INVITED PAPER

PRESENT STATUS ON INTERNAL WIND TUNNEL BALANCE TECHNOLOGY

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Summary

The ever rising accuracy requirements in wind tunnel testing for airplane development enforce continuous improvement of force testing technology. The introduction of the cryogenic tunnel is an additional challenge for the force balance, since now the balance accuracy is requested over an operational temperature range of 200 Kelvin.

More than 28 years ago several teams in the world therefore started with investigations in the area of internal balances for cryogenic wind tunnels. This was the beginning of the last important development period for internal strain gauge balances.

In Germany in 1983 the "Cryogenic Balance Program" was started by the German Ministry for Research and Technology with the target to develop internal balances and calibration technique for the cryogenic wind tunnels Cologne Cryogenic wind tunnel (KKK) and European Transonic Wind tunnel (ETW).

In this program all aspects of force testing technology have been dealt with and developed to new standards by the Technical University of Darmstadt (TUD). After the finish of the program TUD continued as a balance manufacturer and a group of balance experts was established to continue the research work and to conserve knowledge and skills on strain gauge based wind tunnel balances.

Within this period 12 balances for cryogenic wind tunnels and many other conventional balances were built.

The areas of interest are:

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

Principle balance design optimizations are done with finite element analysis. For the routine balance design an interactive computer program was created.

The very successful technique of the Electron Beam Welded Balance was developed. The balance structure is fabricated from parts, which are welded together by electron beam welding. This technique makes it possible to build balances with a complex inner structure to minimize the interferences.

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 gauge 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. This was a requirement for the development of a fully automatic balance calibration machines. The machines perform a six component calibration including all single loads and all combinations of two loads in one working shift. The first machine was built in co-operation between former Carl Schenck AG, Darmstadt; Airbus Bremen and the TUD.

After the completion of the ETW machine further research was done by TUD to improve the design and the concept for a fully automatic calibration machine. The result of this research is a new design and construction of a small second generation calibration machine for TUD.

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.

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The wind tunnel balance business is a rather small one but it has a key function in the aircraft design, because almost all wind tunnel tests for the development of a new aircraft use a wind tunnel balance in some way.

Introduction

The successful design and development of commercial transport aircraft depends (among many other problems!) on excellent aerodynamics. Especially the flight performance reacts very sensitively to aerodynamics. Since flight performance must be guaranteed to the customer 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 and especially the challenge of precise force testing in cryogenic wind tunnels gave a strong impetus for strain gauge balance research in the recent past. Since accuracy limits for conventional strain gauge balances are 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 and of course the results of this research will improve the thermal stability of conventional balances. 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 clever idea respectively 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 it to the limits of the available technology is necessary. The important parts of this technology are:

- Design philosophy
- Design computation and optimization
- Selection of spring material for the balance body Material
- Heat treatment
- Balance fabrication methods
- Strain gauge 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

Beside these scientific and engineering aspects some human factors are also very important to get optimum quality:

- Well trained team in mechanical and electrical manufacture
- Intensive communication between wind tunnel operators and balance designers

In the beginning 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 design phase at that time and the Cryogenic Wind tunnel in Cologne (KKK), which was under construction. We get a long term funding for the development of the Cryogenic Balance. This put us in a position to do concentrated balance research and development in this field. The aim of this research at the TUD was to improve each of these partial aspects of balance technology to the scientific limits available today. Due to this research in cryogenic balances many improvements for balances for conventional wind tunnels resulted also.

The most experienced team in building internal balances at that time was the team around Alice T. (Judy) Ferris and Tom Moore at Langley. They tried to solve the problems caused by the large temperature range by building balances in a conventional design, (Fig.1) special strain gauges and the so called "Gauge Matching Technique".

The gauges were fabricated especially by Micro-Measurements (MM). The grid alloy Karma was treated in a way, that the gauge factor drift due to temperature is matched to Young’s Modulus drift of the spring material (EMC Gauges). Additionally the gauges should have a very good match in apparent strain to the thermal elongation properties of the spring material, so that the zero drift of the bridges is very low (STC). Usually gauge manufacturers only offer gauges with one of these properties matched to the spring material (either thermal compensation STC or sensitivity compensation EMC). The whole procedure was very time consuming and expensive and the match in zero drift was not good enough for the balances. Especially at very low temperatures the zero drift of the bridges was in the range of several percent.

To overcome this problem NASA developed the "Gauge Matching Technique". The individual zero drift of each gauge is measured on the desired balance material. After the test the strain gauges are debonded from the test disk. Gauges with nearly the same drift are matched in pairs which could be bonded on the balance. This procedure leads to reasonable good results. The zero drift was now under 0, 5% F.S.

Temperature tests with the balances showed that beside the problem of zero-and sensitivity drift of the bridges there could be large false signals induced by temperature gradients. These signals depend on the test scenario in the tunnel and the geometry of the model. This problem therefore could not be solved by compensating measures within the strain gauge bridges. NASA tried to solve this problem by calibrating the balance under the influence of temperature gradients.

In Europe several other teams started with research on the problems of cryogenic balances.

At the NLR in the Netherlands a small balance of conventional design was built to investigate the problems (Fig.2). This balance was tested in RAE Test Duct and the TCT at Langley. The major problem with this balance was also the error due to temperature gradients. After the tests with the NLR 771 balance the research at NLR was stopped in the mid eighties.

At ARA in the United Kingdom a kind of an axial force element with three springs as shown in Fig.3 was built after the tests with NLR 771 to investigate the effect of temperature gradients on the axial force signal. The result of these tests showed, that the temperature induced signals of the three spring elements are caused by inner distortion of the element. They showed also very clearly that a asymmetrical distribution of stiffness in the balance will lead to an asymmetrical distribution of signals. It could also be shown that the error signal depends very much on the kind of sleeve over the balance representing the model. This means that the temperature gradient induced signal depends on the model material and geometry.

