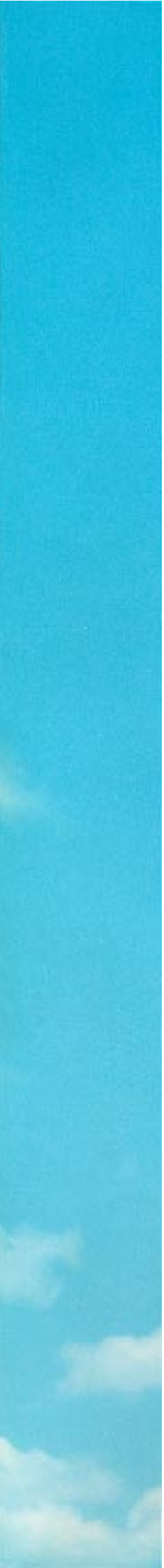

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Strain gauge balance development at NLR

H.B. Vos

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ABSTRACT

The National Aerospace Laboratory (NLR) has developed and manufactured strain gauge balances for more than thirty years. All types of balances were developed, not only for NLR tunnels and models but also for many customers and other research institutes.
Through the years new techniques and new materials became available.
In order to raise the overall accuracy of balance measurements the total process of balance design, manufacture and calibration has been reviewed. Based on extensive investigations many design criteria for the various parts of the balances have been modified and brought into practice.
This paper summarizes the state of the art of balance technology at NLR.

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STRAIN GAUGE BALANCE DEVELOPMENT AT NLR

H.B. Vos
National Aerospace Laboratory NLR
Emmeloord, NL

SUMMARY

The National Aerospace Laboratory (NLR) has developed and manufactured strain gauge balances for more than thirty years. All types of balances were developed, not only for NLR tunnels and models but also for many customers and other research institutes.
Through the years new techniques and new materials became available.

In order to raise the overall accuracy of balance measurements the total process of balance design, manufacture and calibration has been reviewed.

Based on extensive investigations many design criteria for the various parts of the balances have been modified and brought in to practice.

This paper summarizes the state of the art of balance technology at NLR.

INTRODUCTION

NLR has developed and manufactured strain gauge balances for more than thirty years. New techniques and new materials allow more predictable and more accurate designs. Review of the balance creation process shows that ‘the' accuracy of a balance is not a simple design criterium that can be met by using state of the art means and methods. The achieved accuracy will be the result of a very fragile chain of conditions.
Identifying all of the chain links is difficult because of the variation of conditions during balance use. A few links however are easily identified:

- Design: by adequately choosing the balance concept, and in adequate designing of the several functional parts of the balance, a highly predictable behaviour can be achieved.
- Instrumentation: the use of high quality materials and accurate application ensure long term durability of the measuring instrument.
- Calibration: this makes a complexly shaped piece of steel into a measuring instrument. The accuracy of the calibration equipment and of the calibration procedures determine directly the accuracy of the balance.

Other links vary with the use of a balance, e.g. environmental conditions (temperature, pressure, humidity) or dynamic loading. Although for some conditions some generally applicable compensation techniques are valid, most of these conditions have to be evaluated for specific cases. Adaptation of techniques is then often necessary.

In recent years several investigations have been carried out. They included:

- The relationship between load capacity and measuring hysteresis.
- New connections between model and balance, and between balance and sting/earth

- High load capacity balances.
- The predictability of natural frequencies of balance systems.
- Error causes during application of calibration weights and errors due to the use of elastic hinges.
- Optimized measuring strain levels.
- The effect of surface treatment on strain gauge measurements.
- New temperature compensation techniques.
- Improved predictability of thermal behaviour of the balance system.
- New data processing techniques.
- The use of Finite Element Methods (F.E.M.) in the design phase.

Although the results of the investigations have been incorporated in the design of a new generation of balances, the improvement of the accuracy of balance measurements and of the predictability is an ongoing process.

If accuracy is considered as the difference between applied loads and calculated loads NLR has achieved < 0.1% f.s. typically for the new generation sting balances and < 0.05% f.s. for the new half model balances.

A short description of the design and instrumentation concepts, and the evaluation of balance results is given.

