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INTERNAL STRAIN GAGE BALANCES FOR CRYOGENIC WINDTUNNELS

Dipl.-Ing. K. Hufnagel
Prof. Dipl.-Ing. B. Ewald

Technical University of Darmstadt
Faculty of Mechanical Engineering

Dipl.Ing. E. Graewe

Deutsche Airbus GmbH
Bremen

Abstract

For the success of a cryogenic windtunnel like the Cologne Cryogenic Tunnel (KKK) and the European Transonic Tunnel (ETW) the availability of an internal strain gage balance with at least the same accuracy as internal balances for conventional tunnels is a key problem. Therefore a national cryogenic balance program was started by the German Ministry of Research and Technology (BMFT) in 1979. The work was done in a joint effort of the Technical University of Darmstadt and the Deutsche Airbus GmbH at Bremen. Till the end of the program in December 1992 five cryogenic balances are built and calibrated. The results of this work concerning the temperature and temperature gradient effects in the balance are presented in this paper.

A further important problem is the calibration of cryogenic balances. The temperature and temperature gradients in the balance body created by changes in the tunnel temperature are additional parameters in balance calibration. A new concept for a fully automatic calibration machine for conventional and cryogenic balances was developed.

I. Introduction

The basic technology at Deutsche Airbus and TU Darmstadt to built an internal balance is the "Welded Balance" instead of the "One Piece Balance". This technology allows a complicated inner structure of the balance which results in higher stiffness and lower interferences. Four prefabricated parts with finished inner surfaces are welded together by electron beam welding. The outer surfaces are machined after the welding process.

The first balance built in the programme was a conventional one to study the temperature and temperature gradient effects. The main problems that appeared in the tests with this balance were the zero shift of about 1% F.S. and the temperature gradient induced signal on the axial force bridge of up to 20% F.S. in case of a temperature gradient of 10 K along the axial force system of the balance. These problems were examined by several axial-force systems which were built separately. As a consequence of these tests the next balance had double beam axial force elements. With this element the effects of temperature gradients in the balance could be reduced significantly. The remaining axial force false signal is corrected by calibration and numerical correction. The zero shift of the strain gage bridges was minimized by the use of several so called "Matching Techniques". This is a selecting process to fit the temperature behaviour of the individual gages for one bridge.

During the calibration, the balance showed a high interference of the pitching moment on the axial-force signal. This was overcome by an optimized inner structure of the main beams of the third balance.

This general configuration was used for two balances which differ in the geometry only in a few details caused by the load ranges. Both balances are in operation in the KKK Low Speed Tunnel. The main advantage of the second one is a special type of strain gage which was used to minimize the sensitivity shift of the bridges. Beside the optimization of the balance materials, structure and application materials, a calibration method for the remaining temperature and gradient effects has been developed.

To evaluate a better calibration-matrix from the calibration data a third order evaluation method was developed.

II Four Piece Balance Technology

For a very precise internal balance the body should be fabricated from a very homogeneous material. This is usual achieved by using a single piece of maraging steel for the fabrication. The balance geometry is completely machined out of this piece. Therefore the designer is restricted to balance geometries which can be machined (including electric discharge fabrication) only from the outside. More flexibility in design of the interior structure of the body and in consequence much more stiffness could be achieved by using the Electron Beam Welding Technology, see Figure 1.

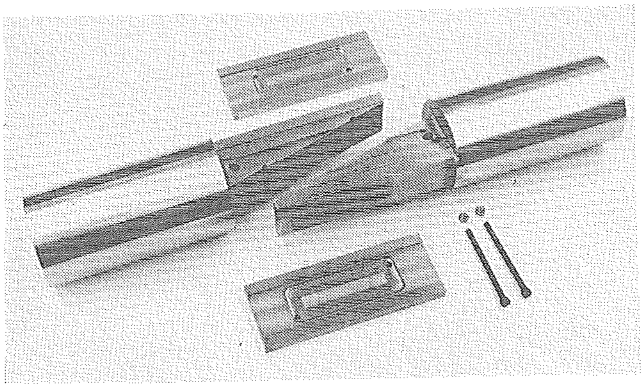

Figure 1. Parts of an Electron Beam Welded Balance

Four pieces from the same material with ready machined inner surfaces are welded together by Electron Beam Welding. After a careful annealing process the balance is ready for final machining and the materials properties are fully restored in the welding seam. The distortion of the balance due to the welding process is negligible.

III. First Balance

The first balance (W 606) in the programme was not a real cryogenic balance. It was designed like a balance for a conventional tunnel.

This balance (see Figure 2) was used to study the behaviour of a conventional balance under cryogenic conditions and to test all application materials (strain-gages, bonds, protection materials, solder, wires etc) for their cryogenic qualification.

