a technical guide for calibrating and interpreting the readings of the flooded cavitation tunnel dynamometer. The equations of static equilibrium provide the basis of the calibration procedure and the determination of the resultant fluid force with its line of action. Typical examples are described.

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Statics and Calibration of Cavitation Tunnel Dynamometer

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Abstract

This report is intended as a technical guide for calibrating and interpreting the readings of the flooded cavitation tunnel dynamometer. The equations of static equilibrium provide the basis of the calibration procedure and the determination of the resultant fluid force with its line of action. Typical examples are described.

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1 Introduction

The dynamometer used in the cavitation tunnel at the Institute for Marine Dynamics is an in-house designed 6-component balance. Inside the dynamometer are 6 load cells each connected to the 'live' surface by flex links. One load cell measures forces parallel to the flow (x direction), two load cells measure horizontal forces transverse to the flow (y direction) and three load cells measure vertical forces transverse to the flow (z direction). A substantial number of experiments are currently being carried out at the IMD cavitation tunnel since the facilities have been upgraded with a modern flow control system, a data acquisition system and a laser Doppler anemometer. A majority of these experiments are devoted to measurements of the hydrodynamic forces and moments acting on a test model using an external flooded dynamometer. In most cases the model is rigidly mounted to the dynamometer through a base plate. In some experiments, however, the model is free to pitch, roll or yaw about body-fixed axes.

Careful calibration of the dynamometer is necessary in order to obtain accurate load measurements. Care has been taken in the design and construction of the load cell flex links so that these are properly aligned within a tolerance of three thousandths of an inch. Any misalignment in the flex links is addressed via a correction calibration. We wish to present (a) the equations which may be used to calibrate the dynamometer and (b) a method of determining (from the dynamometer readings) the resultant fluid force on a model and its line of action. The roll, pitch and yaw moments acting on the model can then be calculated.

Useful hydrodynamic data is obtained only after the fluid forces on the model attachment system have been determined, without the model present. A *tare* calibration must be performed for the range of mean flow velocities in the cavitation tunnel in order to determine these forces.

In steady flow conditions, the force measurements are obtained as a time series. Appropriate data analysis techniques are then required.

2 Dynamometer Calibration Formulae

The calibration consists of applying a known force $\mathbf{R}$ at a known test point C and determining the six dynamometer readings $\{\mathbf{F}_m,\ m = 1, \ldots, 6\}$. These forces are defined such that they act *on the dynamometer plate* as indicated in Fig. 1. The relevant dimensions are given in Table 1. Denote the point of application of force $\mathbf{F}_m$ on the plate by P_m and let $\mathbf{r}_m = \mathbf{OP}_m$ be the position vector of P_m relative to origin O. Denote the magnitude of $\mathbf{F}_m$ by F_m , *defined as positive when the force acts in the* *positive coordinate direction.* The unit vectors parallel to the x, y and z axes are denoted by the usual notation $\mathbf{i}, \mathbf{j}$ and $\mathbf{k}$ respectively. The six forces $\mathbf{F}_m$ and their points of application are written as

$$\begin{array}{ll} \textbf{Force } \mathbf{F}_m & \textbf{Position vector } \mathbf{r}_m \\ \mathbf{F}_1 = F_1\mathbf{i} & \mathbf{r}_1 = x_1\mathbf{i} + \mathbf{z}_0\mathbf{k} \\ \mathbf{F}_2 = F_2\mathbf{k} & \mathbf{r}_2 = x_2\mathbf{i} + \mathbf{y}_0\mathbf{j} \\ \mathbf{F}_3 = F_3\mathbf{k} & \mathbf{r}_3 = x_2\mathbf{i} - \mathbf{y}_0\mathbf{j} \\ \mathbf{F}_4 = F_4\mathbf{k} & \mathbf{r}_4 = -x_2\mathbf{i} \\ \mathbf{F}_5 = F_5\mathbf{j} & \mathbf{r}_5 = -x_3\mathbf{i} + \mathbf{y}_0\mathbf{j} + z_0\mathbf{k} \\ \mathbf{F}_6 = F_6\mathbf{j} & \mathbf{r}_6 = x_3\mathbf{i} + \mathbf{y}_0\mathbf{j} + z_0\mathbf{k} \end{array} \tag{1}$$

The system of forces $\{\mathbf{R}$ at C , $\mathbf{F}_m$ at P_m $(m = 1\ldots, 6)\}$ are in static equilibrium and hence

$$\sum_{m=1}^{6} \mathbf{F}_m + \mathbf{R} = \mathbf{0} \tag{2}$$

$$\sum_{m=1}^{6} \mathbf{r}_m \times \mathbf{F}_m + \mathbf{OC} \times \mathbf{R} = \mathbf{0} \tag{3}$$

Let

$$\mathbf{R} = R_x\mathbf{i} + R_y\mathbf{j} + R_z\mathbf{k} \tag{4}$$

and let C have coordinates (x_c, y_c, z_c) . Equations (2) and (3) are written explicitly as

$$F_1 = -R_x \tag{5}$$

$$F_5 + F_6 = -R_y \tag{6}$$

$$F_2 + F_3 + F_4 = -R_z \tag{7}$$

$$y_0 (F_2 - F_3) - z_0 (F_5 + F_6) = -(R_z y_c - R_y z_c) \tag{8}$$

$$z_0 F_1 + x_2 (F_4 - F_2 - F_3) = -(R_x z_c - R_z x_c) \tag{9}$$

$$x_3 (F_6 - F_5) = -(R_y x_c - R_x y_c) \tag{10}$$

Solving equations (5) to (10) we obtain

$$F_1 = -R_x \tag{11}$$

$$F_2 = -\frac{1}{4}R_z + \frac{1}{4x_2}\left[R_x\left(z_c - z_0\right) - R_z x_c\right] - \frac{1}{2y_0}\left[R_z y_c - R_y\left(z_c - z_0\right)\right] \tag{12}$$

$$F_3 = -\frac{1}{4}R_z + \frac{1}{4x_2}\left[R_x\left(z_c - z_0\right) - R_z x_c\right] + \frac{1}{2y_0}\left[R_z y_c - R_y\left(z_c - z_0\right)\right] \tag{13}$$

$$F_4 = -\frac{1}{2}R_z - \frac{1}{2x_2}\left[R_x\left(z_c - z_0\right) - R_z x_c\right] \tag{14}$$

$$F_5 = -\frac{1}{2}R_y + \frac{1}{2x_3}\left(R_y x_c - R_x y_c\right) \tag{15}$$

$$F_6 = -\frac{1}{2}R_y - \frac{1}{2x_3}\left(R_y x_c - R_x y_c\right) \tag{16}$$

