Achieving drag measurement accuracy from a high load capacity internal balance design

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ABSTRACT

As one aspect of a balance research and development programme, engineers at the Aircraft Research Association (ARA) have addressed the unique problems associated with the design of an internal single piece balance suitable for small military type aircraft models that experience very high loads during a wind tunnel test. The paper details the nature of the problems and the stages undertaken in the design, manufacture and commissioning of an initial prototype balance followed by a re-designed version to meet the stringent requirements. Data from recent tests indicate the quality of the measurements and the suitability of the balance for the testing of fighter type aircraft.

NOMENCLATURE

C_D	drag coefficient
C_{D0}	$C_D - C_L^2/(\pi \times \text{aspect ratio})$
C_L	lift coefficient
C_m	pitching moment coefficient
F_A	axial force
F_N	normal force
M	Mach number
q	dynamic pressure
S	model reference area
α	angle of incidence
δ	difference
AFU	axial force unit
FEA	finite element analysis

1.0 INTRODUCTION

In recent years there has been a continuing requirement for models of military flight vehicles to be wind tunnel tested to the extremes of flight envelopes that are far in excess of what was the traditional experience of wind tunnel establishments. The ARA transonic wind tunnel (TWT) is capable of achieving up to 40° of incidence and Mach numbers up to 1·4. Under such conditions, model loads can potentially be very large and coupled with the relatively small size of models for modern military aircraft, the requirement on the performance of the internal force measuring balance can be very demanding, particularly if accurate drag measurement is a requisite.

In the past, compact multi-piece internal balances have been used at ARA for applications where space is limited and high loads are to be measured. The mechanical failure of two such devices during extensive tunnel test campaigns prompted ARA to embark on a research programme to develop a high load capacity single piece balance.

The available space envelope was extremely limiting and the need for the balance to fit an existing model, designed originally around a fundamentally different style of balance and with minimal modification to the model posed a significant challenge.

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The balance that has evolved has of necessity had to be a departure from the more classical balance layout. To the balance purist, the combination of load capacity and size and space limitations would probably have rendered the undertaking questionable.

However, the accuracy and repeatability in force measurement achieved during wind tunnel testing is not only a function of the balance in isolation. There is also a dependency on a combination of a variety of measurements, calibration processes, tunnel test procedures and data reduction techniques that impact on the overall quality of the final data. To optimise balance load capacity against the accuracy and repeatability achieved in drag measurement an unconventional approach was adopted. This was to design and manufacture a prototype balance with sufficient scope in the structural design for subsequent modification. The prototype balance was tested in the ARA TWT using a representative military model, to essentially quantify the degree to which the performance of the balance had to be improved to be acceptable as a working device. Lessons learnt during this exercise were then fed into the design of a modified version of the prototype.

The development of a prototype balance helped to highlight those aspects of balance technology that featured significantly in the performance achieved and needed to be addressed. These included the axial force load sensitivity, an understanding of balance output drifts due to temperature transients through the structure, the development of a calibration methodology to handle the non-conventional layout, errors in axial force measurement due to the proximity of the live end joint contact surface to the balance structure proper and also from the impact of component load interactions.

Finite element structural analysis was used extensively in the design of the prototype balance and in the modified version. The main task in the re-design was to increase the axial force sensitivity by a factor of three over the prototype, while maintaining as high a load capacity as possible. A factor of safety on material strength of two was considered the minimum that could be accepted.

The modified balance was realised by a relatively small amount of re-machining of the prototype balance. This was then re-gauged and calibrated prior to further evaluation trials in the ARA TWT.

2.0 PROTOTYPE BALANCE DESIGN

2.1 Design criteria

The balance was required to be interchangeable with those previously used for existing models in order to maintain compatibility. The required design therefore had to meet the following criteria and constraints:

- Fit a 57·15mm (2·25in) bore.
- Length inclusive of joints 297mm (11·7in).
- Location of moment reference centre.
- Compatible structural stiffness.
- Compatibility of balance to model joint.
- Minimum safety factor of two
- Eliminate balance/sting joint problems

The combined load range for the balance is shown in Table 1.