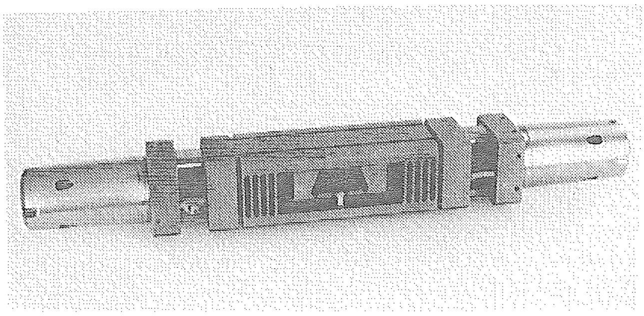

Figure 2. Cryogenic Balance W 606

In the test with this balance two major problems occured. The first problem is the zero shift with temperature (apparent strain) of the strain gage bridges of about 1% of F.S. All bridges are affected by this effect. To correct this false signal the strain gages must be perfectly matched to the required temperature range and to the balance material.

The second problem observed in this balance was a false signal in the axial force element up to 20% of F.S. induced by a temperature gradient of 10 K along the axial force element. For the other components temperature gradients produce only minor effects.

IV Axial Force Elements

After the investigations with the first balance the aim of the following part of the programme was to evaluate and to design a better shape for the axial force element of the balance. After some theoretical studies three separate axial force elements for further research were built. In this paper only the double bending beam element will be shown, see Figure 3.

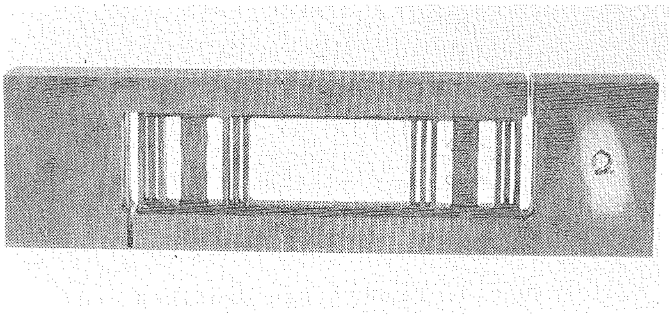

Figure 3. Double Bending Beam Element

The main difference between the new element and the conventional one are two bending beams in both parallelogramme spring packages. In case of a temperature gradient along this arrangement the two bending beams will bend in opposite direction, so that the summ of the two signals is nearly zero. In case of an axial force the two beams will bend in the same direction and the signal summ is twice the signal of a conventional axial force element. To prove this idea tests with local heating and cooling of the element were made. The measured data showed that the temperature gradient induced signals in the two beams nearly cancel out. With this configuration the false signal according to temperature gradients of about 15 K could be reduced to 0.5% F.S. without numerical correction and down to 0.1% F.S. with numerical correction after calibration. A numerical correction is necessary because of the sensitivity tolerance of the bending beams. The reason for the remaining error after numerical correction is the remaining uncertainty of the calibration. The error can be reduced by experience with advanced calibration methods. In every construction of the following balances this double bending beam axial-force system has been used.

The calibration of the axial force element showed that the interference due to the pitching moment was much higher then expected. The difference in the bending line between the upper and the lower cantilever causes also signals in the measuring beams with opposite sign. Figure 4 shows the temperature gradient effect and pitching moment interference on the axial force.

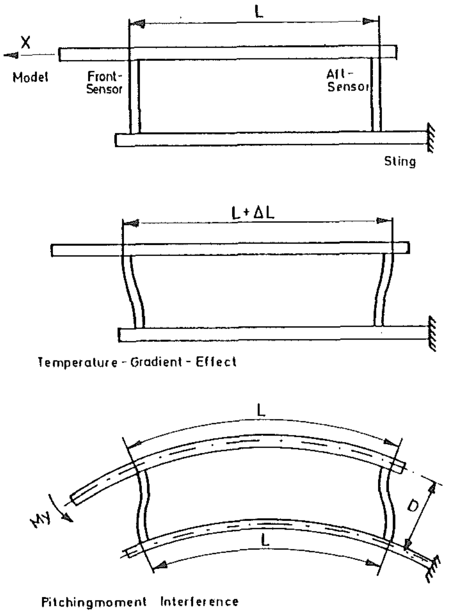

Figure 4. Temperature Gradient and Pitching Moment Effects

The high interference of the pitching moment on the axial force causes also higher inaccuracies in axial force measuring. To minimize this interference a new design for the cantilever beams must be found to achieve higher stiffness and a minimum distance between the bending lines of the two cantilever beams.

V. Balance with Optimized Cantilever Shape

Figure 5 shows the four parts of the balance W 612 before welding. The model side (left) is a cantilever with fork shape and the sting side is a cantilever with tongue shape. After welding the beams are dove tail meshed with only a small slot between the surfaces of the beams. The result of this configuration are nearly identical bending lines so that the interference of the pitching moment on the axial force could be reduced by one order of magnitude. Two balances of this type were built with slight differences in the shape of the axial-force bending beam for the Cologne Cryogenic Windtunnel (KKK).

The aim of the following work was to optimize the shape of the axial-force measuring beams. The experience in calibration showed that a decoupled cantilever beam is not necessary. The interference of lift on axial-force with simple rectangular bars (Figure 3.) in the second axial-force element is as low as in the case of decoupled beams but the heat flow through the beam is much better. This leads to a more uniform temperature distribution in the measuring beam. These beams were used in the balance W 614, which was constructed for the KKK.

