REVIEW ARTICLE

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Multi-component force balances for conventional and cryogenic wind tunnels

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Abstract. The measurement of the total forces acting on the surface of a wind tunnel model is still the most important wind tunnel measurement technology. Either the model is mounted by struts to a balance, which is located outside the test section (an 'external balance'), or the balance is located inside the model and connects the model structure to the mounting sting, which in the case of aeroplane configurations protrudes from the rear fuselage (an 'internal balance'). This review concerns internal balances only. The functional principle is described and some comments on the demand for high accuracy are given. The optimization of designs for strain gauge balances, the fabrication methods and the selection of materials are commented on. The calibration theory of multi-component balances is outlined and the calibration equipment is described. Examples for conventional manual calibration equipment and for an automatic calibration machine are given. Finally the specific design features of cryogenic balances and half model balances are given. This review presents the author's experiences and developments. Since there is hardly any general literature on the subject of strain gauge balances and since the balance engineers in the world have not that much contact with each other, there may be different points of view at other institutions.

Keywords: force measurement, internal strain gauge balances, wind tunnel testing

(Some figures in this article appear in colour in the electronic version; see `www.iop.org`)

1. Introduction

1.1. The principle of multi component strain gauge balances

Normally the flow forces acting on a wind tunnel model are described in terms of three forces and three moments relative to a Cartesian axis system, which is fixed either to the model or to the free stream direction. So for the measurement a multi-component force sensor is required, which either directly and separately measures the six components or allows the evaluation of these six components from measured values.

In the case of an 'internal balance', ever since the invention of this instrument about 50 years ago only one functional principle has been used. The body of the model is connected to the mounting sting, which normally enters the model at the tail (see figure 1), via a piece of metallic spring material. The forces transferred by this element cause strains on its surface, which are measured by strain gauges. By a proper design of the balance and proper positioning of the strain gauges, a partial separation of the forces and moments is possible. Figure 2 clarifies this arrangement.

In wind tunnel practice two different designs of internal balances are used. The 'floating frame balance' is made up of two small platforms, one of which is connected to the model and the other to the mounting sting. These platforms are connected by a number of small force measuring elements. In the case of the 'double bending beam balance' the balance is more or less a simple beam connecting the model and the mounting sting, like shown in figure 2. The majority of modern internal balances follow the bending beam principle, so only this design is dealt with in this paper. The main

Figure 1. An Airbus model mounted on a tail sting in the Deutsch-Niederbindiseher Windkanal tunnel.

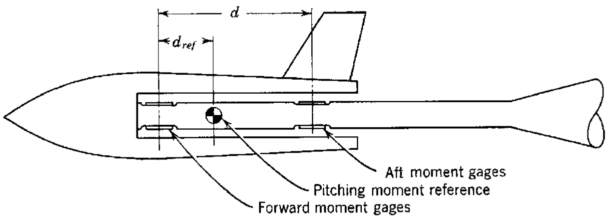

Figure 2. A tail sting mount with strain gauge balance.

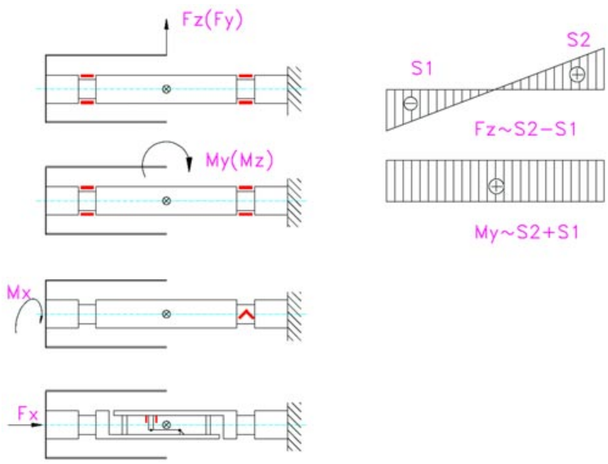

Figure 3. A double bending beam balance.

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 by figure 3. 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.

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 3 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°.

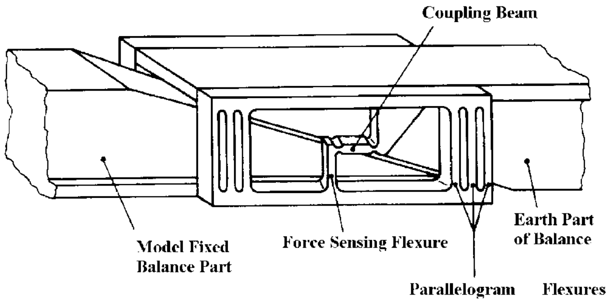

Figure 4. The axial force measuring system.

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 figure 3 and more clearly in figure 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.

For the strain gauges for the measurement of F_Z, F_Y, M_Y and M_Z (the two uppermost sketches in figure 3) two different arrangements are possible. 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.

The latter arrangement seems to be more practical. Nevertheless, the direct measurement of the bending moments and the computational evaluation of forces and moments is generally preferred. The reason is that this arrangement allows the use of locally concentrated bridges, which are less sensitive to temperature differences in the body of the balance.

The functional principle of the six-component balance shown in figures 3 and 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 but 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 behaviour; see section 7.

1.2. The importance of the accuracy of the balance

The successful design and development of commercial transport aircraft depends (among many other things!) on excellent aerodynamics. Especially the flight performance reacts very sensitively to the aerodynamics. Since flight performance must be guaranteed to potential future customers long before the first flight of the prototype, the success of the aircraft depends heavily on wind tunnel tests with the utmost accuracy. This ever rising requirement for accuracy in wind tunnel testing gave a strong impetus to strain gauge balance research in the recent past. This impetus was boosted even more by the development of the cryogenic wind tunnel, in which the temperature of the gaseous medium (normally pure nitrogen) can be varied between ambient temperature and 100 K, which is close to the liquefying temperature of nitrogen. Since accuracy limits for conventional strain gauge balances are set mainly by thermal effects, the target of achieving at least the same or possibly even better accuracy with cryogenic balances in cryogenic tunnels is an extremely difficult one.

To achieve considerable improvements compared with the balances known and used today, a single clever balance design idea or a single successful detail improvement is not sufficient. A systematic search through all parts and aspects of balance technology and the improvement of all details of this technology to the limits of the available technology are necessary. The important aspects of the technology are

(i) the design philosophy,
(ii) computation and optimization of the design,
(iii) balance fabrication methods,
(iv) selection of spring material for the balance body,
(v) strain gauge selection and methods of application and wiring of strain gauges,
(vi) the mathematical calibration algorithm,
(vii) the calibration equipment and
(viii) the strategy for use of the balance in the wind tunnel.