Most basic research for internal balances in the time between 1963 and 1982 has been done in Europe by ONERA (Fig.5) in France. On the field of cryogenic research first the mechanical properties of the possible balance materials were tested. After that strain gauges and material combinations were tested to get the best match for a minimum zero drift and sensitivity shift. Several hardware compensation methods for zero drift and sensitivity shift were developed. To solve the temperature gradient problem an additional gauging of the spring in the front and aft parallelogram system as shown in Fig.4 was proposed.

After these activities in the United States and Europe, the problems balance designers and engineers were faced with were located as:

- Compensation of zero drift to values below 0.1 %
- Compensation of sensitivity shift
- Elimination of the influence of temperature gradients to axial force

Balance Development at Technical University Darmstadt

Based on the work of the other groups a first test balance was built by Airbus in Bremen (Fig.6). The balance was proved for cryogenic environment and the intention was to use it for the determination of all problems related to wind tunnel tests in a cryogenic wind tunnel.

The results of the test with this balance were identical to all the experience of the other groups. Specially the large effect of temperature gradients (Fig.7) seemed to be one of the major problems in building a cryogenic balance with the same accuracy as a conventional one.

Also remarkable is that a few Kelvin difference in temperature can result in a large axial force signal. This might occur also in a conventional tunnel.

The first step in the now beginning evolution in balance design was the so called "Double Bending Beam Axial Force Element". Not only geometrical symmetrical but also symmetrical with respect to the distribution of stiffness. The idea was, to build a balance which is symmetrical to the vertical centerline of the balance and so the mechanical effect of the temperature gradient along the balance will result in a symmetrical deformation of the balance (Fig.8).

The complete balance and a detail of the axial force element is shown in Fig.9 and Fig.10. This balance is used for many tests in the KKK and for some tests with the TST-Model in the ETW.

Both KKK and TUD learned a lot about cryogenic balances during the tests with this balance and a lot of compensation had to be done after the initial delivery to the KKK.

The comparison of two measured polars in the KKK and the DNW with a model of a transport aircraft is shown in Fig.11. The differences at high lift condition are caused by Reynolds Number Effects not by the balance.

Wind tunnel measurements are always affected by several sources of errors. To give an imagination of the quality of the balance, Fig.12 shows the differences of two polars measured under identical conditions to a reference measurement.

The little differences between the two plots show, that the repeatability of the balance is good. The differences at high angle of attack indicate either errors of the balance at high lift, or errors at high lift in the reference measurement.

The intention to compensate the temperature gradient effect with the double bending beam for axial force measuring worked. But, as always, after one gets rid of one problem another one occurred.

The eccentric location of the bending beams causes a high interference of axial force signal due to the pitching moment. This effect is shown in Fig.13. If the sensitivity of the two axial force beams is identical, the signal due to the pitching moment in axial force will be of a high level but they will have opposite sign. So pitching moment has the same effect on axial force as a temperature gradient has.

The next step in balance design must be a reduction of the pitching moment interference. We analyzed, that the effect is proportional to the distance (D in Fig.13) of the bending lines of the two main beams. The reduction of this distance will reduce the interference significantly. The consequence for the design of the main beam was the interconnected geometry of the main beams of balance W612 (Fig. 14).

With this design the interference could be reduced as expected.

The finished balance W612 is shown in Fig.15. The axial force measurement beams are identical to that of balance W609 (Fig.16).

The complex geometry of these beams has been chosen to minimize the influence of lift on axial force measurement. It was very difficult and time consuming to produce the shape of these beams and to manufacture four beams with identical geometry for equal sensitivity. That was the first reason to change to a more simple shape of the axial force beam. The first balance with which we realized this, was the balance W614 (Fig.17 and Fig.18).

The axial force beams in this balance were rectangular bars. The second advantage of this design was the good heat transfer from top to bottom. The temperature difference between the gauging areas is lower than in the decoupled version of the entire balances.

The measured effects of this design on temperature and interference were as expected and there was no significant increase in interference of lift on the axial force measurement. But the differences in sensitivity of the axial force beams remained significant. The measured effects of this design on temperature and interference were as expected and there was no significant increase in interference of lift on the axial force measurement. But the differences in sensitivity of the axial force beams remained significant.

The reason for this behavior was found in the inaccuracy of the positions of the strain gauges. Gauging could not be done with the same precision as the mechanical manufacture.

To overcome this problem the shape of the axial force beam had to be designed in a way, that position errors do not influence the sensitivity of the measurements.

To solve this problem the axial force beams are designed as constant stress beams. This design leads to a constant stress distribution in an area of about 12x10 mm (proved by FE-Calculation). If the strain gauges are applied in that area, little position errors do not have any effect on sensitivity. Constant stress beams for axial force measuring were used in the two following balances W617 and W618 (Figs.20, 21and 22).

With this kind of axial force element the compensation of the mechanical effect of temperature gradients was so excellent, that no further hardware or software compensation was necessary.

All the above mentioned balances are not very high loaded and the overall dimensions allow to design a parallelogram-system with one axial force measuring beam in each of the spring packages.

The last balance (W621 see Fig.23) we designed and built was a very high loaded balance with relatively small dimensions. To keep the overall stress level low and to get a high stiffness, no double bending beam element could be used in this balance. It was the first one we had to redesign after the Finite Element Calculation. The high loads distort the balance body in a complicated three dimensional way, so that the deformations of the balance body do have a feedback on the stresses in measuring sections. The result of this effect are higher stresses in the areas where they are not expected and higher interferences on axial force.

Balance Design Philosophy

For a successful balance design some essentials must be fulfilled :

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 normally 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 point requires the design of dedicated and tailored 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 MDIVE tests.
- Envelope 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

$$S = \frac{Z \, . \, l^{*} + M_{Y}}{D^{3}} \; [N / cm^{2}]$$

The characteristic 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 Fig.24.

So this "Balance Capacity Parameter" is a simplified measure of the bending stress in the balance body close to the balance connection to 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 25 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 diagram. 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 space in the model allows for the larger diameter.

