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Development of a Five-Component Strain-Gauge Balance for the DSTO Water Tunnel

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ABSTRACT

This report gives details of a five-component strain-gauge balance that has been developed to measure flow-induced loads on models in the DSTO water tunnel. The loads are very small and the balance was designed to measure side and normal forces, as well as rolling, pitching and yawing moments, within the ranges ±25 N, ±25 N, ±0.1 N.m, ±0.2 N.m and ±0.2 N.m respectively. These loads are at least 2 to 3 orders of magnitude smaller than those typically measured on aircraft models in the low-speed wind tunnel at DSTO. The balance has not been designed to measure axial forces. Due to the small loads, it was necessary to use semi-conductor strain gauges on the balance. The five-component balance has been developed using similar design principles to a two-component balance developed earlier at DSTO for use in the water tunnel.

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Executive Summary

The Defence Science and Technology Organisation (DSTO) water tunnel in Air Vehicles Division has been used extensively over the years to carry out aerodynamic research investigations. The tunnel has primarily been used to observe detailed flow patterns over models, such as aircraft, missiles, ships and submarines. In recent times, the ancillary equipment used with the tunnel has been developed and improved, enabling new types of measurements to be taken. As part of this upgrade, a low-range five-component strain-gauge balance has been developed, enabling very small flow-induced forces and moments on models to be measured. This followed the successful implementation of a two-component balance into the tunnel. Both balances have been built using similar design methods.

The new balance can be used to measure side and normal forces, as well as rolling, pitching and yawing moments, within the ranges ±25 N, ±25 N, ±0.1 N.m, ±0.2 N.m and ±0.2 N.m respectively. These loads are at least 2 to 3 orders of magnitude smaller than those typically measured on aircraft models in the low-speed wind tunnel at DSTO. The balance was not designed to measure axial forces, since such forces on water-tunnel models cannot be scaled to correspond to those on full-size vehicles in air. The reason for this is that boundary layers on water-tunnel models are laminar whereas those on full-size vehicles are generally turbulent, i.e. there are different drag characteristics for the two cases. Semi-conductor strain gauges have been used on the new balance, as for the two-component balance. The balance was calibrated manually using a conventional dead-weight procedure, whereby different types of forces and moments were systematically applied to the balance and corresponding output voltages from the five channels were measured, enabling the calibration relationships to be determined. For a first-order calibration, the standard errors were found to be less than 0.1% for the different load components, suggesting that loads measured by the water-tunnel balance will be of acceptable accuracy. Details of the design, manufacture and calibration of the five-component balance are given in this report.

Authors

Lincoln P. Erm
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Lincoln Erm obtained a Bachelor of Engineering (Mechanical) degree in 1967 and a Master of Engineering Science degree in 1969, both from the University of Melbourne. His Master's degree was concerned with the yielding of aluminium alloy when subjected to both tensile and torsional loading. He joined the Aeronautical Research Laboratories (now called the Defence Science and Technology Organisation) in 1970 and has worked on a wide range of research projects, including the prediction of the performance of gas-turbine engines under conditions of pulsating flow, parametric studies of ramrocket performance, flow instability in aircraft intakes and problems associated with the landing of a helicopter on the flight deck of a ship. Concurrently with some of the above work, he studied at the University of Melbourne and in 1988 obtained his Doctor of Philosophy degree for work on low-Reynolds-number turbulent boundary layers. Since this time, he has undertaken research investigations in the low-speed wind tunnel and the water tunnel. Recent work has been concerned with extending the testing capabilities of the water tunnel, including developing a two-component strain-gauge-balance load-measurement system for the tunnel and developing a dynamic-testing capability for the tunnel.

Phil Ferrarotto
Air Vehicles Division

Phil Ferrarotto obtained a degree in Electronic Engineering from Swinburne University in 1980. Prior to obtaining the degree, Phil worked in the Instrumentation Section of the Aerodynamics Division of the Aeronautical Research Laboratories. Most of the work he was associated with was related to the Instrumentation requirements of the 9 foot by 7 foot working section of the wind tunnel and inevitably involved the use of micro processors to control measuring devices associated with model orientation and positioning in the tunnel. In 1982 he moved on from there to the Structures Division where he has been involved in Structural Instrumentation for large fatigue testing of both fixed-wing and rotary-wing aircraft and Naval craft. Specifically he has designed and manufactured the transducers required to measure and control the buffet loads applied by the Electrodynamic Shakers used in the successful IFOSTP (International Follow on Structural Test Program) Test for the F/A-18. He has accumulated detailed knowledge in Strain Gauge Instrumentation relative to fatigue testing and for use in field testing aircraft and seacraft.

Contents

Notation

$[A]$	Matrix defined by equation A19.
$[E]$	Matrix defined by equation A18.
e	Sum of squares of residuals, (used when calculating calibration coefficients for a strain-gauge balance).
F_x, F_y, F_z	Axial, side and normal forces respectively associated with the balance and the model coordinate systems, (N). Positive directions are given in Figure 3.
f	Number of degrees of freedom in the calibration equations.
H	Load applied to a strain-gauge balance.
$\tilde{H}$	Load estimated using a calibration equation.
K	Gauge factor of a strain gauge, $K = (\Delta R / R) / (\Delta L / L)$
L, ΔL	Length of a strain-gauge, change in length of a gauge under load (m).
M_x, M_y, M_z	Rolling, pitching and yawing moments respectively associated with the balance and the model coordinate systems, (N.m). Positive directions are given on Figure 3.
N	Total number of points used in a calibration.
P	Index of summation.
R, ΔR	Electrical resistance of a strain-gauge, change in resistance of a gauge under load (Ω).
R	Voltage ratio, $R = V_{OUT} / V_{IN}$.
se	Standard error, used to assess the accuracy of a calibration.
V_{OUT}, V_{IN}	Output and input voltages respectively for a channel on a strain-gauge balance, (V).
x, y, z	Axes for the balance and model coordinate systems. Positive directions are given in Figure 3.

Subscripts

2, 3, 4, 5, 6	Refer to channels 2 to 6 on the five-component strain-gauge balance.

1. Introduction

Equipment used with the water tunnel at the Defence Science and Technology Organisation (DSTO) has recently been developed and improved to enable new types of measurements to be obtained. As part of the upgrade, a technique has been developed to measure the very small flow-induced pressures on the surface of models in the tunnel (see Erm, 2000). A low-range two-component strain-gauge balance system has also been manufactured, enabling the very small flow-induced normal forces and pitching moments on models in the tunnel to be measured (see Erm, 2006 a). A dynamic-testing capability has also been developed, enabling loads to be measured on a model while it is in motion, undergoing a specified dynamic manoeuvre (see Erm, 2006 b).

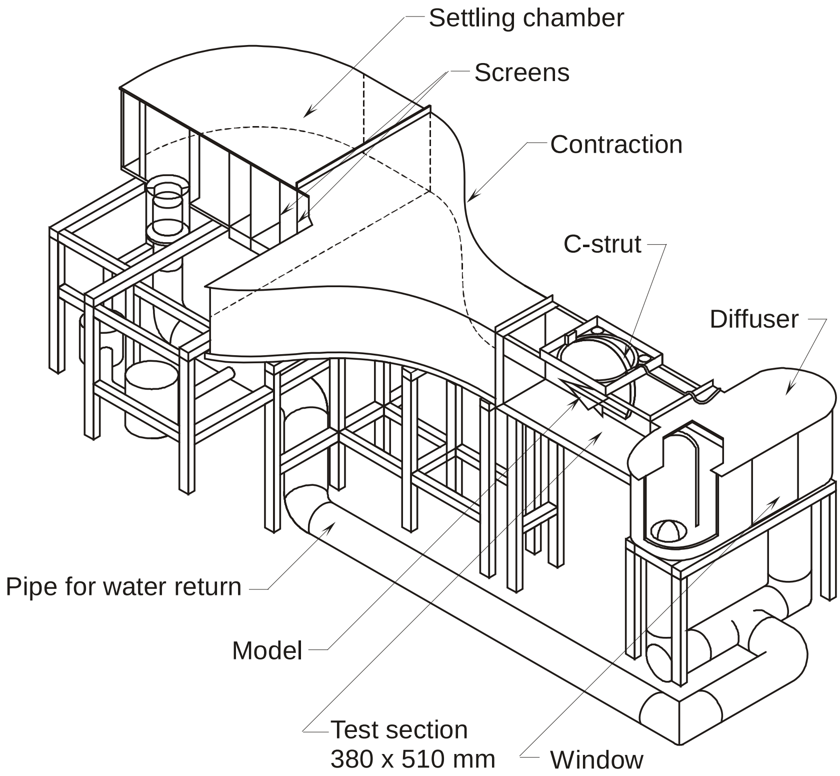
Following the successful commissioning of the two-component balance, a five-component balance has now been built using similar design methods. Once again, semi-conductor strain gauges have been used on the balance. The new balance can be used to measure side and normal forces, as well as rolling, pitching and yawing moments, within the ranges ±25 N, ±25 N, ±0.1 N.m, ±0.2 N.m and ±0.2 N.m respectively. The balance has not been designed to measure axial forces, since scaled tangential skin-friction drag forces on water-tunnel models are not representative of those on full-size aircraft. The reason for this is that boundary layers on models in water tunnels are generally laminar, whereas corresponding boundary layers on full-size vehicles are predominantly turbulent. By restricting the balance to the above five components (no capability to measure axial forces), it is generally not possible to measure lift forces on models, which are normal to the direction of the free-stream velocity. This is a major shortcoming of this and other water-tunnel balances. However, the balance significantly increases the usefulness of the tunnel, since it is still possible to measure a wide range of different types of loads on models, while simultaneously capturing images of the flow over the models, enabling the loads and the flow patterns to be correlated directly. Details of the design, manufacture and calibration of the five-component balance are given in this report.