3 Experimental Verification of Calibration Formulae

To verify the above formulae, a series of known forces were applied to the dynamometer at known locations. A vertical plate (DWG 875J40) was mounted to the dynamometer such that the locations of the cable attachment points are known with respect to origin O. Oblique forces $\mathbf{R}$ (i.e. having components in x, y and z directions) were applied at various known points C (one point for each test). A photograph is shown in Fig. 2. The loads in two directions was held constant at 20 kg, while the load in the third direction was varied from 0 to 75 kg for x or z directions, and 0 to 50 kg for y direction. There was a 5 kg pre-load and the load cell readings due to this were subtracted from the recorded readings. The load cell readings were then compared to the values calculated from equations (11) to (16). The calculated values of $F_1, \ldots, F_6$ were plotted against the measured values and the results are shown in Figs. 3 to 8. A least squares linear fit was used with the origin (0,0) added to the data points. These graphs can be used to relate the actual load cell readings to the theoretical values given by equations (11) to (16).

3.1 Experimental notes :

(1) *Positive* readings on load cells 1,2,3 and 4 correspond to *positive* values of F_1, F_2, F_3, F_4 respectively, i.e. *tensile* forces in the flex links apply loads on the dynamometer plate in the *positive* coordinate direction in each case.

(2) *Positive* readings on load cells 5 and 6 correspond to *negative* values of F_5 and F_6 respectively, i.e. *tensile* forces in the flex links apply loads on the dynamometer plate in the *negative* y direction.

(3) During an experimental test, two bolts holding the F_1 load cell were damaged and required replacement. In doing so, it was believed some mis-alignment had occurred and a re-calibration was recommended. The results from the first calibration, completed on July 19, 2002, and the second calibration, completed on July 24, 2002, are shown in Figs 3 to 8. Both calibrations show very good correlation between the calculated and measured load cell readings, indicating that the dynamometer performs extremely well for the determination of static loads.

4 Determination of Fluid Forces from Dynamometer Readings

The system of fluid forces S_{fluid} on the model induces the system of forces on the dynamometer plate S_{dyn} which consists of $\{\mathbf{F}_m\,(m = 1, \ldots, 6)\}$ (see Fig. 1). Since the model and dynamometer plate are in static equilibrium, the resultant of system S_{fluid} is the negative of the resultant system S_{dyn}. The system S_{dyn} is equivalent to (and can be replaced by) a single force $\mathbf{R}$ acting at some point C together with a couple vector $\mathbf{M}$ that is parallel to $\mathbf{R}$ (see Appendix). The equivalent system $\{\mathbf{R}$ at C , couple $\mathbf{M}\}$ is called a *wrench* or , more appropriately, a *screw*. Given the six dynamometer readings $\mathbf{F}_m\,(m = 1, \ldots, 6)$, we have the following algorithm for determining the resultant $\mathbf{R}$, its line of action given by the set of positions of the point of application C, and the couple $\mathbf{M}$ which is parallel to $\mathbf{R}$. The algorithm is based on the analysis presented in the Appendix.

(1) Evaluate $\mathbf{R}, \mathbf{M}_O$ as

$$\mathbf{R} = \sum_{m=1}^{6} \mathbf{F}_m = \begin{pmatrix} F_1 \\ F_5 + F_6 \\ F_2 + F_3 + F_4 \end{pmatrix} \tag{17}$$

$$\mathbf{M}_O = \sum_{m=1}^{6} \mathbf{OP}_m \times \mathbf{F}_m = \begin{pmatrix} y_0\,(F_2 - F_3) - z_0\,(F_5 + F_6) \\ z_0 F_1 + x_2\,(F_4 - F_2 - F_3) \\ x_3\,(F_6 - F_5) \end{pmatrix} \tag{18}$$

(2) Evaluate unit vectors $\mathbf{u}, \mathbf{w}, \mathbf{v}$ as

$$\mathbf{u} = \frac{\mathbf{R}}{\|\mathbf{R}\|} \tag{19}$$

$$\mathbf{w} = \frac{\mathbf{R} \times \mathbf{M}_O}{\|\mathbf{R} \times \mathbf{M}_O\|} \tag{20}$$

$$\mathbf{v} = \mathbf{w} \times \mathbf{u} \tag{21}$$

(3) Evaluate β as

$$\beta = \frac{\mathbf{M}_O \cdot \mathbf{v}}{\|\mathbf{R}\|} \qquad (22)$$

(4) Locate the point C in the $\mathbf{u}-\mathbf{w}$ plane by defining its position vector $\mathbf{OC}$ as

$$\mathbf{OC} = \alpha\mathbf{u} + \beta\mathbf{w} \qquad (23)$$

where α is an unspecified scalar parameter. The vector $\mathbf{OC}$ given by equation (23) defines a line, as the parameter α varies. This is the line of action of the force resultant $\mathbf{R}$. Its equation is written in terms of parameter α as

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \alpha \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} + \beta \begin{pmatrix} w_x \\ w_y \\ w_z \end{pmatrix} \qquad (24)$$

where the usual notation is used for the $x-y-z$ coordinates of vectors $\mathbf{u}$ and $\mathbf{w}$.

(5) Evaluate couple $\mathbf{M}$ as

$$\mathbf{M} = (\mathbf{M}_O \cdot \mathbf{u})\,\mathbf{u} \qquad (25)$$

(6) Since $S_{\text{dyn}} \equiv \{\mathbf{R} \text{ at } C \text{ , couple } \mathbf{M}\}$ we have $S_{\text{fluid}} \equiv \{-\mathbf{R} \text{ at } C \text{ , couple } -\mathbf{M}\}$

A MATLAB program implementing this procedure is given at the end of this report.