Table 1

Component	N,Nm	lbf, lbf.in
Normal force	22,241	5000
Pitching moment	1,580	14,000
Side force	3,113	700
Yawing moment	447	3,960
Rolling moment	610	5,400
Axial force	2,224	500

2.2 Balance accuracy

The basic unit of measurement in the determination of the drag of an aircraft is the 'drag count', which is a variation in drag coefficient of 0·0001. The drag on an aircraft model is determined from the resolved axial and normal forces on the structure and the drag coefficient, *CD*, is given by:

$$C_D = \frac{F_A \mathrm{Cos}\alpha}{qS} + \frac{F_N \mathrm{Sin}\alpha}{qS} \quad \ldots (1)$$

A variation of ±1 drag count in the overall measurement system is the required accuracy of the aerodynamicist[1], however, this is usually relaxed for military aircraft testing. Unfortunately for the balance designer this requirement is independent of the balance capacity and requires balance accuracy to be defined in absolute rather than relative terms.

From the above equation it can be deduced that the variation in drag coefficient due to the imperfections in the balance is given by:

$$\delta C_D = \frac{\delta F_A \mathrm{Cos}\alpha}{qS} + \frac{\delta F_N \mathrm{Sin}\alpha}{qS} \quad \ldots (2)$$

where δF_A and δF_A are the differences in the measured values from the true values.

From which it could be further deduced that the maximum allowable error in the measurement of axial force is given by:

$$\begin{aligned} \delta F_A &= q.\,S.\,\delta C_D \\ &= 0{\cdot}0001\ q.S \end{aligned} \quad \ldots (3)$$

In practice it can be shown[2] that in order to maintain an overall accuracy of one drag count it is necessary to reduce this by a factor of about three due to other error sources.

The requirements on the balance for the accurate measurement of drag are therefore independent of the balance capacity and are a function of the dynamic pressure and the model reference area. A small model (for which this balance has been designed) has a greater requirement on the accurate measurement of the absolute axial and normal forces than a larger model.

Drag is normally of greatest interest at the cruise conditions. The following example is to determine the maximum allowable errors in axial and normal forces if the drag coefficient is to be in error by no more than 1 drag count. If we take the case of a model with a reference area of 0·25m^2 being tested at a Mach number of 0·9 and an angle-of-attack of 2° the required accuracy in the measurement of axial and normal forces is about:

$$\delta F_A = \frac{0{\cdot}0001\ q\ S}{3\ \mathrm{Cos}\ \alpha}$$

$$\delta F_N = \frac{0{\cdot}0001\ q\ S}{3\ \mathrm{Sin}\ \alpha} \quad \ldots (4)$$

where, $q = 35{,}000\mathrm{N/m}^2$

$S = 0{\cdot}25\mathrm{m}^2$

i.e. $\delta F_A = 0{\cdot}29\mathrm{N}$

$\delta F_N = 8{\cdot}36\mathrm{N}$

(1 bar stagnation pressure)

The above requirements are independent of the full range capacity of the balance.

If the above figures are used in conjunction with the required load ranges of 2,224N axial force and 22,240N normal force the

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accuracy in percentage terms is:

Axial Force ±0·01%

Normal Force ±0·03%

Accuracies of this order are currently not achieved from the internal strain gauge balances typically used in wind tunnel establishments.

2.3 Basic design

The criteria outlined in Section 2.1 represented severe limitations within which an initial design solution had to be found. The confined space prevented the use of a conventional joint between the balance and the support sting. Previous experience with highly loaded taper joints of this size had shown them to be less than satisfactory and thus an integral sting was adopted to overcome these problems. While this approach would make manufacture a little more difficult, the sting was extended as far as an ARA standard 4 inch taper joint to make the task manageable. The limitation in overall length of the balance coupled with the definition of the position of the moment reference centre relative to this length, resulted in the unconventional layout shown in Fig. 1. In this figure the axial force unit (AFU) is shown ahead of the section of balance where the other five components are measured. After consideration on the form of balance to model joint, the limit in bore diameter only allowed a working diameter of the balance of 53mm. To the authors knowledge for this size of balance, the load capacity requirement is well in excess of anything that has ever been attempted for this style of balance.

Finite element analysis (FEA) was used extensively in the design of the AFU, essentially an iterative process to achieve a design that gave as high an axial force measuring sensitivity as possible commensurate with maintaining a material factor of safety of two within this highly stressed region of the balance. Early on in the design phase it was decided to manufacture the balance from Grade 300 maraging steel. Figure 2 shows an FEA stress result for the balance under full combined loading.

The manufactured sting/balance is shown in Fig. 3 being readied for calibration and in a little more detail in Fig. 4.