2. DSTO Water Tunnel

The DSTO water tunnel was manufactured by Eidetics International Incorporated[1] and is designated Model 1520. The tunnel, shown in Figure 1, has a horizontal-flow test section 380 mm wide, 510 mm deep and 1630 mm long. It is a recirculating closed-circuit tunnel and there is a free water surface in the test section. The side walls and floor of the test section are made from glass to facilitate flow-visualisation studies. The free-stream velocity in the test section can be varied between 0 and 0.6 m/s. The contraction upstream of the test section has an inlet/outlet area ratio of 6:1. There are six dye canisters on the tunnel that can be pressurised with air to force dye through plastic tubes to selected locations on a model for flow-visualisation studies. There is a suction pump on the tunnel that can be used to suck or blow water through models, such as when studying the effects of intake flows on the aerodynamic performance of an aircraft. Models are mounted on a C-strut so that the required

[1] Now called Rolling Hills Research Corporation, 420 N. Nash St., El Segundo, CA 90245, USA.

centre of rotation of a model is at the centre of the imaginary circle formed by the strut, ensuring that all angular motion of the model is about this point. The model supporting system is attached to the top of the test section by a hinge, so that a model can be lowered into the test section, or removed from the test section, as required. Further details of the tunnel are given by Erm (2006a).



(a)

(b)

Figure 1: Eidetics Model 1520 water tunnel. (a) diagrammatic view of the tunnel, (b) photograph of the tunnel

3. Strain-Gauge Balance

A sensitive five-component strain-gauge balance, shown in Figure 2, has been designed, manufactured and calibrated to measure side and normal forces, as well as rolling, pitching and yawing moments. The construction of the balance is based on the traditional cantilever-beam type of design, and consists of a system of precisely-machined flexure members upon which strain gauges are attached. The dimensions of the flexure members and the likely deflection of the balance under load were determined using a finite-element analysis. The balance is an integral unit, machined out of stainless steel rod, having a specification AISI 630 Condition H480. A model is attached to the balance at its tapered end, and the other end of the balance is mounted on a tunnel supporting system, such as a roll-pitch-yaw rig. When the model is loaded, the surface strains in the flexure members cause the attached strain gauges to deform. This causes the resistances of the gauges to change, which in turn affects the output voltages of the gauges. Loads on a model can then be determined using balance calibration relationships (see Section 6). Basic principles of balance construction and operation are given, for example, by Edwards (2000).

The flow-induced loads on aircraft models in the water tunnel are small by conventional wind-tunnel standards, and the balance has been designed to measure side and normal forces within the range ±25 N, rolling moments within the range ±0.1 N.m, and pitching and yawing moments within the range ±0.2 N.m. The load ranges were determined by scaling force and moment data measured on full-size combat aircraft during manoeuvres. For comparison, the balances used in the DSTO low-speed wind tunnel (LSWT) are typically designed to measure normal forces and pitching moments within the ranges ±3500 N and ±300 N.m respectively.

The relatively low free-stream velocities used in the water tunnel will produce corresponding small loads on the models. The need to detect such small loads necessitated the use of semi-conductor strain gauges, having a resistance of 1000 Ω, a gauge factor of 145, and dimensions of 1.27 mm by 0.15 mm (active area, length by width). The gauge factor, K, is given by $(\Delta R / R)/(\Delta L / L)$, where R is the resistance of a strain gauge, ΔR is the change in the resistance of the gauge under a load, L is the length of the gauge, and ΔL is the change in length of the gauge. The gauges were manufactured by PSI-TRONIX Incorporated[2] and the model number of the gauges is P01-05-1000. The balance contains 4 gauges in each of 5 different channels, to measure the 5 different load components, so that there are 20 gauges on the balance. The positioning of the gauges on the flexure members for each of the 5 channels is as shown in Figure 3. For the rolling-moment channel, gauges are positioned at 45° on the upper and lower flexure members (but not the side flexure members). The four gauges for each channel have been positioned on flexure members and wired together in a Wheatstone-bridge configuration to minimise the output response of each bridge due to other load components, i.e. cross coupling. However, in practice, there is a small amount of cross coupling (see Figure 7) and the different load components are computed using the outputs from all 5 channels.

[2] PSI-TRONIX Incorporated, 3950 South “K” Street, Tulare, CA, 93274, USA.

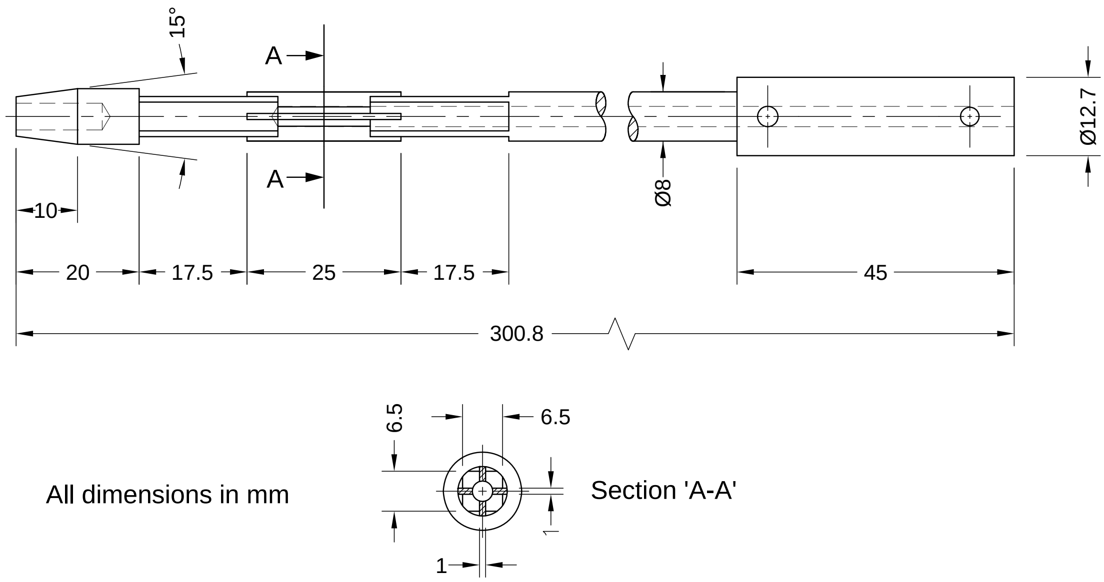


Figure 2: Five-component balance, showing the main dimensions

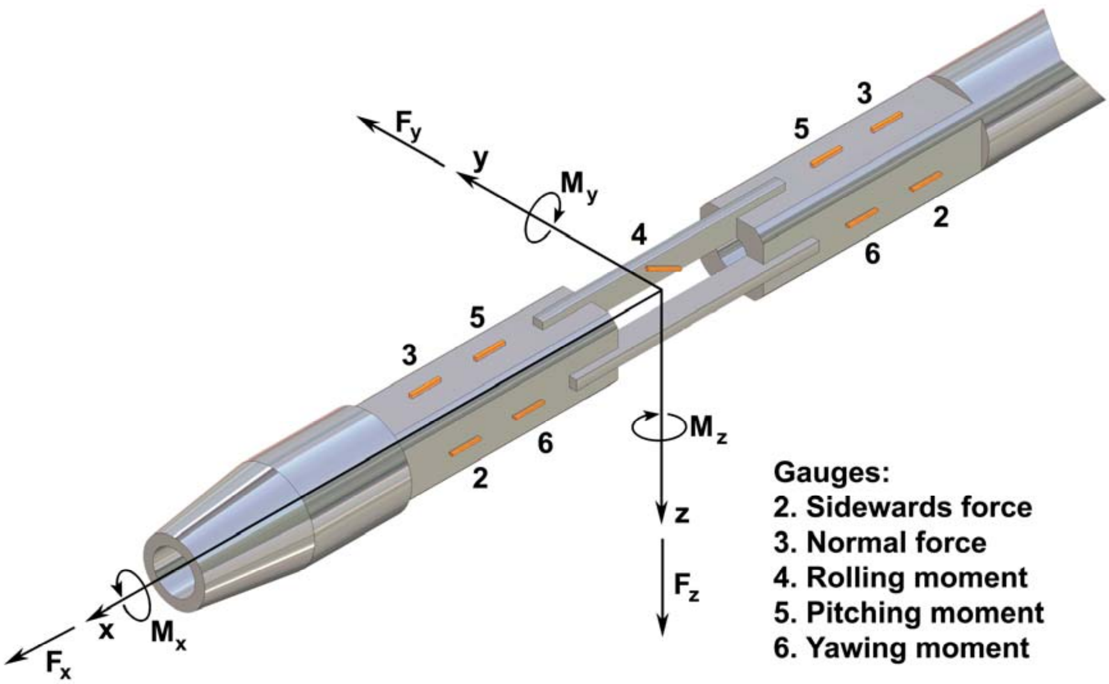


Figure 3: Five-component strain-gauge balance, showing the position of the gauges for the different channels

The right-handed orthogonal balance coordinate system is shown in Figure 3. The coordinate system remains fixed to the balance, with the origin located on the longitudinal axis of the balance at the geometric centre of the gauges. The directions of the corresponding forces and moments are as shown, with the positive directions of the moments determined by the right-hand screw rule about the respective axes.