More than twelve years ago we convinced the German Ministry for Research and Technology that the force measurement technology is perhaps the most important key technology for the success of the new European Transonic Wind Tunnel (ETW), which was in the early stages of planning and design at that time. We were happy enough to get long term funding for the development of the cryogenic balance. This put us in a position to do concentrated research and development on balances. The aim of this research at the Technical University of Darmstadt was to improve each of these partial aspects of balance technology to the scientific limits available today. From this research into cryogenic balances many improvements also for balances for use in conventional wind tunnels resulted. Part of the work was done in close co-operation with the Daimler–Chrysler Aerospace Airbus GmbH at Bremen with some contributions from the Deutsches zentrum für Luft- und Raumfahrt.

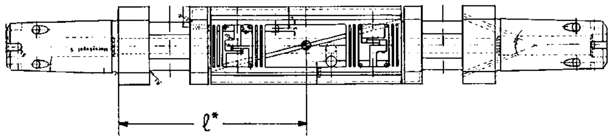

Figure 5. The definition of the characteristic length l^*.

2. The balance design philosophy

For a successful balance design some essentials must be fulfilled.

(i) Choose the balance ranges as close as possible to the actual measuring task. In defining the ranges, take into account that ranges of the balances can be overloaded, if other ranges are not fully used in the tests.
(ii) Choose the geometrical dimensions of the balance as large as allowed by the available space in the model.
(iii) Design the balance structure for maximum stiffness.

The first essential requires the design of dedicated and tailored balances for the various tasks of a wind tunnel. As an example, for a typical transport aeroplane configuration model matched in scale to the test section dimensions in a transonic wind tunnel, at least three different balances are required for high accuracy testing:

(i) a very sensitive balance for cruise condition lift/drag optimization work;
(ii) a less sensitive balance for buffeting tests, maximum lift tests and $M_{never\ exceed}$ (henceforth M_{NE}) tests; and
(iii) an envelope balance for stability and control tests up to M_{NE} including full control surface deflections and large angles of attack and yaw.

This requirement results in a need for complex and expensive balance equipment for a wind tunnel but improves wind tunnel accuracy greatly.

The maximum load capacity of a balance design within a fixed diameter is limited even if an ultra-high tensile strength steel (high grade maraging steel) is used. In our balance design method we introduced a balance load capacity parameter S, which is defined as

$$S = \frac{Zl^* + M_\gamma}{D^3}\ \mathrm{N\ cm^{-2}}.$$

The characteristic length l^* of the balance is defined as the distance from the reference centre to the end of the active part of the balance, see figure 5; D is the diameter of the balance. So this 'balance capacity parameter' is a simplified measure of the bending stress in the body of the balance close to the connection to the model or sting, which may be a cone or a flange. In most balance designs this is the critical position with respect to stress.

Figure 6 shows a balance load capacity diagram for a range of balances with diameters between 4 and 11 cm. A group of curves of constant load capacity parameter S is plotted. The messages of figure 6 are that

(i) precise balances including an axial force system have been fabricated so far only up to a value of $S = 2000\ \mathrm{N\ cm^{-2}}$ and

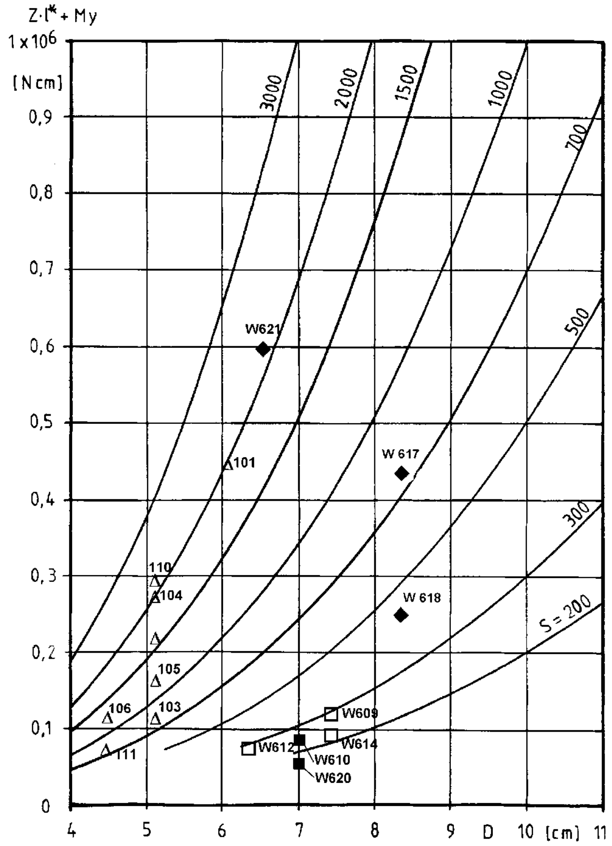

Figure 6. A balance load capacity diagram.

(ii) for a transport balance the load capacity parameter normally is below about $S = 700$ N cm^{-2}.

Even lower load capacity parameters are recommended for utmost precision in drag measurement, if the space in the model allows use of the larger diameter.

The third essential mentioned above (high stiffness of the body of the balance) is difficult to achieve with conventional fabrication of the balance by electrical discharge machining (EDM). With this method all internal cuts in the body of the balance must be accessible to the electrode from the outer side of the body of the balance. This compromises the requirement for stiffness. So the fulfilment of the requirement for stiffness is mainly a question of the fabrication method.

The solution of this problem is the concept of an electron beam welded balance, which was developed by the author at VFW (now Daimler–Chrysler Aerospace Airbus GmbH) about 20 years ago. For detailed information on this fabrication method see section 5.

3. Computation and optimization of the balance design

A strain gauge balance is a complicated structure with a very large number of dimensions. So the balance design cannot be achieved as an analytical solution from the external dimensions and the required component ranges.

At the Technical University of Darmstadt the initial design computation is done with the interactive computer

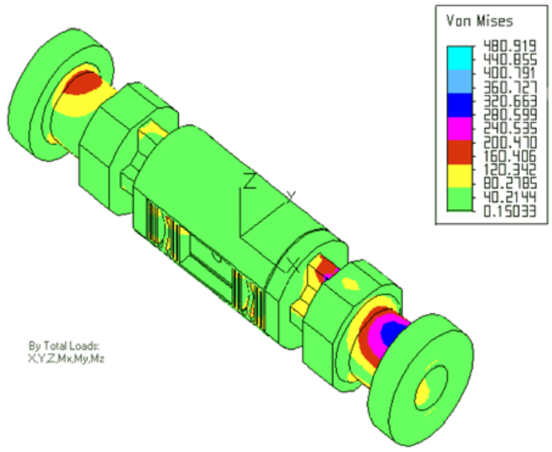

Figure 7. A finite element computation for balance W617.

program 'SEKOWA'. With each step this program completely computes the stress situation at all critical positions of the body of the balance and some additional characteristic parameters. All results are printed. The operator checks the results and, according to his experience with the design process, he modifies one or several geometrical dimensions. Each step is designated a 'run'. An experienced balance designer needs about 40–60 runs to obtain a final satisfying result or the understanding that a good balance with the specified ranges cannot be designed within the given dimensions. This work can easily be done in 2 or 3 h. The computation is based on a basic stress and strain formula for short bending beams and short torsion beams. Provision is made in the program for notch stress concentration. The computer program also creates overload diagrams, which give information on the allowed ultimate loads of components, if other components are not used to their maximum design capacity.

