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ADVANCED FORCE TESTING TECHNOLOGY FOR CRYOGENIC AND CONVENTIONAL WIND TUNNELS

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Abstract

The ever rising requirements for accuracy of six component force testing in the wind tunnel for airplane development enforce continous improvement of force testing technology. The introduction of the cryogenic tunnel with its much improved simulation potential is an additional challenge for the force balance, since now the balance accuracy is requested over an operational temperature range of 200 Kelvin. Nevertheless this problem must be solved; otherwise big investments in cryogenic tunnels will give little or no benefit for airplane development.

In more than 15 years of research all aspects of force testing technology have been dealt with and developed to new standards by the author in cooperation with Deutsche Aerospace, Airbus GmbH, Bremen, and with contributions of the DLR. Most of the work was financed by the German Ministry for Research and Technology.

Basic research on the aspects of metallic spring materials resulted in new understandings about material selection and material treatment for optimum results in hysteresis and creep.

Principal balance design optimizations are done with finite element analysis. For the routine design of different balance types an interactive computer programme was developed.

The technology of the **Electron Beam Welded Balance** was developed. The balance structure is fabricated from parts, which are welded together. This allows a much stiffer design than the conventional fabrication by EDM. This successful concept was used with small balances as well as very big balances (DNW balances).

For cryogenic balances the main problems are zero shift and sensitivity shift over the large temperature range and false signals especially in the axial force element due to temperature gradients. The problems were overcome by a very careful strain gage matching process, by use of special gages, by application of numerical corrections and by a special design of the axial force system with tandem measuring elements in the flexure groups.

For the calibration of the balance a new third order numerical algorithm was developed. The algorithm works with arbitrary load combinations. So the desired loads (single components, all pairs of two components) may be superimposed by arbitrary small loads in all other components. This was a requirement for the development of a fully automatic balance calibration machine. The machine (the first specimen is already operational at the ETW) performs a six component calibration including all single loads and all combinations of two loads in one working shift. The high speed and low manpower used with this calibration machine allows frequent recalibration of balances. This increases accuracy and reliability of the measurements very much.

So all components of the wind tunnel force testing technology have been developed to new standards with the result of considerable accuracy improvements of the wind tunnel results.

Table of Contents

1. Introduction

The ever rising requirements for accuracy in wind tunnel testing and especially the challenge of precise force testing in cryogenic wind tunnels gave a strong impetus for strain gage balance research in the recent past. Since accuracy limits for conventional strain gage balances were set mainly by thermal effects, the target to achieve at least the same or possibly even better accuracy with cryogenic balances in cryogenic tunnels is an extremely difficult task. For the research work on cryogenic balances a target of one drag count repeatability for transonic transport performance testing was set.

To achieve considerable improvements compared to balances known and used today, a single idea respectively a single successful detail improvement is not sufficient. A systematic search through all aspects of balance technology and an activation of improvement potentials in all details of this technology is necessary. The important parts of the technology are :

- Balance design philosophy
- Balance design computation and optimization
- Balance body material selection and material heat treatment
- Balance fabrication methods
- Strain gage selection and wiring method
- Moisture proofing respectively cryogenic environment proofing
- Data acquisition electronics
- Mathematical calibration algorithm
- Calibration equipment
- Strategy of balance use in the wind tunnel

The aim of about 10 years of research at the Technical University of Darmstadt was to improve each of these partial aspects of balance technology to the scientific limits available today. Part of the work was done in close cooperation with the Deutsche Aerospace Airbus GmbH at Bremen with some contributions of the DLR and most of the work was funded by the German Ministry for Research and Technology.

2. Balance Design Philosophy

The essentials for successful balance designs are :

1. *Choose the balance ranges as close as possible to the actual measuring task. In defining the ranges include the consideration, that ranges of the balances can be overloaded, if other ranges are not fully used in the tests. This overload capacity of a balance is defined by the 'load rhombus'.*

2. *Choose the geometric dimensions of the balance as large as allowed by the available space in the model.*

3. *Design the balance structure for maximum stiffness.*

The first essential requires the dedicated design of balances for the different tasks of a wind tunnel. As an example for the same transport configuration model in a transonic wind tunnel at least three different balances are required for high accuracy testing:

- Very sensitive balance for cruise condition L/D optimization work.
- Less sensitive balance for cruise condition work including buffet tests, maximum lift tests and M_{DIVE} tests.
- Enveloppe balance for stability and control tests including full control surface deflections and large angles of attack and yaw.

This requirement results in an expensive and numerous balance equipment of a tunnel but improves tunnel accuracy very much.

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

$$S = \frac{Z \cdot l^* + M_y}{D^3} \quad [\mathrm{N/cm^2}]$$

The charcteristic length l^* of the balance is defined as the distance from the reference center to the end of the active part of the balance, see Figure 1.

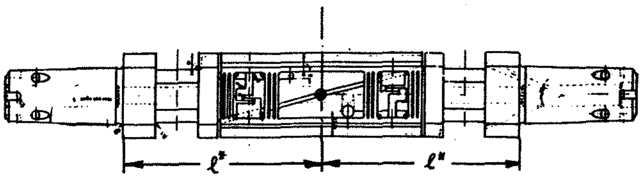


Figure 1 Characteristic Length l^*

Figure 2 shows a range of balances with diameters between 40 and 110 mm. A group of curves of constant load capacity parameter S is plotted in the diagramme. The messages of this figure are :

- Beyond a value of S = 2000 N/cm^2 the design of a precise balance including an axial force system is not possible.
- For a transport performance high precision balance the load capacity parameter should not exceed S = 500 N/cm^2.