The strain gauges have been glued onto the balance using a bonding material designated M-BOND 600[3], which is the same as that used for conventional strain gauges. The gauges and the connecting leads have been waterproofed by coating them with a compound designated M-coat C[3], a solvent-thinned (naphtha) RTV (room temperature vulcanising) silicone rubber. For additional waterproofing, the gauges and leads were also covered with a thin sleeve made from silicone rubber. It was important to use a thin sleeve, since previously it was found that a thick sleeve stiffened the balance and caused it to exhibit hysteretic behaviour during oscillating loading. Figure 4 shows the gauges glued onto the balance prior to waterproofing. The gauges were found to be slightly sensitive to both temperature and light, but this did not have any significant effect on measured data. When gauges are wired in a Wheatstone-bridge configuration, the effects of temperature on the different gauges ideally nullify each other, so that there is no resultant change in bridge output voltage, provided that all gauges are subjected to the same temperature. The temperature of the water in the tunnel was very stable, varying typically by less that 0.2°C throughout a day, and the balance was mounted deep inside a model when testing, well protected from strong light sources used when visualising the flow.

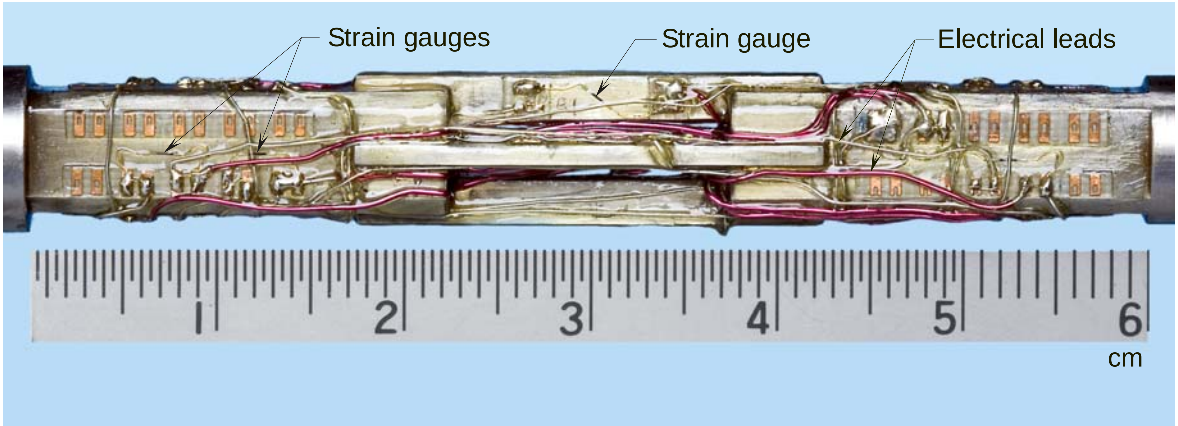


Figure 4: Five-component strain-gauge balance, showing gauges and leads, prior to waterproofing

4. Signal-Conditioning System

An existing six-channel signal-conditioning system was modified and recommissioned for use with the water-tunnel five-component balance. The system can be used to null, amplify and filter output voltages from the Wheatstone bridges on the balance, before the signals are sampled by a PC-based data-acquisition system (see Section 5). A simplified circuit diagram of one of the bridges, the power supplies, a nulling unit, an amplifier, a filter, and the data-acquisition system, are shown diagrammatically in Figure 5.

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[3] M-BOND 600 and M-Coat C are manufactured by Vishay.

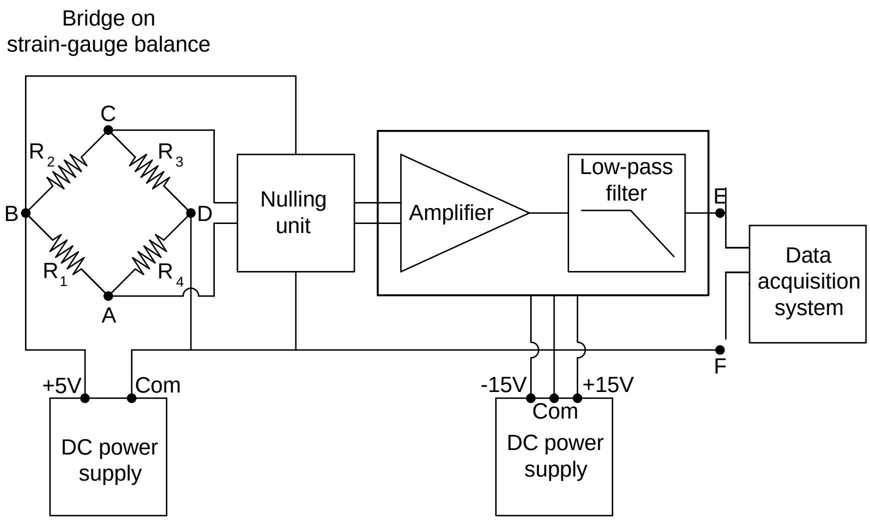

Figure 5: Simplified circuit diagram of a bridge on the balance, together with ancillary components

An adjustable power supply is used to provide a +5.0 V DC excitation voltage to the strain-gauge bridges and the nulling units, and another power supply is used to provide a ±15 V DC excitation voltage to the amplifiers and filters. Each channel contains a bridge nulling unit, with both coarse and fine adjustments, which can be used to null the output voltage from a Wheatstone bridge, i.e. the bridge output voltage can be set to 0 V. Each channel also contains an amplifier, whose gain can be set to 100, 200, 400, 500 1000 or 2000, as well as a third-order Butterworth low-pass filter whose 3 dB cut-off frequency can be set to 1, 2, 5, 10, 20, 50, 100, 200 or 500 Hz. The filter can also be switched out, in which case the cut-off frequency of the filter is about 50 kHz, which is the inherent bandwidth of an amplifier.

When nulling a bridge, the voltage at the output of a filter (points E and F on Figure 5) is monitored rather than the voltage at the output of the bridge (points A and C on Figure 5). The voltage at the output of the filter can be read from a dial on a console, or alternatively, can be read by connecting a voltmeter across the terminals labelled OUTPUT on the console. A sampling program, named NULL BALANCE, based on LabVIEW[4] software, has also been developed so that the voltage can be read on a monitor using a graphical user interface.

5. PC and Data-Acquisition Card

The PC used has a Windows™ XP Professional operating system, a 3.2 GHz central processing unit, a 220 GB hard disk drive and 1 GB of RAM.

The data-acquisition card interfaced with the PC was manufactured by National Instruments™ and the product code is NI 6013. The card features 16 channels (8 differential) of 16-bit analogue input, a 68 pin connector and 8 lines of digital input/output. Analogue

[4] LabVIEW™, a graphical programming language, is a product of National Instruments.

input voltages varying between –5 V and +5 V can be sampled. For the 16-bit card, the resolution of the sampled voltages is $10.0/2^{16}$, i.e. $10.0/65536 = 0.000153$ V/LSB = 0.153 mV/LSB (LSB denotes least significant bit).

6. Calibration of the Strain-Gauge Balance

6.1 Balance Calibration Equations

The format of the calibration relationships depends upon which particular balance calibration model or set of equations is chosen to represent the data. There are a number of different sets of equations that can be used, but the one currently used at DSTO for the wind-tunnel balances assumes that balance output voltages are functions of the calibration coefficients and the applied loads (see Lam 1989, Leung & Link 1999, Blandford 2004). This model is also used for the water-tunnel balances.

Ideally, the output voltage from say the normal-force channel is only affected by the normal force applied to the balance, and similarly for other channels. However, in practice, balances are not ideal and there may be interactions between the different channels, so that the output voltage from each channel generally depends on all of the load components applied to the balance.

For the five-component balance, the calibration is always described by five different equations, but the number of terms in each equation can vary depending on whether the equations are first-order, second-order, third-order and so on. A first-order calibration is described in this report. The first-order equations will also be used for actual measurements in the water tunnel.

The calibration procedure (see Section 6.2) would have been complicated significantly by using a second- or third-order calibration. It would have been necessary to apply two or more load components simultaneously during calibration (such as loads applied in the y and z directions). For a well-designed balance, second- and third-order terms are small. For the first-order calibration used, the standard errors for the balance were found to be small, being less than 0.1% for the different load components (see Section 6.5), showing that such a calibration is adequate for the type of testing to be undertaken in the water tunnel.

The five first-order equations are given by

$$R_2 = C_{2,2}H_2 + C_{2,3}H_3 + C_{2,4}H_4 + C_{2,5}H_5 + C_{2,6}H_6 \tag{1}$$
$$R_3 = C_{3,2}H_2 + C_{3,3}H_3 + C_{3,4}H_4 + C_{3,5}H_5 + C_{3,6}H_6 \tag{2}$$
$$R_4 = C_{4,2}H_2 + C_{4,3}H_3 + C_{4,4}H_4 + C_{4,5}H_5 + C_{4,6}H_6 \tag{3}$$
$$R_5 = C_{5,2}H_2 + C_{5,3}H_3 + C_{5,4}H_4 + C_{5,5}H_5 + C_{5,6}H_6 \tag{4}$$
$$R_6 = C_{6,2}H_2 + C_{6,3}H_3 + C_{6,4}H_4 + C_{6,5}H_5 + C_{6,6}H_6 \tag{5}$$

R_2, R_3, R_4, R_5 and R_6 are the voltage ratios for channels 2 to 6, i.e. the output voltages from the channels divided by the corresponding input voltages to the channels ($R \equiv V_{OUT} / V_{IN}$). The H terms are the corresponding applied loads and the C terms are the calibration coefficients. Note that there are no terms for axial forces (subscript 1) for the five-component balance.