The third point 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 for the electrode from the outer side of the balance body. This compromises the stiffness requirement. So the fulfillment 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 Prof. Ewald at Deutsche Airbus more than 30 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 Fig.26, Fig.27 and Fig.28.

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 most balances constructed by TUD. This fabrication method gives complete freedom in the internal design of the balance structure and allows a much stiffer design of the balance.

Balance Design Computation and Optimization

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

At the TUD the design computation is done with an interactive computer program. With each step the program 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. 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 cannot 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 program for notch stress concentration.

The computer program also gives overload diagrams similar to the conventional overload rhombus.

The use of finite element analysis for routine balance design is still relative complex, but the stress information of every part of the balance is needed to be sure that no overload or stress concentrations occur somewhere in the balance.

Nevertheless for principle optimization of strain gauge balance designs finite element analysis proved to be an extremely valuable tool, this was demonstrated by the work of Junnai Zhai at the TUD. Work on balance optimization with the instrument of finite element analysis is continued at the TUD. Fig.29 shows the stress distribution of the balance W 617 under full combined loads computed by finite element analysis. In a balance optimization study based on this design a minimization of interference effects was achieved by a fully symmetrical design. The constituents of this new design are shown in Fig.30 and Fig.31 demonstrate the stress distribution under full combined loads. This study demonstrated, that the finite element analysis allows the valid computation of those balance interference effects, which are caused by the balance deformation under load.

Another investigation of the balance interactions by FE-analysis showed that significant sources of interactions are the misalignments of the strain gauges.

Material Selection

The conventional material for strain gauge balances is either 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 electron 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 TUD. 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. The Maraging steel hysteresis may be considerably reduced by three provisions

- Multiple heat treatment for grain refinement as described in.
- Deep cooling (77 K, 20 hours) before the aging treatment.

- Under-aging, if a lower ultimate strength can be tolerated.

Additionally at TUD a successful method for numerical correction of hysteresis was developed. Nevertheless this method was not applied to strain gauge 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 in this material. Nevertheless more experience especially in electron beam welding and in gauge application must be gathered before application of titanium for strain gauge 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 extremely low and 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 ETW from copper beryllium was designed and constructed at TUD (Fig.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 gauge positions are covered with a protecting coating before the nickel plating process. So the gauges are bonded on the uncovered Maraging steel.

Strain Gauge Wiring Methods

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

The other possibility is the use of Modulus Compensated (MC) gauges if they are available for the used balance material. These gauges are made for the primary correction of Young's 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 gauges for extreme temperature range compensation of Young's modulus is possible. Gauges of this special type were used for the ETW balances constructed by TUD.

For a very low zero drift over the temperature range of cryogenic balances mismatch of STC-factor, close coupled arrangement of the gauges of one bridge etc. is not sufficient. Even the gauges from one pack of five show considerable scatter in thermal behavior. Gauge matching improves this situation very much and was first proposed by Judy Ferris (NASA Langley). Since the thermal behavior of gauges can be evaluated only from the applied gauge, each individual gauge is applied to a common Maraging steel sample. After a measurement of the zero drift of each gauge in climate chamber the gauges are debonded and 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 very much.

For final gauge application on strain gauge balances epoxy hot bonding is used exclusively. Preparing the surfaces, preparing the gauges 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 gauge application.

For conventional balances temperature correction copper wires are integrated in the bridge wiring. To use only this procedure for cryogenic balances this is not very successful, since the strong non-linear behavior of the apparent strain cannot be compensated by the copper behavior with a different non-linearity. After the installation of the bridges with matched gauges the wire compensation method can be used for a further reduction of the remaining zero drift.

At least a numerical correction method using the measurement of temperatures on the balance is necessary reduce the zero drift to an absolute minimum. For this numerical correction a number of PT 100 temperature sensors (6-10) are installed on the balance and a temperature calibration test must be performed.

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 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 85 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 deteriorate the balance accuracy due to their stiffness to an extent that force testing and testing with the use of balance bridging lines must be done separately, so the wind tunnel productivity is reduced very much.

At the TUD 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 (Fig.32).

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 gauge manufacturers instructions may be sufficient. For cryogenic balances moisture proofing is perhaps the most difficult detail of balance construction. Strain gauge 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. The only real moisture proof is a totally sealed metal cover over the whole gauge including the wiring. This can be realized by chemical vapor deposition. The disadvantage of this method is that is very expensive and the thin layer is destroyed by almost every mechanical contact.

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 quality digital multimeters.

In recent years some commercial developments, especially the MGC data acquisition unit (600 Hz carrier frequency) of the German company Hottinger established the AC measuring technique back into the field again. This AC equipment is superior to the best of 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. Nevertheless dynamic signals up to 200 Hz can be monitored with this equipment satisfactorily.

The Hottinger measuring system DMCplus resp. its successor MGCplus is used successfully in the Aerodynamics Lab and the Wind Tunnel of the Technical University of Darmstadt, the Aerodynamic Department and Wind Tunnel Department of Deutsche Airbus, the Cologne Cryogenic Tunnel (KKK) and the ETW Calibration Machine. The system can be equipped with up to 28 data channels. The maximum speed of this system is 100 000 measurements per second for all channels and the resolution is up to 300 000 parts. The system is fully computer controlled; several systems may be managed in parallel by one PC. The system provides also the excitation for the strain gauge bridges.

As a general rule identical electronic measurement hardware or even better the same equipment should be used for balance calibration and for balance use in the wind tunnel.

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 behavior. 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 behavior

$$S_i = R\,0_j + \sum_{j=1}^{6} A_{ij} F_j + \sum_{j=1}^{6} \sum_{k=j}^{6} B_{ijk} F_j F_k + \sum_{j=1}^{6} C_{ij} F_j^3$$

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 non-linearity of the characteristic line of one component of a strain gauge balance (or other Force Sensor) as shown in the positive quadrant of Fig.33. Since a strain gauge balance is a symmetrical structure, almost certainly in the third quadrant the non-linearity of the characteristic line should be mirror inverted to the line in the positive quadrant as shown in Fig.33 by the continuous line. There is no reason to expect a monotone curvature like shown by the dotted line.

