A WIND TUNNEL STRAIN GAUGE BALANCE CALIBRATION SYSTEM

Stephen S.W. Lam and Bruce D. Fairlie
Air Operations Division
Aeronautical and Maritime Research Laboratory
Defence Science and Technology Organisation, Australia

ABSTRACT

An innovative machine to calibrate wind tunnel strain gauge balance has been designed, developed and constructed at the Aeronautical and Maritime Research Laboratory. The design is based on the "master balance" concept in which the applied loads to the calibration body are measured by the master balance fitted with highly accurate load cells. This does away with the tediousness and difficulties of load alignments and levelling associated with the traditional gravity loading methods. With this machine, the effort and time required to calibrate a six-component strain gauge balance can be reduced considerably.

INTRODUCTION

The relationship between the outputs (R_i, i = 1, ..., 6) of a six-component wind tunnel strain gauge balance and the applied loads (H_j, j = 1, ..., 6) are usually represented by a second-order polynomial function (see for example Cook 1959), which may be written as:

$$R_i = C_{i.1}H_1 + C_{i.2}H_2 + \cdots + C_{i.6}H_6 + C_{i.11}H_1^2 + C_{i.22}H_2^2 + \cdots + C_{i.66}H_6^2 + C_{i.12}H_1H_2 + C_{i.13}H_1H_3 + \cdots + C_{i.16}H_1H_6 + C_{i.23}H_2H_3 + \cdots + C_{i.56}H_5H_6 \qquad i = 1,\ldots,6 \qquad (1)$$

where Cs are the calibration coefficients determined during balance calibration. The six load components are usually referred to the forces: *Lift*, *Drag* and *Side-force* along three orthogonal axes, and to the moments about these axes: *Yaw*, *Roll* and *Pitch*. To better account for the characteristics of the balance under both tension and compression, it is necessary to include "load cubed" terms $C_{i.111}H_1^3 + C_{i.222}H_2^3 + \cdots + C_{i.666}H_6^3$ in the right hand side of equation (1) to provide a more accurate relationship between the balance outputs and the loads applied. For a six-component balance, this gives a total of 198 coefficients for the full non-linear calibration equation.

Calibrating such a balance using the conventional gravity loading method involves applying single and combinations of pure components of the loads to the balance compensating for the deflection of the calibration body. A complex loading system, and accurate levelling and alignment equipment are required to accomplish the task which can become tedious, and the determination of a full set of non-linear calibration equations of a six-component strain gauge balance can take up to several months. This leads to a reluctance to conduct a full balance calibration more often than is absolutely necessary. The lack of frequent balance calibration poses a potential threat to the accuracy of the results derived from the balance.

A calibration machine using the "master balance" concept has been designed and constructed at the Aeronautical and Maritime Research Laboratory (AMRL) to reduce the time and alleviate the tediousness of calibrating wind tunnel strain gauge balances. A similar concept has been adopted in calibration machines built in R.A.E. Bedford (Brown 1979) and in Technical University of Darmstadt, Germany (Edwald 1987). Their implementations of the concept, however, differ significantly from the machine described here.

THE MASTER BALANCE CONCEPT

Gravity loading is the simplest and most reliable method of providing a force accurately known in magnitude and direction. However, the alignments and levellings involved are tedious and difficult. One of the major objectives of the calibration machine is to do away with these procedures.

An alternative method to obtain forces known in magnitude and direction is to use a master balance between the balance under calibration and the earth. This concept is illustrated in Figure 1. Force generators, which react to earth, are used to apply loads to the balance under calibration. These loads are measured by the master balance via a separate calibration.

The use of the master balance concept in the design of a balance calibration machine has the following major advantages:

- As the loads on the balance under calibration are measured by the master balance, calibration loads may be applied by any convenient means (e.g. pneumatic or hydraulic actuators). Thus the problems associated with gravity loads and the errors involved with highly loaded pulleys and cables may be avoided.
- It is not necessary to provide a separate force generator for each of the six load components.
- The master balance can be calibrated with respect to a system of axes which is fixed with respect to the attachment point of the balance under calibration. If the *model end* (the end which is fixed with respect to the measurement and calibration axes system) of the balance under calibration is attached to this point while loads are applied to the *earth end*, the axes systems of both balances remain locked together regardless of deflections in either balance. Thus the need to re-align the balance to correct for deflection may be avoided.
- The non-linearity of the calibration equation of a balance presents a problem in defining the true zero point on the load scale. This is because of the different zero conditions used in calibration and in load measurement. The use of a master balance provides a convenient way of defining the zero load condition. Before the balance to be calibrated is mounted on the master balance, the master balance outputs are zeroed. This condition, which is the *zero model end load* condition, may be used as the reference zero load condition. This condition is equivalent to the *buoyant zero* introduced by Galway (1980). The mass of the fixtures attached to the balance under calibration is not required to be determined explicitly under such a scheme.
- Simultaneously loading of multiple components allows the actual loading of the balance under calibration to be much more representative of the load combinations it will experience during actual usage in wind tunnel testing.