4.1 Example

Determine the fluid force-couple system acting on a model when the load cell readings are (in N) : $F_1 = 139.03$, $F_2 = 832.40$, $F_3 = -696.56$, $F_4 = 12.23$, $F_5 = 217.30$, $F_6 = 217.96$

Results : From the MATLAB program provided, the fluid load is a force $\mathbf{F}_{\text{fluid}} = -139.03\ \mathbf{i} - -435.26\ \mathbf{j} - 148.07\ \mathbf{k}$ (N) together with a couple $\mathbf{M}_{\text{fluid}} = 0.9291\ \mathbf{i} + 2.9088\ \mathbf{j} + 0.9895\ \mathbf{k}$ ($N.m$). The line of action of the force has the equation

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \alpha \begin{pmatrix} 0.2895 \\ 0.9062 \\ 0.3083 \end{pmatrix} + \begin{pmatrix} 0.0198 \\ 0.0543 \\ -0.1782 \end{pmatrix} \qquad (26)$$

where α is an arbitrary parameter.

5 Conclusions

(1) The calibration formulae given in equations (11) to (16) provide the theoretical load cell readings due to a known force $\mathbf{R}$ acting at a known point C, assuming there is no misalignment. If there is some

misalignment, graphs of calculated vs measured readings, such as in Figs 3 to 8, may be used to correct the measured readings.

(2) A given set of dynamometer readings $(F_1, \ldots, F_6)$ corresponds in general to a fluid force-couple system which can always be expressed as a wrench $\{\mathbf{R}, \mathbf{M}\}$ consisting of a resultant force $\mathbf{R}$ and couple $\mathbf{M}$ parallel to $\mathbf{R}$. The equation of the line of action of $\mathbf{R}$ is also determined. The point of application may be inferred from the intersection of this line with the model being tested.

6 Appendix : Reduction of a System of Forces to a Wrench

Let S be a system of N forces $\mathbf{F}_m$ acting at points P_m $(m = 1, \ldots, N)$. The objective is to replace S by an equivalent system S'consisting of a force $\mathbf{R}$ acting at a point C together with a couple $\mathbf{M}$ which is parallel to $\mathbf{R}$. The system S' is known as a *wrench* or *screw.*

Let O be an arbitrary point. We know that $\mathbf{F}_m$ acting at P_m is equivalent to $\mathbf{F}_m$ acting at O together with a couple of moment $\mathbf{OP}_m \times \mathbf{F}_m$. Hence the system S is equivalent to (and can be replaced by) a force $\mathbf{R}$ at O and a couple $\mathbf{M}_O$ where

$$\mathbf{R} = \sum_{m=1}^{N} \mathbf{F}_m \tag{27}$$

$$\mathbf{M}_O = \sum_{m=1}^{N} \mathbf{OP}_m \times \mathbf{F}_m \tag{28}$$

We now define an orthogonal triad of unit vectors at O as follows. In general, the vectors $\mathbf{R}$ and $\mathbf{M}_O$ are not parallel and define a plane. Let $\mathbf{u}$ be the *unit vector* along $\mathbf{R}$ i.e.

$$\mathbf{u} = \frac{\mathbf{R}}{||\mathbf{R}||} \tag{29}$$

The *unit vector* $\mathbf{w}$ normal to the $\mathbf{R} - \mathbf{M}_O$ plane is

$$\mathbf{w} = \frac{\mathbf{R} \times \mathbf{M}_O}{||\mathbf{R} \times \mathbf{M}_O||} \tag{30}$$

Define

$$\mathbf{v} = \mathbf{w} \times \mathbf{u} \tag{31}$$

Then $\mathbf{v}$ is a *unit vector* in the $\mathbf{R} - \mathbf{M}_O$ plane and $\mathbf{u}, \mathbf{v}, \mathbf{w}$ form an orthogonal triad of unit vectors (see Fig. A.1). Since $\mathbf{M}_O$ lies in the $\mathbf{u} - \mathbf{v}$ plane we write it in terms of $\mathbf{u} - \mathbf{v}$ components as

$$\mathbf{M}_O = (\mathbf{M}_O \cdot \mathbf{u})\, \mathbf{u} + (\mathbf{M}_O \cdot \mathbf{v})\, \mathbf{v} \tag{32}$$

Let C be any point and let its position vector, written in $\mathbf{u} - \mathbf{v} - \mathbf{w}$ coordinates, be

$$\mathbf{OC} = \alpha \mathbf{u} + \beta \mathbf{w} + \gamma \mathbf{v} \tag{33}$$

where $\alpha, \beta$and γ are scalars. Then the system $\{\mathbf{R}$ at O, couple $\mathbf{M}_O\}$ is equivalent to the system $\{\mathbf{R}$ at C, couple $\mathbf{M}\}$ where

$$\begin{aligned}\mathbf{M} = \mathbf{CO} \times \mathbf{R} + \mathbf{M}_O &= -(\alpha \mathbf{u} + \beta \mathbf{w} + \gamma \mathbf{v}) \times ||\mathbf{R}|| \mathbf{u} + (\mathbf{M}_O \cdot \mathbf{u})\, \mathbf{u} + (\mathbf{M}_O \cdot \mathbf{v})\, \mathbf{v} \\ &= -\beta ||\mathbf{R}|| \mathbf{v} + \gamma ||\mathbf{R}|| \mathbf{w} + (\mathbf{M}_O \cdot \mathbf{u})\, \mathbf{u} + (\mathbf{M}_O \cdot \mathbf{v})\, \mathbf{v}\end{aligned} \tag{34}$$

We now choose the point C such that

$$\beta = \frac{\mathbf{M}_O \cdot \mathbf{v}}{\|\mathbf{R}\|} \text{ and } \gamma = 0 \tag{35}$$

with α unspecified. Then from (34) we have

$$\mathbf{M} = (\mathbf{M}_O \cdot \mathbf{u})\,\mathbf{u} \tag{36}$$

which is parallel to $\mathbf{R}$. The system S is therefore equivalent to the system $\{\mathbf{R}$ at C, couple $\mathbf{M}\}$ with $\mathbf{M}$ parallel to $\mathbf{R}$.