The non-linearity of the continuous line in Fig.33 can be described in a polynomial by the third order term only. This is the only reason why we use the third order description of the balance behavior. 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 coefficients have a considerable size and the second order terms come out smaller than in the case of a second order approximation. Nevertheless the quadratic terms should not be neglected. Very often a strain gauge force sensor has a slightly different sensitivity in the positive and the negative quadrant. This behavior 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 approximation 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 polynomial approximation is possible. The complete coefficient matrix is successively compiled from such evaluations of loading sequences. This results in a system of equations

Component Signal = Function (Loads)

that must be converted to a different set of equations.

Loads = Function (Signals)

for the 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 approximate solutions must be used for the conversion.

The automatic calibration machine invented at TUD 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 conventional method. So at TUD 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.

Calibration Equipment

With the first balances designed and constructed for the DNW, VFW 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 Prof. Ewald at TUD. 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. Fig.34 shows the system of the machine and this measuring platform is hatched for clarity.

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 Fig.35. 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.

All functions of the machine are controlled a PC computer. 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 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 Transonic 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. Fig.36 shows this machine in the calibration room of ETW.

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.

Based on the good experience with the ETW machine the concept was further improved and developed by the University of Darmstadt. This development led to some improvements of the machine and to a simplified design. A prototype of the improved design with a Normal Force Range of +/-10000 N has been build at the TUD. Fig.37 demonstrates the design of this machine in principle.

Cryogenic Balance Design

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 promoters 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 we are 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 to condition the balance to ambient room temperature. The result most probably will be even worse temperature gradients in some regions of the balance body. From our 14 point of view the more promising solution is a special balance design that 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 (Fig.38). 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 temperature gradients are canceled. The unavoidable tolerances in bending beam dimensions and gauge 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 earlier.

The Black Box Balance Principle

A distinguished balance expert well known to the author once said: *"The best way to protect a balance is: Never give it to the tunnel"*. Obviously this aphorism is not quite correct since also a lot of good measurements have been performed by the "wind tunnel people" using strain gauge 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.), programming axis system transformation etc. offers so many 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*. To avoid these sources of human errors we invented the ‘Black Box Balance’ concept.

With this concept a standard electronic hardware for the balance signal conditioning, signal read out and force evaluation for the calibration of the balance and for the use of the balance in the tunnel 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 fully computer controllable. The balance is delivered by the manufacturer together with software, which contains the standard balance evaluation program, which sets all parameters of the signal acquisition 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 software is fed into the balance measurement controller (Standard PC) of the wind tunnel computer system and the balance itself is plugged to the measurement 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 automatically burned into the memory chip (EEPROM) 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.

Although the Black Box Balance Concept will simplify the use of the balance very much and will exclude nearly all 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.

Future Developments

Some plans for future developments of the balance technology were already indicated in the previous pages. Our most important plans for future developments are

- Black Box Balance Concept
- Evaluation of Copper-Beryllium Balance Concept
- Evaluation of Titanium Balance Concept
- Integrated Balance Bridge for signal lines, power lines and pneumatic lines
- On Board Measurement for pressure distribution with light transmission of data into the earth system
- Further optimization of balance design by finite element analysis
- Further development of the Automatic Calibration Machine

Conclusion

The extensive research on strain gauge balances done at the TUD (Technische Universitt Darmstadt) 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, gauging methods and calibration equipment and algorithms. So all these details where included into our balance research efforts and any detail was improved to the technological limits available today. The outcome is a balance technology, which leads to much improved balances for conventional tunnels and to cryogenic balances which up to now bring the target of less than one drag count repeatability for transport configuration performance measurements within reach. Beside all technical improvements, high sophisticated balance technology is always a product of a team of engineers and a well experienced workshop staff. The success of this team even depends on a good cooperation and communication with the wind tunnel people.