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

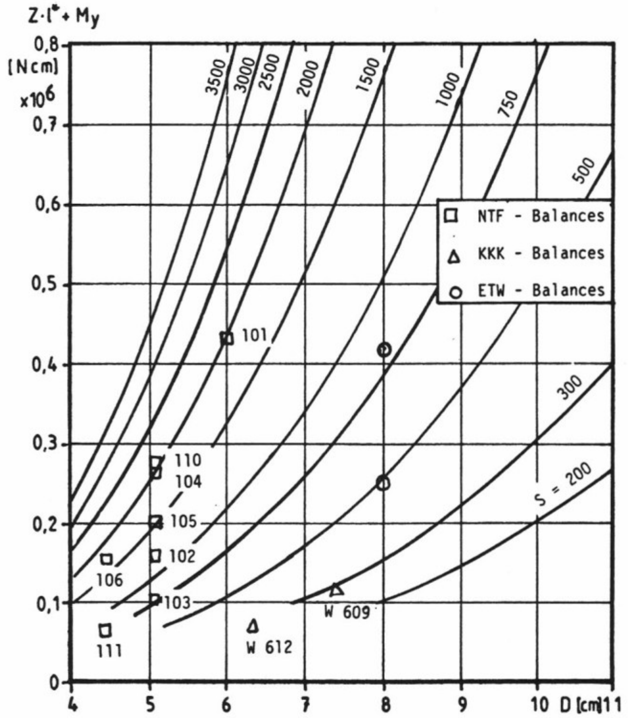
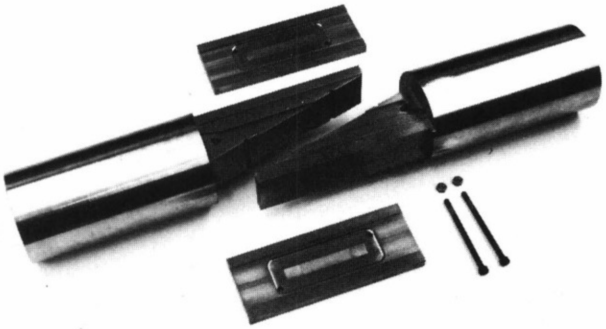


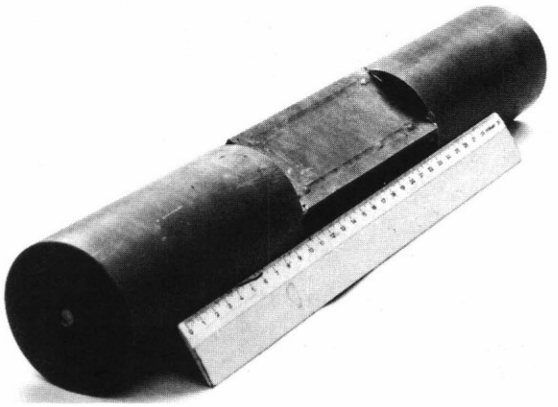
Figure 2 Load Capacity Parameter S

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

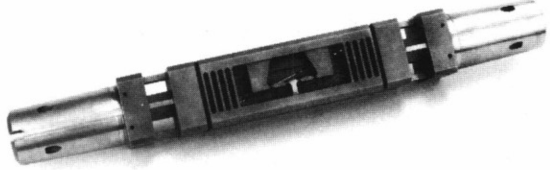
The ultimate solution of this problem is the Electron Beam Welded Balance concept, which was developed by the author at VFW (now Deutsche Airbus) more than fifteen years ago. The balance is fabricated from four pieces, which are prefabricated to the final dimensions of all internal surfaces and welded together by electron beam welding. All external machining including opening of the flexure systems is done after welding. The production steps are clarified by the Figures 3.



Prepared Balance Parts



Welded Balance Body



Finished Balance Body

Figure 3. The concept of the Electron Beam Welded Balance (Balance W 606)

Provided that a proper material is selected and a sophisticated heat treatment after the welding process is done, full material strength 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..

The concept of the Electron Beam Welded Balance turned out to be highly successful and was used since the invention for all balances constructed by the Deutsche Airbus GmbH and by the Technical University of Darmstadt. This fabrication method gives complete freedom in the internal design of the balance structure and allows a much stiffer design of the balance.

3. Balance Design Computation and Optimization

A strain gage balance is a complicated piece of structure with a very large number of dimensions. So the balance design can not be achieved as a closed solution from the external dimensions and the required component ranges.

At the Technical University of Darmstadt the design computation is done with an interactive computer programme. With each step the programme completely computes the stress situation at all critical positions of the balance body and some additional characteristic parameters. All results are printed. The user checks the results and according to his experience with the design process he modifies one or several geometric dimensions. Each step is designated as a "RUN". An experienced balance designer needs about 40 to 60 runs for a final satisfying result or for the understanding, that a good balance with the specified ranges can not be designed in the given dimensions. This work can easily be done in some hours.

The computation is based on basic stress and strain formula for short bending beams and short torsion beams. Provision is made in the programme for notch stress concentration.

The computer programme also gives overload diagrammes similar to the conventional overload rhombus. An improved version of the overload rhombus diagramme is used. An example for the case of normal force/pitching moment is given in Figure 4.

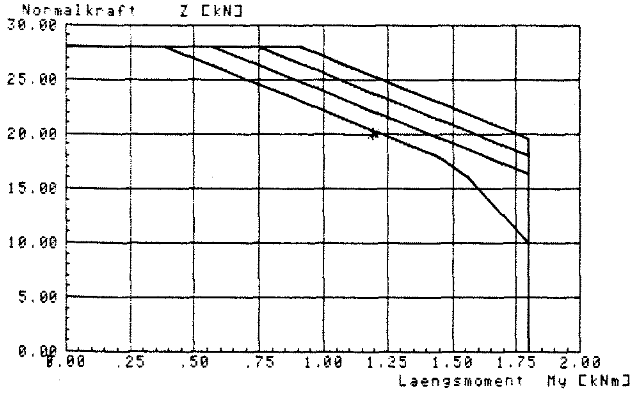


Figure 4. Overload Diagramme

The inner curve is valid for simultaneous application of all design loads; the asterix marks the design point. The outer curves are valid under the assumption, that the lateral loads are acting with 80%, 60% or 40% of their nominal magnitude. Overload diagrammes can be generated by the programme with arbitrary combinations of other load reductions.