DESIGN AND DESIGN TOOLS

Design tools

The design of balance bodies has been modified to ensure an optimal amount of measuring strain under the strain gauges and to minimize ‘parasitic' strain caused by other loadings (interactions from other components, thermal loads, centrifugal loads). In order to improve the accuracy of the strain measurements, and to make the behaviour of the balance more predictable, the use of Finite Element Methods (COSMOS/M, ELFINI) has become indispensable.

The F.E. methods have been used for:
- Stress concentration optimization.
- Strain level optimization.
- Thermal expansion calculations of axial force elements.
- Calculation of thermal stresses.
- Natural frequencies of balance systems.
- Calculation of centrifugal effects on strain gauge bridges of rotating systems.

Also the CAD/CAM system CATIA has increasingly been used for the design and manufacturing of complex balance bodies.

Beside these commercially available software programs, NLR has developed computer programs for special purposes. These programs include F.E.M. postprocessing and algorithms for calculating stress and strain.

Short description of the design process

The predesign of a new balance is based on conventional calculation methods. This predesign should satisfy all conditions and constraints that have been set for the design.

The predesign then is modelled for F.E.M. and analysed. This F.E.M. model consists of BEAM-elements only so that it still can be changed quite easily. Modification of the geometry is usually necessary and is continued until again all conditions are satisfied.

With this BEAM-element model stress and strain are calculated and also thermal expansion of parts of the balance construction is analysed. Sometimes this analysis dictates the changing of the basic concept so radically that a new predesign has to be made.

After this a SOLID-element model is made of the total balance construction. With this F.E.M. model stress concentration effects, plane stress effects and thermal effects on strain gauge bridge output can be analysed. Usually only small dimensional changes are necessary in this phase. With this model a good prediction of the strain gauge bridge output can be given. On basis of these results changing the instrumentation configuration (location of the strain gauges) could be necessary. See figure 1 for an example of a F.E.M.-model.

For an internal six-component balance this process can be very time consuming and the evaluation of the results is very elaborate. For less complex balance bodies however quick reliable results can be obtained within a few days.

After this the balance body can be drawn.

Several balances have been specially gauged after manufacturing to be able to measure at locations where the highest stresses were expected. In this way the calculated stresses can be verified. At this moment calculated values fall within 10% of real values, which is considered sufficient at this moment for design purposes.

Reasons for discrepancies are:

- Physical properties of the used materials not exactly known.
- Exact dimensions of the real balance body not known on all gauge locations; measuring them could be very elaborate and not always possible.
- Exact position of strain gauges not known and often difficult to measure.
- The loads are applied by means of calibration equipment which could influence the load path through the balance; the theoretical loading point (balance centre) as used in the calculations could be different from the real loading point which is determined by the dimensions of the calibration equipment.

  Especially this effect can be found in the interaction output of a certain load on the other strain gauge bridges.
- F.E.M. model can not have the exact geometry of the real balance due to the finite geometry of the elements. Also the element mesh fineness will influence the results.

Of course none of these single reasons will cause the 10% deviation, but all the small contributions add up to this percentage.

Until now the safety factor adopted is four on ultimate strength; in case of small balances with a high loading capacity this factor limits the design possibilities significantly. With the gaining of more experience with F.E.M. and comparing this with experimental results, more confidence in the predictability can be gained. This could mean that in some cases lower safety factors can be accepted.

Connections

The connections of the balance with the model and sting (or some other non metric part of the model support) have been thoroughly investigated in recent years. These connections are of paramount interest to the balance performance. It is shown that the effects of the model/balance interface (but sometimes also of the balance/sting- interface) can jeopardize an otherwise excellent balance behaviour.
It has become clear that there is no type of connection that can be universally used for all balance ranges. Depending on the type and range of the balance a connection has to be evaluated on its merits.
The connections investigated for sting balances were:

- Cone: enhanced by reducing contact area, determinate positioning, modified mounting and dismounting procedures. As model/balance interface this connection has been rejected because of unavoidable hysteresis and bad reproducibility. The matching of the mating cones (male and female) is an important aspect. Especially the female cones are difficult to manufacture and can easily be less accurate than the male cones. This results in large hysteresis and possible damage. The way the loads are transferred in a cone connection can have a significant influence on nearby measuring sections. Due to the slightly varying transfer area (as a result of bad fits or micro movement during external loading) the stress distribution in the measuring section could be influenced. This has led to significant hysteresis in the strain gauge bridge output, and to a sensitivity variation of the bridge in the measuring section. To avoid this a certain minimum distance is necessary between the cone and the measuring section. This distance is dependent on the load range of the balance, the diameter of the measuring section and the dimensions of the cone. It is worthwhile to determine this minimum distance in order to keep the balance as short as possible.
  Cones still are used as balance/sting connection because in most cases the model incidence is directly measured by means of instrumentation inside the model and small position hysteresis in this connection is therefore acceptable.
  The advantages of this connection are its large load carrying capability and yet compact dimensions and robust form.
- Cylindrical bush and cylindrical tap: always a clearance fit with relative movement between the connecting parts. Movement can be avoided by means of expandable elements but this introduces position hysteresis. Vulnerability of joint faces (galling!) is a main problem. The manufacture of cylinders can be very accurate but to have a good clearance fit every balance housing of new models must be matched to the already existing balance. This could give a discrepancy with the calibration model and hence influence the calculated results.
- Flange: two types of flanges have been investigated: so called ‘lip' flanges of which the interfaces are parallel to the balance centre line, and ‘end face' flanges which are perpendicular to the balance centre line.
  Both types have been used on NLR balances and both show very low hysteresis and very good position reproducibility.
  The disadvantage of lip flanges is that they require much space on both sides of the measuring part of the balance. This type of connection has for this reason only been used for balances for low speed wind tunnel models which have enough space available.
  The end face flanges have been widely used in several shapes. This connection is much more compact in axial direction of the balance and has the same outer diameter as the balance body. For small diameters (e.g. use in slender wind tunnel models) and relatively highly stressed balances this connection is not suitable.
  NLR has developed a hydraulically prestressed end flange connection for the model side of the balance which has the same outer diameter as the balance. This connection is virtually hysteresis

free (< 0,005°) and has a high position accuracy (< 0,015 mm). If possible this type of connection will always be used for new balances. Figure 2 shows a schematic drawing of this connection.

At this moment the general purpose six-component sting balances of the new generation have an enhanced cone at the sting side and an end face flange at the model side.
For other types of balances (external, model parts) only flange connections are used.

Measuring elements

Axial Force Element: Several constructions have been designed to improve the decoupling and to minimize temperature effects. By analysing the deformation of the element due to thermal expansion it is possible to place strain gauge bridges that give output of opposite sign as compared to the axial force bridge thermal output. If such a compensation bridge is used, care must be taken to optimize (in the design phase!) also the strain level for this bridge otherwise the signal will lower the accuracy of the combined signal. NLR has used a compensation bridge on several axial force elements. The design of the axial force element has been adjusted in such a way that a compensation bridge is no longer necessary. Figure 3 shows an axial force with double decoupling beams. This setup copes with most of the thermal expansion problems.
This is the most complex part of the balance which is most sensitive to error causes. Compared to the other strain gauge bridges the axial force bridge gives generally the highest measuring hysteresis. This could be caused by ‘heaping up' of material hysteresis in the thin flexures of the element thus giving micro deformation of the measuring flexure.
In the axial force element usually also the rolling moment is measured.

Other measuring elements for the remaining components: Normal setup is the presence of two measuring sections symmetrically placed with respect to the axial force element. These sections could be massive or have a cage form, depending on the desired bridge output and the specified load range.
In each section two strain gauge bridges are placed. These bridges primarily react on the moments (pitching moment, yawing moment) and on the loads due to normal force and side force.
The effect of radial temperature gradients in these sections is partly compensated by measuring also the lateral contraction strain. In this case the strain gauge bridge is self-compensating.

Specific design aspects

Each type of balance has its own specific design problems.

Internal strain gauge balances
Universal six component balances: one piece design with several measuring sections
Problems: quality of model/balance interface; higher order interactions to be determined correctly.
Dedicated compact six component balances with high axial capacity: possible temperature problems when used in small models. By using self-compensating strain gauge bridges the problems can be minimized.

External balances
Half model balances almost completely statically determinate with high accuracy dynamometers, either commercially available load cells or developed in house e.g. if dictated by available space.
Figure 4 shows a photograph of a balance for non-aerospace research.
At this moment the design experience allows excellent balances to be realized.