The use of finite element analysis for routine balance design is not possible, since the discretization of the complicated structure with many modifications for the optimized design is too laborious. Nevertheless, for principal optimization of strain gauge balance designs, finite element analysis proved to be an extremely valuable tool. This was demonstrated by the work of Dr Junnai Zhai at the Technical University of Darmstadt [22, 26, 27, 29, 31, 36]. Work on balance optimization with finite element analysis is being continued at the Technical University of Darmstadt. Figure 7 shows the stress distribution of the balance W617 under full combined loads computed by finite element analysis.

The analysis of balance structures by the finite element method demonstrated that the computation and the minimization of linear and nonlinear interference effects by this method is possible. For more details on this work see [26].

4. Balance fabrication methods

The classical fabrication method for a strain gauge balance is to cut the body of the balance from a single piece of material. The complicated structure is machined mainly by EDM. This fabrication method restricts the design of the structure;

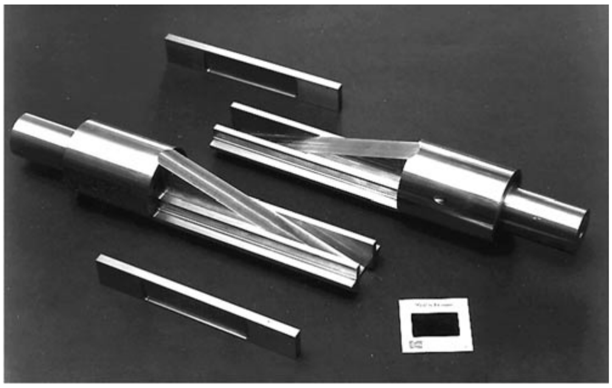

Figure 8. Prefabricated parts of balance W607.

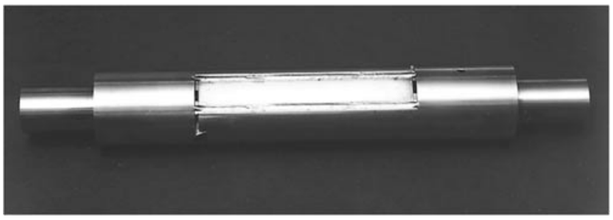

Figure 9. The body of W607 after welding.

all cuts must be accessible from the outer side. Necessarily this compromises the request for maximum stiffness.

When we designed the first balance for the German–Netherlands Wind Tunnel DNW, we had no EDM machines available at the company VFW (now Daimler–Chrysler Aerospace Airbus GmbH) but excellent electron beam welding equipment was available. This was the reason for the development of the electron beam welded balance, which turned out to be an optimum solution.

With this technology the balance is fabricated from four pieces, which are prefabricated to the final dimensions of all internal surfaces and welded together by electron beam welding. All external machining, including opening of the flexure systems, is done after welding. The first production step is shown in figure 8.

After the welding process the body of the balance looks like that shown in figure 9. The body of the balance is assembled using four straight welding seams.

All final machining can now be done from the outside of the body of the balance by milling or EDM where necessary. The final appearance of the balance before the application of strain gauges is shown in figure 10. Provided that a suitable material is selected and a sophisticated heat treatment is applied after the welding process, full strength of the material is restored in the welding zone and the finished balance *is* a one-piece balance and, with respect to strength and hysteresis, definitively behaves like a one-piece balance. In a polished cut of the welding seam the welding zone is hardly visibly.

The concept of the electron beam welded balance turned out to be highly successful and has been used since its development for nearly all balances constructed by the Daimler–Chrysler Aerospace Airbus GmbH and by the Technical University of Darmstadt. This fabrication method

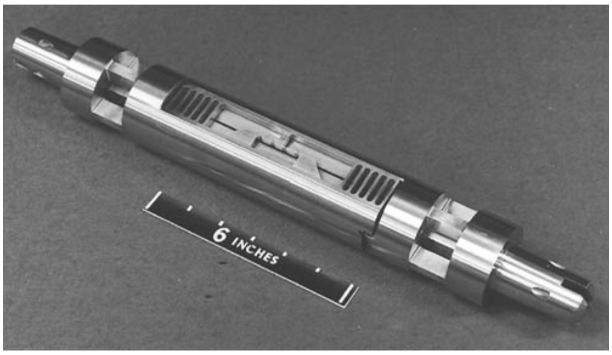

Figure 10. The balance W607 after external machining.

gives complete freedom in the internal design of the balance structure and allows a much stiffer design of the balance.

5. Material selection

The conventional material for strain gauge balances is either maraging steel or a precipitation hardened steel like PH 13.8 Mo (1.4534) or 17.4 PH (1.4548). For the welded balance concept we use maraging steel 300 (1.6354) for conventional balances and maraging steel 250 (1.6359) for cryogenic balances. Maraging steel is excellent for electron beam welding; the precipitation hardened steels should be good for welding as well, but no experience has been gathered up to now with balances welded from precipitation hardened steels.

A very comprehensive study on force sensor spring materials was performed at the Technical University of Darmstadt [61]. One important result of this study was the discovery of a general trend of increasing hysteresis with increasing nickel component in the alloy. So the hysteresis quality of the maraging steels is not optimal. With maraging steel hysteresis may be considerably reduced by three provisions:

(i) multiple heat treatment for grain refinement, as described in [17];
(ii) by deep cooling (at 77 K for 20 h) before the ageing treatment the hysteresis is reduced considerably; and
(iii) if a lower ultimate strength can be tolerated, underageing reduces the hysteresis of maraging steel considerably.

Additionally, at the Technical University of Darmstadt, a successful method for numerical correction of force sensor hysteresis was developed. Nevertheless, this method has not yet been applied to strain gauge balances.

An excellent material for force sensors may be the titanium alloy $TiAlMg_4$ (3.7164). There is hardly any hysteresis with this material. Nevertheless, more experience, especially in electron beam welding and in gauge application, must be gathered before application of titanium as a strain gauge balance material.