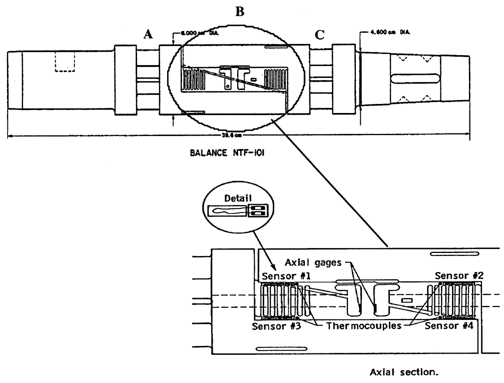

Fig.1 Sideview of NTF-Balance 101 B

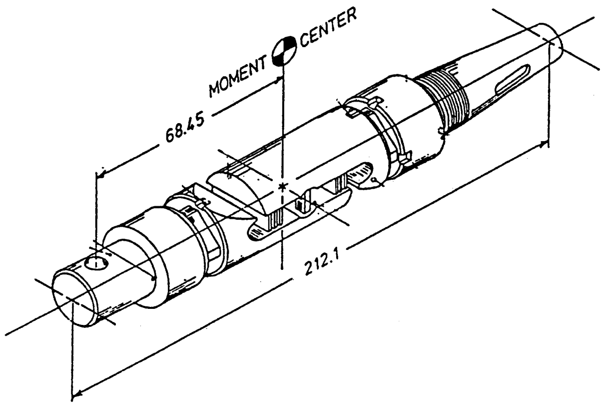

Fig.2 NLR-Balance 771

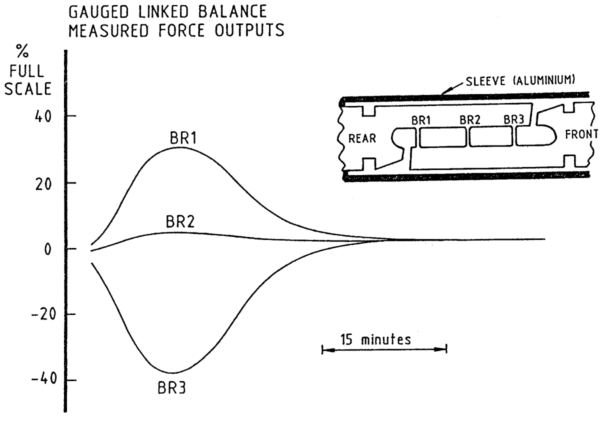

Fig.3 Signals of RAE - Test Balance Due to Temperature Gradients

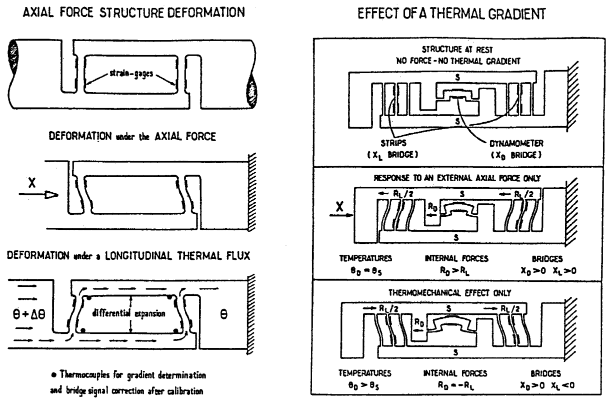

Fig.4 Compensation of Temperature Gradient Effect

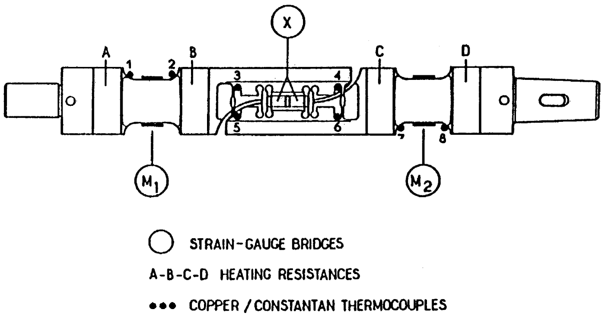

Fig.5 Three Component Cryogenic Balance of ONERA

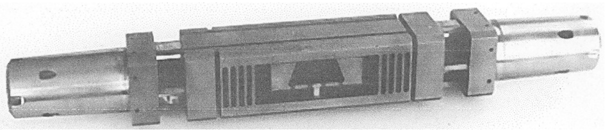

Fig.6 Cryogenic Balance W606 of VFW (Now Deutsche Airbus Bremen)