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 to laborious. Nevertheless for principal optimization of strain gage balance details finite element analysis is a valuable tool. Figure 5 shows an example of the computing net of a balance finite element analysis. The main problem with balance finite element analysis is the required very fine discretization of all edges and corners. Work on balance optimization with the instrument of finite element analysis is continued at the Technical University of Darmstadt.

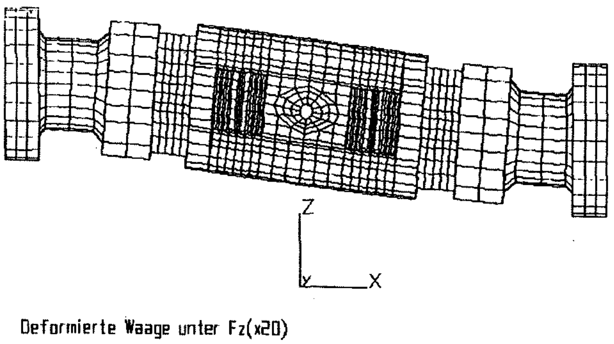


Fig. 5 Example for Finite Element Balance Computation

4. Material Selection

The conventional material for strain gage balances is maraging steel or precipitation hardening steel like PH 13.8 Mo (1.4534) or 17.4 PH (1.4548). For the welded balance concept we use Maraging 300 (1.6354) for conventional balances resp. Maraging 250 (1.6359) for cryogenic balances. Maraging steel is excellent for elektron beam welding; the precipitation hardening steels should be good for welding as well, but no experience was gathered up to now.

A very comprehensive study on force sensor spring materials was performed at the Technical University of Darmstadt. One important result of this study was a general trend of increasing hysteresis with increasing nickel component in the alloy. So the hysteresis quality of the maraging steels is not the best one. If the ultra high strength of these materials is not requested, relatively simple tempering steels offer much less hysteresis.

With maraging steel hysteresis may be considerably reduced by three provisions :

- Multiple heat treatment for grain refinement as described in [17].

- By deep cooling (77 K, 20 hours) before the aging treatment the hysteresis is reduced considerably.

- If a lower ultimate strength can be tolerated, underaging reduces the hysteresis of maraging steel considerably.

Additionally at the Technical University of Darmstadt a successful method for numerical correction of hysteresis was developed. Nevertheless this method was not applied to strain gage balances up to now.

An excellent material for force sensors may be the titanium alloy Ti Al Mg 4 (3.7164). Hysteresis is almost non existing with this material. Nevertheless more experience especially in electron beam welding and in gage application must be gathered before application of titanium for strain gage balances.

A very promising material for conventional and cryogenic balances is Copper Beryllium (2 % Beryllium), if the load capacity factor allows for the lower tensile strength of this material compared to maraging steel. Hysteresis is very low and electron beam weldability is excellent. The excellent heat conductivity of copper beryllium will considerably reduce the temperature gradient problems with cryogenic balances. A cryogenic balance for the ETW from copper beryllium is under construction at the Technical University of Darmstadt (see Figure 19).

The low corrosion resistance 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 gage positions are covered with a protecting lacquer before the nickel plating process. So the gages are bonded on the uncovered maraging steel.

5. Strain Gage Selection, Application and Wiring methods.

Up to now we used strain gages exclusively from Micro Measurement (Vishay). From the available range of gages types can be selected, which are well suited for the cryogenic range. For the extreme temperature range of cryogenic balances misadaption of the STC-Factor is recommended. We use SCT-Factors of 11 or 13 for balances constructed from maraging steel.

A more complicated problem is the primary correction of Youngs modulus over the extreme temperature range of cryogenic balances. Normal KARMA-alloy is not satisfactory. For a special cryogenic balance production MM has demonstrated, that a special tuning of KARMA gages for extreme temperature range compensation of Youngs modulus is possible. Gages of this special type were used for the ETW balance constructed by the Technical University of Darmstadt and Deutsche Airbus.

For a very low zero drift over the temperature range of cryogenic balances misadaption of STC-factor, close coupled arrangement of the gages of one bridge etc. is not sufficient. Even the gages from one pack of five show considerable scatter in thermal behaviour. Gage matching improves this situation very much and was proposed by Judy Ferris (NASA Langley) first. Since the thermal behaviour of gages can be evaluated only from the applicated gage, each individual gage is applicated to a common maraging steel sample by cyano cryalate bond. After a measurement of the zero drift of each gage in the cryogenic chamber the arrangement is heated beyond the stability of the cyano cryalate bond and the gages are carefully cleaned. From the results of this process the gages for each bridge are individually selected for minimum bridge zero drift. This procedure is time consuming but reduces bridge zero drift very much.

For final gage application on strain gage balances epoxy hot bonding is used exclusively. Preparing the surfaces, preparing the gages and the bonding procedure must be done with the utmost care, patience and perfect observance of the manufacturers instructions. Even the utmost care is not sufficient, it must be combined with years of experience in the art of strain gage application.

For conventional balances temperature correction copper wires are integrated in the bridge wiring. For cryogenic balances this procedure is not very successful, since the strong nonlinear behaviour of the apparent strain can not be compensated by the copper behaviour 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 for symmetric length and symmetric temperature on all internal bridge wire connections. All bridges are wired separately for exitation lines, exitation 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 detoriate the balance accuracy due to their stiffness. This stiffness of the bridging lines becomes crucial under cryogenic conditions. At the Technical University of Darmstadt a concept was developed to integrate these bridging lines into the design of the balance. With such an integrated electric 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.