Although the concept of the master balance introduces an extra calibration process, viz, that of the master balance itself, the design constraints which normally apply to an internal strain gauge balance no longer exist. Thus the master balance may be made sufficiently stiff to eliminate all non-linear terms from its calibration. It may be supported in a kinematically correct manner, maintaining constant load paths to earth and therefore avoiding non-repeatabilities caused by changing load paths under differing applied loads. It may also be designed with good load separation for each load sensing element. All these considerations can lead to a master balance design which has a highly repeatable, linear calibration.

THE BALANCE CALIBRATION MACHINE

An isometric view of the master balance and its supporting structure is shown in Figure 2. Figure 3 shows the assembled calibration machine with the load generators attached. The *balance* to be calibrated (B) is attached to the *floating frame* (F) at its model end. The floating frame is attached to the master balance which reacts the loads applied to the floating frame via an *earth frame* (E) to the *supporting structure* (S). Loads are applied, using the *force generators* (G) attached to the supporting structure, to a *loading frame* (L) connected to the earth end of the *balance* under calibration.

The Master Balance

The master balance has six highly accurate load cells arranged so that each load cell measures predominantly one of the six components of the applied load. Each load cell is connected to the floating frame with a 350 mm long rod. The rod is constructed with machined cross flexures at each end to ensure that only axial force is transmitted along the rod to the load cell. The connecting rods and loads cells are arranged so that the moment centre of the master balance coincides with that of the balance under calibration.

Since the strain gauge balances are calibrated against the master balance, the accuracy of the master balance should, ideally, be an order of magnitude better than that of the calibrations to be carried out with it. The aim was for the master balance to be capable of measuring applied loads to within an accuracy of ±0.05% of its maximum design loads.

The Earth Frame

The earth frame provides reaction support to all six load cells. It is made from 100 × 100 × 6 mm square section steel tube and welded together with cross-bracing to make it extremely rigid. It is supported at one lower corner on a spherical bearing mounted on the calibrating machine supporting structure. The remaining three rotational degrees of freedom are constrained by links between the earth frame and the supporting structure, one link in each of the three orthogonal directions supporting the earth frame at the three corners closest to the spherical bearing. This arrangement provides a statically determinate system with no redundant constraint. This avoids hysteresis and non-repeatable variations in calibrations when the applied load changes.

The Floating Frame

The floating frame is made of a substantial cast iron structure providing a rigid link between the ends of the six load-cell connecting rods and the mounting block for the balance under calibration. The mounting block was accurately located on the floating frame by a keyed slot thus ensuring precise location of the axes of the balance under calibration.

The Loading Frame

The loading frame is fixed to the earth end of the balance being calibrated, providing load paths between the force generators and the balance. Its design is governed mainly by the need to provide for the convenient application of loads.

The Load Generators

Double acting pneumatic actuators are used as load generators. The loads are applied to the loading frame via loading linkages. Three actuators are arranged to generate forces in three orthogonal directions (corresponding to *Lift*, *Drag* and *Side-Force*). Three other actuators are arranged to generate torques about each of the three orthogonal axes (corresponding to *Yaw*, *Roll* and *Pitch* moments). Each actuator is controlled by a five-way solenoid valve which may be operated under computer control so that applying loads to the balance during calibration can be automated.

With the elimination of the needs to align the applied loads, and the automation of load generations it is estimated that the time required to calibrate a strain gauge balance can be reduced from several months to a few hours.

CALIBRATION OF THE MASTER BALANCE

The master balance is calibrated using gravity loads in the traditional manner. A calibration bar is mounted onto the floating frame in the same manner as for a balance under calibration. A weight hanger, on which loads are applied, is hung onto the calibration bar which sits on a ball bearing in a groove at precisely located positions. With the loading frame and force generators removed, the whole calibration machine may be rotated and levelled to allow gravity loads to be applied in three orthogonal directions and in both negative and positive senses.