Problems: Size and accuracy of the calibration equipment

Rotary balances

Compact balances which are able to measure six components in propeller constructions
Problems: Temperature and centrifugal effects on bridge readings, and to avoid damage to the instrumentation due to centrifugal loading.
NLR has gained experience to cope with these problems.
Figure 5 shows a photograph of a rotary balance.

Model part balances

Dedicated balances for use in wind tunnel models of which the loads on model parts have to be measured (fins, rudders, tail plane etc.).
Problems: limited space, low strain gauge bridge output. Often the earth side has to be included in the design and calibration.

INSTRUMENTATION

All used materials (strain gauges, resistances, wiring, coating material) are commercially available.

Description of the procedure

- Definition of instrumentation location: for complex balance bodies optimized with help of F.E.M.

- Surface preparation: all locations where instrumentation material has to be placed (strain gages, compensation resistances) are given a roughness Ra 0,4 - 0,8 µm.
- Bonding strain gauges and compensation resistances: special attention is given to accurate positioning and the required clamping force.
- Wiring: the most time consuming part.
  To have enough slack in the wiring (especially in an axial force element) is essential, but due to complex geometry sometimes difficult to create.
- Checks: electrical measurements and temperature runs must make clear that the gauges are bonded well and that all wiring is correctly.
- Three hardware compensations are applied:
  - Sensitivity shift due to temperature changes.
- Criterium: < 0,003% f.s./°C (0°- 50°C).
  - Zero shift due to temperature changes.
    - Criterium: < 0,01% f.s./°C (0°- 50°C).
  - Bridge (un)balance: < 1000 µV.

  All compensation resistances are placed as close as possible to the bridges, or to the half bridges if compensated per half bridge.
  The resistance values are determined by changing the temperature at a rate that is typical for the NLR wind tunnel conditions. This is done in a computer controlled oven. By recording the bridge outputs almost continuously (triggered by 2°C balance temperature change or half an hour no temperature change) the relation between temperature change and output can be accurately determined. See figure 6 for typical compensation results.
  A great advantage of this procedure is also that the behaviour of the bridge signals can be evaluated during the complete temperature run and in a number of cases faults in the instrumentation have been detected in this way. Also a better understanding of the thermal

expansion behaviour of the balance construction can be obtained.
If no further hardware compensation is possible (for example in case of output due to thermo-mechanical effects) software compensation can be applied on basis of the same temperature run results or based on the temperature distribution as measured by temperature sensors on the balance.

Development of instrumentation techniques

New instrumentation materials or new techniques are investigated with standard test beams. New strain gauges or a new coating material are evaluated on test beams. Completely compensated strain gauge bridges are placed and coated. The beams are tested with dead weight loading.
Instrumentation techniques (e.g. temperature compensation, bonding techniques) are also optimized with these test beams.
If the use of a new balance body material is considered, standard test beams of this new material are made and tested with several types of strain gauges.

EVALUATION OF BALANCE RESULTS

After design and manufacture of a new type of strain gauge balance several tests are performed to determine if the balance satisfies the design requirements:

- Strain measurements on non-bridge locations.
- Bridge output due to nominal loading.
- First order interactions.
- Behaviour at increased temperatures and temperature gradients.
- Quality of the individual bridge signals: hysteresis, mean and maximum deviation of curve fit (second or third order polynoms) through bridge output, zero shift with temperature.
- Difference between measured loads and applied loads and the distribution of deviations.
- Determination of balance deformation due to nominal loading.
- Repeatability of the results.
- Influence of data processing is evaluated: matrix inversion or iteration. At this moment NLR is testing a new processing system (based on an iteration method) which will also improve presentation capabilities and analysis of the calibration results.
- Creep.

The analysis of these test results can be very elaborate due to the many possible error causes as already mentioned in the introduction.
Evaluation of the results is often difficult because of the absence of uniquely defined criteria for several aspects. The determination and/or definition of relevant criteria is one of the main subjects of investigation at this moment. The sum of these criteria must give the maximum *inaccuracy* of the balance in carefully conditioned environments. The definition of such an inaccuracy number (% f.s. or % rated load?, not in dragcounts!) should be done in a way that the value of this number can be determined under reproducible conditions. This inaccuracy number makes direct comparison of balances possible and can be used as design feedback. Essential is that the definition of the number is clear and unique.
The inaccuracy of the load measurements in the wind tunnel is higher than the balance inaccuracy under calibration conditions due to extra possible error causes in tunnel conditions. The balance inaccuracy number therefore can only give information about the *expected* balance behaviour in tunnel conditions.

