INTERNAL BALANCE DEVELOPMENT FOR DRAG MEASUREMENTS

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The measurement of steady and fluctuating aerodynamic forces acting on a body is one of the main tasks in wind tunnel experiments. In aerodynamic testing, strain gauge balances will usually be applied as, particularly in the past, the main focus was directed to the measurement of steady forces. During the early years of wind tunnel testing, forces and moments were literally measured through pan-type balances, called internal balances. Nevertheless, technology has advanced since those early days, the term "balance" is still applied to different devices used for force and moment measurements. Internal balances are almost universally used for measurements in supersonic and transonic tunnels and are also becoming popular in subsonic tunnels, indeed they can be used in different wind tunnels, ranging from low-speed to transonic, from short to continuous running time and encompassing cryogenic and high pressure principles. The aim of this project is to manufacture a low cost internal balance, that will be useful in many experimental campaigns, specially in drag measurements, in the Pilot Transonic Wind Tunnel of the Institute of Aeronautics and Space (IAE) from DCTA. Thus, an internal balance was designed and will be properly produced, calibrated and tested, but it is very important that the balance displays high rigidity and low interference between the individual force components so that it is possible to obtain a satisfactory calibration.

Keywords: *Force measurements, Internal balance, Strain gages, Wind tunnel testing.*

1. INTRODUCTION

An aircraft in flight through the atmosphere has six degrees of freedom, so it can translate along three mutually perpendicular axes and rotate about these three axes. Consequently, its motions during flight are dependent on forces along and moments about three mutually perpendicular axes as illustrated in Fig. 1. Force and moment measurements normally made in wind tunnels are for the purpose of obtaining forces along and/or moments about one or more of the axes produced by air loadings (Pope and Goin, 1978).

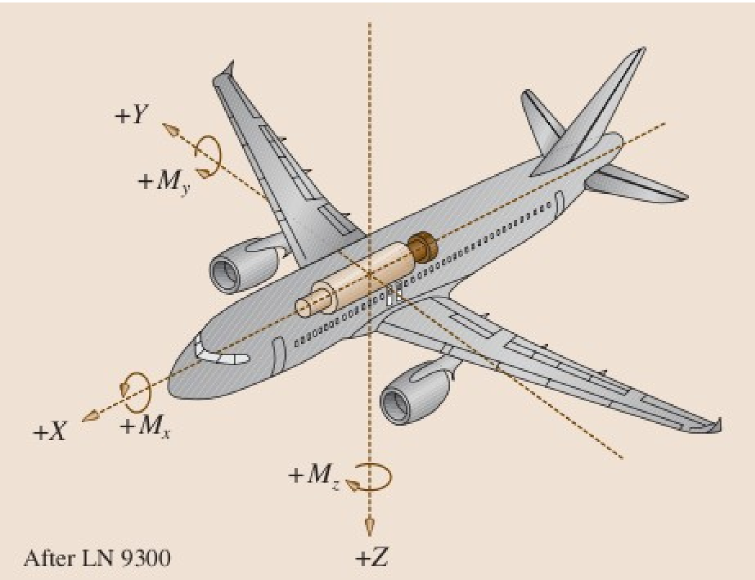

Figure 1. Definition of model-fixed axis system in Europe (Tropea *et al.*, 2007).

Following Pope and Goin, the main objective of such measurements is to obtain an estimate of loadings that will prevail on the full-scale aircraft in flight, both for structural integrity and for performance reasons. Forces and moments acting on an aircraft in flight or on a model in a wind tunnel are generally divided into the two broad categories of static and dynamic loadings. Static loadings are those resulting from the motion of air over an aircraft or model having a fixed alignment with respect to the relative wind. So, the aircraft or model is not rolling about or accelerating along its axes. Conversely, dynamic loads are those resulting from variations in time of roll orientation, and/or linear accelerations (1978).

Static loads are measured with devices called balances and these measurements are large in comparison to dynamic loads and are easier to measure with reasonable accuracy. Much of the wind tunnel time testing is devoted to the measurement of static loads (Pope and Goin, 1978).

Internal balances are designed to fit within the hollowed-out cavity of a model as illustrated in Fig. 2. They are normally designed for the measurement of 2 to 6 of the loading components. The cost of a six component internal balance will typically be in the neighborhood of some thousand of dollars (Pope and Goin, 1978).