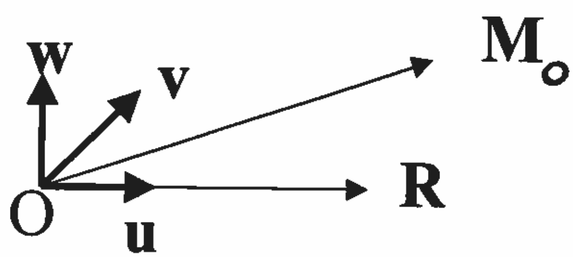


Fig. A.1

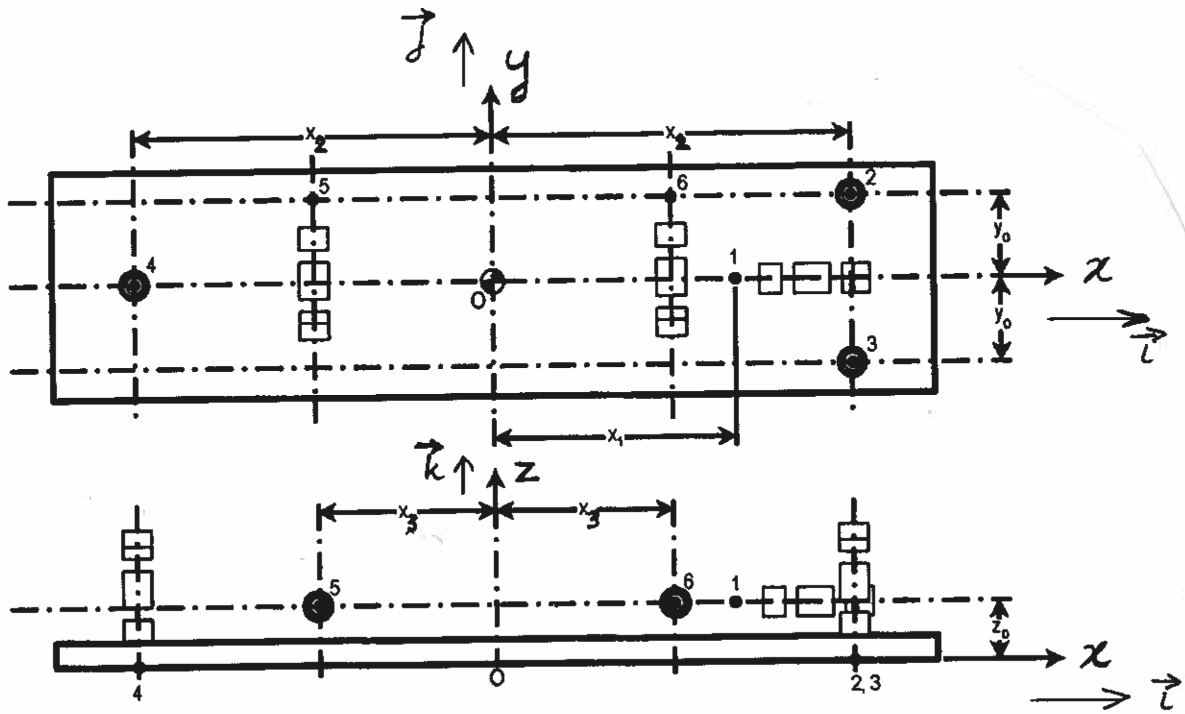


Figure 1. Schematic of Load Cell and Flex-link Layout in Dynamometer

Table 1. Measured Distances for Dimensions in Figure

Dimension	Distance (mm)
x_1	209.8
x_2	305.5
x_3	152.5
y_0	70.0
z_0	51.4

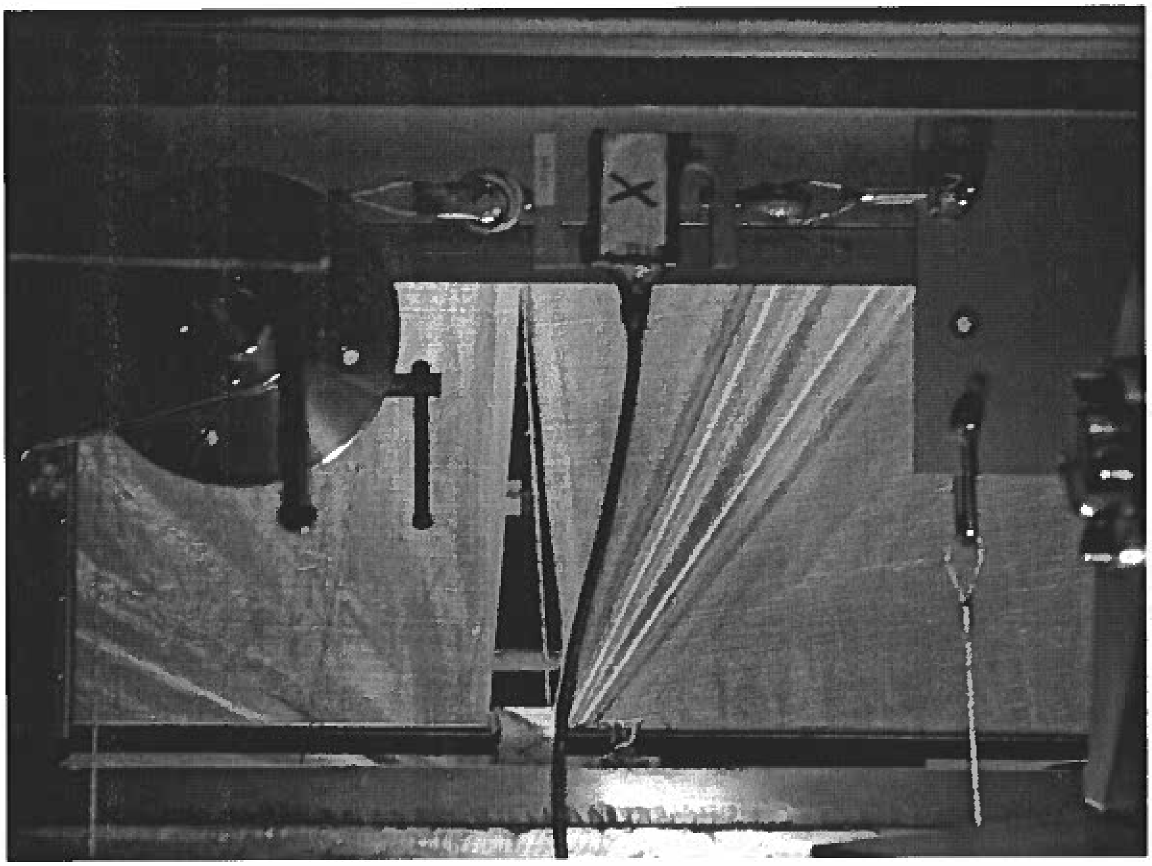


Figure 2. Set-up for static calibration of dynamometer

Figure 3. F1 Calibration Curve

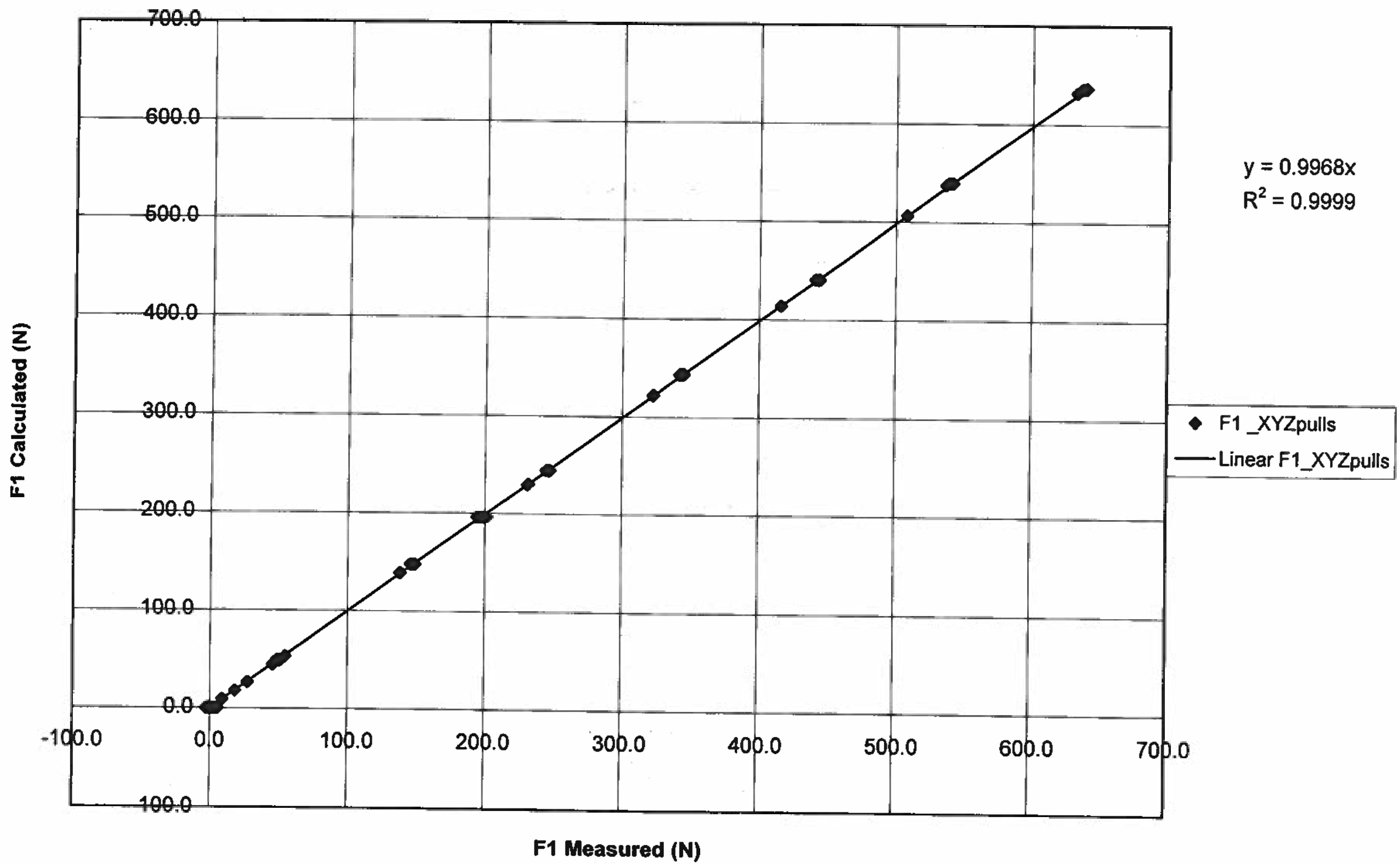


Figure 4. F2 Calibration Curve

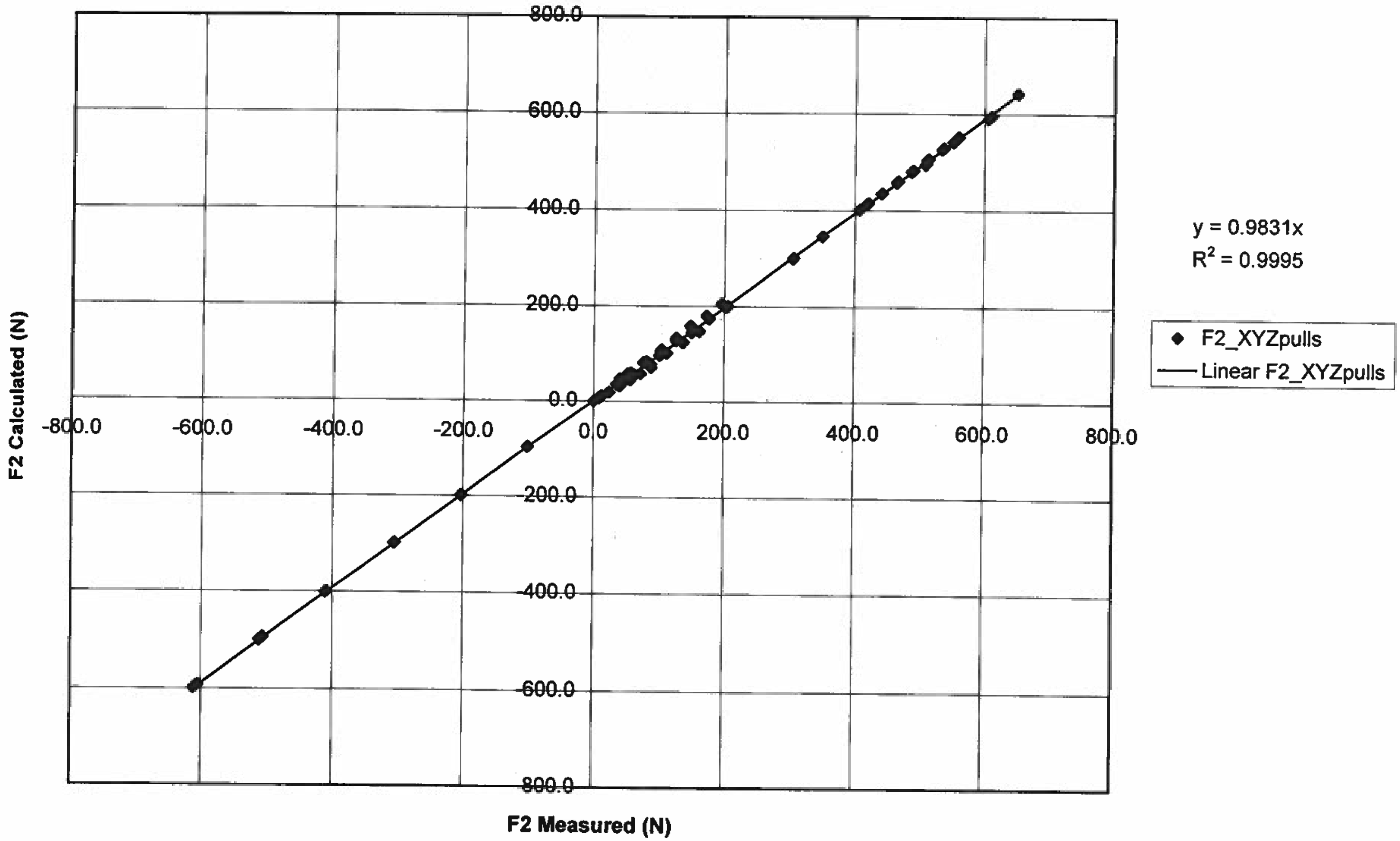