The low resistance to corrosion of maraging steel is troublesome for balances, especially in the case of cryogenic balances. Nickel plating proved to be an efficient counter-measure. In this case the strain gauge positions are covered

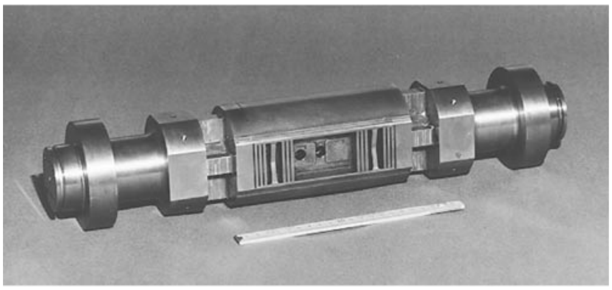

Figure 11. The copper–beryllium balance W617.

with a protecting lacquer before the nickel plating. So the gauges are bonded onto the uncovered maraging steel.

A very promising material for conventional and cryogenic balances is copper–beryllium (2% Be), if the load capacity factor allows for the tensile strength of this material being lower than that of maraging steel. The hysteresis is extremely low and the electron beam weldability is good. The excellent heat conductivity of copper–beryllium will considerably reduce the temperature gradient problems with cryogenic balances. A cryogenic balance for the European Transonic Wind Tunnel was designed and constructed from copper–beryllium at the Technical University of Darmstadt, see figure 11.

6. Strain gauging and wiring methods

Up to now we have used strain gauges exclusively from Micro Measurement (Vishay). From the available range of gauges types which are very well suited for the cryogenic range and for conventional tunnel conditions can be selected. For the extreme temperature range of cryogenic balances misadaptation of the self-temperature-compensating (STC) factor is recommended. We use STC factors of 11 or 13 for balances constructed from maraging steel.

A more complicated problem is that of the primary correction for the change in Young's modulus over the extreme temperature range of cryogenic balances. Normal KARMA alloy is not satisfactory. For a special cryogenic balance production, Micro Measurement has demonstrated that a special tuning of KARMA gauges for extreme temperature range compensation for Young's modulus is possible. Gauges of this special type were used for some cryogenic balances constructed by the Technical University of Darmstadt and Daimler–Chrysler Aerospace Airbus GmbH.

For a very low zero drift over the temperature range of cryogenic balances, misadaptation of the STC factor, a closely coupled arrangement of the gauges of one bridge etc are not sufficient. Even the gauges from one pack of five exhibit considerable scatter in thermal behaviour. Gauge matching improves this situation very much and was first proposed by Judy Ferris (NASA Langley) [13]. Since the thermal behaviour of gauges can be evaluated only from the applied gauge, each individual gauge is applied to a common maraging steel sample by cyanocryalate bonding. After a measurement of the zero drift of each gauge in the cryogenic chamber the arrangement is heated beyond the stability of the cyanocryalate bond and the gauges are carefully cleaned. From the results of this process the gauges for each bridge are individually selected for minimum bridge zero drift. This procedure is time consuming but reduces bridge zero drift greatly.

Another very effective measure against temperature induced zero drift is the use of very closely concentrated Poisson bridges. This minimizes the possibility of there being different temperatures at the gauges in one bridge.

For final gauge application on strain gauge balances hot bonding with an epoxy resin is used exclusively. Preparing the surfaces, preparing the gauges and performing the bonding procedure must be done with the utmost care, patience and perfect observance of the manufacturer's instructions. Even the utmost care is not sufficient, for it must be combined with years of experience in the art of strain gauge application.

For conventional balances temperature correction copper wires are integrated into the bridge wiring. For cryogenic balances this procedure is not very successful, since the strongly nonlinear behaviour of the apparent strain cannot be compensated by the behaviour of copper with a different nonlinearity. If, for special temperature correction methods, the measurement of temperatures on the balance is necessary, a number of temperature sensors (6–10) is installed on the balance. Pt 100 sensors are used for the temperature measurement. For very high precision the Pt 100 sensors are individually calibrated.

The internal wiring of the bridge circuits is carefully designed to provide a symmetrical length and symmetrical temperature on all internal bridge wire connections. All bridges are wired separately for excitation lines, excitation voltage sensing lines and signal lines. All circuits are connected to the tunnel data system via a high quality miniature connector mounted at the sting end of the balance. Normally 80 pin connectors are used.

Very often in wind tunnel testing practice it is necessary to bridge the balance with other electrical signal and power lines as well as pneumatic lines. These lines may cause the accuracy of a balance to deteriorate due to their stiffness to such an extent that force testing and testing with the use of balance bridging lines must be done separately, so that the wind tunnel productivity is reduced greatly. At the Technical University of Darmstadt there was developed the concept of integrating these bridging lines into the design of the balance. With such an integrated electrical or pneumatic line bridging, the balance has connectors at the sting and the model end for the lines. Thus any hysteresis due to the bridging is avoided.

7. Mathematical calibration algorithms

In this chapter the following nomenclature is used:

A, A_i, A_{ij}	linear matrix coefficients
B, B_i, B_{ij}	square matrix coefficients
C, C_i, C_{ij}	cubic matrix coefficients
$E_{i,m}$	approximation error of component 'i' in loading case 'm'
F_i, F_j, F_k	calibrated loads of components i, j and k

min	minimum
R_{0_i}	zero reading component 'i'
$R_{i,m}$	reading of component 'i' for loading case 'm'
S_i	computed signal of component 'i'
$S_{i,m}$	computed signal of component 'i' for loading case 'm'
SFQ_i	sum of squared errors of component 'i'

An internal balance needs a careful calibration. The calibration is achieved by loading the balance with calibrated forces. The signals of the balance are evaluated as a 'calibration matrix', which gives a set of equations for 'signals as functions of loads'. An inverse version of this set of equations, 'loads as functions of signals', is used to evaluate the balance signals recorded during tests in the wind tunnel. Most methods for evaluation of calibration data in routine use today had their origins at a time when no or only very simple computers were available for the evaluation.

Research on balance calibration was stimulated recently for two reasons. The manpower used for the conventional calibration became more and more expensive. Experience demonstrated that nearly one third of the total cost of a new balance is consumed by manpower used for calibration. On the other hand, the introduction of the cryogenic tunnel brought the temperature into the calibration as an additional parameter, so the calibration manpower soared even more beyond an affordable price and the cryogenic tunnel with its much improved simulation capability asked for even more accurate balances. So automatic calibration was investigated and new methods of calibration and calibration algorithms became necessary.

The calibration of an internal balance must be valid for a body fixed axis system of the wind tunnel model (which may be shifted and turned relative to the reference axis system of the model). This is identical to a high accuracy with the axis system of the model end connection of the balance. To calibrate the balance accordingly, in conventional rigs the balance is connected to the calibration rig via its sting end and a stiff 'calibration sleeve' is connected to the model end of the balance.

Loads are generated by hanging dead weights from precisely defined loading points on the sleeve. The use of pulleys or levers is avoided insofar as this is possible in order to have the minimum possible hysteresis and avoid the introduction of additional errors. Moments are also generated by hanging dead weights from the loading sleeve at appropriate distances from the axis. Lateral loads (side force and yawing moment) are generated after turning the balance through 90° around its x axis. Figure 12 shows the system for this conventional calibration.