2.4 Balance to model joint

To attach the front of the balance to the parallel bore of the model, a split sleeve adaptor was devised (see Fig. 4). The sleeve has an internal taper compatible with a shallow external taper on the front of the balance. In assembly, as the balance is pulled into the sleeve a positively clamped joint is formed between the balance and the model. While the friction developed in the joint is designed to transmit rolling moment, a back-up roll key is provided for safety reasons.

Unfortunately, the split sleeve did not prove to be a success. During the calibration of the balance it was found that loading the balance in Pitching moment resulted in a large, unacceptable hysteresis in axial force. Hysteresis is one of the worst forms of error in that its magnitude is dependent on the magnitude of the change in applied load and is therefore virtually impossible to adequately quantify or provide an accurate correction for.

A series of investigations were performed in order to identify and resolve the cause of this error. The plots shown in Fig. 5 indicate both the magnitude and nature of the problem and the means taken to finally eliminate it. The cause was thought to be a combination of distortion of the split sleeve under load and the proximity of the joint contact surface to the AFU. The problem was finally resolved by the adoption of a continuous taper, integral with the adaptor body but cut back internally to locate the most aft point of contact further forward along the balance taper.

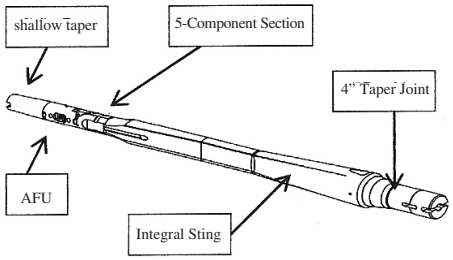


Figure 1. Outline of prototype 53mm diameter integral sting/balance.

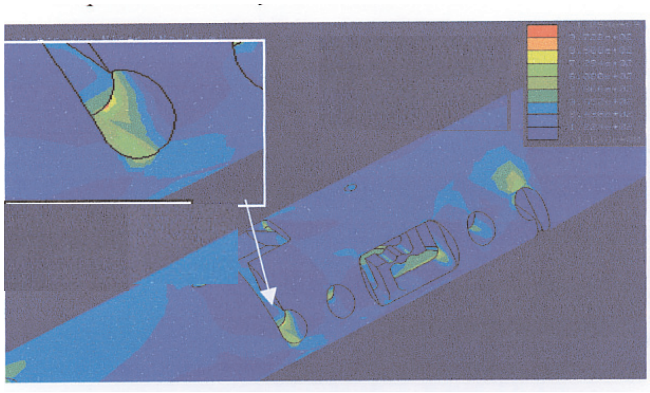


Figure 2. FEA of Prototype 53mm diameter integral sting/balance.

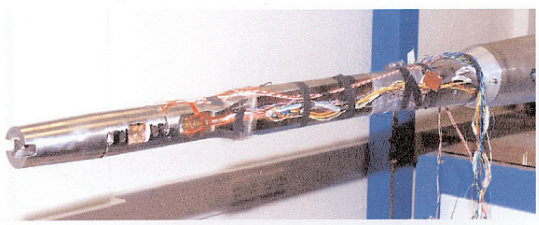


Figure 3. Prototype balance in preparation for load calibration.

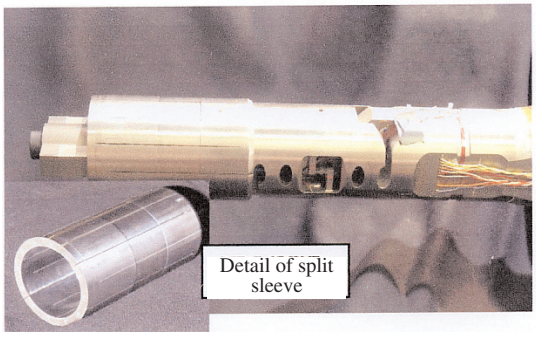


Figure 4. Prototype 53mm diameter integral sting/balance with split Sleeve.