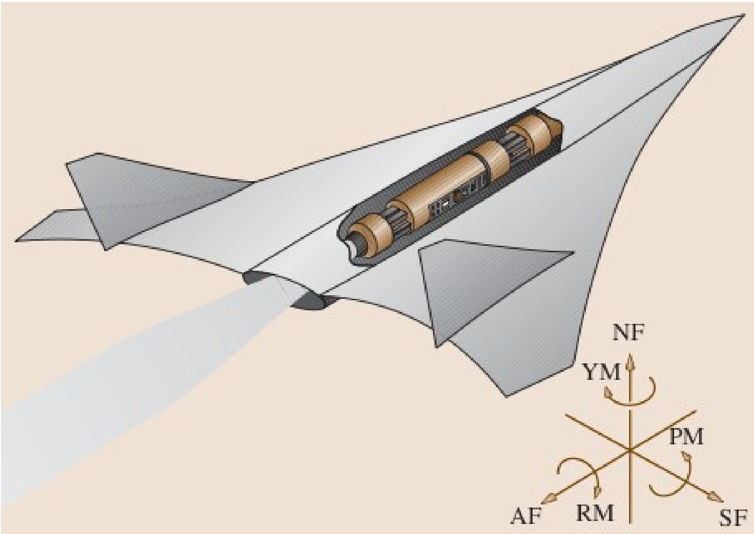

Figure 2. Internal balance mounting in a model (Tropea *et al.*, 2007).

Electric resistance “strain gages” are extensively used as the load-sensing element of internal balances. The gages consist of a fine wire grid or of a very thin foil embedded in a sheet of bakelite having a thickness comparable to that of heavy paper. The grid material is usually constantan, nichrome, or nichrome with small additions of iron and aluminum (Pope and Goin, 1978 ; Vishay, 1988).

The principle of operation of the strain gage is when this is connected to the surface of a structure, it will stretch or contract as the outer fibers of the structure to which it is attached. As the grid wires are stretched, their cross-sectional area decreases, causing an increase in electrical resistance. Similarly, as the grid wires are compressed, their cross-sectional area increases, causing a decrease in electrical resistance. In both instances the change in resistance is actually more than the change of area would indicate because of the change in length. It has been found in practice that the changes of resistance of the types of strain gages normally used in wind tunnel balances is directly proportional to the stress in the outer fibers of the structure to which it is attached. Hence it follows that a great care must be exercised in the installation of the strain gages (Pope and Goin, 1978 ; Vishay, 1988).

Previously referred to, the most common setup using an internal balance is the back-sting arrangement: the body of the model is connected to the mounting sting, which normally enters the model at the tail, as illustrated in Fig. 3, via a piece of metallic spring material. Because this, the internal balance is commonly called sting balance. The forces transferred by this element cause strains on its surface, which are measured by strain gauges. By a properly design of the balance and positioning of the strain gauges, a partial separation of the forces and moments is possible (Ewald, 2000).

Figure 3. An Airbus model mounted on a tail sting in the Deutsch-Niederbindiseher Windkanal tunnel (Ewald, 2000).

Strain gages in wind tunnel balances are normally located on a member in which the desired component of loading is a bending moment (Pope and Goin, 1978). Therefore, the majority of modern internal balances follow the bending beam principle. The main advantage of the beam balance is that the balance body normally can be fabricated from a single piece of material, thus avoiding any hysteresis caused by screwed or bolted joints in the structure. The principle of the bending beam balance is demonstrated in Fig. 4 (Ewald, 2000).