6. Moisture Proofing resp. Proofing for Cryogenic Environment

To achieve excellent zero point stability, moisture proofing is most important. For conventional balances a careful observance of strain gage manufacturers instructions may be sufficient. For cryogenic balances moisture proofing is perhaps the most difficult detail of balance construction. Strain gage manufacturers give no sufficient instructions and offer no sufficient materials for these environmental conditions. A very careful application of multiple thin layers of nitril rubber is the best conventional moisture proofing method we found up to now.

In the cryogenic balance development for the KKK the DLR tried a novel method of moisture proofing. With this method the complete balance after gage application and wiring is sputtered with a ceramic cover. Experience gathered up to now shows a moisture proofing superior to any other method.

7. Data Acquisition Equipment

It stands to reason, that for balance signal acquisition top quality equipment is used only. Nevertheless there is a certain disagreement on the basic type of equipment. In most tunnels DC measuring techniques are used in form of specially designed signal conditioning and digitizing units or in form of high qualitiy digital multimeters.

In recent years some commercial developments, especially the DMC data acquisition unit (600 Hz carrier frequency) of the german company Hottinger has brought back into the field the AC measuring technique. AC equipment is equivalent and in some cases even superior to the best DC equipment and has the big advantage of blocking any thermal voltage signals. In the case of cryogenic tunnels with their large temperature differences in the test region this may be essential. The disadvantage of the AC measuring method is the limited frequency range, which may cause concern, if dynamic balance stresses shall be monitored.

8. Mathematical Method of Calibration

The field of calibration perhaps includes the largest improvement potential of the balance technology. The first item in this field is the mathematical description of the balance behaviour. The generally used method is the so called second order calibration. Since many years we extended this to a third order approximation of the balance characteristic :

$$S_i = R0_i + \sum_{j=1}^{6} A_{ij}F_j + \sum_{j=1}^{6}\sum_{k=j}^{6} B_{ijk}F_jF_k + \sum_{j=1}^{6} C_{ij}F_j^3$$

In this description for the direct component calibration terms a third order term is taken into account. The advantage of this description compared to 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 gage balance (or other Force sensor) as shown in the positive quadrant of Figure 6. Since a strain gage balance is a symmetrical structure, almost certainly in the third quadrant the nonlinearity of the charcteristic line should be mirror inverted to the line in the positive quadrant as shown in Figure 6 by the continuous line. There is no reason to expect a monotonic curvature like shown by the dotted line.

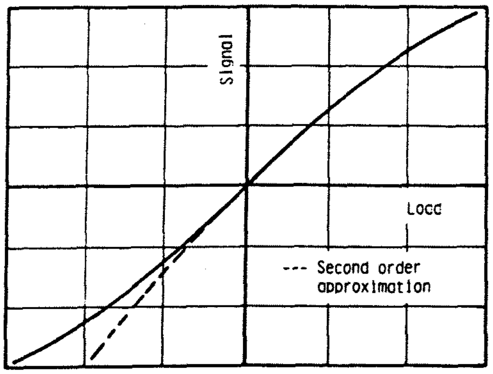


Figure 6 Second and third order nonlinearity

The nonlinearity of the continuous line in Figure 6 can be described in a polynom by the third order term only. This is the only reason why we use the third order description of the balance behaviour. Applied to actual calibration data the comparison of second and third order calibrations shows that in the case of the third order approximation the third order coefficient have a considerable size and the second order terms come out much smaller than in the case of a second order approximation. Nevertheless the quadratic terms should not be neglected. Very often a strain gage force sensor has a slightly different sensitivity in the positive and the negative quadrant. This behaviour is approximated by the quadratic term. Since all the work is done very fast by the computer, the higher mathematical complexity of the third order approximaton is no argument against this algorithm.

The conventional evaluation of the calibration data is based on the method to apply pure single loads stepwise to the balance plus combinations of two pure single loads. In the latter case one load is constant and the other load is applied stepwise. So a simple evaluation of each loading sequence in the sense of a least square error second order polynom approximation is possible. The complete coefficient matrix is successively compiled from such evaluations of loading sequences. This results in an system of equations

Component Signal = Function (Loads)

which must be converted to a different set of equations

Loads = Function (Signals)

for use in the wind tunnel. This conversion is not possible in a mathematical sense since a conversion matrix only exists for a linear matrix. So more or less accurate or questionable approximative solutions must be used for the conversion.

The automatic calibration machine (see chapter 9) invented at the University of Darmstadt produces calibration data, where the desired loads (normally a single component or a combination of two single components) are superimposed by small interfering loads in the other balance components. Though the interfering loads are known precisely, the evaluation of a calibration matrix from such "mixed" loading conditions is not possibly with the convential method. So at the University of Darmstadt we use a different mathematical algorithm, where a system of equations

Loads = Function (Signals)

is extracted in one step from the complete calibration data set (ca 1000 different loading conditions) as a closed solution in the sense of least square errors. So the questionable conversion of the matrix is no longer necessary and the result is the absolutely best evaluation of the calibration data in a mathematical sense. For more details see [18], [19] and [20].

9. Calibration Equipment

With the first balances designed and constructed for the DNW we made the experience, that the man power consumed for calibration on a conventional calibration rig caused more than 30 % of the total balance manufacturing expenses. The large amount of man power required for the calibration procedure gave rise to considerations about an automatic calibration machine.

Such a machine is necessary even more in the case of cryogenic balances, where the temperature is an additional parameter and the total amount of calibration work may be 4 - 6 times higher than in the conventional case. Obviously this problem is a common problem in the wind tunnel community, since at a number of places all over the world research in automatic calibration started during the last decade.

A concept of an automatic calibration machine was developed by the author at the Technical University of Darmstadt. In this concept the balance is clamped with its model end to a device - called 'measuring machine' - which is very similar to an external wind tunnel balance. Figure 7 shows the system of the machine and this measuring platform is hatched for clarity.