The balance is distorted by the calibration loads. To realign the loading sleeve and the balance relative to the geodetic axis system, the conventional rig is equipped with a facility for adjustment of the pitch angle and roll angle. After each loading step the loading sleeve is realigned relative to the geodetic axis system either manually or by using a servo drive.

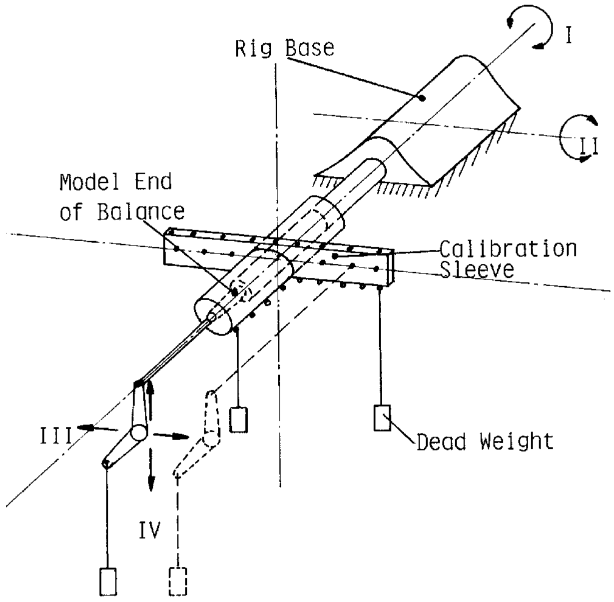

Figure 12. The conventional calibration rig.

This principle allows no complete freedom in the component loading. The application of moments is possible only in combination with forces if the use of pulleys is to be avoided. The need for realignment (which is normally done by hand) results in a lengthy calibration procedure.

The simplest useful description of the behaviour of the balance is the linear calibration matrix. In this case the signal of the strain gauge bridge for the component 'i' is given by the equation

$$S_i = R_{0_i} + \sum_{j=1}^{6} A_{ij} F_j. \tag{1}$$

For the use of the balance in the wind tunnel this system of equations is inverted to

'loads' = functions of 'signals'

by a simple inversion of the coefficient matrix. This method neglects any nonlinear behaviour as well as effects generated by the simultaneous actions of two components.

The state of the art in most wind tunnels is the so-called 'second-order calibration'. In this case the signal of one strain gauge bridge is described by the equation

$$S_i = R_{0_i} + \sum_{j=1}^{6} A_{ij} F_j + \sum_{j=1}^{6} \sum_{k=1}^{6} B_{ijk} F_j F_k. \tag{2}$$

This description covers nonlinearities by virtue of the quadratic terms and it also covers 'product interferences', which are caused by the simultaneous actions of two components. Interferences of this type may occur with considerable magnitudes, so the use of 'second-order calibration' is mandatory. Nevertheless, this method causes problems.

The full 'second-order' description of the balance according to equation (2) requires calibration loads with all six single loads and with all combinations of two loads (15 combinations). Some of these load cases cannot

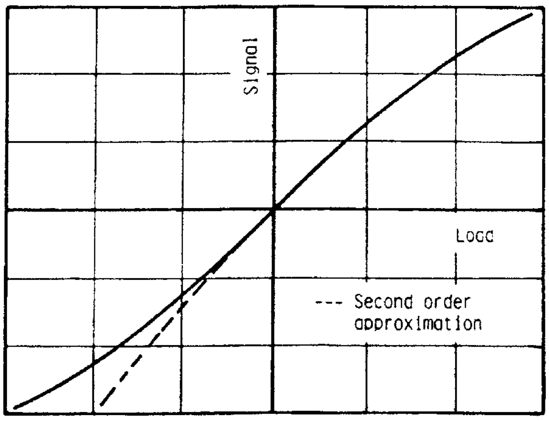

Figure 13. Second- and third-order descriptions.

be generated with the conventional calibration rig. A combination of two moment loads requires an additional load of one or two forces. So the evaluation of the matrix coefficients becomes very complicated.

The other problem is the matrix inversion for the use of the balance in the tunnel. In a mathematical sense inversion is possible only for a linear matrix. So iterative methods must be used for the 'inversion'.

The matrix coefficient evaluation methods used by most wind tunnel organizations are still influenced by thinking from the old time when no computers were available for the evaluation. The loads are applied in loading sequences for one pure component with all other components zero or at least constant. With least square error methods the coefficients of the matrix were evaluated and compiled step by step from such loading sequences.

Many years ago we extended the second-order description given above to a third-order description:

$$S_i = R_{0_i} + \sum_{j=1}^{6} A_{ij} F_j + \sum_{j=1}^{6} \sum_{k=1}^{6} B_{ijk} F_j F_k + \sum_{j=1}^{6} C_{ij} F_j^3. \quad (3)$$

In this description terms a third-order term for the direct component calibration terms is taken into account. The advantage of this description compared with the conventional second-order calibration was often questioned by other experts; nevertheless, the use of the third-order approximation is simply logical.

Certainly there are physical reasons for a nonlinearity of the characteristic line of one component of a strain gauge balance (or any other force sensor), as shown in the positive quadrant of figure 13. Since a strain gauge balance is a symmetrical structure, almost certainly the nonlinearity of the characteristic line in the third quadrant should be mirror inverted to give the line in the positive quadrant shown in figure 13 as the full line. There is no reason to expect a monotonic curvature like shown as the dotted line.

The development of automatic balance calibration machines resulted also in calibration procedures for which the application of one pure single load component or the application of two pure single loads is no longer possible. Certain types of automatic calibration machines create a calibration data base, such that, in each loading case, the desired loads (normally one or two components) are superimposed upon small loads in the other components. So a new algorithm had to be developed. This method was developed at the Technical University of Darmstadt [18] and was further improved and tested by the Experimental Aerodynamics Department of Daimler–Chrysler Aerospace Airbus GmbH [19] (Possibly there had been similar developments at other places. Nevertheless, since these developments were not published, from the point of view of the Darmstadt University of Technology this was a new development.)

With this method the total coefficient matrix is computed in one mathematical step from the total calibration data set. This means that each loading case contributes to all matrix coefficients. The criterion of the evaluation is again the least square error sum, but now it is the total sum of errors over the total set of loading cases. For a given order of approximation the result is the absolute best fit in a purely statistical sense.