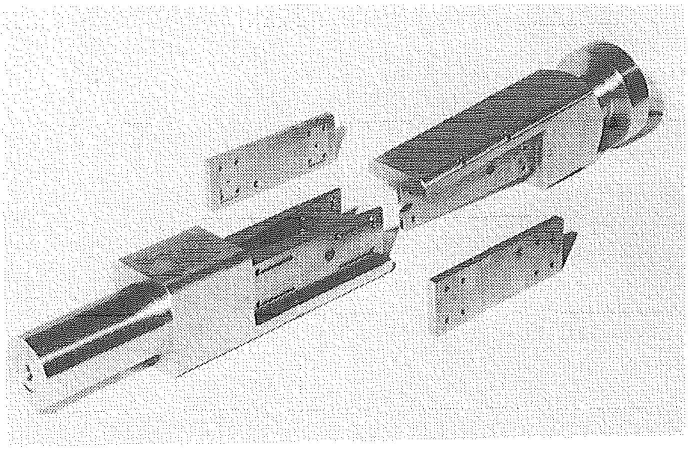

Figure 5. Parts of the Balance W 612

Figure 6 shows the finished balance W 614.

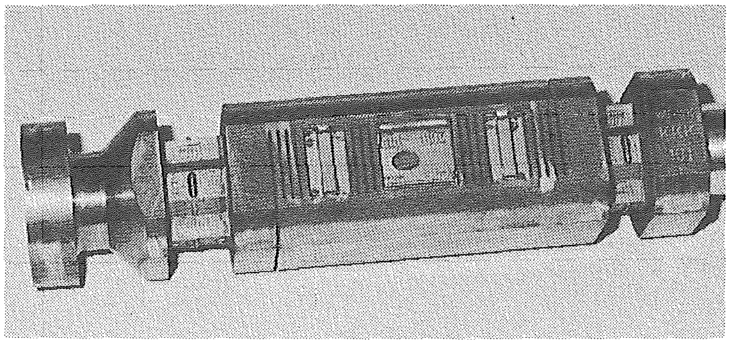

Figure 6. Cryogenic Balance W 614

VI Balance for the European Transsonic Windtunnel

The major target of the whole programme was to built balances for the European Transsonic Windtunnel (ETW). In 1991 the ETW ordered a first production balance. This balance (W 618) has a lift capacity of 12 kN and is especially designed for very precise transport performance measurements with only very small lateral components. At the moment this balance is under construction. The balance will be delivered to the ETW early next year.

As a final effort of the cryogenic balance development programme we will design an advanced technology balance for performance measurements of transport airplanes in the ETW. The external appearance of the balance is much the same as the balance W 614. The lift range of the balance will be 16 kN and the drag range will be 1.5 kN. Model and sting connectors are flanges. The shape of the flanges is a standardized shape specified by the ETW. The balance body part between the flanges and the active part of the balance body is a thin walled pipe. The intention of this pipe is to reduce the heat flow through the balance and so to reduce temperature gradients in the active part of the balance. The possible overall dimensions of the balance allow to built it from copper-beryllium which is qualified as an excellent spring material for strain gage based transducers. Even more important is the fact that copper beryllium has a heat conductivity five times higher than maraging steel. The result will be a more uniform temperature distribution in the balance. Similar temperature distribution as in a maraging steel balance can be achieved in a much shorter time after a tunnel temperature change. Figure 7 shows the drawing of this balance W 617.

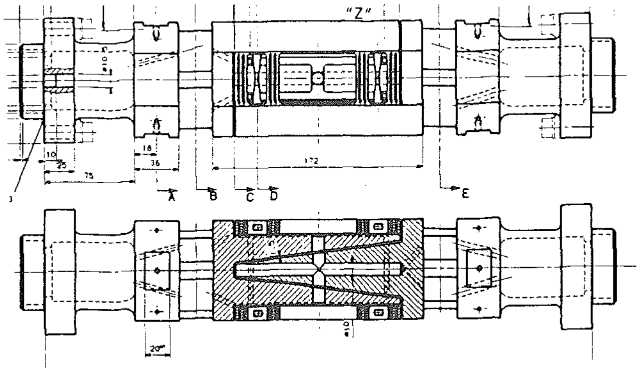

Figure 7. Cryogenic Balance W 617

VII. Accuracy and Reliability

Beside all the technical details wind tunnel people and wind tunnel users are mainly interested in how reliable and how accurate are our balances for a cryogenic wind tunnel.

The cryogenic balance reliability (if it is handled properly!) is nearly the same as in the case of a conventional balance. There is one very important restriction: the balance must be used all the time in an absolutely dry atmosphere. The influence of moisture to the repeatability of the strain gage zero signal is significant. The coatings for the gages, which are proposed by the strain gage manufacturers are not reliable enough in cryogenic conditions even if they are applied with outmost care. In our experience only chemical vapor deposition (CVD) or sputtering with silicon oxide is sufficient. With such a good moisture protection the balance has a very good repeatability of less then 0.002 mV/V for thermal effects.