CONCLUDING REMARKS

The development of a new generation general purpose sting balances was the beginning of a complete review of the balance creation process. This has resulted in a more extensive use of modern computational tools and the adaptation of instrumentation techniques. Predictability of results has improved significantly. The design tools could easily be adopted for other types of balances (external, rotary).

Other aspects (e.g. calibration and calibration equipment) are still being reviewed and investigations are going on.

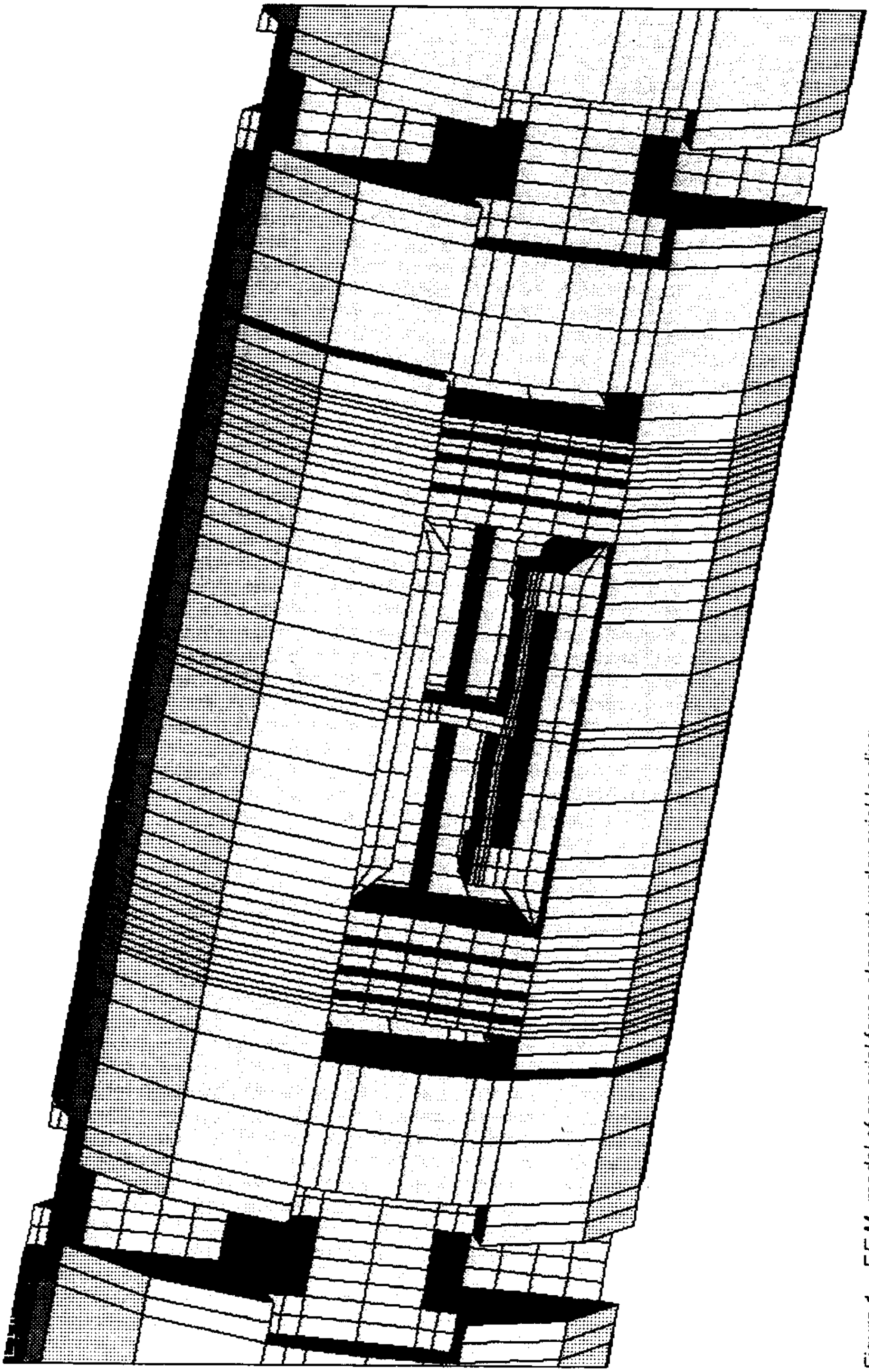