The five first-order equations, expressed in matrix form, are given by

$$\begin{bmatrix} R_2 \\ R_3 \\ R_4 \\ R_5 \\ R_6 \end{bmatrix} = \begin{bmatrix} C_{2,2} & C_{2,3} & C_{2,4} & C_{2,5} & C_{2,6} \\ C_{3,2} & C_{3,3} & C_{3,4} & C_{3,5} & C_{3,6} \\ C_{4,2} & C_{4,3} & C_{4,4} & C_{4,5} & C_{4,6} \\ C_{5,2} & C_{5,3} & C_{5,4} & C_{5,5} & C_{5,6} \\ C_{6,2} & C_{6,3} & C_{6,4} & C_{6,5} & C_{6,6} \end{bmatrix} \begin{bmatrix} H_2 \\ H_3 \\ H_4 \\ H_5 \\ H_6 \end{bmatrix} \tag{6}$$

Equation 6 can be expressed in a simplified matrix form as follows:

$$[R] = [C]\,[H] \tag{7}$$

6.2 Acquisition of Calibration Data

The balance was calibrated manually using the experimental setups shown in Figure 6. Figure 6a shows the setup used for applying side forces, normal forces, pitching moments and yawing moments, and Figure 6b shows the setup used for applying rolling moments. The balance was clamped onto a calibration supporting rig (not shown) so that its centreline was horizontal. A calibration cage was bolted onto the model end of the balance at the tapered adaptor (see Figures 2 and 3). The roll angle of the balance and the attached cage was set to either 0º, 90º, 180º or 270º, as appropriate. The only contact between the balance and the cage was at the tapered adaptor. For the setup shown in Figure 6a, a pan was suspended from a knife edge along the top of the cage. Forces and moments were applied to the balance by placing weights in the pan when it was positioned at different x locations along the balance. For the setup shown in Figure 6b, the pan was suspended from a rod attached, in turn, to both sides of the cage, and forces and moments were applied to the balance by placing weights in the pan when it was positioned at different y locations along the rod. The maximum forces and moments applied to the balance during a calibration were chosen to correspond to the range of loads likely to be experienced by a model during subsequent tests.

Details of the loading schedule corresponding to the current calibration are given in Table 1. Weights were progressively added to the pan, and then progressively removed, for the pan positioned at different positions as shown. Altogether there were 14 different loading/ unloading sequences, each using 15 different loads (which includes 0 g). Prior to commencing each loading sequence, when there were no weights in the pan, the output voltages from the five channels were nulled, i.e. the bridge output voltages were set close to 0.0 V. The method used to null the bridges is described in Section 4. For each of the 15 loads used, the output voltages from the five channels were sampled 20 times at 0.1 s intervals and each set of 20 samples was then averaged to obtain mean values. Altogether, 210 calibration points were taken for each channel (15 loads for each of 14 loading sequences).

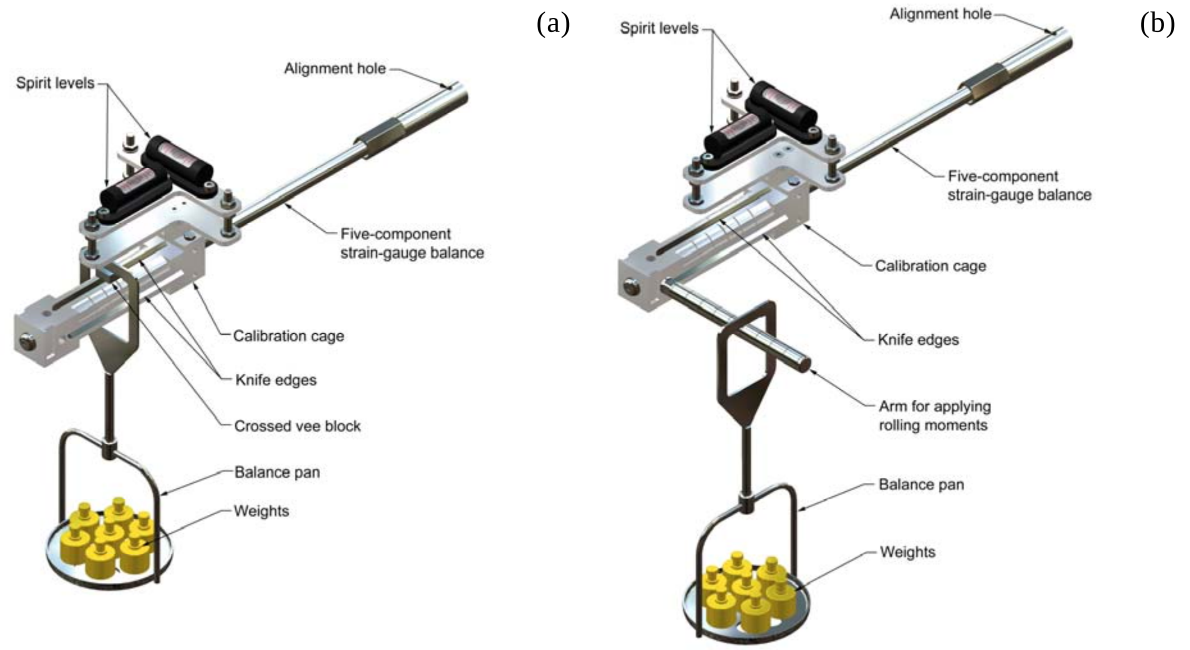

Figure 6: Experimental setup used when calibrating the five-component balance. (a) setup for applying side and normal forces, pitching and yawing moments, (b) setup for applying rolling moments.

Table 1: Loading schedule used when calibrating the five-component balance

Channel	Gain of Amplifiers	Filter Settings (Hz)	Coordinates of Load Application (mm)	Loading Sequence (g)
1 (Axial Force, F_x) (not fitted)				
2 (Side Force, F_y)	500	1	(1) $x = -10$ (2) $x = 0$ (3) $x = +10$	0 to 140 to 0 g in 20 g increments
3 (Normal Force, F_z)	500	1	(1) $x = -10$ (2) $x = 0$ (3) $x = +10$	0 to 140 to 0 g in 20 g increments
4 (Rolling Moment, M_x)	100	1	(1) $x = 46.4$, $y = 40$ (2) $x = 46.4$, $y = -40$	0 to 35 to 0 g in 5 g increments
5 (Pitching Moment, M_y)	500	1	(1) $x = -10$ (2) $x = 0$ (3) $x = +10$	0 to 140 to 0 g in 20 g increments
6 (Yawing Moment, M_z)	500	1	(1) $x = -10$ (2) $x = 0$ (3) $x = +10$	0 to 140 to 0 g in 20 g increments

A sampling program, named SCAN, based on LabVIEW™, was developed to facilitate the calibration process. For each of the 210 sets of calibration points, the user had to specify the number of samples, time between samples, output file name, applied load, excitation voltage, temperature, gain settings and filter settings. The program was then run and the output voltages from the different channels were displayed on the monitor in graphical form as they were being sampled. The voltages were written to a spreadsheet file along with other information specified by the user. Input conditions were updated for the next set of calibration points and the procedure was repeated. Fourteen individual data files were created for the complete calibration.

6.3 Plots of Voltage Ratios *vs* Loads

For the calibration data, plots of V_{OUT} / V_{IN} *vs.* F_y, M_z, F_z, M_y and M_x are shown in Figure 7. V_{OUT} is the output voltage from a Wheatstone bridge for a channel and V_{IN} is the input voltage to the bridge for that channel (V_{IN} is nominally 5.0 V). On each plot, each set of calibration points for the different channels corresponds to two loading / unloading sequences (positive and negative values of F_y, M_z, F_z, M_y and M_x). Corresponding points for the loading and the unloading phases are effectively coincident for all cases, with no discernable evidence of hysteretic behaviour. The voltage ratios *vs* the applied loads of all 5 channels on the balance behave linearly.

6.4 Evaluation of Calibration Coefficients

The calibration coefficients were determined from the discrete applied loads and associated balance output / input voltages using the least-squares regression method proposed by Ramaswamy *et al.* (1987). Details of the procedure used are given in Appendix A.