The accuracy of the balance depends now only on the accuracy of the calibration and the measuring equipment. In our labatory we calibrate in a conventional rig with dead weights. The thermal calibration is done in a cryogenic chamber which is mounted on the rig. The overall repeatability for the drag measurement with the first real cryogenic balance which is in operation in the KKK is better than 0.001 mV/V for two polars at any temperature.

To give a realistic value for the absolute accuracy of measured windtunnel data is not yet possible. The difference of two curves measured in the DNW and the KKK at nearly the same Mach- and Reynolds-Number is shown in Figure 8. The final goal is an accuracy of one drag count in the case of transport performance measurements.

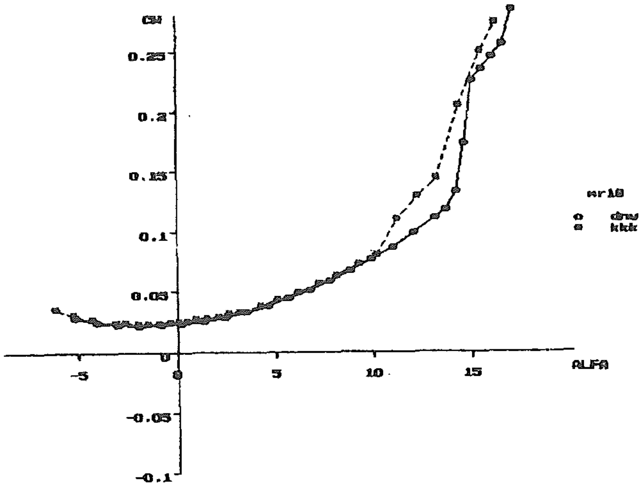

Figure 8. Comparison of Polars Measured in DNW and in KKK with balance W 609 at the same Reynolds Number

VIII. Calibration Method

In the case of a cryogenic tunnel the balance temperature and even temperature gradients in the balance are additional calibration parameters. The complete force calibration must be repeated at several temperature levels and additional calibrations like zero shift through the complete temperature range and temperature gradient effects have to be done. The necessary man power on a conventional rig becomes unacceptable as well as the necessary time.

The accuracy of internal balances may be improved by novel calibration data evaluation algorithms. These algorithms nevertheless nead a larger calibration data base than conventional methods and again man power and time for calibration is increased.

So the design of a fully automatic calibration machine becomes mandatory. The work was started with a feasability study as a part of the ETW Technology Programme. In the meantime the ETW ordered one calibration machine with a lift force capacity of 20 kN. Design and construction of the machine and the computer software is done in a joint effort of the Technical University of Darmstadt, Deutsche Airbus GmbH and the Carl Schenck AG at Darmstadt; the latter partner has the overall responsibility. The machines shop tests are completed and the machine will be ready for use at the ETW mid 1992. A smaller machine for lower load capacities is under design for the Technical University of Darmstadt.

General Requirements

The requirements on the machine are divided into two sections in the following list. The asolutely essential requirements are summarized in section I; during the predesign of the machine any solution, which failed with respect to one of these requirements, was excluded. Section II covers the "second priority" items.

Section I

1. Total accuracy in the order of 0.01 % .
2. Repeatability at least twice as good as accuracy.
3. Resolution (smallest detectable load increment) at least five times better than accuracy.
4. Performance of a complete calibration without any modificattion of original balance mounting or alignment.
5. Extremely precise controlling and measurement of balance alignment. This is a prime requirement to reach the required accuracy.
6. Considerably increased operation speed compared with conventional calibration rigs. A target is a complete six component force calibration in one working shift.

Section II

7. Free access to the balance and free space around the balance for optimum alignment control and for the installation of a cryogenic climate chamber.
8. Minimum number of openings through the climate chamber walls in order to reduce temperature exchange and risk of force bypassing caused by icing problems.
9. Safeguarding system to prevent overloading of the examinee in case of malfunctions.

The requirements listed above force a completely new calibration rig design. In consequence of the speed requirement a fully automatic machine is necessary. The accuracy requirement is not compatible with the conventional calibration rig design as well.

General Principle of the Selected Machine Design.

Figure 9 demonstrates the basic design of most conventional calibration rigs. The sting end of the balance is mounted to the rig. The balance is enclosed by a loading sleeve, which is fastened to the model end of the balance. Loads are applied to the loading sleeve by hanging deadweights only. The exception is the axial force. The axial force is generated by deadweights as well but is transfered to the horizontal direction by a lever.