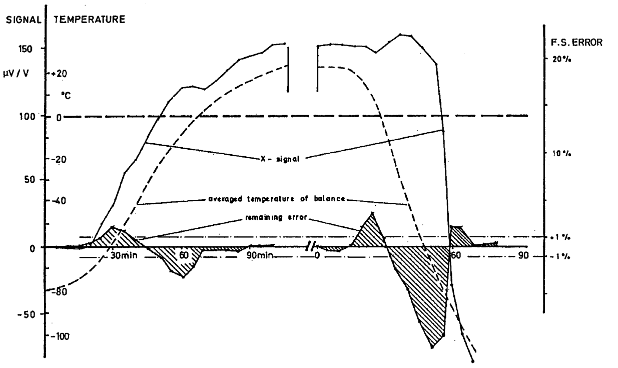

Fig.7 Behavior of Axial Force of Balance W606

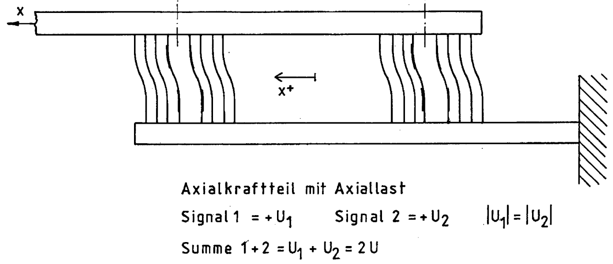

Fig.8 Deformation of Axial Force Element Due to Temperature Gradient

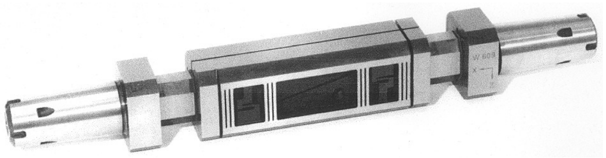

Fig.9 Balance W609. First Balance for KKK

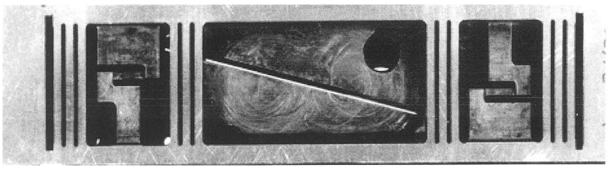

Fig.10 Axial Force Element of W609 with Double Bending Beam

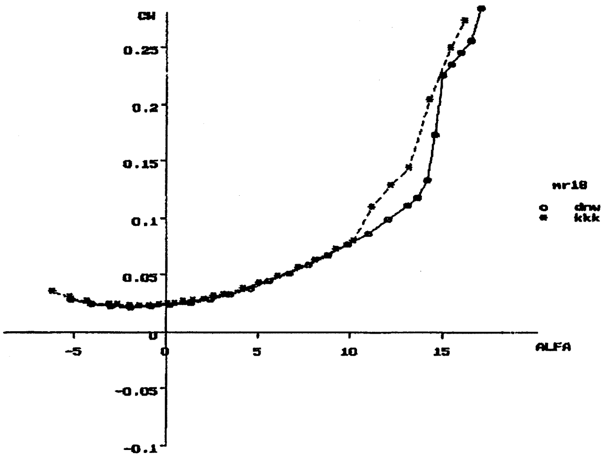

Fig.11 Comparison of Polars Measured in the KKK and the DNW

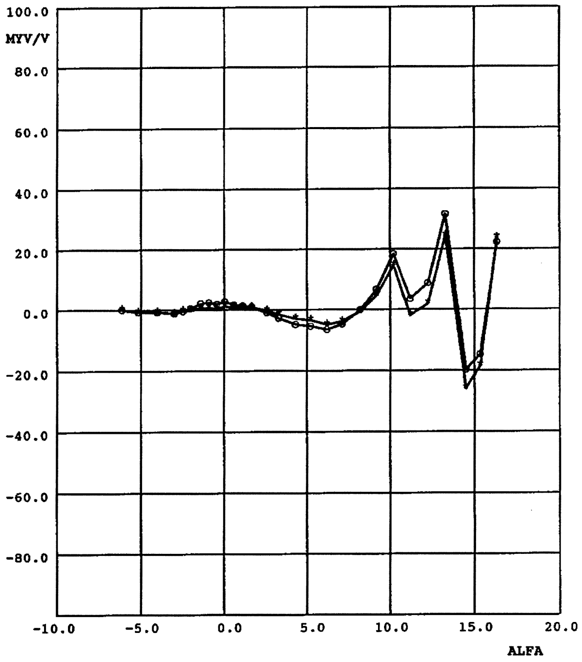

Fig.12 Repeatability of Balance W609

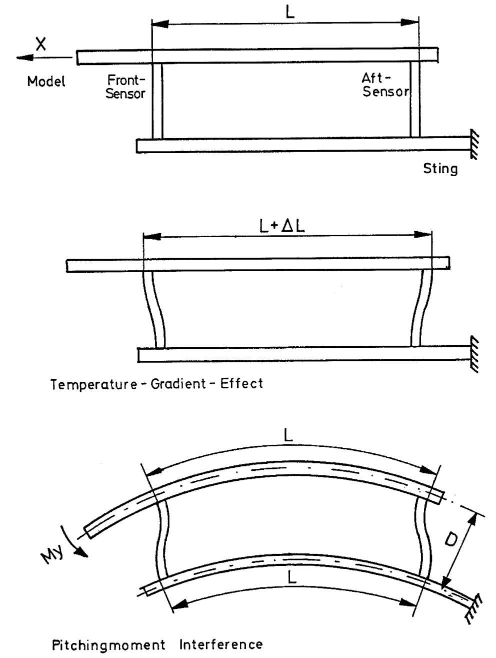

Fig.13 Pitching Moment Interference on Axial Force

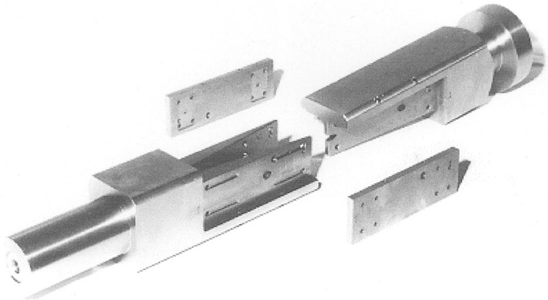

Fig.14 Parts of Balance W612 with New Design

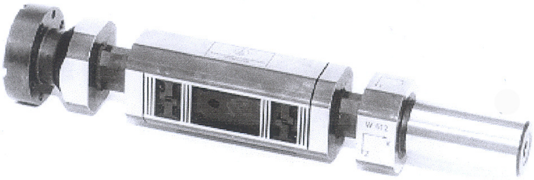

Fig.15 Balance W612 for KKK

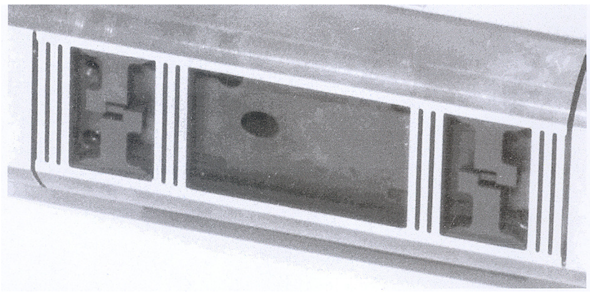

Fig.16 Axial Force Element of Balance W612

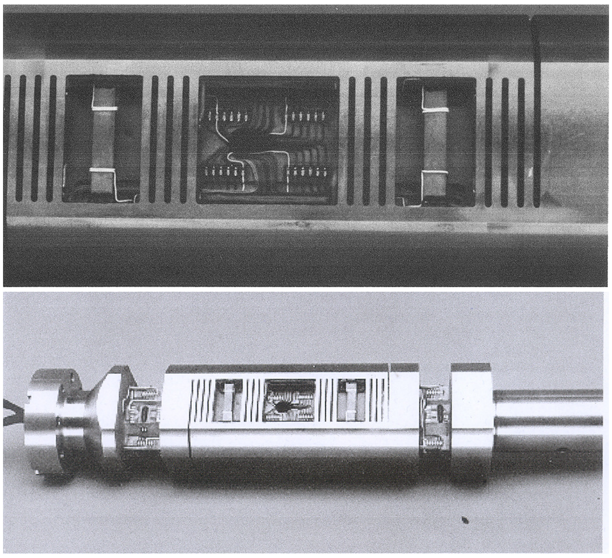