Figure 5. F3 Calibration Curve

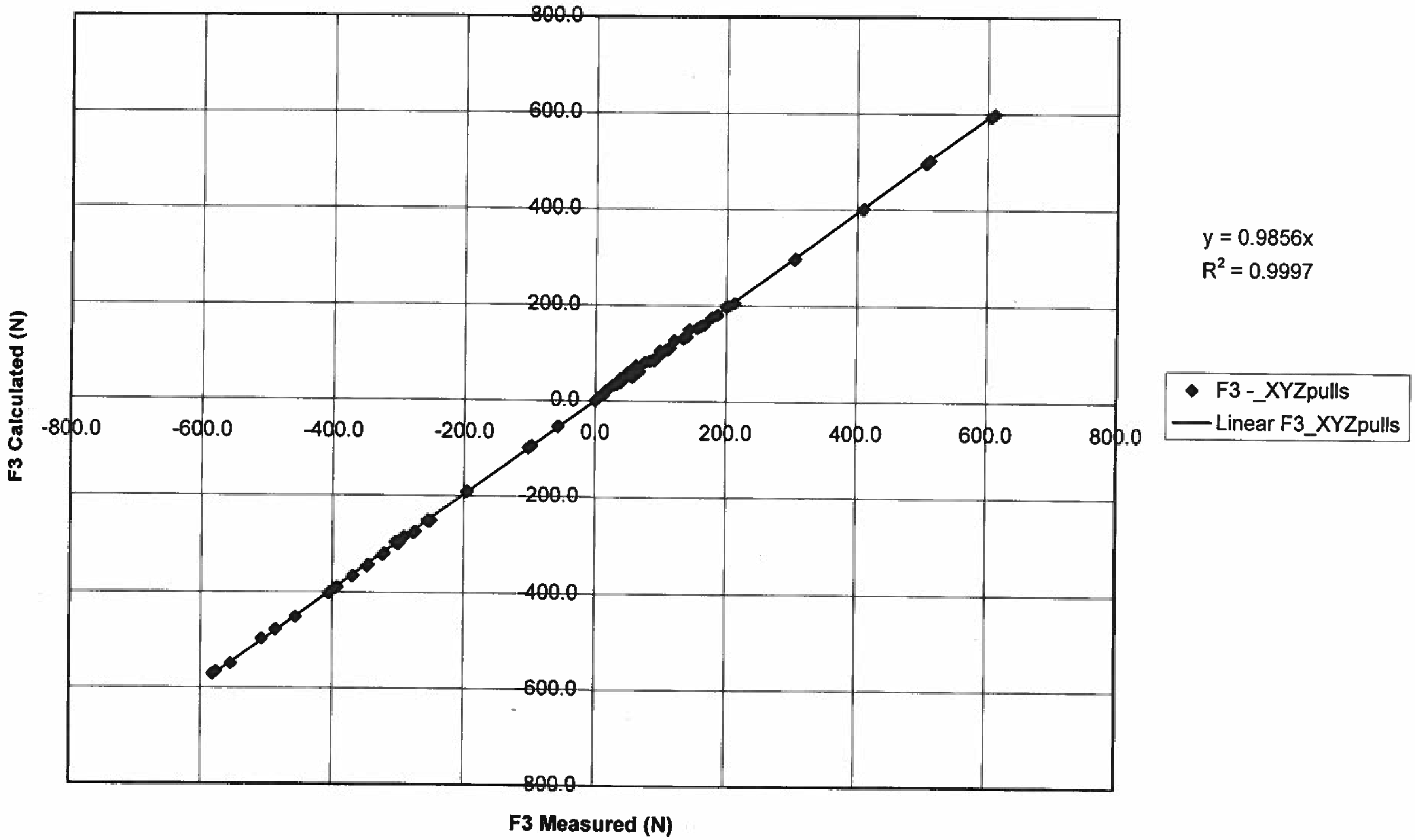


Figure 6. F4 Calibration Curve

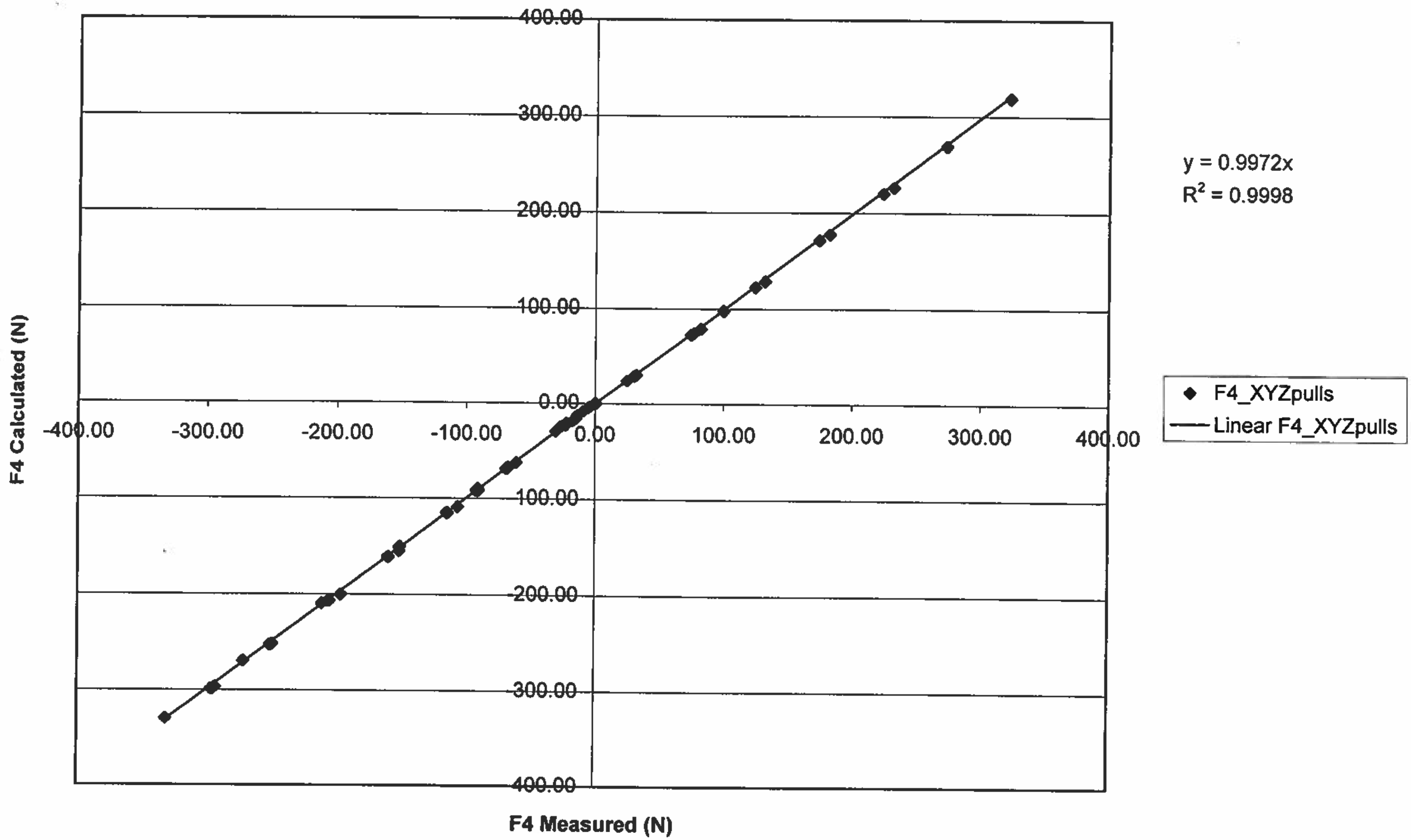


Figure 7. F5 Calibration Curve

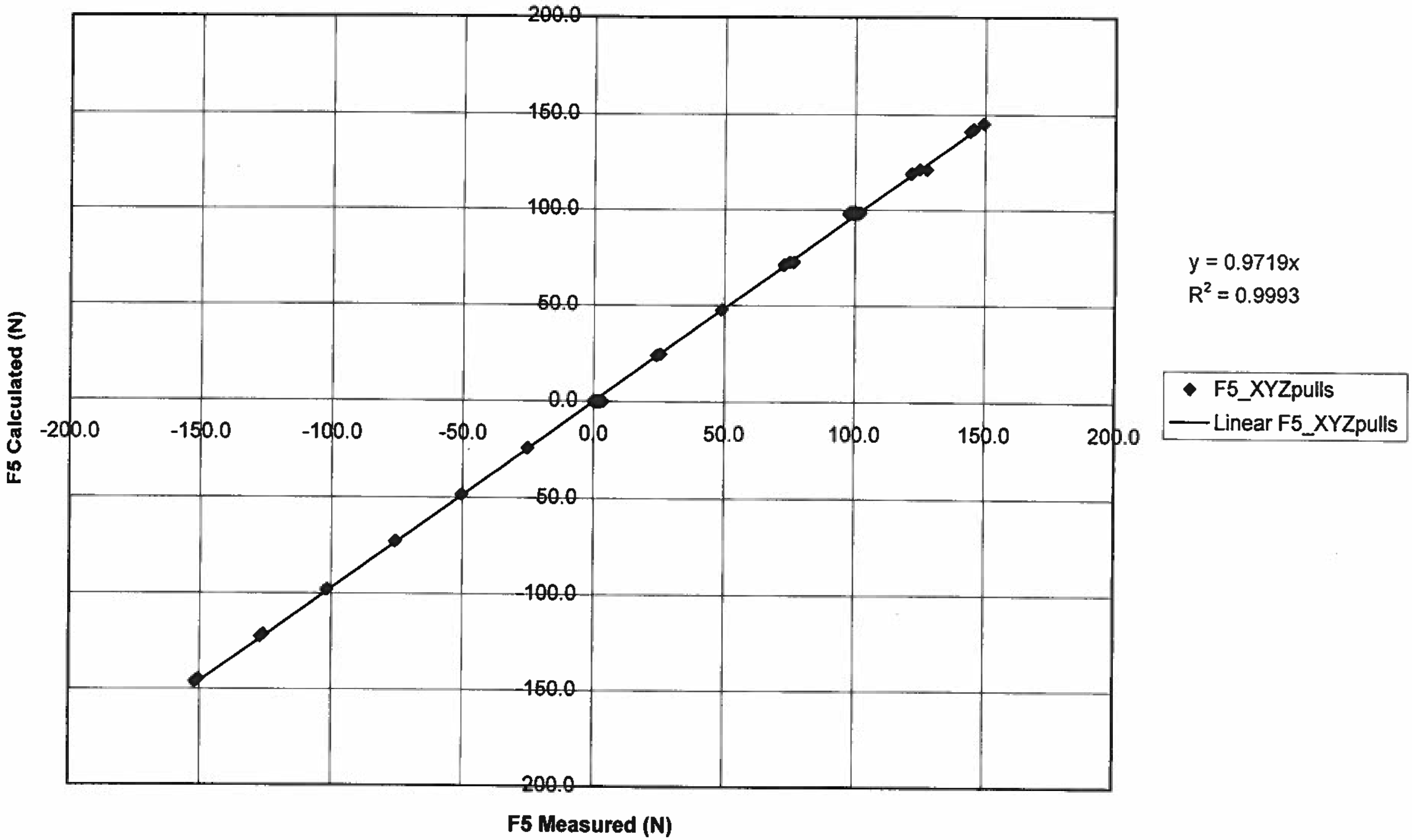
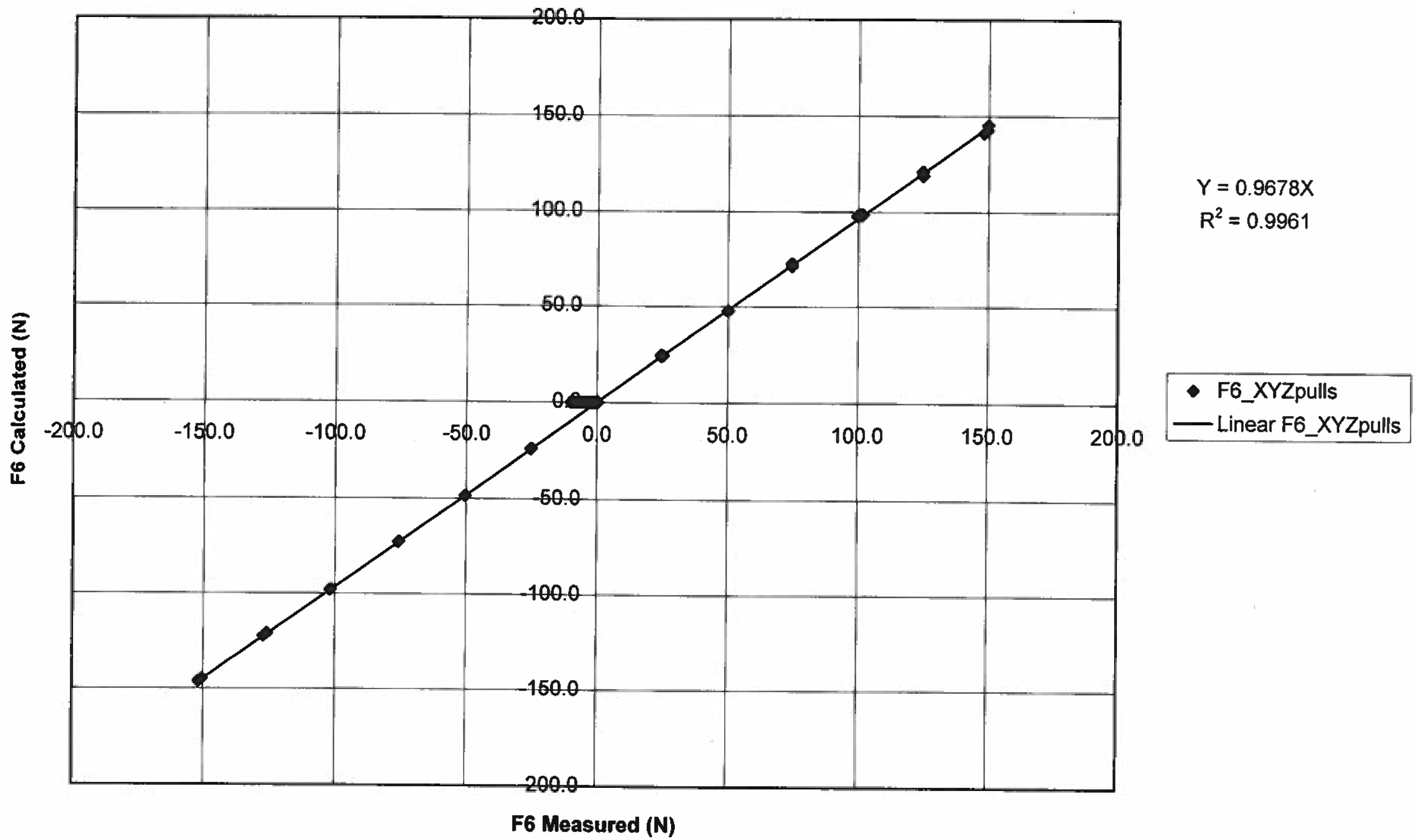


Figure 8. F6 Calibration Curve



```
% Determination of Fluid Loads from Dynamometer Readings (Cavitation Tunnel
Dynamometer)
% W. Raman-Nair, Institute for Marine Dynamics, May 2002
% The system of 6 forces acting on the dynamometer plate is equivalent to a wrench