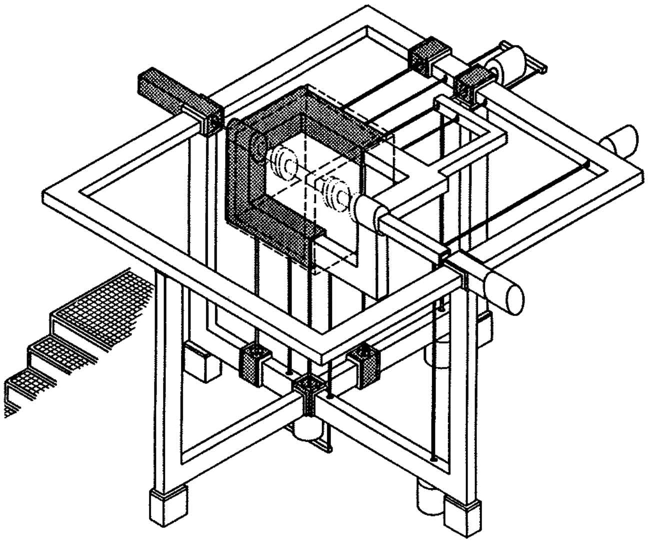


Figure 7 Calibration Machine, Measurement Platform

The master calibration of the 'measuring machine' is done with reference to the reference center of the balance and in the axis system of the measuring platforms flange, so this is a correct measurement of the calibration loads applied to the balance. The 'master calibration matrix' of the measuring machine makes provision for the elasticity of the connecting parts between measuring machine and model end of the balance.

The balance is flanged with the sting end to a loading tree, which is hatched for clearance in Figure 8. Loads are applied to the loading tree by push-pull acting pneumatic force generators with rolling diaphragms. There is ***no realignment*** of the force generators and connecting rods to the loading tree. So due to the distortion of the balance the system becomes misaligned and the small interference loads mentioned in chapter 8 occur.

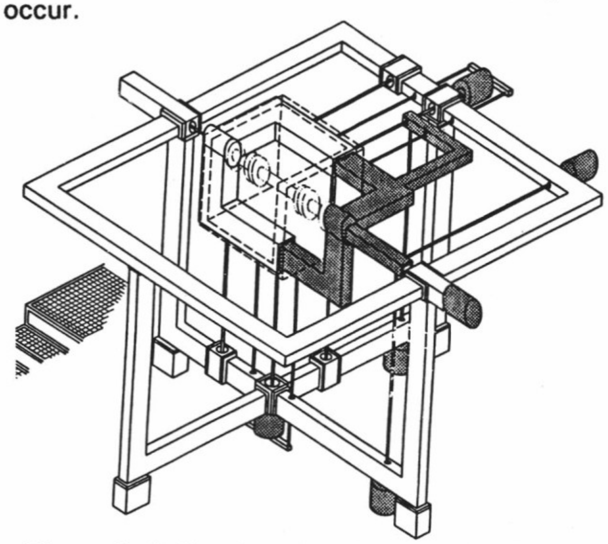


Figure 8 Calibration Machine, Loading System

All functions of the machine are controlled by a network of simple PC computers. This network consists of a network server, a supervisory computer and of one controller each for the measuring machine, the balance signal acquisition and the load generation. In the case of a calibration machine for cryogenic balances there is an additional controller for the cryogenic climate conditioning chamber. A sophisticated safeguarding system prevents the demolition of a balance by overloading due to malfunction (or mal-programming) of the load generation.

The management of the machine by a computer-network was necessary to guarantee the desired speed of the machine and to guarantee for safegarding at the same time. The target was to perform one full six component calibration including application of all single loads and of all combinations of pairs of single loads in one working shift, i.e. in 8 hours. This results in 20-25 seconds time for one loading condition.

A first prototype of the machine was designed and constructed by the Schenck Company at Darmstadt for the European Transsonic Wind Tunnel with subcontracts to the Technical University of Darmstadt (Cryogenic Chamber and Load Generator System) and to Deutsche Airbus (Computer-System and Software). Since spring 1993 the machine is operational at ETW and fulfills the specifications. Figure 9 shows this machine in the calibration room of ETW.

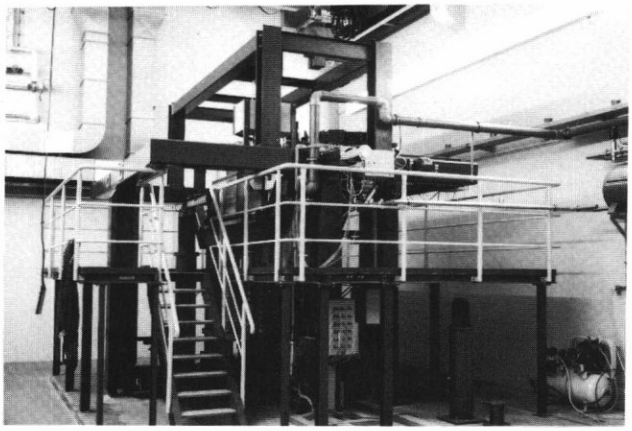


Figure 9 ETW Calibration Machine

The big improvement that this machine gives to wind tunnel force measurement is not only the improved accuracy of calibration. The fast operation of the machine reduces manpower for calibration so much, that wind tunnel operators can afford frequent recalibrations of the balances; this improves accuracy and reliability of the wind tunnel tests considerably.

10. Cryogenic Balance Design

Some aspects of the design of cryogenic balances were covered already in the different balance design aspects discussed above. Nevertheless a cryogenic balance is necessarily a special design, which may be very different from the conventional balance. A standard design philosophy for cryogenic balances is not yet established, among the cryogenic community there is even no agreement if unheated or heated balances are to be preferred. The majority of cryogenic balances is unheated up to now but the promotors of heated balances argue, that this type will not develop spatial temperature gradients in the body and will not require stabilization times if tunnel temperature is changed. This is a strong argument, since the stabilization time will deteriorate the productivity of the tunnel.