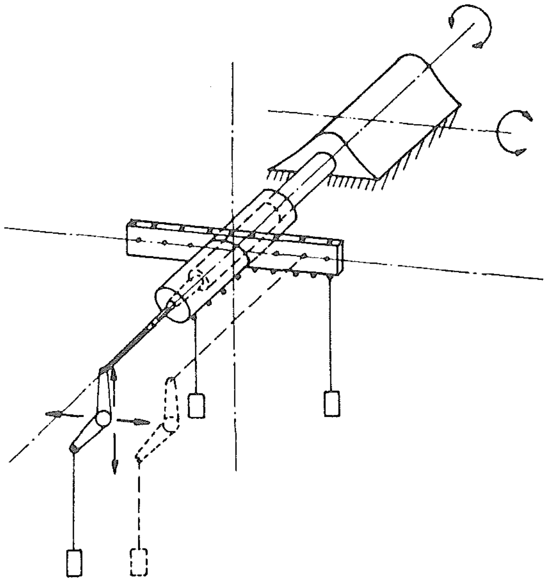

Figure 9. Basic Design of a Conventional Calibration Rig

Moments are generated by excentric application of forces. Pure moment loadings are not possible (pulleys are excluded). Side forces, yawing moments and negative load directions are generated by rotating the balance through 90 or 180 degrees.

The balance is distorted (bended) by the calibration loads. In order to maintain the model end (loading sleeve) of the balance in the geodetic axis system of the loadings forces, for each loading step a realignment of the rig in two axes is necessary.

Obviously this conventional design failes with respect to several of the above requirements and is not compatible with an automated operation. The basic idea to solve the problem is quite simple, the basic design is shown in Figure 10.

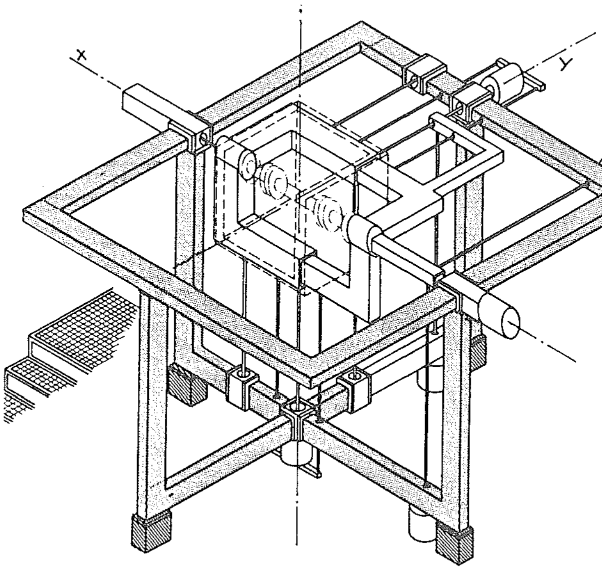

Figure 10. Basic Frame of the Automatic Calibration Rig

For clarity in this figure the basic frame of the rig is marked by dots. The frame is fastened to the foundation by four blocks (hatched parts). In the middle of the upper frame the examinee is visible (faint dotted lines). The model end flange of the examinee point to the left side, the sting end flange to the right side. The axis system of the examinee is indicated in this figure.

The model end of the balance is connected to a measuring device, which is very similar to an external wind tunnel balance. This 'External Balance' part of the machine is marked by dots in Figure 11. The model end of the examinee is fastened to a frame (called 'platform' in the case of an external wind tunnel balance). This frame is connected to the load cells by rods.

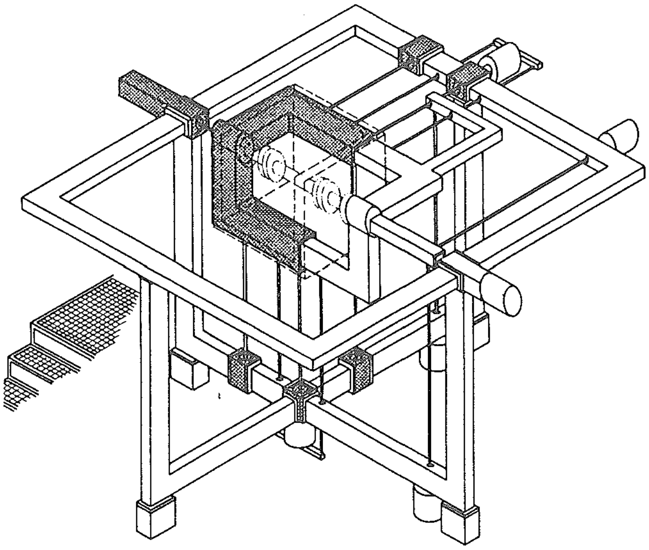

Figure 11. External Balance System of the Calibration Machine

This external balance measures all calibration force applied to the examinee with very high accuracy.

The load generation system of the calibration rig is marked in Figure 12 by dots. The 'Loading Tree' is fastened to the sting end of the balance (right side) and is connected by rods to six load generators. The load components are indicated at the load generators in Figure 12.