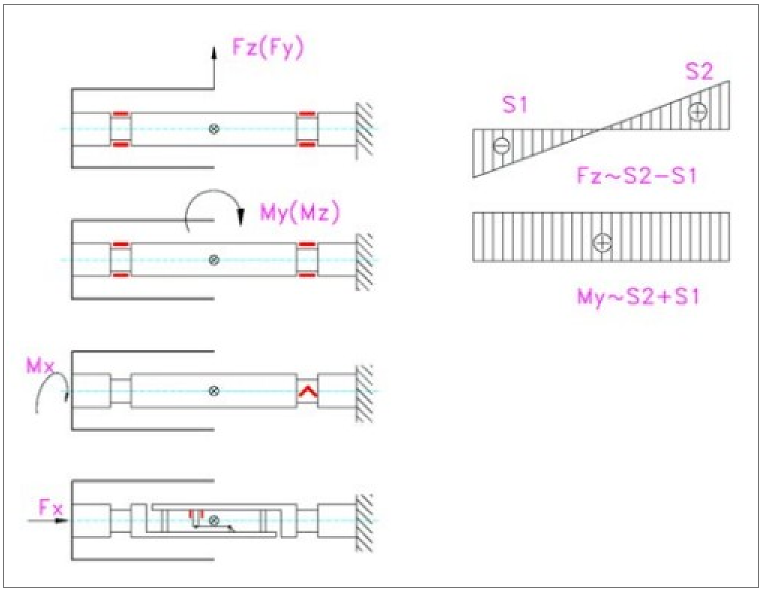

Figure 4. A double bending beam balance (Ewald, 2000).

The model, symbolized by the shell, is connected to the left-hand side of the beam. The mounting sting, symbolized by the earth symbol, is connected to the right-hand side. All forces and moments are measured relative to the reference centre in the middle of the beam and relative to an axis system fixed to the beam's axis. The beam has two positions at equal distance from the reference centre, where strain gauges are applied (Ewald, 2000).

The uppermost sketch shows the measurement of the normal force F_Z acting on the model. This force results in bending strains of equal magnitude but opposite sign at the strain gauge positions. The subtraction of these strains results in the normal force F_Z. The second sketch shows the measurement of the pitching moment M_Y around the y-axis, which is perpendicular to the plane of the drawing. This moment results in a constant bending moment along the beam, so the addition of the stresses at the strain gauge positions gives a signal proportional to the moment M_Y. In the same arrangement strain gauges are applied to the side of the beam. These gauges measure the side force F_Y and the yawing moment M_Z. The third sketch in Figure 4 shows the measurement of the moment M_X, which acts around the longitudinal axis of the beam. This moment results in torsional stresses in the beam, which may be measured by strain gauges applied on one of the bending positions at an angle of 45 degrees (Ewald, 2000).

The remaining component, the axial force F_X poses a problem. On the one hand this component in normal cases is much smaller than the normal force F_Z and on the other hand this force results only in longitudinal stresses in the beam, which are much smaller than the bending stresses. So the sensitivity and accuracy of this measurement would be poor. The standard solution is shown in the lowest sketch in Fig. 4. By an inclined cut the balance is separated into a model fixed part and a sting fixed part. These two parts are connected to each other by four packages of parallelogram flexures. The flexibility of these elements allows the balance parts to move against each other in the axial direction. This movement is transferred to the force sensing flexure, which is equipped with strain gauges. So, also the axial force is transformed into a bending stress, which is measurable with high sensitivity (Ewald, 2000).

For the strain gauges for the measurement of F_Z, F_Y, M_Y and M_Z which are illustrated by the two uppermost sketches in Fig. 4, there are two different arrangements possibles. Each bending position may be equipped with a complete strain gauge bridge in the vertical and lateral directions. These bridges would measure the bending stress at the bending positions. The forces and the moments with respect to the reference point are computed by adding or subtracting the signals from the bending positions. The alternative arrangement is to compose one complete bridge of strain gauges each from two gauges on the left-hand bending positions and two gauges from the right-hand bending position. With proper wiring of these bridges, one bridge directly measures the difference between the two bending moments and the other the sum of the two bending moments. So the normal force, pitching moment, side force and yawing moment are measured directly (Ewald, 2000).

The functional principle of the six-component balance shown in Figure 4 gives the impression that a totally independent and separate measurement of the six components is possible. In reality this is not the case; the signal from each strain gauge bridge is not only proportional to the component to which this bridge is assigned but also contains a small and complicated mixture of signals proportional (linearly or nonlinearly) to some or all of the other components. This problem must be solved with a sophisticated calibration and mathematical description of the balance’s behavior (Ewald, 2000).

The aim of this project is the design, manufacturing and calibration of a low cost internal balance that will be very useful in many experimental campaigns in the Pilot Transonic Wind Tunnel (PTT) of the Institute of Aeronautics and Space (IAE) from DCTA. More technical and historical information about the PTT can be found in the references Falcão *et al.* (2009) and Falcão and Mello (2002).