The relationship between the load cell output signal (Q_i, $i = 1, ..., 6$) and the loads (H_j, $j = 1, ..., 6$) applied to the master balance is represented by the first order equation

$$Q_i = A_{i1}H_1 + A_{i2}H_2 + A_{i3}H_3 + A_{i4}H_4 + A_{i5}H_5 + A_{i6}H_6 \quad i = 1, \ldots, 6 \quad (2)$$

The coefficients, $A_{i,j}$, are evaluated by means of a least squares method described by Ramaswamy, Srinivas and Holla (1987). As a result of the calibration, the R.M.S. error, based on the full scale load, of each load component as indicated by the master balance is given in Table 1. With the exception of the *Pitch* and *Yaw* components, the master balance performed within the design target. The larger than expected errors in the *Pitch* and *Yaw* components may be attributed to the fact that the calibration bar is the most flexible member of the master balance during the calibration procedure. This flexibility contributes to non-linearities and possibly to non-repeatable behaviour which have not been accounted for in the calibration equation.

The effects of non-linear interactions of the master balance may be examined qualitatively by fitting a second order equation of the form given by equation (1) to the calibration data for the *Roll*, *Pitch* and *Yaw* components. Comparisons of the residual percentage errors, based on the full scale reading, of the estimated load cell output signals for the first and second order calibrations are given in Figure (4). The results showed that while the residual errors based the second order equation are generally lower than those based on the first order equation, the differences are small. The first order representation of the calibration can be improved by using a more rigid calibration bar when calibrating the master balance. The design of the calibration bar is currently being reviewed.

CONCLUSIONS

A machine for calibrating internal strain gauge balances has been designed and constructed at AMRL. The machine is based on the master balance concept in which applied loads are measured by a balance equipped with highly accurate load cells. Preliminary calibration of the master balance has indicated that the machine meets the design criteria in the *Drag*, *Side-force*, *Lift* and *Roll* components. The larger than expected errors in the *Pitch* and *Yaw* components may be attributed to the flexibility of the calibration bar used during the calibration process. The calibration machine can reduce the time and effort required to carry out a full calibration of an internal strain gauge balance considerably.

TABLE 1. R.M.S. ERRORS, BASED ON FULL SCALE LOAD, OF EACH LOAD COMPONENT AS INDICATED BY THE MASTER BALANCE.

Drag	*Side-Force*	*Lift*
0.036%	0.042%	0.049%

Roll	*Pitch*	*Yaw*
0.034%	0.126%	0.160%

REFERENCES

Brown, E.C., 1979, "A Heavy Duty Calibration Machine for the R.A.E. 5m Low Speed Wind Tunnel", R.A.E. Tech. Report 79039, Royal Aircraft Establishment, Bedford.

Cook, T.A., 1959, "A Note on the Calibration of Strain Gauge Balances for Wind Tunnel Models", R.A.E. Tech. Note No. 2631, Royal Aircraft Establishment, Bedford.

Edwald, B.,1987, "Balance Accuracy and Repeatability as a Limiting Parameter in Aircraft Development Force Measurements in Conventional and Cryogenic Wind Tunnels", Presented at the AGARD Fluid Mechanics Panel Symposium on *Aerodynamic Data Accuracy and Quality: Requirements and Capabilities in Wind Tunnel Testing*, Naples, Italy.

Galway, R.D., 1980, "A Comparison of Methods for Calibration and Use of Multi-Component Strain Gauge Wind Tunnel Balances", N.R.C. Aero Report LR-600, National Research Council, Canada.

Ramaswamy, M.A., Srinivas, T. and Holla, V.S., 1987, "A Simple Method for Wind Tunnel Balance Calibration Including Non-linear Interaction Terms", *International Congress on Instrumentation in Aerospace Simulation Facilities*, Williamsburg, Virginia, ICIASF '87 RECORD, pp.263-267.

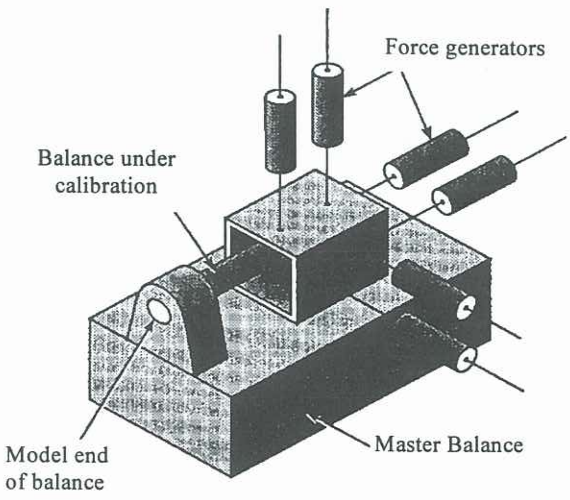


FIGURE 1. The master balance concept.