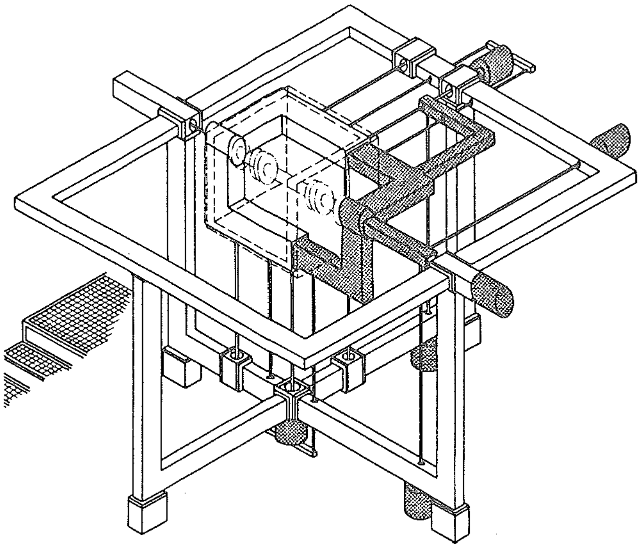

Figure 12. Calibration Load Generation System of the Machine

Obviously the generation of a moment (Yawing Moment Mz e.g.) also produces a force (Side Force Y in that example). In principle the evaluation algorithm is not disturbed by this combination. If a pure moment loading is desired, the force can be counterbalanced by the force generator Y.

Compared with conventional rigs a major problem occurs with this system. As soon as loads are applied, the examinee is distorted and the rods, which transfer the loads from the generators to the examinee, become misaligned. Due to this misalignment the balance is loaded not only with the desired load or load combination but with additional small interference loads in the other components. Of course these interferences are precisely known, since they are measured with the external balance.

These interferences are the key problem of the new calibration machine design. With conventional methods the first and second order calibration coefficients are evaluated from load sequences with single load components or combinations of two single load components. These conventional algorithms are unable to process calibration data mixed with interferences.

This problem was overcome with a new algorithm developed at the Technical University of Darmstadt. This algorithm extracts a third order calibration matrix as a closed least square error solution from the complete calibration data set. In a mathematical sense this is the absolutely best matrix which can be extracted from a given set of calibration data. For an accurate six component evaluation this algorithm needs a data set of 1500 to 2000 different loading conditions. The loading conditions are a combination of single component loads and two component loads (plus the unavoidable interferences).

The choice of a third order calibration matrix with cubic terms for the single components is logical. There are physical reasons for a nonlinear behaviour of a balance. Nevertheless, since a balance is a symmetrical body, nonlinearities should be mainly symmetrical to the zero point. This behaviour can be described with a third order approximation.

An 'Inverted Matrix' is not used in the tunnel since a real inverted matrix does not exist for a second or third order matrix. With a fast solver for nonlinear equation systems the components are extracted directly from the balance signals and the calibration matrix. The inverted linear part of the calibration matrix is used as a start solution. With a fast computer (386 PC) this can be done ON LINE during the wind tunnel measurements.

'External Balance' Technology

Apart from the fact, that the general arrangement of the rods and the force sensors is different, the technology of the external balance is identical to the successful technology of the C. Schenck External Wind Tunnel Balances. In comparison to a normal wind tunnel balance design, the device used in the calibration machine is even simpler and more accurate :

- There is no need for a turntable (normally required to change angle of yaw)
- The position of the reference point may be selected with regard to accuracy optimization only.

The interference matrix for this system contains only very small values outside the main diagonal. So the component accuracies are practically the same as for the load cells.

Obviously the external balance load cells dominate the quality of the rig, so their accuracy must be considerably better than the desired accuracy of the examinees calibration. The C. Schenck AG Axisymmetrical Load Cells, the so-called 'Master Load Cells' offer unequalled accuracy and stability. Typical data of the specimens selected and especially tuned for the calibration machine are :

- Sensitivity 2.85 mV/V, Excitation 60 Volts
- Hysteresis and creep below .004 %
- Resolution more than 500 000 digits
- Long term stability for many years
- Tension/compression crossing without additional zero hysteresis

Figure 13 shows a section through a C. Schenck Master Load Cell. The torsional ring, which is the actual measuring element, is clearly visible.

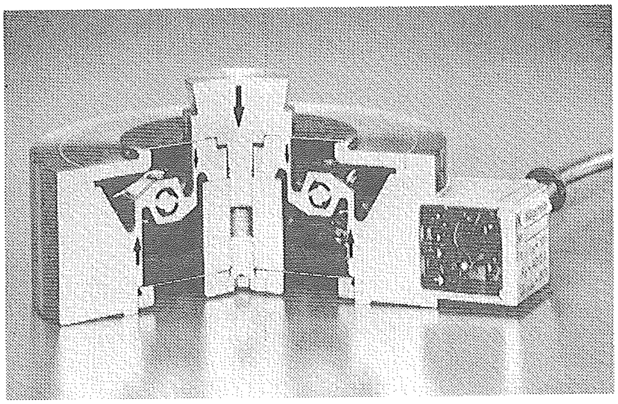

Figure 13. Schenck Master Load Cell

The initial calibration of the external balance will be done with a deadweight system, which is not shown in the figures. Experience with the Schenck wind tunnel balances shows, that a recalibration is necessary only in intervals of several years.

Load Generation System

The load generators have to fulfill three requirements :

- Compensation of mechanical creep of calibration rig, examinee and loading system with an accuracy of better than one part in 50 000.
- Quick changes of loading steps within ten seconds time until constant load.
- Self releasing behaviour in order to protect the examinee in cases of faulty operation.