For any loading condition 'm' achieved during the calibration procedure equation (3) gives the expected signal '$S_{i,m}$' from one strain gauge bridge 'i'. This computed signal will differ from the real signal '$R_{i,m}$'. The difference is

$$E_{i,m} = R_{i,m} - S_{i,m}. \quad (4)$$

The final target of the evaluation is to minimize the overall error sum SFQ_i for all components 'i':

$$SFQ_i = \sum_{m=1}^{M} E_{i,m}^2 = min. \quad (5)$$

This is achieved by application of the Gaussian least square error method. So the partial derivatives of SFQ_i for all coefficients of equation (3) must be set to zero. This gives a linear system of equations for the coefficients of equation (3):

$$\frac{\partial SFQ_i}{\partial R_{0,i}} = 0$$
$$\frac{\partial SFQ_i}{\partial A_{i,j}} = 0$$
$$\frac{\partial SFQ_i}{\partial B_{i,j,k}} = 0$$
$$\frac{\partial SFQ_i}{\partial C_{i,j}} = 0. \quad (6)$$

The new algorithm has some characteristics which are very different from those of the conventional methods.

7.1. The sequence of loading conditions

The conventional methods depend on a stepwise evaluation of loading sequences, starting with sequences of pure loads of a single component. Load sequences of combinations of two single loads are evaluated for the product term coefficients. This evaluation is possible only with carefully organized sequences.

The Darmstadt algorithm uses each loading condition with equal weight for the computation of the complete coefficient matrix. The sequence of the single component loadings has no significance at all. Nevertheless, a quick look on-line evaluation of the actual loading sequence is a very useful way to discover malfunctions in the calibration procedure, so the loading sequences certainly should not be generated by a random generator (but it would work!).

7.2. Load combinations

With the conventional methods, loading cases with pure single components and combinations of two pure single components are required. This requirement calls for realignment of the load application system for each loading condition.

With the new methods for each loading case the complete vector of six components is used for evaluation. In principle each such loading case may consist of a combination of six loads. Nevertheless, the observance of certain rules is advantageous for an optimum calibration.

Since equation (3) describes only the influence of single components and the influence of products of two components, the main contribution of the loading cases should be one component or a pair of two components. The other components occurring in each loading case should be small compared with these loads. Another rule is to put more weight on the single load cases, since the linear coefficients describe approximately between 80% and 99% of the signal. So the single load sequences should contain more narrow steps than do the sequences with two combined loads.

Naturally, during the use of the balance in the wind tunnel, cases with only one or two components acting on the balances are rare, so the calibration theory should include cases with more than two components. Nevertheless, this would complicate the calibration process greatly, perhaps beyond practicability. Since in the balance literature very little is known about higher order effects, they may play a noticeable role. This must be a subject of future research.

7.3. The zero reading of the balance

The most popular definition of the zero reading is the mean value between a reading with the balance in an upside orientation and an upside down reading of the balance (the 'weightless balance model end'). Since this condition is not reached in a real calibration process, this balance zero reading must be evaluated by interpolation procedures.

If the balance is not rotated upside down during the calibration, which normally is not necessary in an automatic calibration machine, the Darmstadt method automatically gives the zero readings R_{0_i} of the component 'i' for the unloaded balance in the orientation used during the calibration. These zero readings are evaluated by the method even if this condition was never exactly achieved during the calibration procedure. This standard orientation of the balance in the calibration machine should be identical to the standard orientation of the model in the wind tunnel.

7.4. The 'calibration matrix' and the 'tunnel matrix'

With all conventional methods a 'calibration matrix'

$$\text{signals} = \text{function(loads)}$$

is evaluated during the calibration. For the use of the balance in the wind tunnel the inverted 'tunnel matrix'

$$\text{loads} = \text{function(signals)}$$

is required. A mathematically exact inversion of the matrix is possible only in the case of a linear matrix, so approximation or iterative methods are used for the inversion. The Darmstadt method in a mathematical sense does not distinguish between 'signals' and 'loads' and so allows a direct evaluation of the matrix

$$\text{loads} = \text{function(signals)}.$$

The evaluation of the 'calibration matrix' is no longer necessary.

The concept of direct evaluation of the tunnel matrix loads = function(signals) was questioned by other experts. The main argument is that the simple theory of regression analysis states that the independent variable (loads) is flawless while the dependent variable (balance signals) is flawed. So the variables do not have equal rights and the direct evaluation loads = function(signals) is not allowed.

From our point of view the problem is not that simple, since without doubt in the calibration of a balance also the independent variable (the loads) is flawed since no calibration rig or calibration machine is perfect. There is hardly any published documentation on the uncertainties of balance calibration rigs and calibration machines. A correct uncertainty analysis of the complete balance–calibration machine system is very complicated since it is almost impossible to separate balance uncertainty and calibration machine uncertainty. According to recent research results the calibration machine uncertainty may be similar in magnitude to the uncertainty of an excellent balance.

So the much more complicated theory of regression analysis with both variables flawed has to be used, which is not even available for the case of nonlinear evaluation. Nevertheless, in the case of a good balance calibrated and used with good equipment, generally the errors are very small and so the difference between the results of the direct method and the iterative method (although it exists in a mathematical sense) is very small and has no relevance for the final result.

Regardless of the development of our algorithm, the calibration theory of multi-component balances is not yet finished. There are several unanswered questions.

(i) Up to now all calibration methods observe only the application of single loads or combinations of two single loads. During the use of a balance in the wind tunnel more or less all components are used simultaneously. There are clear physical reasons for there being interference effects of two components acting simultaneously, but very little is known about the possibility of there being interference effects of more than two components acting simultaneously. Fundamental research is necessary.

(ii) It is already common practice to improve the accuracy of the calibration by using only those calibration cases for the matrix evaluation which are actually covered by the load cases reached in an actual wind tunnel test programme. A prerequisite for this strategy is that also

Figure 14. A conventional calibration rig.

in this limited part of the total calibration data base enough calibration data are available for an accurate matrix evaluation. An even more sophisticated strategy may become possible soon with very fast wind tunnel computers. With this strategy, for each actual data point in the wind tunnel a new calibration matrix is computed, such that the calibration data points closely matching the actual tunnel data point are more heavily weighted than is the remainder of the calibration data base. Also for ideas like this more fundamental research is necessary.

Also in the accuracy analysis of wind tunnel force measurements questions remain unanswered. In the total system of force measurements the final accuracy of force data is the result of a complicated mixture of the balance accuracy, the calibration equipment accuracy, the electronic signal acquisition accuracy and the calibration method. Also in this field basic research is necessary. Such research is being planned at the Darmstadt University of Technology.

8. The calibration equipment

The principle of conventional calibration was illustrated in figure 12. An example for a conventional manually operated calibration rig with data acquisition equipment designed by the TU Darmstadt is shown in figure 14.

The calibration loads are manually applied in the form of dead weights to the calibration sleeve surrounding the balance. After each loading step the calibration sleeve is realigned relative to the geodetic axis system in pitch and roll, so that the distortion of the balance is compensated.