Fig.17 Balance W614 for KKK

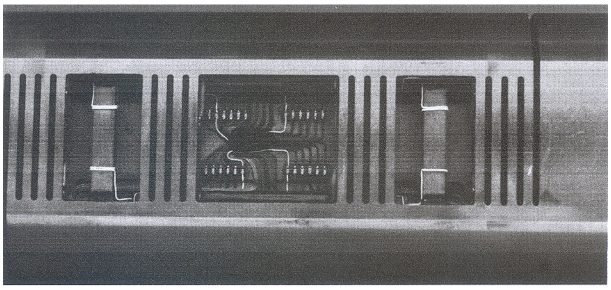

Fig.18 New Axial Force Beam Design in Balance W614

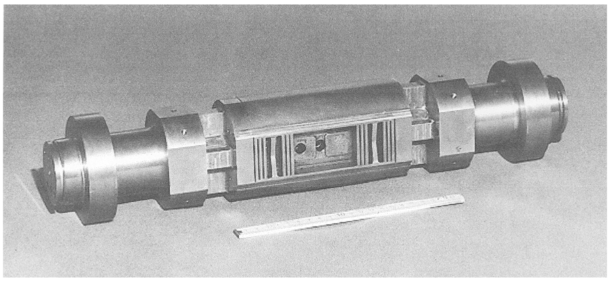

Fig.19 Copper-Beryllium - Balance W617 for ETW Ready for Gauging

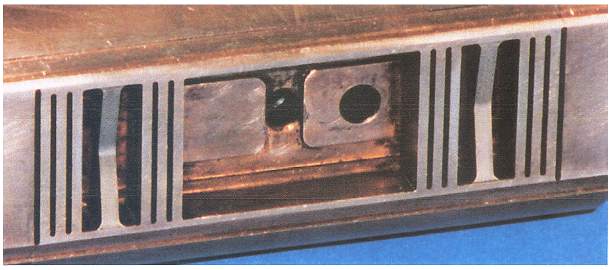

Fig.20 Constant Stress Beams for Axial Force Measurement in Balance W617

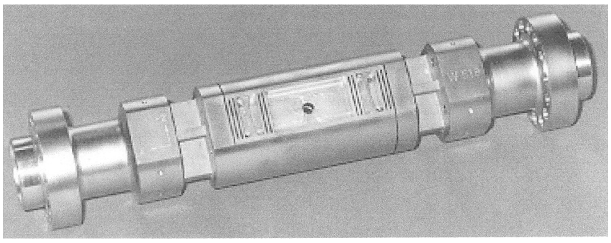

Fig.21 ETW - Balance of W618 Ready for Gauging

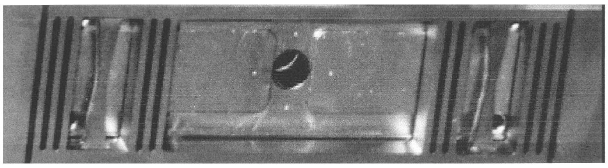

Fig.22 Constant Stress Axial Force Beam in Balance W618

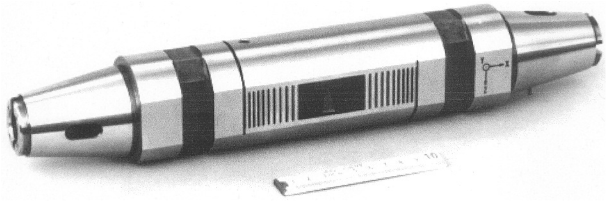

Fig.23 ETW Combat Balance W621

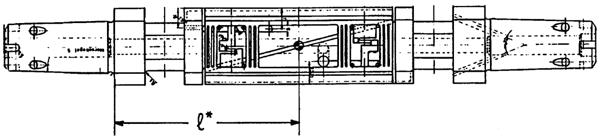

*Fig.24 Characteristic Length l**

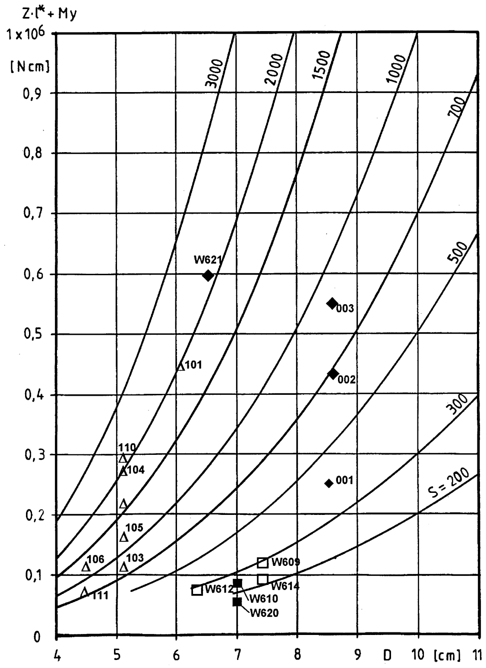

Fig.25 Load Capacity Parameter S

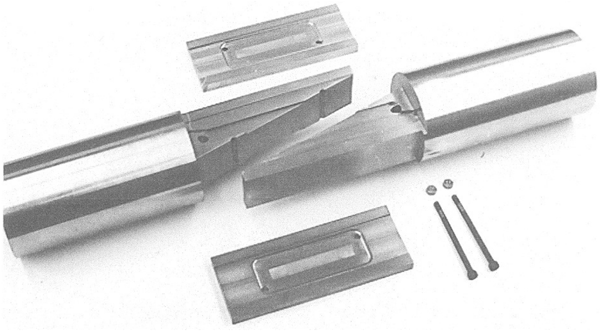

Fig.26 Prepared Balance Parts

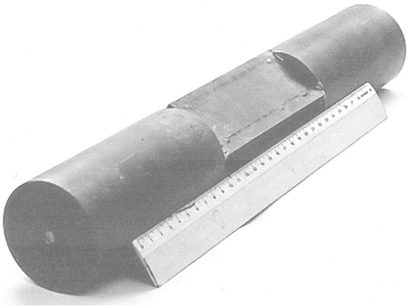

Fig.27 Welded Balance Body

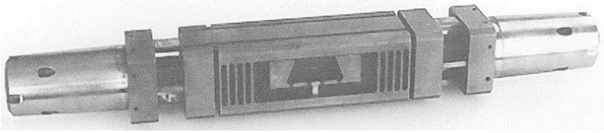