Different basic possibilities for the force generators were examined.

A pneumatic push-pull piston assembly with double rolling diaphragm sealing was designed and comprehensively tested. Figure 14 shows the principle design of this force generator.

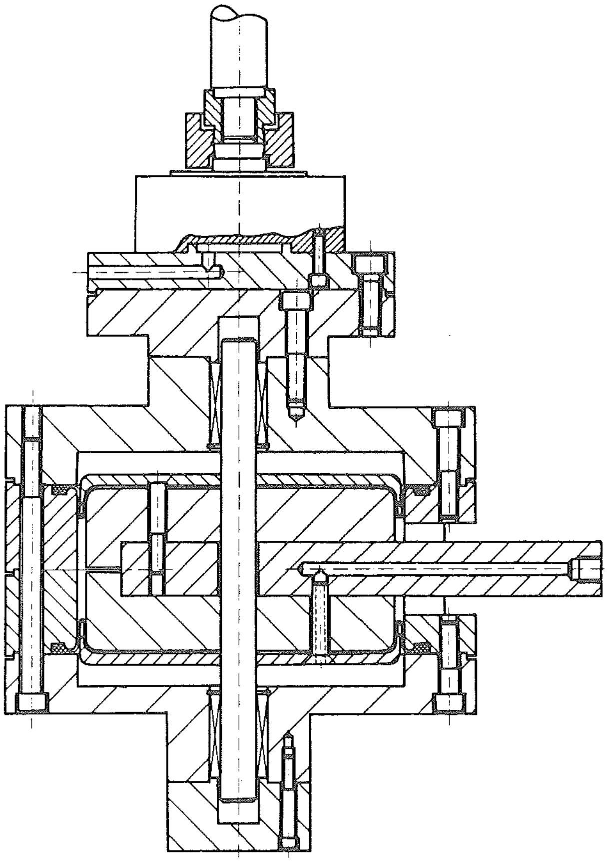

Figure 14. Load Generator Design

The force generators are fed with compressed air or nitrogen, the pressure is up to 15 Bar. The gas is fed to and from the generator by an electrically operated valve unit. A 386 PC is used for a control loop to build up the force and to hold it constant within a band width of 1:50000 referred to the range of the generator. The test results demonstrated, that about 10 seconds are sufficient to reach and to stabilize a force step of 10 % of the generator range.

Computer Control and Data System

The speed requirement (complete six component calibration in one working shift) and the necessary size of the data base results in only 15 to 20 seconds available time for the acquisition of one loading condition. The very fast operation is possible only with a sophisticated computer control of the machine. The safeguarding requires nearly real time operation of the main functions :

- readout and preevaluation of the examinees signals
- readout and evaluation of the external balance
- control of the force generators

So a powerful computer system is required. The final optimized compromise is a fast PC (386 processor, 25 MHz) as a supervisor coupled by LAN to a number of PC controllers :

- Network Server
- External Balance Controller
- Examinee Controller
- Load Generator Controller
- Climate Chamber Controller

For simplicity and reliability PC hardware (286/386 processors) are used for all controllers. These controllers are started and served automatically by the supervisor. Nevertheless they may be used in a manual mode for checking all functions of the equipment and for special calibration operations. The screens of the controllers offer additional informations on the operation and condition of the machine; nevertheless the operator normally works only with the supervisory screen.

The final evaluation of the examinees calibration matrix is done OFF LINE on the Supervisor Computer since this number crunching process needs some time (15 to 20 minutes). The final information on the balance calibration may be carried to the wind tunnel on a floppy disc; the calibration machine may be linked to the computer network of a wind tunnel as well.

The required calibration accuracy asks for a signal acquisition system of the highest available quality. AC amplifiers and digitizers are used exclusively in the machine and this technology is highly recommended also for the use of the balance in the wind tunnel. The main arguments for the AC system are given here :

- The AC system perfectly removes all thermo-couple voltages from the balance signals. Especially in the case of the cryogenic tunnel this is of prime importance for the accuracy.
- Stability and accuracy of top class AC equipment is superior to most DC equipment.
- A new development of the German company Hottinger, the digital measuring system DMC 9012, gives top class accuracy and resolution with perfect computer compatibility at a cost per channel, which is considerably less than in the case of top class DC equipment.

Hottinger DMC 9012 systems are used for the acquisition of the examinee signals (strain gage signals and temperature signals) and for the control of the force generators. For the readout of the external balance load cells the Hottinger DK 38 digital compensators are used.

Obviously for the calibration and for the use of the balance in the wind tunnel the same type of measuring system should be used. This idea led us to the "Black Box Balance System". In this system each balance is identified by a resistor code soldered into the wiring of the balance. So the data system automatically identifies the balance, activates the calibration data of this balance from the wind tunnel computer memory and evaluates the measurements without any manual operatiom. The necessary informations are stored into the wind tunnel computer simply by loading the calibration machine result discette into the wind tunnel computer.