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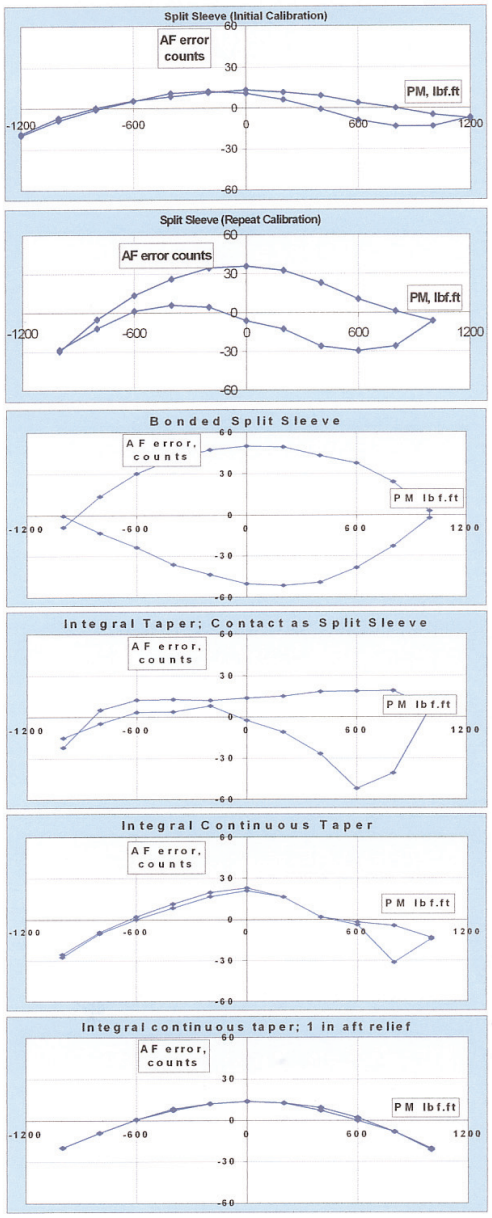


Figure 5. Development of balance to model joint.

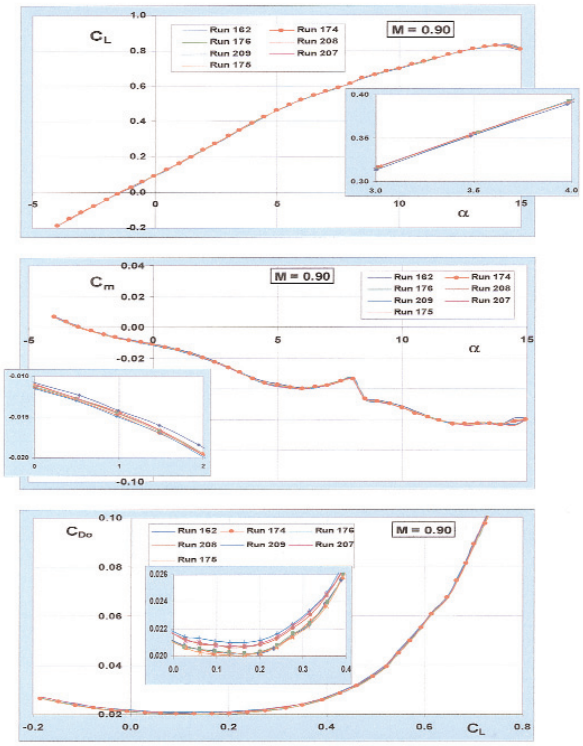


Figure 6. Sample results from TWT test of prototype balance.

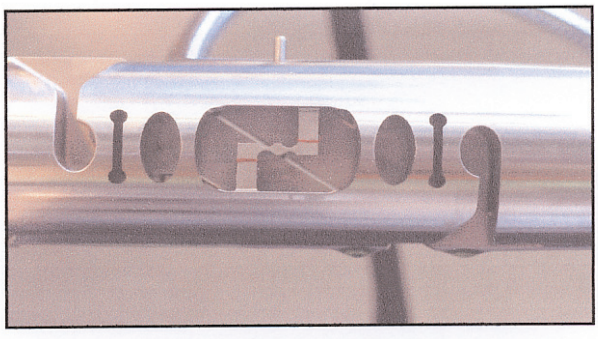


Figure 7. Modified balance showing axial force unit.

2.5 Strain gauging

For the prototype balance, the compromise between strength and axial force load sensitivity had to be biased in favour of strength. As a consequence the maximum attainable strain underneath the strain gauges was insufficient to produce the required output from the wheatstone bridge without recourse to an unacceptably high excitation voltage. The use of semi-conductor gauges, which have high gauge factors, was dismissed on account of an inherent gauge factor and apparent strain sensitivity to temperature.

Modulus compensated karma foil gauges were used throughout to minimise any variation in sensitivity due to temperature. Multiple gauges were used in the individual arms of some of the Wheatstone bridges in order to reduce interactions.