Fig.28 Finished Balance Body

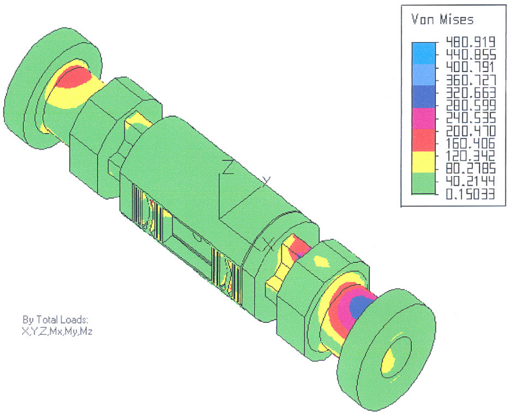

Fig.29 Balance W617, FE Computation

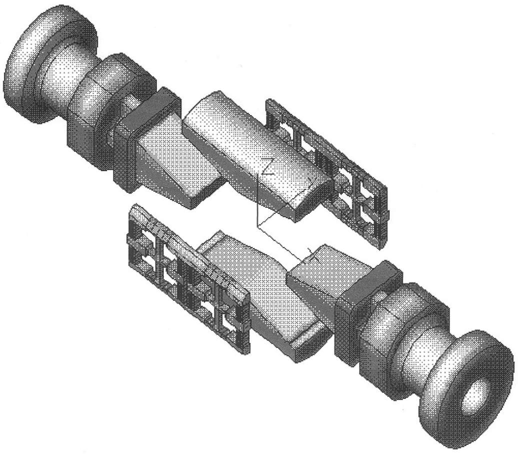

Fig.30 Parts of New Balance Design

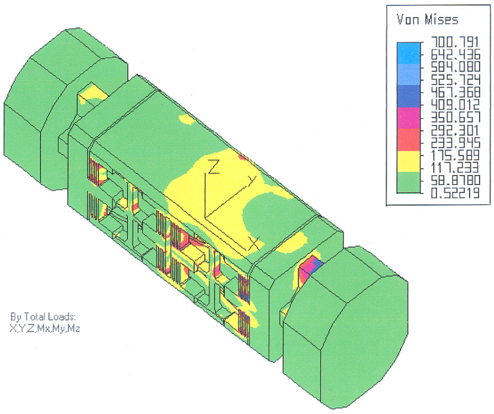

Fig.31 New Balance FE Computation

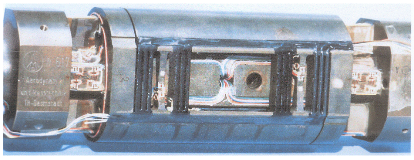

Fig.32 Balance W617 with Electrical and Pneumatic Lines for Model Instrumentation

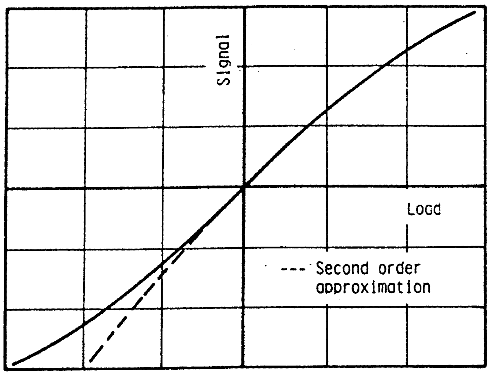

Fig.33 Second/Third Order Approximation

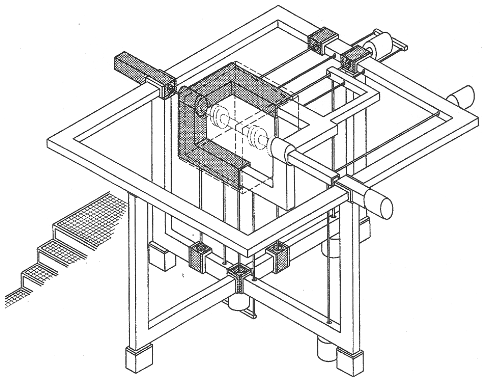

Fig.34 Calibration Machine, Measurement Platform

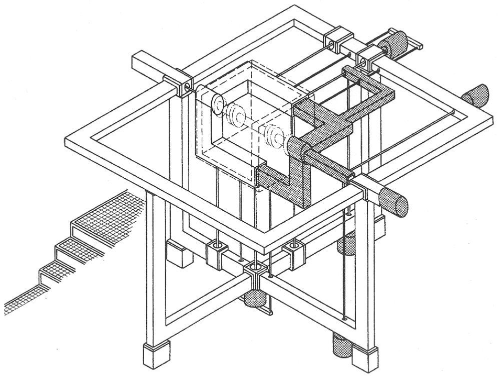

Fig.35 Calibration Machine, Load Generation System

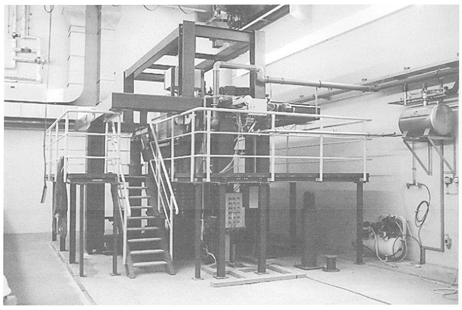

Fig.36 ETW Calibration Machine

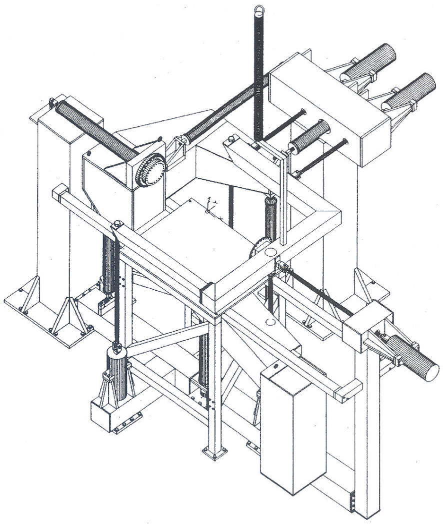

Fig.37 Calibration Machine of Darmstadt University

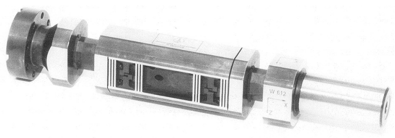

Fig.38 Cryogenic Balance W612 (KKK) with Tandem Axial Force Elements