The first-order calibration coefficients are

$$\begin{bmatrix} C_{2,2} & C_{2,3} & C_{2,4} & C_{2,5} & C_{2,6} \\ C_{3,2} & C_{3,3} & C_{3,4} & C_{3,5} & C_{3,6} \\ C_{4,2} & C_{4,3} & C_{4,4} & C_{4,5} & C_{4,6} \\ C_{5,2} & C_{5,3} & C_{5,4} & C_{5,5} & C_{5,6} \\ C_{6,2} & C_{6,3} & C_{6,4} & C_{6,5} & C_{6,6} \end{bmatrix} = \begin{bmatrix} 0.22793 & -0.00962 & -0.38905 & 0.36854 & 0.16638 \\ 0.01056 & 0.23426 & 0.00390 & 0.03656 & 0.03167 \\ 0.00635 & -0.00248 & 32.86634 & -0.24769 & 0.00160 \\ -0.00277 & 0.00502 & -0.11615 & 10.19147 & -0.34131 \\ -0.00413 & 0.00104 & 0.09769 & 0.53388 & 10.09930 \end{bmatrix} \quad (8)$$

6.5 Checking Accuracy of Calibration

When calibrating a balance, loads are applied to the balance and corresponding output / input voltage ratios are measured. To check the accuracy of the calibration, the reverse procedure is used, whereby the calibration equations are used to estimate loads corresponding to the voltage ratios measured during the calibration. For an ideal calibration, the applied and estimated loads should be the same, but in practice small discrepancies do occur. Provided that [C] is a non-singular square matrix, as it is for a first-order calibration, then $[C]^{-1}$ (inverse of [C]) can be formed and equation 7 can be rearranged to give

$$[H] = [C]^{-1}[R] \quad (9)$$

enabling the loads to be estimated directly.

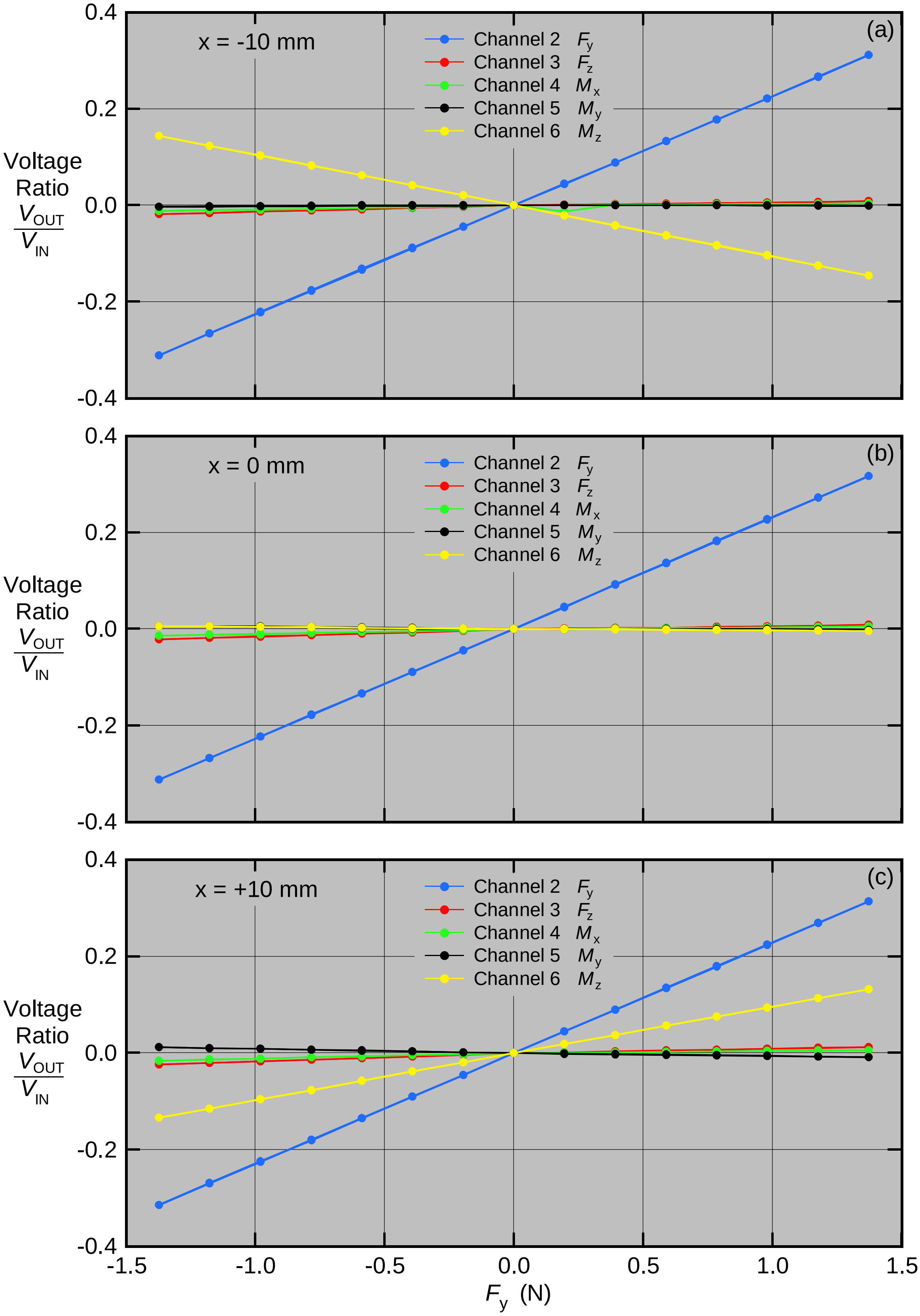

Figure 7a, b, c: Voltage ratios for the five channels vs F_y for x = −10, 0, +10 mm

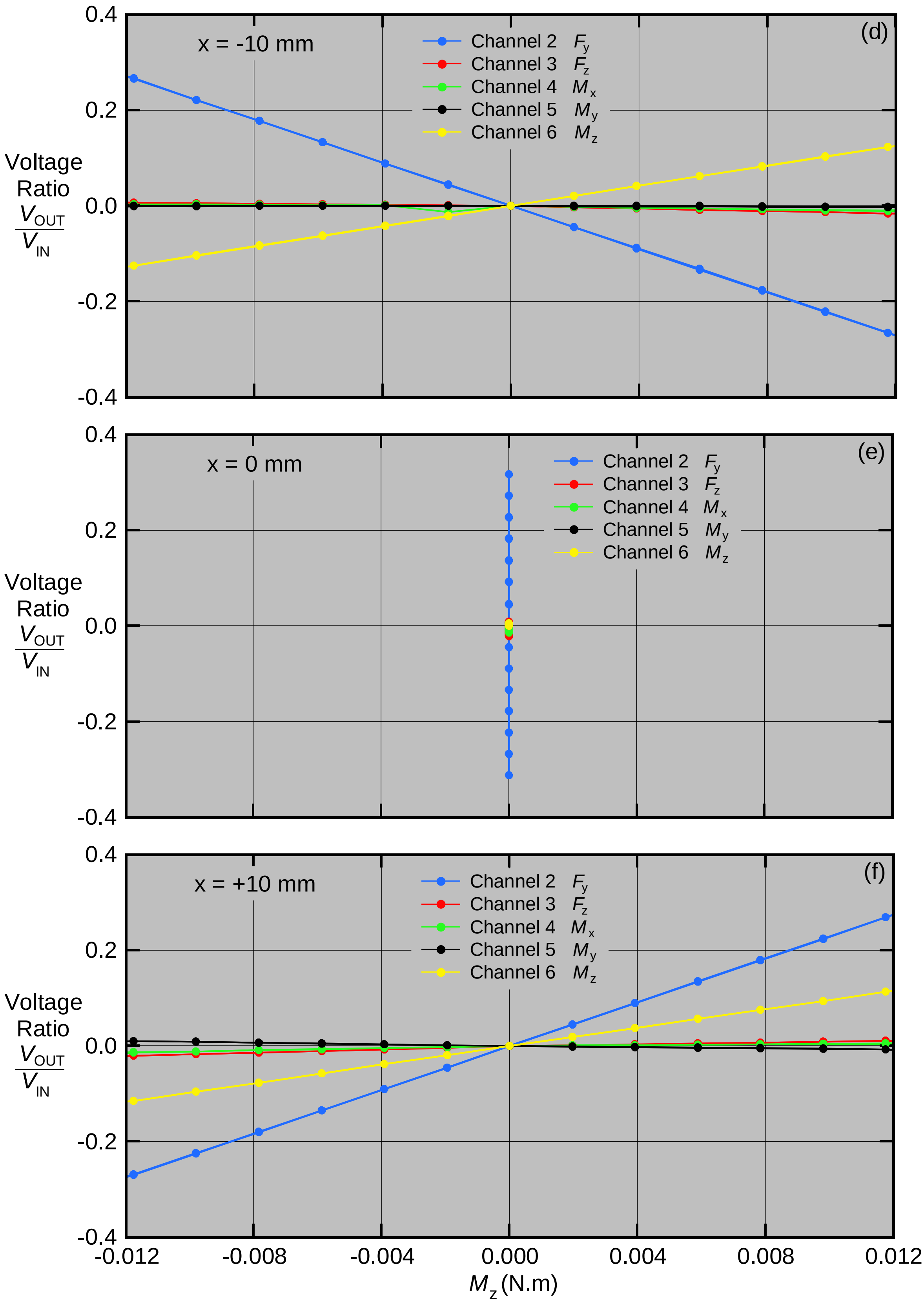

Figure 7d, e, f: Voltage ratios for the five channels vs M_z for x = –10, 0, +10 mm