Nevertheless the author is pessimistic with respect to the heated balance. The massive joints on model and sting end of the balance will cause considerably large heat flows, so a lot of heating power will be required here. The result most probably will be even worse temperature gradients in some regions of the balance body. From the authors 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 in the front and aft flexure groups of the axial force system.

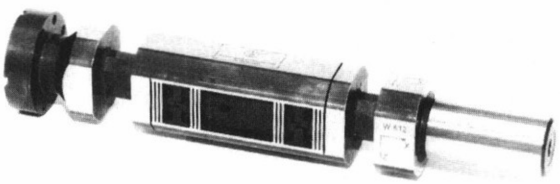


Figure 10 Cryogenic Balance W 612 (KKK) with tandem axial force elements

The predominant part of temperature gradient generated axial force errors is generated by the mean temperature difference in the upper and lower cantilever beam 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 front and in the aft bending beam element have the same magnitude and opposite signs. By adding the signals of the front and the aft sensor the signals due to temperatur gradient are canceled. The unavoidable tolerances in bending beam dimensions and gage position result in small residual error signals 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 successful. For temperature gradients of 5 degrees centigrade along the balance length the gradient induced error of the axial force signal without additional numerical correction is only 1 μV/Volt in the case of the ETW balance W 618.

The advantage of using copper beryllium as a material for cryogenic balances was mentioned already in chapter 4.

11. The Black Box Balance Principle

A distinguished balance expert well known to the author once said : *"You should never hand out a good strain gage balance to the wind tunnel people, they make everything wrong and they will demolish this delicate instrument"*. Obviously this aphorism is not quite correct since also a lot of good measurements have been performed by the "wind tunnel people" using strain gage balances !

Nevertheless there is some truth in it. The use of a balance in the tunnel, that means connecting it to the data acquisition system, adjusting amplifiers, adjusting excitation voltage, programming the signal evaluation (evaluation matrix, numerical corrections etc), pogramming axis system transformation etc. offers so much opportunities for human errors, that an actually acting aerodynamic positive yawing moment may well be printed out by the computer as a negative rolling moment multiplied by xx plus a constant yy. These sources of human errors shall be avoided by the 'Black Box Balance' concept.

With this concept a standard electronic hardware for the balance signal conditioning, signal read out and force evaluation is specified between client and manufacturer of the balance or is even delivered by the balance manufacturer. The operating parameters of this balance data acquisition hardware must be computer controllable. The balance is delivered by the manufacturer together with a floppy disk. This floppy disk contains the standard balance evaluation programme, which sets all parameters of the signal akquisition electronics and converts the balance signals into interference free and corrected forces and moments in physical dimensions.

In the balance itself a miniature memory chip is integrated. This memory chip contains a balance identification code and the calibration matrix.

For the use of the balance in the wind tunnel simply the disk is fed into the balance controller (Standard PC) of the wind tunnel computer system. So always the standard evaluation software is used without the possibility of introducing errors. The balance controller automatically checks the balance identification code and compares it with the identification code of the calibration data. With today's miniature memory chips the calibration data are an integrated part of the balance body at least for conventional tunnel balances. So the balance itself tells the wind tunnels balance computer her calibration data without any additional error source. The calibration data are automaticly burned into the memory chip (EPROM) on the balance by the data evaluation system of the Automatic Calibration Machine. The data are refreshed by each recalibration. In the case of a recalibration the calibration software checks for substantial differences between the old calibration matrix and the new one. Such differences may indicate a faulty balance.

Unless the Black Box Balance Concept will simplify the use of the balance very much and will exclude most of the possible human errors, it was not realized so far. The main argument of possible clients against the concept was, that a wind tunnel operator is bound to one balance manufacturer with this concept. Nevertheless, if the balance manufacturer is well qualified, this commitment may be not to bad.

12. Half Model Balances

Half model testing is advantageous for a part of the transport airplane wind tunnel development work and so half model testing becomes more and more popular. The balance for half model testing may be

- The tunnels normal external balance.
- A compact balance assembled from rods and load cells.
- A one piece compact strain gage balance.

Normally the latter type is used in high speed tunnels but in some low speed tunnels as well. Only this type of half model balance will be addressed here.

The measuring system of a half model balance is similar to one bending moment cage of normal sting balance shown in several examples in this paper. This moment cage measures Normal Force, Axial Force, Pitching Moment, Yawing Moment and Rolling Moment (designations in the normal body fixed axis system of the airplane). The Rolling Moment of a half model is designated also as the 'Root Bending Moment'.

This Root Bending Moment is a very large moment compared to the other components. To accept this large moment, a large diameter of the balance is necessary. This leds to a distinct sensitivity of half model balances against temperature gradients in the balance body. So a half model balance shall be installed in an isolated enclosure. Obviously this is especially important and critical in the case of a cryogenic tunnel.

A half model balance for the Cologne Cryogenic Tunnel (KKK) is under construction in a joint effort of the Technical University of Darmstadt and the DLR Cologne, see Figure 11 for the principle design. This balance will be installed in a case conditioned to ambient temperature. For more details on this development see [21].

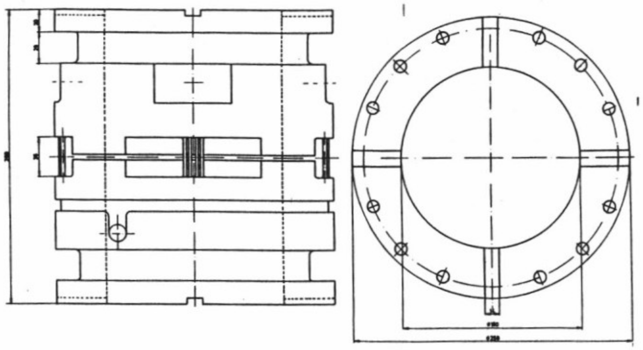


Figure 11. Principal Design of KKK Half Model Balance.