Due to the size and mass of the balance/sting combination, a new technique had to be developed for 'thermal matching'. In essence, 'thermal matching' consists of introducing temperature compensation wire into the bridge circuit in order to minimise thermal strain effects due to mismatches between the gauge characteristics. In this technique, the balance was heavily lagged with thermal insulation, heated to a temperature in excess of the maximum operating temperature of the ARA TWT and allowed to stabilise. Data were only recorded as the balance cooled with no heating applied. The cooling period was sufficiently long for the balance to be effectively at a quasi steady state temperature throughout the transient as it cooled to ambient.

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2.6 Calibration

The balance was calibrated in the ARA balance calibration facility using dead weights. In this process, load sensitivity and load interaction characteristics are determined as well as a measure of any creep and hysteresis inherent in the balance. FEA had shown that interactions of normal force and pitching moment on axial force would be significant and this was confirmed. A 'balance matrix' was formed which mathematically represents the transfer function of the balance as a sensor.

2.7 TWT trial

To evaluate the prototype balance, the balance was installed in a representative military model and tested in the ARA TWT. The main purpose of these tests were to quantify the repeatability in load measurement, to quantify drag accuracy and to identify any error sources. Testing consisted mainly of moving the model continuously in incidence sweeps while recording data every 0·5°, at Mach numbers ranging between 0·4 and 1·2. The sample data shown in Fig. 6 are those from seven incidence traverses recorded during three separate tunnel runs for a Mach number of 0.9.
The main conclusions that can be drawn from these plots are:

- The repeatability of the data for lift coefficient, C_L is 0·005 and pitching moment coefficient, C_m is 0·001. The repeatability is satisfactory in both cases.
- The plot of drag against lift (C_D *v* C_L) shows that the individual polars are not repeatable in level but are parallel to each other in shape.
- The repeatability of the drag coefficient, C_D, is about ±6 drag counts i.e. a spread of about 12 drag counts.

Data taken during the constant rate of pitch traverse, from the high incidence condition at the end of one traverse to the starting incidence at the beginning of the next, indicated that the small shifts in drag polar were due to an effect occurring during this phase between each polar. It is thought that temperature effects may be the cause, however, the mechanism for the drift has not been isolated.

During the TWT trials it was noted that the relatively high structural stiffness of the balance coupled with the absence of an aft balance joint, resulted in excellent dynamic behaviour of the model/balance/sting assembly. Notably, far more benign than had been experienced in the past.

Post test analysis of the data produced the following conclusions:

- The interactions of normal force and pitching moment on Axial Force were high and were not being adequately accounted for in the calibration matrix.
- The sensitivity of the axial force bridge needed to be increased by a factor of about three.
- It is unlikely that a balance of this capacity can be used for high accuracy drag measurements.

3.0 MODIFIED BALANCE DESIGN

3.1 Balance Refinements

The prototype design was subject to a further design study using FEA and an increase in axial force sensitivity by a factor of 2·4 achieved while still retaining a workable load capacity for the types of test campaign envisaged. The modified balance was realised by re-machining the prototype. The AFU of the modified version is shown in Fig. 7 and an FEA of the structure in Fig. 8.

The location of the normal force gauges was changed to improve the discrimination between thenormal force and pitching moment outputs. This was an important issue, as errors in the measurement of these component loads will produce axial force errors by virtue of their interaction characteristics.

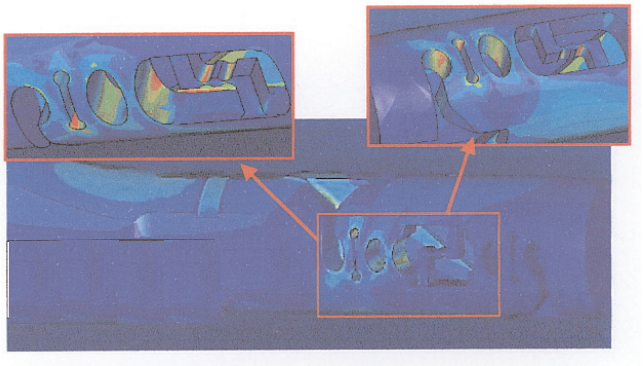


Figure 8. Finite element analysis of modified balance.

Finally, again based on FEA data, the strain gauging of the axial force bridges was modified to minimise interactions rather than temperature effects.