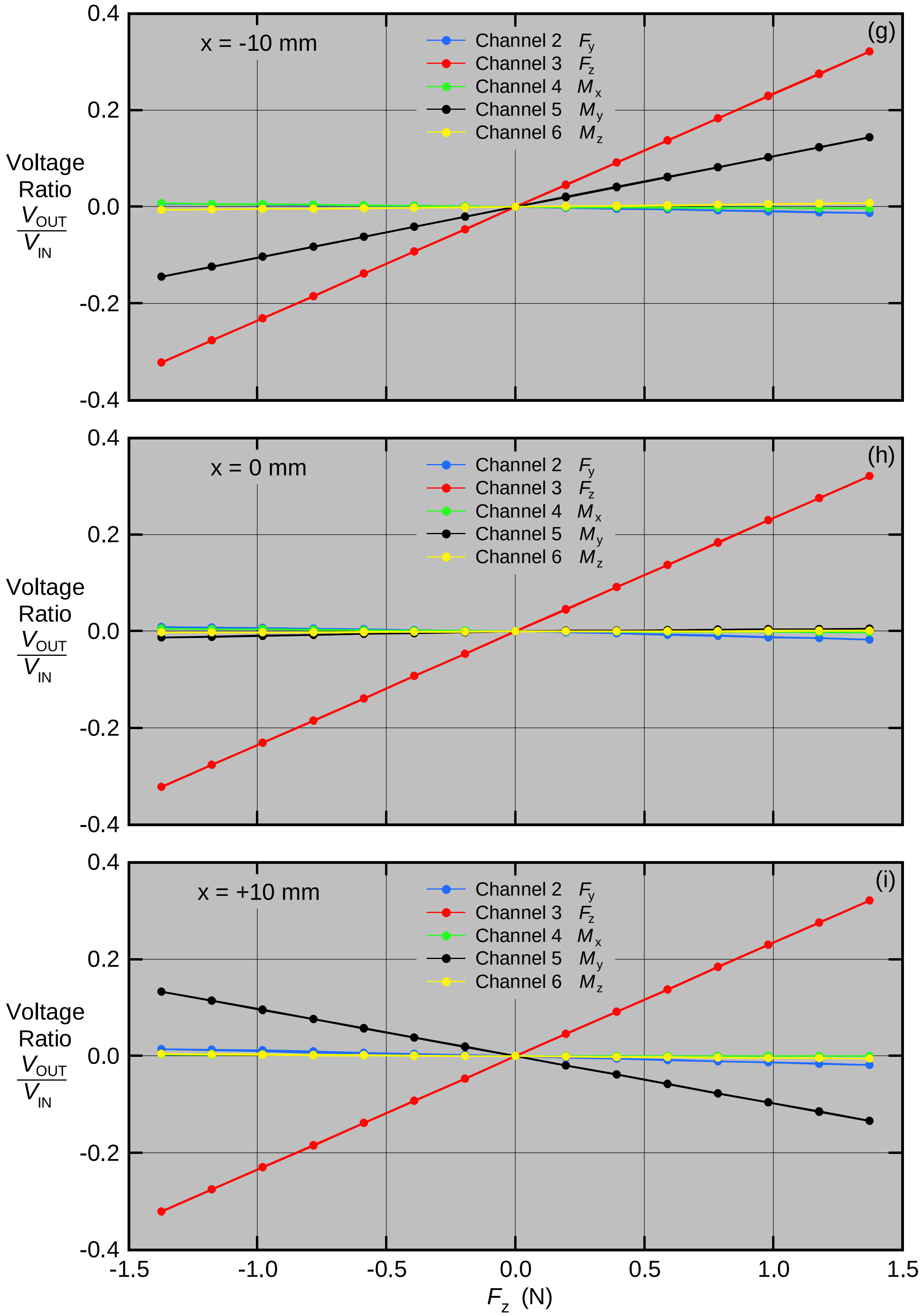

Figure 7g, h, i: Voltage ratios for the five channels vs F_z for x = −10, 0, +10 mm

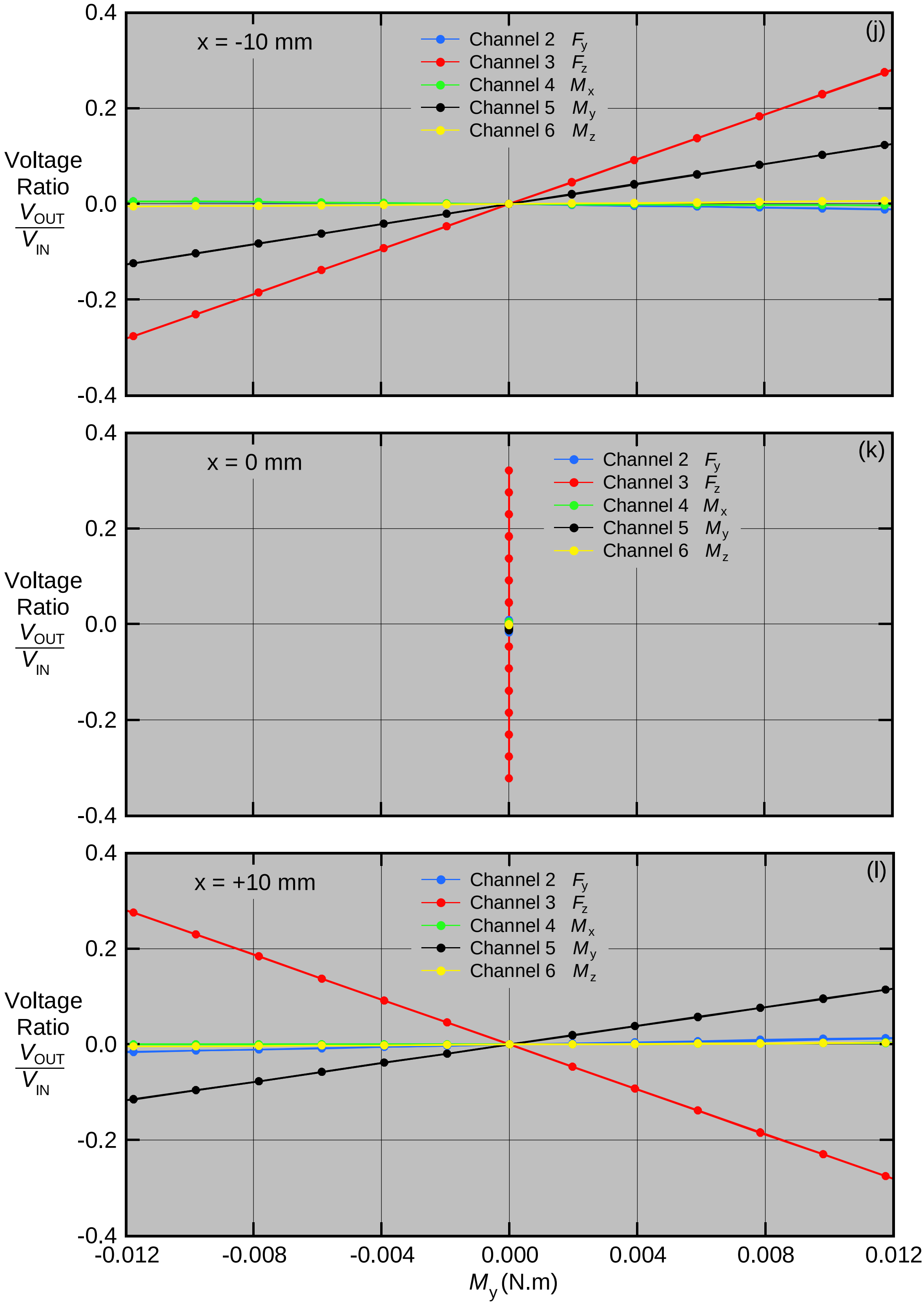

Figure 7j, k, l: Voltage ratios for the five channels vs M_y for x = –10, 0, +10 mm

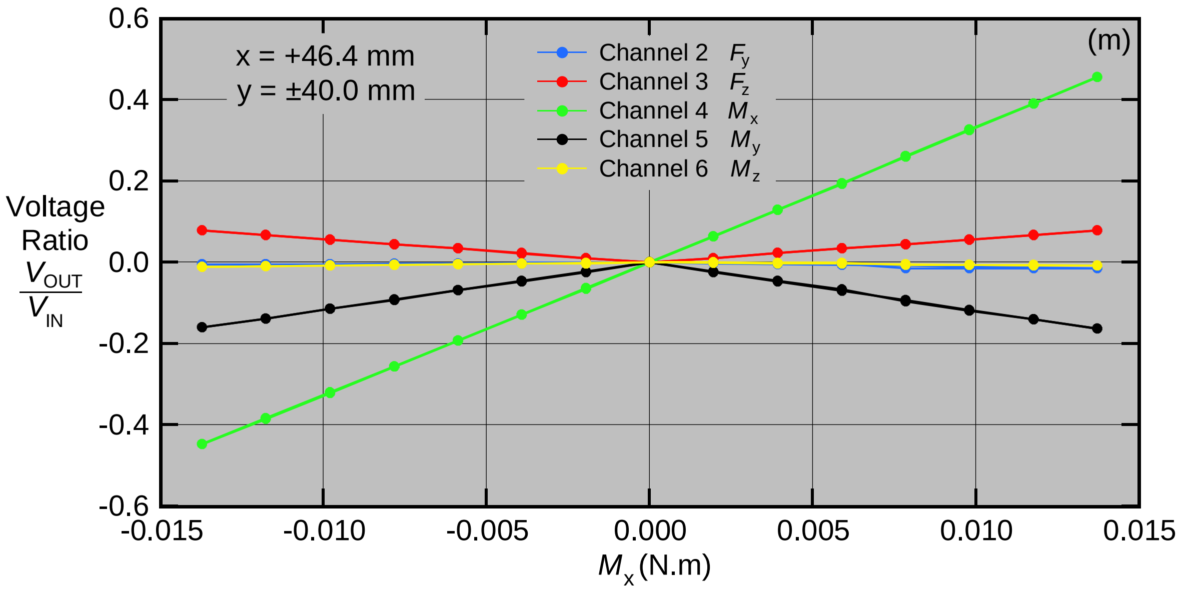

Figure 7m: Voltage ratios for the five channels vs M_x for x = +46.4, y = ±40 mm

A statistical indicator commonly used to assess the accuracy of the calibration is the standard error (see Lam 1989 and Leung & Link 1999). The parameter indicates the goodness of the fit of the calibration equation and the uncertainties in the coefficients determined by the least-squares method. The standard error for the side force (for example) is given by the following expression.