13. Examples of Balances

Some of the six component balances designed and manufactured by the University of Darmstadt and Deutsche Airbus are illustrated here. For a complete overview and for the load ranges see Table 1 in the annex.

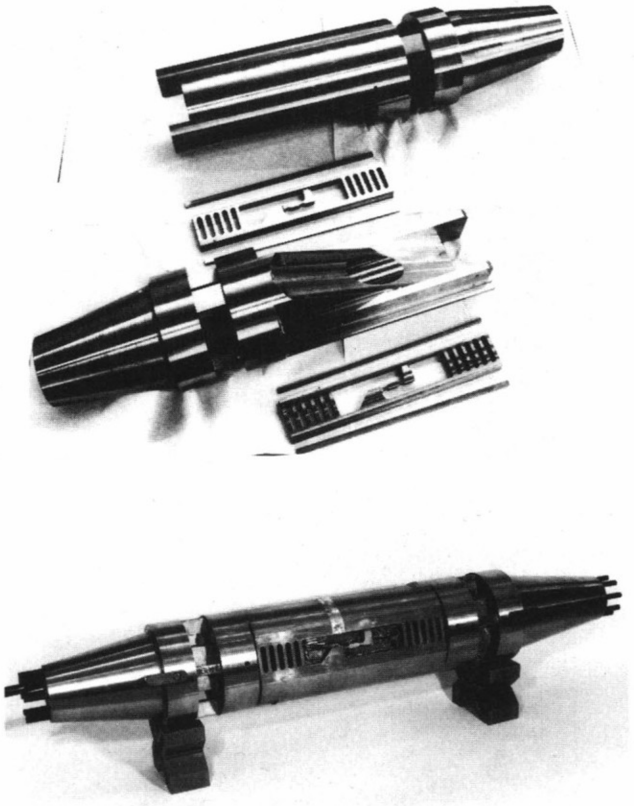


Figure 12. Balance W 605 (DNW-Balance, 3 ton Normal Force Capacity). (Above: Parts before welding.)

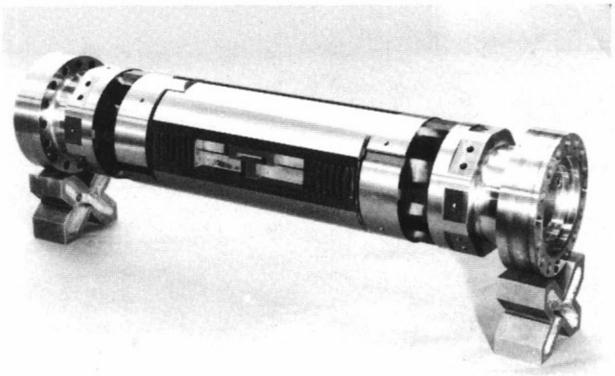


Figure 13. Balance W 608 (DNW-Balance, 3 ton Normal Force Capacity.