2. EXPERIMENTAL DESCRIPTION

Internal balances are used to measure the six components of the load applied (3 forces and 3 moments), as it has been explained in the introduction. The normal force capacities range from 60 to 200,000 N, and the axial capacities from 100 to 27,000 N, in the various types of internal balances produced by ONERA, for example. Generally, the central portion of each balance has two drag flexures of the push-pull type, to minimize the thermal effects between two sets of specially design decoupling blades. In ONERA, they are manufactured using the Electro Discharge Machining Technique (EDM) as one single unit and normally internal balances is in a range from 8 to 210 mm in diameter (ONERA, 2004). The Figure 5 illustrate some examples of internal (or sting) balances produced by ONERA.

Figure 5. Some examples of sting balances manufactured by ONERA (ONERA, 2004).

In the most of cases, the internal balances are manufactured using a rigid material like steel-250 grade. For specific applications, such as propulsion systems simulation in wind tunnel models, the air supply pipes and wiring must pass through the balance with negligible interaction (ONERA, 2004).

The balance was defined using design software (CATIA) and finite element software. The design was optimized according to the specified parameters (loading capacity, dimensions, interfaces and user environment). The mechanical and electrical characteristics, sensitivities can be reliably predicted. Thermal effects could be carefully avoided by specially designing the balance to avoid thermal expansion effects and gauging techniques to avoid zero and sensitivity shifts (ONERA, 2004).

In this project it is expected that the internal balance will be constructed out of a single piece of metal, on which strain gauges will be properly applied. On the other hand, we predict some experimental difficulties to install the strain gages and a second option can be designed if it has been necessary.

2.1 Design of the Internal Balance

For an internal balance the available space is a major concern as it is restricted by the fuselage diameter. As transport aircraft becomes larger, the scale for models also becomes larger, complicating matters since the cross sections of wind tunnels have do not grow at the same rate. As a result the available diameter for internal balances has become smaller.

The specification for an internal balance should therefore be made according to the model and the loads on this model during the tests, and not on the tunnel capabilities themselves. If these specifications are not carefully performed, the internal balances will provide insufficient sensitivity and accuracy for the tests.

So, the specifications of loading ranges and available space for the internal balance has been required. This was a challenging step prior to the design of a balance, since cost and accuracy considerations must be made long before the first tests will be performed. The main parameters considered to design a first prototype are described in Table 1.

Table 1. Main parameters specified to design a first prototype.

Material	Steel
Young's modulus(N/m^2)	2.00E+011
Poisson's ratio	0.266
Density (kg/m3)	7,860
Coefficient of thermal expansion (K)	1.17 E-5
Yield strength (N/m^2)	2.5 E+8

Initially, in this project, aerodynamic drag will be the only evaluated factor and the dimensions of the balance can be considered as 10 mm diameter and 150 mm length. A previous design performed using CATIA (Version 5) is illustrated in Fig. 6.