3.2 TWT trial of the modified balance

The modified balance was evaluated in the ARA TWT using the same model used for the prototype balance trial. Close attention was paid to determining the repeatability of the measurement of drag coefficient. In common with the earlier trials, the majority of the testing consisted of continuously traversing the model in the pitch plane while recording data every 0·3 degrees of incidence. The data presented in Fig. 9 were acquired from a total of 10 traverses in four separate tunnel runs. Inset figures are included to illustrate the degree of repeatability achieved in more detail. Included in the inset plot of the drag polars are an additional 10 single point drag measurements acquired from a series of 'C_{D0}' runs (Mach number traverses) undertaken at a constant low C_L condition. A 'C_{D0}' run is a test technique employed at ARA to determine accurate baseline drag data. The run is devised in such a way that balance drift errors due to thermal transients, are kept to an absolute minimum.

Comparison of the data acquired from the two balances (Figs 6 and 9) show close agreement, one major difference being the improvement in drag repeatability. The test demonstrated that the increase in the sensitivity of axial force measurement had brought about the anticipated improvement in the repeatability in drag coefficient. While there was no discernible improvement in the repeatability in either C_L or C_m, the variation in drag coefficient at a Mach number of 0·9 was improved from ±6 drag counts to ±2·5. Similar improvements were exhibited at all Mach numbers. In its modified form the balance is considered perfectly suitable for use in the ARA TWT for stability and control tests with an adequate drag measuring performance.

Differences can be seen in the C_L and C_m plots between the two balances, see Figs 6 and 9. This is probably as a consequence of the improved discrimination between the measurement of normal force and pitching moment achieved with the modified version of the balance. Unfortunately, no comparative test data are currently available for the model tested with an alternative balance.

A definitive accuracy for this new 53mm diameter balance has yet to be specified. For the most recent TWT test using the modified version, time constraints only permitted the formulation of a very basic calibration matrix. The matrix does require some refinement and extension. This will be followed by a re-computation of calibration residual errors and accuracies derived.

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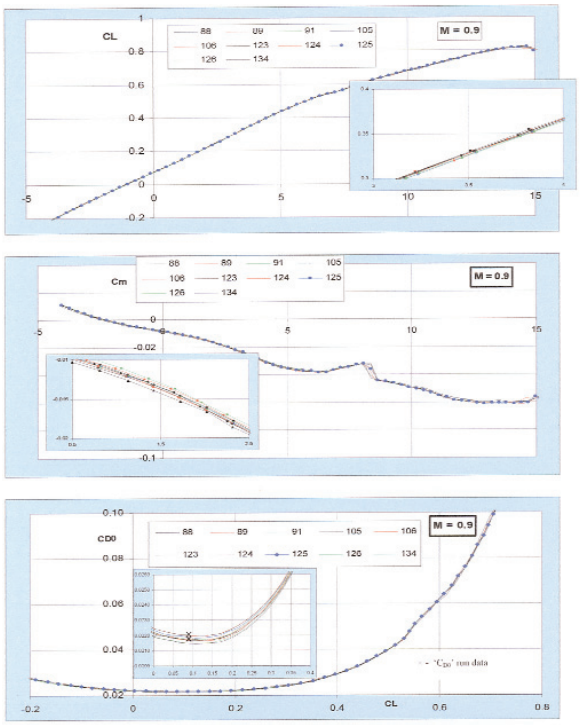


Figure 9. Sample results from TWT test of modified balance.

4.0 FUTURE DEVELOPMENTS

Testing of a very high capacity 53mm diameter balance has demonstrated suitability for the primary task of measuring large longitudinal and lateral forces and moments within the normally accepted accuracy criteria. A 53mm balance of the same overall shape and model attachment is being designed in order to acquire high quality drag data. The main criteria are the resolution and accuracy of the axial force measurement and the minimisation of component load interactions and thermal effects. Such a balance design has been specified with a load carrying capacity allowing sub and supercritical testing to beyond cruise condition but precluding deep buffet penetration.

5.0 CONCLUSIONS

A very high load capacity 53mm diameter integral sting balance has been developed for use in the ARA TWT, with adequate drag performance for the stability and control testing of small, highly loaded models of flight vehicles. To augment this A very high load capacity 53mm diameter integral sting balance has been developed for use in the ARA TWT, with adequate drag performance for the stability and control testing of small, highly loaded models of flight vehicles. To augment this device, a balance of the same overall outline is being designed to meet the criteria of high quality drag measurement. Acquisition of drag data at an accuracy consistent with that obtained during the testing of transport aircraft models in the cruise condition will only be possible with a balance of lower maximum normal force and pitching moment capacity.

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