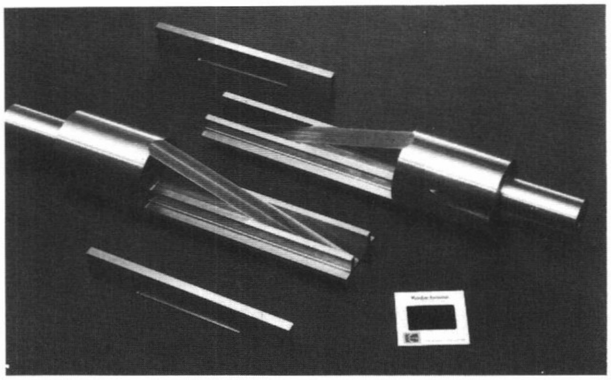


Figure 14 Balance W 607, Parts

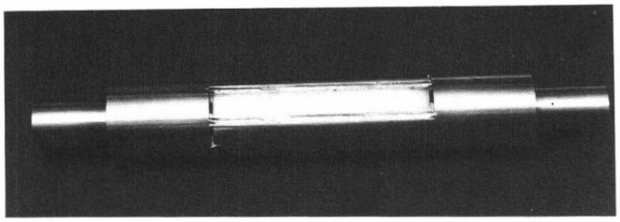


Figure 15 Balance W 607, Welded Balance Body

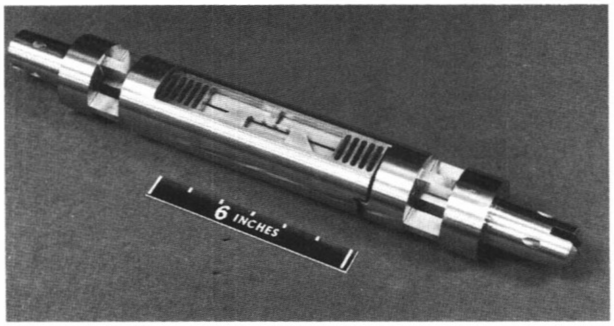


Figure 16. Balance W 607 Ready for Gaging

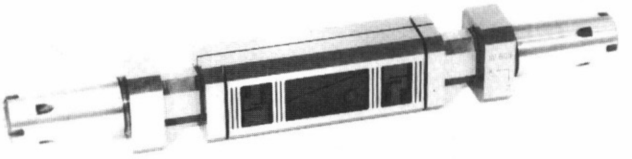


Figure 17. Cryogenic Balance W 609

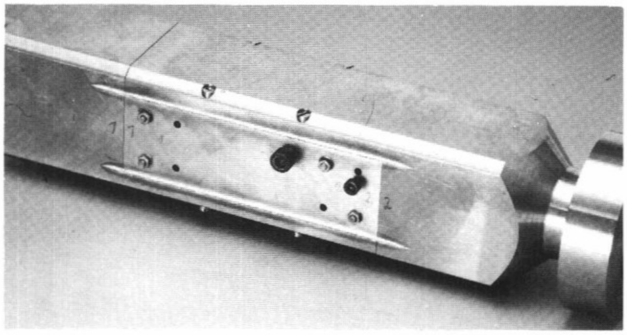


Figure 18. Cryogenic KKK-Balance W 614 after welding process

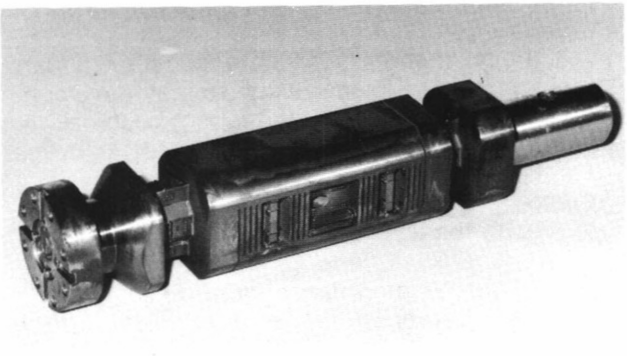


Figure 19. Cryogenic KKK-Balance W 614

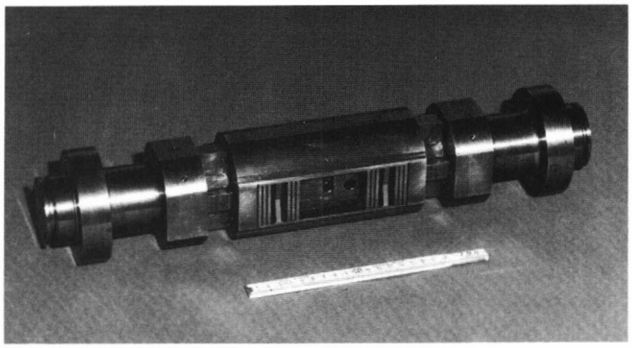


Figure 20. Copper-Beryllium Balance W 617 (for ETW) ready for gaging

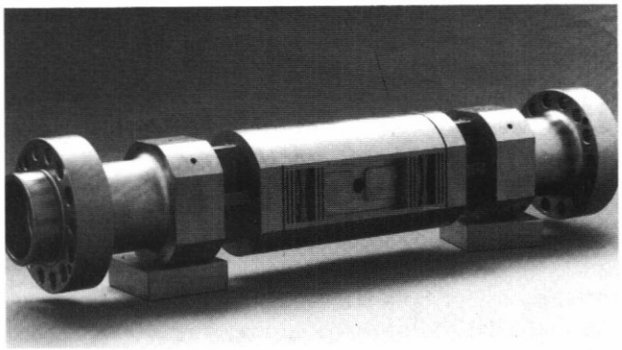


Figure 21 ETW-Balance W 618 ready for gaging

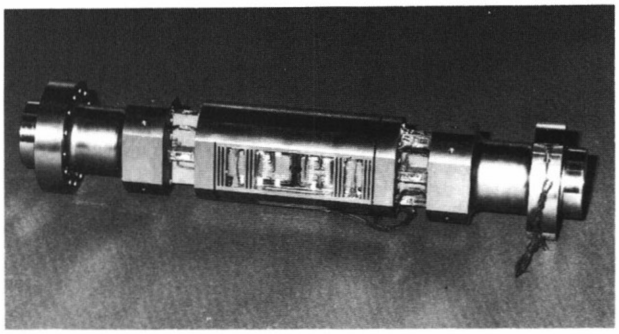


Figure 22 Finished ETW-Balance W 618

14. Summary

The extensive research on strain gage balances done at the University of Darmstadt in cooperation with Deutsche Airbus demonstrated, that a substantial improvement of the wind tunnel force testing technology requires engineering progresses in any detail of balance design concepts, actual balance designs, material selection, balance fabrication method, gaging methods and calibration equipment and calibration algorithms. So all these details where included into our balance research efforts and any detail was improved to the technological limits available to us. The outcome is a balance technology, which leads to much improved balances for conventional tunnels and to cryogenic balances which up to now (this development is not finally finished) bring the target of less than one drag count repeatability for transport configuration performance measurements within reach.

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Annex. Existing Balances

Balance Name and Purpose	Component Range					
	X [N]	Y [N]	Z [N]	Mx [Nm]	My [Nm]	Mz [Nm]
W 64 Spin/Roll-Balance Constr. for DLR	200	325	1500	80	150	100
W 605 General Purpose Balance for DNW	12500	12500	30000	9000	11500	9000
W 606 First Cryogenic KKK-Balance	200	500	2000	120	160	140
W 607 Missile Balance (AEDC)	700	2300	2300	70	460	460
W 608 General Purpose Balance for DNW	20000	6250	50000	4500	15000	4500
W 609 Second Cryogenic KKK-Balance	1400	1700	4000	400	500	400
W 610 Darmstadt Univers. Low Speed Tunnel	800	1000	2700	400	450	300
W 611 For Tech. Univ. of Braunschweig	120	100	500	10	30	10
W 612 Third Cryogenic KKK-Balance	900	400	3000	200	240	70
W 614 KKK-Balance, Fabricated for DLR	1400	1700	4000	400	400	300
W 615 Life Dummy for Calibration Mach.	1500	3000	20000	2000	1200	1000
W 616 Transport Perfor. Balance for DNW	6500	10000	20000	4500	7500	3000
W 617 ETW Advanced Research Balance	2000	1500	20000	350	1250	180
W 618 Transport Balance ordered by ETW	1000	1000	12000	100	700	80
W 519 Half Model Balance for KKK	650	-	3500	2850	320	515
W 620 Deutsche Airbus Low Speed Tunnel	700	700	2000	200	200	200