(screw)
% consisting of a force R and a couple M which is parallel to R. The equation of the line of
action of R is determined.
% The fluid loads on the model are therefore equal and opposite to the system {R,M}

clear all
% Dynamometer characteristics : See diagram
x1=0.2098;
x2=0.3055;
x3=0.1525;
y0=0.070;
z0=0.0514;

%********************************************************
% Dynamometer readings interpreted as forces acting ON dynamometer plate : See
diagram
% Tensile forces (positive readings)in load cells 1,2,3,4 indicate positive F1,F2,F3,F4
% Tensile forces (positive readings) in load cells 5 and 6 indicate negative F5 and F6
F1=139.03;
F2=832.40;
F3=-696.56;
F4=12.23;
F5=217.30;
F6=217.96;
%********************************************************

R=[F1 F5+F6 F2+F3+F4];
M0=[y0*(F2-F3)-z0*(F5+F6) z0*F1+x2*(F4-F2-F3) x3*(F6-F5)];

Rmod=sqrt( R(1)^2+R(2)^2+R(3)^2 );
uu=R/Rmod;% Unit vector along R
RM0=cross(R,M0);
RM0mod=sqrt( RM0(1)^2+RM0(2)^2+RM0(3)^2 );
ww=RM0/RM0mod;% Unit vector perpendicular to the R-M0 plane
vv=cross(ww,uu);% Unit vector in the R-M0 plane normal to uu
beta=M0*vv'/Rmod;
M=(M0*uu')*uu;% Couple vector parallel to R
p=(M0*uu')/Rmod;% p=pitch of screw defined by the relation M=p*R
% The equation of the line of action of R in terms of a parameter alpha is
% [x y z]=alpha*uu+beta*ww

% Outputs
F_readings=[F1 F2 F3 F4 F5 F6]
F_fluid=-R
M_fluid=-M
uu
'beta*ww',beta*ww
'The equation of the line of action of R in terms of a parameter alpha is'
'[x y z]=alpha*uu+beta*ww'
%************************************************************************************************
```