The manual application of the calibration loads is limited to balances with a maximum of about 3000–5000 N normal force. For balances with higher design loads, mechanical load application systems are necessary. In any case this conventional calibration method is a very time consuming process. Ever since the cryogenic wind tunnel brought the temperature into the balance calibration procedure as an additional parameter, the search for an automatic calibration procedure has been going on.

For the European Transonic Wind Tunnel (ETW) the Technical University of Darmstadt in co-operation with the Schenck Company and Daimler Benz Aerospace Airbus developed the first prototype of a fully automatic balance calibration machine. Figures 15 and 16 demonstrate the principles of this machine.

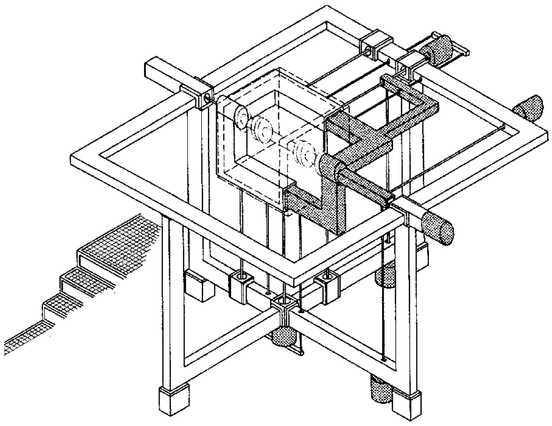

Figure 15. The loading frame and load generators.

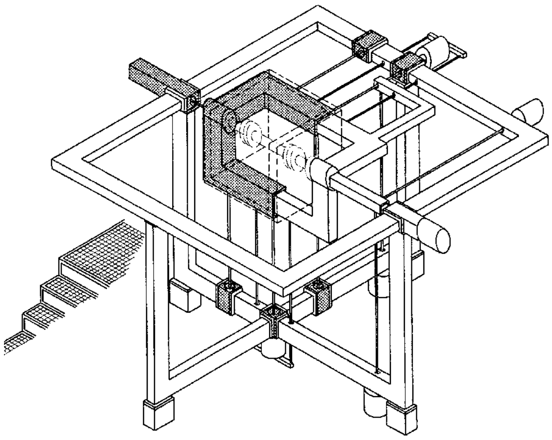

Figure 16. The measuring machine.

The balance is attached to the load generation system via the string end (the nonmetric end), which in figure 15 is hatched for clarity. Loads are generated by six push–pull pneumatic force generators. With the model end (the left-hand end in figure 15 and 16) the balance is attached to a measuring machine, which is similar to a six-component external wind tunnel balance. The measuring frame is suspended by six high precision load cells. The total calibration load measuring system is hatched in figure 16 for clarity.

Since all calibration loads applied to the balance by the force generators are precisely measured at the other end of the balance, the force generation can be done without any need for high precision, the only requirement being that the load generation system must hold the loads constant for the required measuring time (some few seconds) with high accuracy. Since, due to the elasticity of the balance, the load generation system is slightly distorted, the load generation results not only in the desired load components but also in small interference loads in the other components. This peculiarity of this calibration machine design required the development of the new matrix evaluation software described in section 7.

Figure 17. The ETW calibration machine.

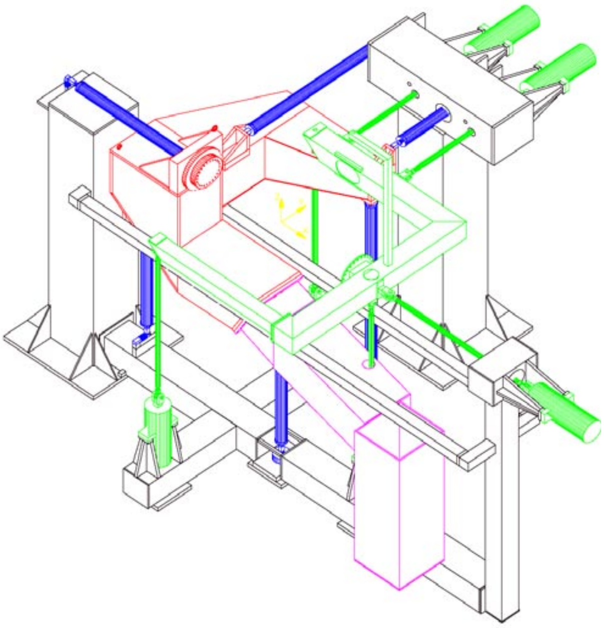

Figure 18. The second-generation calibration machine.

Figure 17 shows the automatic calibration machine constructed for the European Transonic Wind Tunnel. This machine has been in operation for several years.

From the experiences accumulated with this machine, a second-generation machine was designed with the targets of achieving a lower cost and even better operation; see figure 18. The main difference is the compact arrangement of the loading frame. This calibration machine is under construction at the Darmstadt University of Technology.

9. The cryogenic balance design

A standard design philosophy for cryogenic balances has not yet been established; among the cryogenic community there is not even agreement on whether unheated or heated balances are to be preferred. The majority of cryogenic balance designs to date have been unheated but some promoters of heated balances argue that this type will not develop spatial temperature gradients in the body and will not require stabilization times if the tunnel temperature is changed. This is a strong argument, since the need for a stabilization time will cause the productivity of the tunnel to deteriorate.

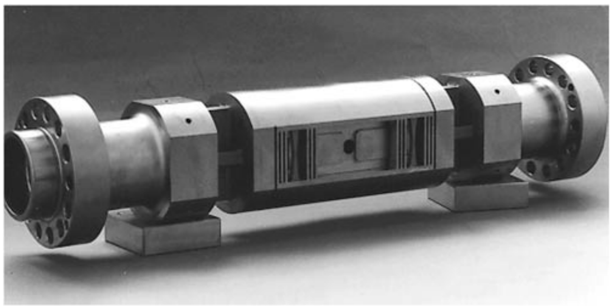

Figure 19. The cryogenic balance W618 (ETW) with a tandem axial force element.

Nevertheless, the author is pessimistic with respect to the heated balance. The massive joints on the model and sting ends of the balance will cause very large heat flows, so a lot of local heating power will be required to condition the balance to ambient room temperature with no spatial temperature gradients. The result most probably will be even worse temperature gradients in some regions of the body of the balance. From the author's point of view the more promising solution is a special balance design which tolerates temperature gradients without unacceptable deterioration of the accuracy, especially in the axial force measurement.

This was achieved successfully with the concept of the tandem axial force elements, which are integrated into the fore and aft flexure groups of the axial force system (see figure 19 for an example). The predominant part of temperature gradient generated axial force errors is proportional to the mean difference in temperature between the upper and lower cantilever beams of the axial force system. With the conventional central position of the axial force bending beam, the error signals are a function of the arbitrary temperature distribution in the cantilever beams.