$$se_2 = \sqrt{\frac{\sum_{P=1}^{N}\left[H_{2,P} - \tilde{H}_{2,P}\right]^2}{N - f}} \tag{10}$$

where se_2 is the standard error for the side forces, $H_{2,P}$ is an applied side force, $\tilde{H}_{2,P}$ is the corresponding side force estimated using the calibration equation, N is the total number of points used in the calibration for each channel (N = 210), P is an index of summation and f is the number of degrees of freedom in the calibration equations. (The number of degrees of freedom is equal to the number of calibration coefficients per component, i.e. f = 5 for the first-order calibration equations). The corresponding terms for the other load components (normal forces, rolling, pitching and yawing moments) are similarly defined. To convert the standard errors to dimensionless parameters, they are divided by the appropriate maximum design load, either a force or a moment.

The standard errors were found to be less than 0.1% for the different load components, which is comparable to the standard errors of 0.19% obtained for the Collins balance used in the LSWT –see Blandford (2004). This suggests that loads measured by the water-tunnel balance will be of acceptable accuracy.

6.6 Loads Measured by the Balance

When carrying out tests in the water tunnel with the balance, loads can be computed from sampled voltages using equation 9.

7. Checking Waterproofing of Balance

Tests were undertaken to see whether the strain gauges and the electrical leads on the balance were affected by water. The balance was submerged in water for a period of 10 hours, and during this time the output voltages from the five channels were measured at 1 minute intervals. The voltages showed no unusual behaviour over the 10 hour sampling period, indicating that the waterproofing agent on the balance was effective. Submersion of the balance in water had no noticeable effect on subsequent readings.

8. Concluding Remarks

This report gives details of the design, manufacture and calibration of a five-component strain-gauge-balance used to measure flow-induced loads on models in the DSTO water tunnel. The loads are small by conventional standards and the balance can measure side and normal forces, as well as rolling, pitching and yawing moments, within the ranges ±25 N, ±25 N, ±0.1 N.m, ±0.2 N.m and ±0.2 N.m respectively. The balance has not been designed to measure axial forces. To measure the small loads, it was necessary to use semi-conductor strain gauges on the balance. The calibration of the balance was found to be accurate to within ±0.1% for the different load components, and the waterproofing of the balance was found to be effective.

9. Acknowledgements

The authors are grateful for the help given by others during the development and commissioning of the five-component balance. Michael Konak recommissioned an existing strain-gauge balance signal-conditioning system and wrote software for a data-acquisition system. John Clayton, Kevin Desmond, Alberto Gonzalez, Peter O'Connor and Paul Jacquemin helped with the experimental program. Stephen Lam gave many helpful suggestions during the course of the work and he also vetted the report.

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Appendix A: Evaluation of Calibration Coefficients

In Section 6.1, it was indicated that the first-order calibration relationships for the five-component balance were

$$R_2 = C_{2,2}H_2 + C_{2,3}H_3 + C_{2,4}H_4 + C_{2,5}H_5 + C_{2,6}H_6 \quad \text{(A1)}$$
$$R_3 = C_{3,2}H_2 + C_{3,3}H_3 + C_{3,4}H_4 + C_{3,5}H_5 + C_{3,6}H_6 \quad \text{(A2)}$$
$$R_4 = C_{4,2}H_2 + C_{4,3}H_3 + C_{4,4}H_4 + C_{4,5}H_5 + C_{4,6}H_6 \quad \text{(A3)}$$
$$R_5 = C_{5,2}H_2 + C_{5,3}H_3 + C_{5,4}H_4 + C_{5,5}H_5 + C_{5,6}H_6 \quad \text{(A4)}$$
$$R_6 = C_{6,2}H_2 + C_{6,3}H_3 + C_{6,4}H_4 + C_{6,5}H_5 + C_{6,6}H_6 \quad \text{(A5)}$$

R_2, R_3, R_4, R_5 and R_6 are the voltage ratios for channels 2 to 6, i.e. the output voltages from the channels divided by the corresponding input voltages to the channels. The *H* terms are the corresponding applied loads and the *C* terms are the calibration coefficients.

The coefficients appearing in these equations can be determined from the discrete applied loads and associated voltage ratios using a least-squares regression model. Various types of regression methods have been reported in the literature, but the method used for calibrating the water-tunnel balances is that developed by Ramaswamy *et al.* (1987). This method was also used when calibrating the wind-tunnel balances in Air Vehicles Division. Lam (1989) gives mathematical details of the method, and only an outline of the method will be given here –also see Leung & Link (1999) and Blandford (2004). The method will only be described for the first-order calibration equations, but the same principles apply for equations of higher orders.

For this method, the calibration coefficients are established when the sum of the squares of the differences between the measured strain-gauge output voltage ratios and those obtained from a calibration equation is a minimum. That is,

$$e_2 = \sum_{\mathrm{P}=1}^{\mathrm{N}} \left[C_{2,2}H_{2,\mathrm{P}} + C_{2,3}H_{3,\mathrm{P}} + C_{2,4}H_{4,\mathrm{P}} + C_{2,5}H_{5,\mathrm{P}} + C_{2,6}H_{6,\mathrm{P}} - R_{2,\mathrm{P}}\right]^2 \quad \text{(A6)}$$
$$e_3 = \sum_{\mathrm{P}=1}^{\mathrm{N}} \left[C_{3,2}H_{2,\mathrm{P}} + C_{3,3}H_{3,\mathrm{P}} + C_{3,4}H_{4,\mathrm{P}} + C_{3,5}H_{5,\mathrm{P}} + C_{3,6}H_{6,\mathrm{P}} - R_{3,\mathrm{P}}\right]^2 \quad \text{(A7)}$$
$$e_4 = \sum_{\mathrm{P}=1}^{\mathrm{N}} \left[C_{4,2}H_{2,\mathrm{P}} + C_{4,3}H_{3,\mathrm{P}} + C_{4,4}H_{4,\mathrm{P}} + C_{4,5}H_{5,\mathrm{P}} + C_{4,6}H_{6,\mathrm{P}} - R_{4,\mathrm{P}}\right]^2 \quad \text{(A8)}$$
$$e_5 = \sum_{\mathrm{P}=1}^{\mathrm{N}} \left[C_{5,2}H_{2,\mathrm{P}} + C_{5,3}H_{3,\mathrm{P}} + C_{5,4}H_{4,\mathrm{P}} + C_{5,5}H_{5,\mathrm{P}} + C_{5,6}H_{6,\mathrm{P}} - R_{5,\mathrm{P}}\right]^2 \quad \text{(A9)}$$
$$e_6 = \sum_{\mathrm{P}=1}^{\mathrm{N}} \left[C_{6,2}H_{2,\mathrm{P}} + C_{6,3}H_{3,\mathrm{P}} + C_{6,4}H_{4,\mathrm{P}} + C_{6,5}H_{5,\mathrm{P}} + C_{6,6}H_{6,\mathrm{P}} - R_{6,\mathrm{P}}\right]^2 \quad \text{(A10)}$$

are all minimum, where e_2, e_3, e_4, e_5 and e_6 are sums of squares of residuals for channels 2 to 6, P is an index of summation and N is the number of calibration points for each channel

(N = 210 –see Section 6.2). The procedure involves partial differentiating e_2 with respect to each of its coefficients and equating the resultant expressions to zero, and likewise for e_3 to e_6. This results in a set of five simultaneous equations for each of the five channels as follows[5]:

$$\begin{aligned}
&\sum\left[C_{2,2}H_2 + C_{2,3}H_3 + C_{2,4}H_4 + C_{2,5}H_5 + C_{2,6}H_6 - R_2\right] H_2 = 0\\
&\sum\left[C_{2,2}H_2 + C_{2,3}H_3 + C_{2,4}H_4 + C_{2,5}H_5 + C_{2,6}H_6 - R_2\right] H_3 = 0\\
&\sum\left[C_{2,2}H_2 + C_{2,3}H_3 + C_{2,4}H_4 + C_{2,5}H_5 + C_{2,6}H_6 - R_2\right] H_4 = 0\\
&\sum\left[C_{2,2}H_2 + C_{2,3}H_3 + C_{2,4}H_4 + C_{2,5}H_5 + C_{2,6}H_6 - R_2\right] H_5 = 0\\
&\sum\left[C_{2,2}H_2 + C_{2,3}H_3 + C_{2,4}H_4 + C_{2,5}H_5 + C_{2,6}H_6 - R_2\right] H_6 = 0
\end{aligned} \tag{A11}$$