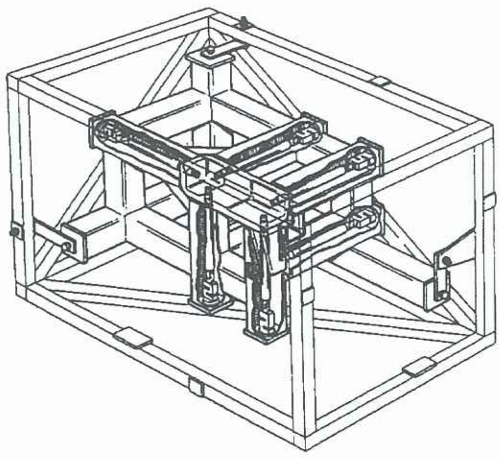


FIGURE 2. Isometric view of the master balance and support frame.

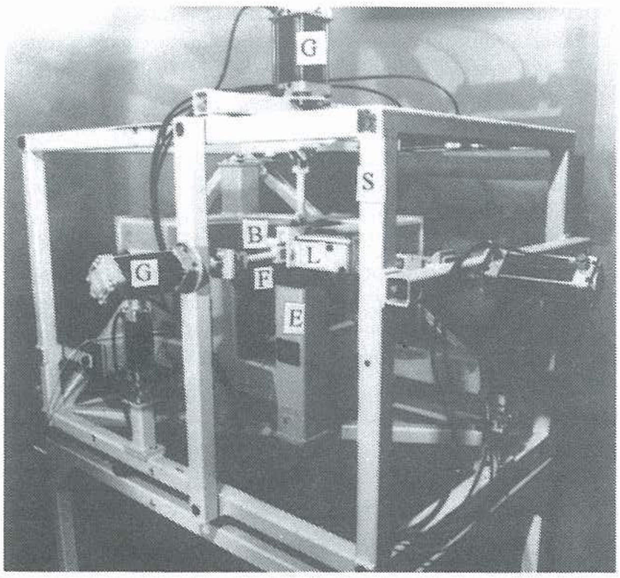
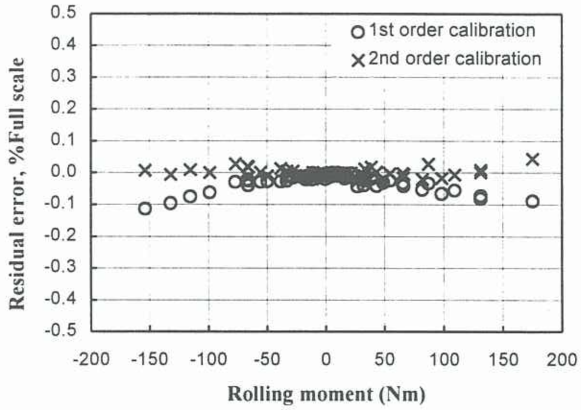
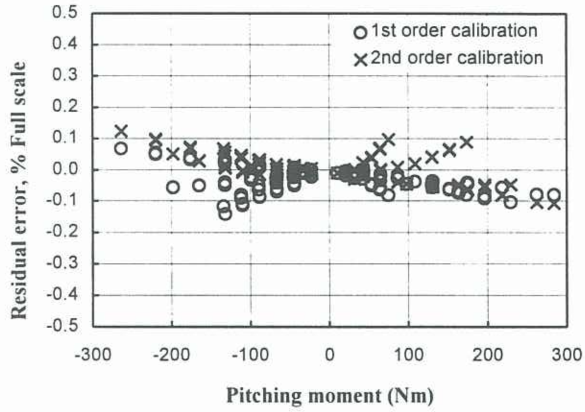


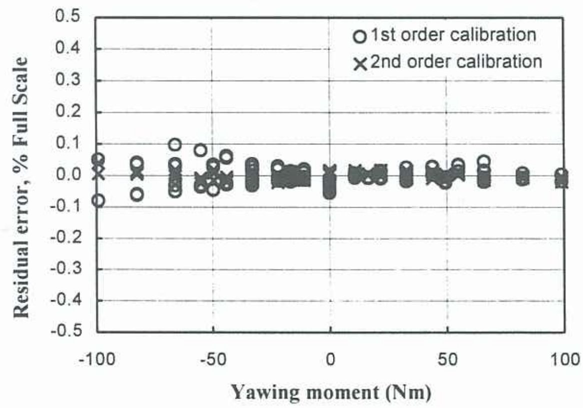
FIGURE 3. Photograph of the balance calibrating machine. (B) Balance under calibration, (E) Earth frame, (F) Floating frame, (G) Force generators, (L) Loading frame, (S) Supporting frame.



(a)



(b)



(c)

FIGURE 4. Comparisons of residual error percentage, based on full scale readings, of the load cell output signals between the 1st order and 2nd order calibrations of the master balance. (a) Rolling, (b) Pitching, and (c) Yawing moment.