Accuracy

In technical specifications the meaning of the term 'accuracy' must be identified. In the case of the calibration machine the term accuracy specifies the ability of the machine to identify (to measure !) the calibration loads acting on the balance. There are other error sources in the calibration process, which can not be charged on the machine :

- Instabilities, hysteresis and all other errors generated in the examinee or in its data acquisition equipment.
- faulty identification of the examinees reference center due to inadequate construction of the examinee.

For the ETW machine the estimated overall accuracy is slightly different for the components and varies between .015 to .025 % . The value of 0.015 % is achieved for X and Z with only small loads in the other components. The 'worst' value of 0.025 % is expected for X, Y and Z in the case that all other components are fully applied. The accuracy of the moment components is expected with 0.02 % with no or only small influence of the other load components.

Climate Chamber

The philosophy for cryogenic balance calibration is based on the following rules :

- The complete force calibration performed at ambient conditions has to be repeated at several temperature levels between ambient and the lowest operational temperature of the tunnel. In a favourite case only the single loadings have to be repeated (sensitivity of strain gage bridges). In the worst case complete force calibrations have to be done at several temperature levels.
- Of prime importance for the accuracy of the calibration is the perfect isolation of the different temperature effects. So zero shift has to be calibrated without any force and without any spatial temperature gradient in the balance. Force calibration has to be done at constant temperature and without any gradient in the balance body. Finally a careful temperature gradient calibration has to be done starting with gradient free condition at several temperature levels.

The realization of these rules is possible only with a sophisticated cryogenic climate chamber around the examinee. A prototype was designed at the Technical University of Darmstadt and operated successfully since years.

The climate chamber is mounted in the calibration machine as shown in Figure 10 with the dotted lines. The chamber is fastened to the machines frame. The earth end and the model end balance adaptors penetrate the wall of the chamber. The chamber is conditioned by injection of liquid nitrogen. A uniform temperature distribution is obtained by injecting the nitrogen into a blower, who distributes the gas through the chamber.

The connections of the examinee to the external balance at the model end and to the loading tree at the sting end penetrate the chamber walls. These wall penetrations are the main design problem of the climate chamber. At least at the model end, where the balance is mounted to the external balance, no force transmission at all is allowed. At the sting end transmission of small forces has no effect, since the forces are measured in the machine.

The connections of the balance ends through the chamber walls have to transmit all calibration loads; so they must be very stiff. At the same time the connections must block any heat flow from ambient into the cryogenic chamber as perfectly as possible.

Off all metallic materials titanium has the largest ratio of strength to heat conductivity. So the connections were designed as thin walled titanium tubes.

For the model end a labyrinth seal is used for the penetration of the wall, which avoids any force transmission. To keep the moisture of the ambient air out of the climate chamber, a weak overpressure in the chamber is adjusted.

At the loading tree connection the transmission of small forces does not disturb the calibration. So a double teflon bellow seal is provided here.

All functions of the climate chamber are controlled by the climate chamber controller. Temperature cycles are controlled under automatic or manual operation, the moisture level in the chamber is measured and the function of the sealings is controlled.

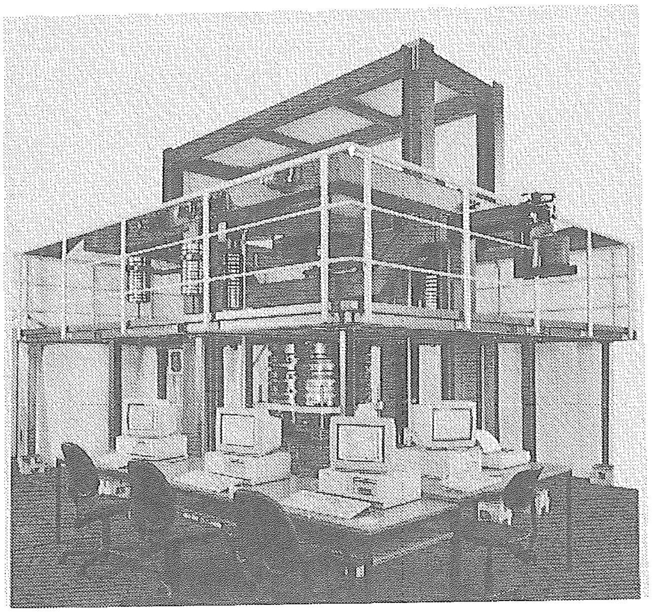

Figure 15. Shop Test Arrangement of ETW Calibration Machine

VIII Conclusions

From our experience a cryogenic wind tunnel balance with the same accuracy and repeatability as a conventional balance is possible.

The application techniques and the materials have been improved for the cryogenic range. The effect of temperature gradients could be minimized by a new design of the axial-force element and an advanced calibration. The zero shift could also be reduced by matching procedures and calibration.

The design of a fully automatic internal strain gage balance calibration machine greatly reduces the man power and time required for balance calibration. So at acceptable cost the calibration may be repeated frequently, which improves accuracy and reliability of the calibration. The special design of the machine improves the accuracy of the calibration compared with the conventional calibration rig especially in the case of a cryogenic balance.

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