$$\begin{aligned}
&\sum\left[C_{3,2}H_2 + C_{3,3}H_3 + C_{3,4}H_4 + C_{3,5}H_5 + C_{3,6}H_6 - R_3\right] H_2 = 0\\
&\sum\left[C_{3,2}H_2 + C_{3,3}H_3 + C_{3,4}H_4 + C_{3,5}H_5 + C_{3,6}H_6 - R_3\right] H_3 = 0\\
&\sum\left[C_{3,2}H_2 + C_{3,3}H_3 + C_{3,4}H_4 + C_{3,5}H_5 + C_{3,6}H_6 - R_3\right] H_4 = 0\\
&\sum\left[C_{3,2}H_2 + C_{3,3}H_3 + C_{3,4}H_4 + C_{3,5}H_5 + C_{3,6}H_6 - R_3\right] H_5 = 0\\
&\sum\left[C_{3,2}H_2 + C_{3,3}H_3 + C_{3,4}H_4 + C_{3,5}H_5 + C_{3,6}H_6 - R_3\right] H_6 = 0
\end{aligned} \tag{A12}$$

$$\begin{aligned}
&\sum\left[C_{4,2}H_2 + C_{4,3}H_3 + C_{4,4}H_4 + C_{4,5}H_5 + C_{4,6}H_6 - R_4\right] H_2 = 0\\
&\sum\left[C_{4,2}H_2 + C_{4,3}H_3 + C_{4,4}H_4 + C_{4,5}H_5 + C_{4,6}H_6 - R_4\right] H_3 = 0\\
&\sum\left[C_{4,2}H_2 + C_{4,3}H_3 + C_{4,4}H_4 + C_{4,5}H_5 + C_{4,6}H_6 - R_4\right] H_4 = 0\\
&\sum\left[C_{4,2}H_2 + C_{4,3}H_3 + C_{4,4}H_4 + C_{4,5}H_5 + C_{4,6}H_6 - R_4\right] H_5 = 0\\
&\sum\left[C_{4,2}H_2 + C_{4,3}H_3 + C_{4,4}H_4 + C_{4,5}H_5 + C_{4,6}H_6 - R_4\right] H_6 = 0
\end{aligned} \tag{A13}$$

$$\begin{aligned}
&\sum\left[C_{5,2}H_2 + C_{5,3}H_3 + C_{5,4}H_4 + C_{5,5}H_5 + C_{5,6}H_6 - R_5\right] H_2 = 0\\
&\sum\left[C_{5,2}H_2 + C_{5,3}H_3 + C_{5,4}H_4 + C_{5,5}H_5 + C_{5,6}H_6 - R_5\right] H_3 = 0\\
&\sum\left[C_{5,2}H_2 + C_{5,3}H_3 + C_{5,4}H_4 + C_{5,5}H_5 + C_{5,6}H_6 - R_5\right] H_4 = 0\\
&\sum\left[C_{5,2}H_2 + C_{5,3}H_3 + C_{5,4}H_4 + C_{5,5}H_5 + C_{5,6}H_6 - R_5\right] H_5 = 0\\
&\sum\left[C_{5,2}H_2 + C_{5,3}H_3 + C_{5,4}H_4 + C_{5,5}H_5 + C_{5,6}H_6 - R_5\right] H_6 = 0
\end{aligned} \tag{A14}$$

[5] For clarity, the subscript P on R and H is omitted in the remainder of this report. Whenever the summation symbol is used, it is to understood that the sum is to be taken over the range P = 1 to N.

$$\begin{aligned}
&\sum\left[C_{6,2}H_2 + C_{6,3}H_3 + C_{6,4}H_4 + C_{6,5}H_5 + C_{6,6}H_6 - R_6\right] H_2 = 0\\
&\sum\left[C_{6,2}H_2 + C_{6,3}H_3 + C_{6,4}H_4 + C_{6,5}H_5 + C_{6,6}H_6 - R_6\right] H_3 = 0\\
&\sum\left[C_{6,2}H_2 + C_{6,3}H_3 + C_{6,4}H_4 + C_{6,5}H_5 + C_{6,6}H_6 - R_6\right] H_4 = 0\\
&\sum\left[C_{6,2}H_2 + C_{6,3}H_3 + C_{6,4}H_4 + C_{6,5}H_5 + C_{6,6}H_6 - R_6\right] H_5 = 0\\
&\sum\left[C_{6,2}H_2 + C_{6,3}H_3 + C_{6,4}H_4 + C_{6,5}H_5 + C_{6,6}H_6 - R_6\right] H_6 = 0
\end{aligned} \tag{A15}$$

Equations A11 to A15 can be combined and put into matrix notation as follows:

$$[E]\,[C]^{\mathrm{T}} = [A] \tag{A16}$$

$[C]^{\mathrm{T}}$ is the transpose of the matrix of calibration coefficients and is given by

$$[C]^{\mathrm{T}} = \begin{bmatrix} C_{2,2} & C_{3,2} & C_{4,2} & C_{5,2} & C_{6,2} \\ C_{2,3} & C_{3,3} & C_{4,3} & C_{5,3} & C_{6,3} \\ C_{2,4} & C_{3,4} & C_{4,4} & C_{5,4} & C_{6,4} \\ C_{2,5} & C_{3,5} & C_{4,5} & C_{5,5} & C_{6,5} \\ C_{2,6} & C_{3,6} & C_{4,6} & C_{5,6} & C_{6,6} \end{bmatrix} \tag{A17}$$

$[E]$ and $[A]$ are given by

$$[E] = \begin{bmatrix} \Sigma H_2 H_2 & \Sigma H_2 H_3 & \Sigma H_2 H_4 & \Sigma H_2 H_5 & \Sigma H_2 H_6 \\ \Sigma H_3 H_2 & \Sigma H_3 H_3 & \Sigma H_3 H_4 & \Sigma H_3 H_5 & \Sigma H_3 H_6 \\ \Sigma H_4 H_2 & \Sigma H_4 H_3 & \Sigma H_4 H_4 & \Sigma H_4 H_5 & \Sigma H_4 H_6 \\ \Sigma H_5 H_2 & \Sigma H_5 H_3 & \Sigma H_5 H_4 & \Sigma H_5 H_5 & \Sigma H_5 H_6 \\ \Sigma H_6 H_2 & \Sigma H_6 H_3 & \Sigma H_6 H_4 & \Sigma H_6 H_5 & \Sigma H_6 H_6 \end{bmatrix} \tag{A18}$$

and

$$[A] = \begin{bmatrix} \Sigma H_2 R_2 & \Sigma H_2 R_3 & \Sigma H_2 R_4 & \Sigma H_2 R_5 & \Sigma H_2 R_6 \\ \Sigma H_3 R_2 & \Sigma H_3 R_3 & \Sigma H_3 R_4 & \Sigma H_3 R_5 & \Sigma H_3 R_6 \\ \Sigma H_4 R_2 & \Sigma H_4 R_3 & \Sigma H_4 R_4 & \Sigma H_4 R_5 & \Sigma H_4 R_6 \\ \Sigma H_5 R_2 & \Sigma H_5 R_3 & \Sigma H_5 R_4 & \Sigma H_5 R_5 & \Sigma H_5 R_6 \\ \Sigma H_6 R_2 & \Sigma H_6 R_3 & \Sigma H_6 R_4 & \Sigma H_6 R_5 & \Sigma H_6 R_6 \end{bmatrix} \tag{A19}$$

The 25 elements comprising $[E]$ and the 25 elements comprising $[A]$ can each be determined from the known applied calibration loads and the corresponding measured voltage ratios, so that the 25 elements in $[C]^{\mathrm{T}}$ can be determined by making use of equation A16. It is not possible to determine $[C]^{\mathrm{T}}$ directly from this equation, and the equation must be rearranged to obtain an explicit expression for $[C]^{T}$. Provided $[E]$ is a non-singular square matrix, then $[E]^{-1}$ (inverse of $[E]$) can be formed and equation A16 can be rearranged as follows:

$$[C]^{T} = [E]^{-1}[A] \tag{A20}$$

Once $[C]^{T}$ is known, $[C]$ can be determined by simply transposing $[C]^{T}$ (equation A17) to give

$$[C] = \begin{bmatrix} C_{2,2} & C_{2,3} & C_{2,4} & C_{2,5} & C_{2,6} \\ C_{3,2} & C_{3,3} & C_{3,4} & C_{3,5} & C_{3,6} \\ C_{4,2} & C_{4,3} & C_{4,4} & C_{4,5} & C_{4,6} \\ C_{5,2} & C_{5,3} & C_{5,4} & C_{5,5} & C_{5,6} \\ C_{6,2} & C_{6,3} & C_{6,4} & C_{6,5} & C_{6,6} \end{bmatrix} \tag{A21}$$

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19. ABSTRACT
This report gives details of a five-component strain-gauge balance that has been developed to measure flow-induced loads on models in the DSTO water tunnel. The loads are very small and the balance was designed to measure side and normal forces, as well as rolling, pitching and yawing moments, within the ranges ±25 N, ±25 N, ±0.1 N.m, ±0.2 N.m and ±0.2 N.m respectively. These loads are at least 2 to 3 orders of magnitude smaller than those typically measured on aircraft models in the low-speed wind tunnel at DSTO. The balance has not been designed to measure axial forces. Due to the small loads, it was necessary to use semi-conductor strain gauges on the balance. The five-component balance has been developed using similar design principles to a two-component balance developed earlier at DSTO for use in the water tunnel.