With the tandem axial force system the error signals due to temperature gradients in the fore and in the aft bending beam element have the same magnitude but opposite signs. By adding the signals of the fore and the aft sensors, the error signals due to temperature gradients are cancelled out. The unavoidable tolerances in bending beam dimensions and gauge position result in a small residual error signal due to temperature gradients. Nevertheless, these residual errors may be removed by a simple numerical correction. The concept of the tandem axial force elements is very successful. For temperature gradients of 5 °C along the balance length, the gradient induced error of the axial force signal without additional numerical correction is less than 1 μV V^{-1} in the case of the ETW balance W618. The advantage of using copper–beryllium as a material for cryogenic balances was mentioned in section 5.

10. Half model balances

10.1. Use of half models

For transport aeroplane wind tunnel development, half model testing is becoming more and more attractive. In a given wind tunnel the half model technology allows an increase

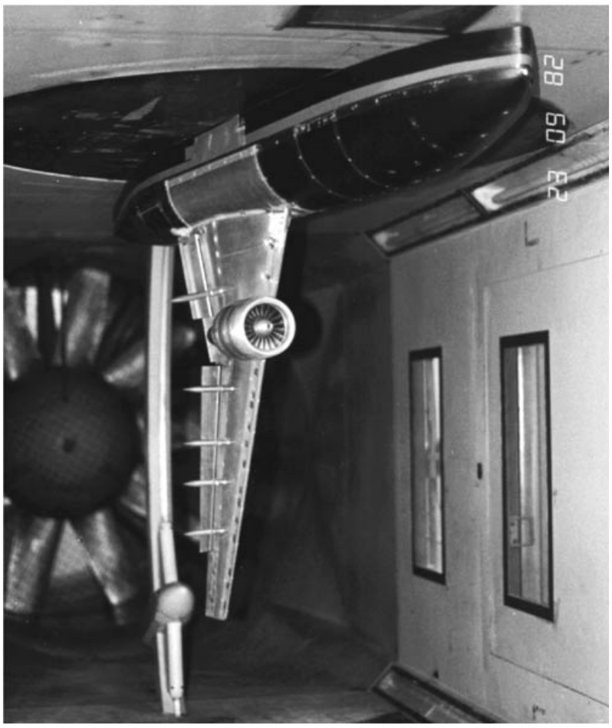

Figure 20. The Airbus half model.

Figure 21. The Airbus model in the ONERA F1 tunnel.

of the Reynolds number by a factor of two with less cost. The half model method is unable to produce accurate total forces and moments; especially the accuracy for the total drag force is reduced. Since most of the wind tunnel test results are evaluated on an incremental basis, the reduced accuracy of the total forces is no real disadvantage. In the Airbus development half models were used for various tasks.

Figure 20 shows a half model in the Daimler–Chrysler Aerospace Airbus GmbH Low Speed Tunnel. With this model the engine interference effects are studied with turbine powered simulators (TPS). Figure 21 shows a high Reynolds number test in the pressurized wind tunnel ONERA F1.

Figure 22 shows a very large half model in the transsonic wind tunnel ONERA S1. The large scale of the model (4.5 m half span) allows the simulation of small geometrical details and allows a complicated instrumentation of the model. The test set-up shown in figure 22 was used for measurements of unsteady aerodynamics associated with fast aileron movements.

Figure 22. A large half model in the ONERA S1 tunnel.

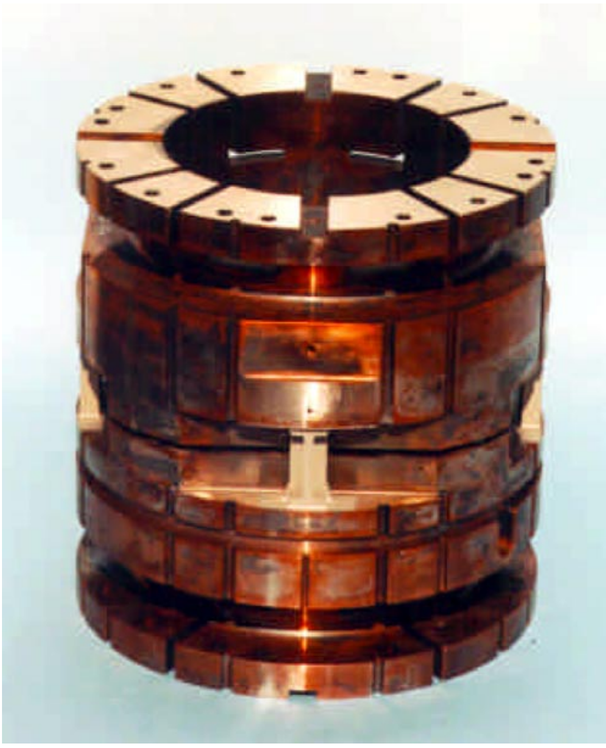

Figure 23. The KKK half model balance W526.

10.2. Half model balance technology

In the past half model balances have been built using various technologies. Some examples have been designed like a very compact external balance built up from elements such as rods, levers and load cells; other half model balances follow the design principle of internal balances fabricated from a single piece of metal. The latter design principle was used for the majority of recently balance designs. We designed half model balances following this principle only.

Figure 23 shows a half model balance designed and fabricated for the cryogenic Low Speed Tunnel KKK in Cologne. The normal force capacity of this balance (W526) is 5800 N and the diameter is 250 mm. In figure 23 the balance is shown just ready for the application of gauges.

Past experience showed that balances of this type are very sensitive to temperature gradients. So obviously there was no chance of using this balance as an unheated balance and letting its temperature float with the tunnel temperature. From the very beginning we decided together with the KKK staff to install this balance in an isolated and heated environment.

We found out that we had underestimated the temperature gradient sensitivity of the balance as well as the difficulty of avoiding any temperature gradients by isolating and heating it. Very sophisticated development work on the isolation and temperature conditioning system was necessary in order to get this balance into satisfactory operation.

For future half model balances we performed a detailed finite element study on the problem of the temperature of such balances. We found a special design of the connection between the active balance block and the end flanges which keeps all distortions away from the active balance block and thus reduces the temperature gradient sensitivity by nearly one order of magnitude. A second half model balance for the KKK with different load ranges is being fabricated according to this design. The details of this design are still a matter of a patent pending. For more details on half model balances see [21, 29, 31, 33].

11. Conclusion

The extensive research on strain gauge balances done at the University of Darmstadt in co-operation with Deutsche Airbus demonstrated that a substantial improvement of the wind tunnel force testing technology requires engineering progress in many details of balance design concepts, actual balance designs, selection of materials, balance fabrication methods, gauging methods and calibration equipment and calibration algorithms. So all these details were included in our efforts at balance research and any detail was improved to the technological limit possible today. The outcome is a balance technology which leads to much improved balances for conventional tunnels and to cryogenic balances which soon (this development is not yet finally finished) will bring the target of reproducibility to within one drag count for transport configuration performance measurements within reach.

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