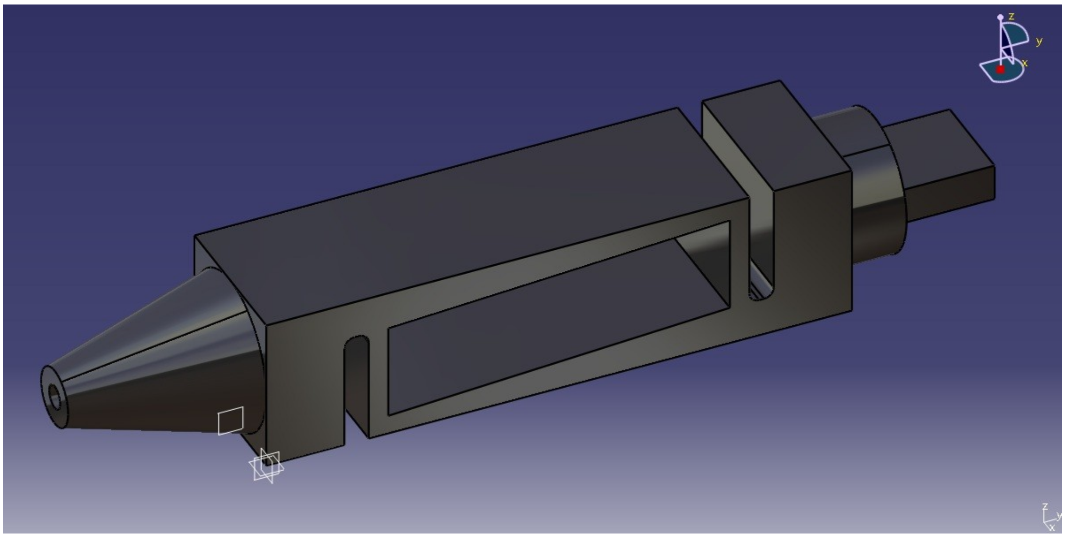

Figure 6. First prototype of the internal balance design using CATIA, v.5.

An analysis through finite elements method was performed using 427 thousand nodes and 2 millions of elements as can be viewed in Fig. 7. The von Mises stress calculation was performed and the maximum equivalent stress was 82.5 Mpa in the parallelogram flexures, so that the material is in the elasticity region.

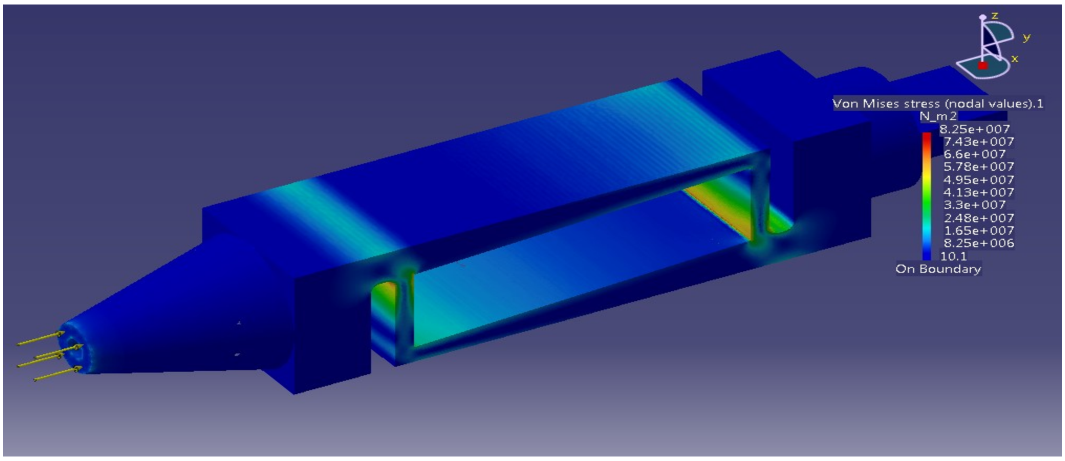

Figure 7. Three dimensional view of the first project of the internal balance.

The analysis of strength by the simulation it is a very important step in the design of balance because the strain gages must be exactly placed where the forces or moments act in the balance and in the model.

It is predict to use four strain gages in a Wheatstone bridge and it is possible use two Wheatstone bridge for each variable for a great accuracy. Using a Wheatstone bridge with four gauges applied, the output of such a transducer related to the force F will be nonlinear, but this is not a big disadvantage as long as these nonlinearities are taken into account through calibration (Pastore, 1995).

For standard load cells a nonlinear characteristic is not very common, however, for applications in wind tunnel testing they are some times advantageous since they do not require much space. Another advantage of such a transducer is that the strain gauges are placed very close to each other, remaining at the same temperature level. This minimizes the zero-drift and temperature-gradient sensitivity of the transducer (Saback, 1974).

3. CONCLUSIONS

An internal balance has been designed according to the main characteristics of drag measurements that are expected to be performed in the PTT. Although, there is a consensus in the literature that manufacturing, calibration and measurement using an internal balance can be very difficulty in many aspects. On the other hand, this type of project is very interesting because the research to design and produce an internal balance based on strain gauge measurements that will be done at IAE probably will demonstrate that a substantial improvement of the wind tunnel force testing technology requires engineering progress in many details concerning balance design concepts, actual balance designs, selection of materials, balance fabrication methods, gauging methods, calibration equipment and calibration algorithms. The expected outcome is an internal balance technology which leads to improved measurements for conventional tunnels and will bring the target of reproducibility to within one drag count for transport configuration performance measurements within reach.

4. ACKNOWLEDGEMENTS

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