Figure 1 F.E.M.-model of an axial force element under axial loading

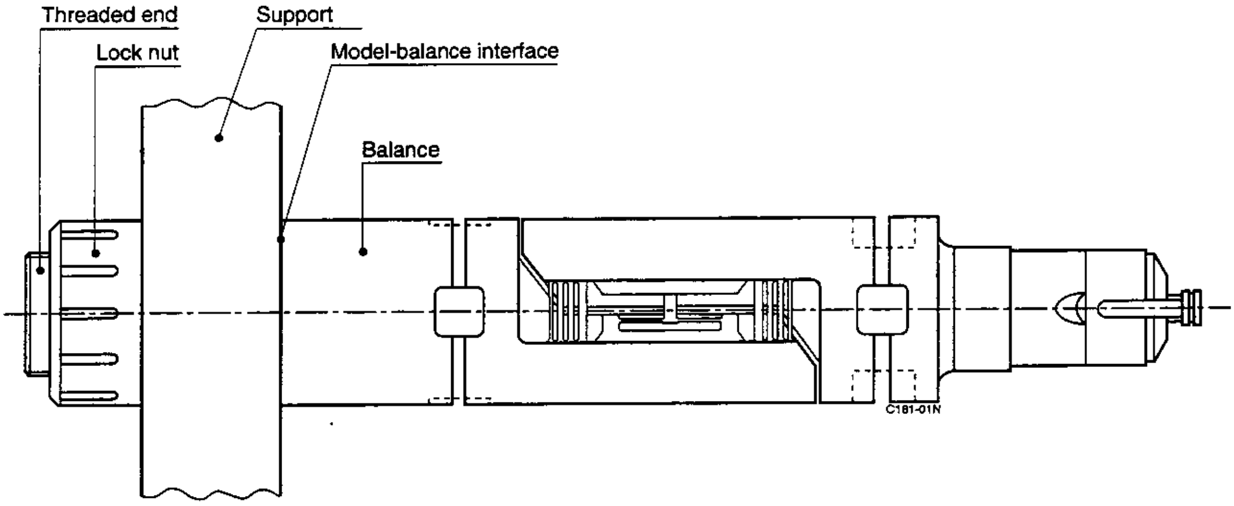

Figure 2 Model/balance connection

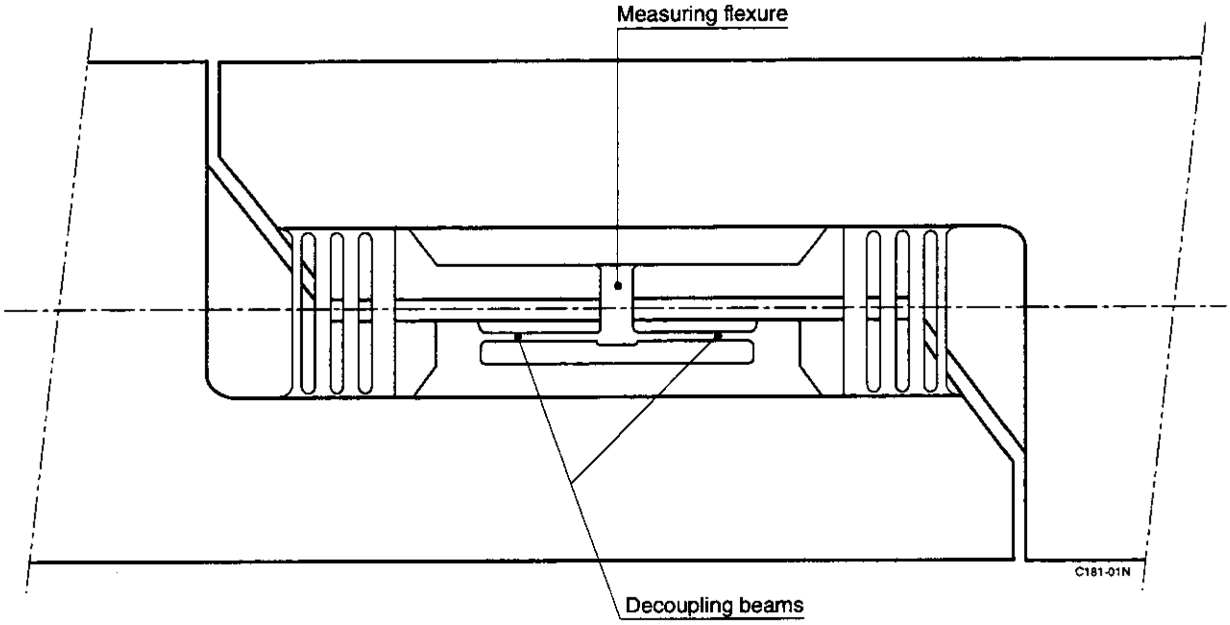

Figure 3 Axial force element with double decoupling beams

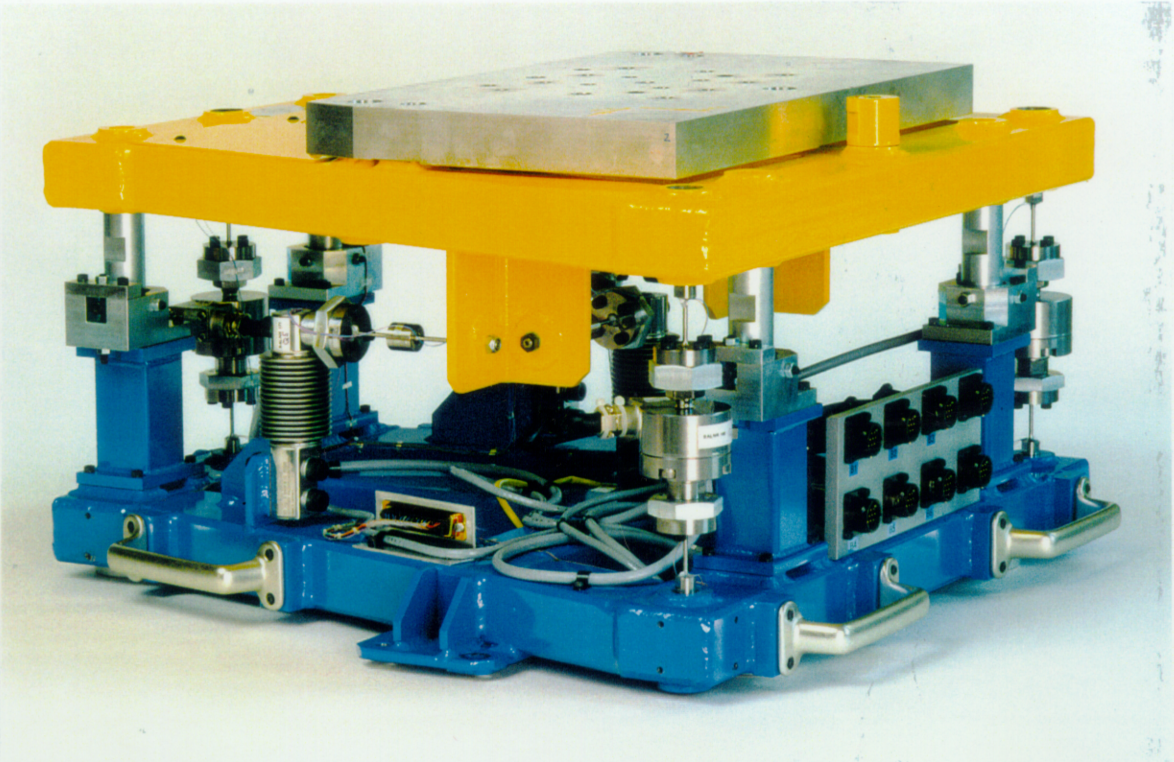

Figure 4 Balance for non-aerospace research

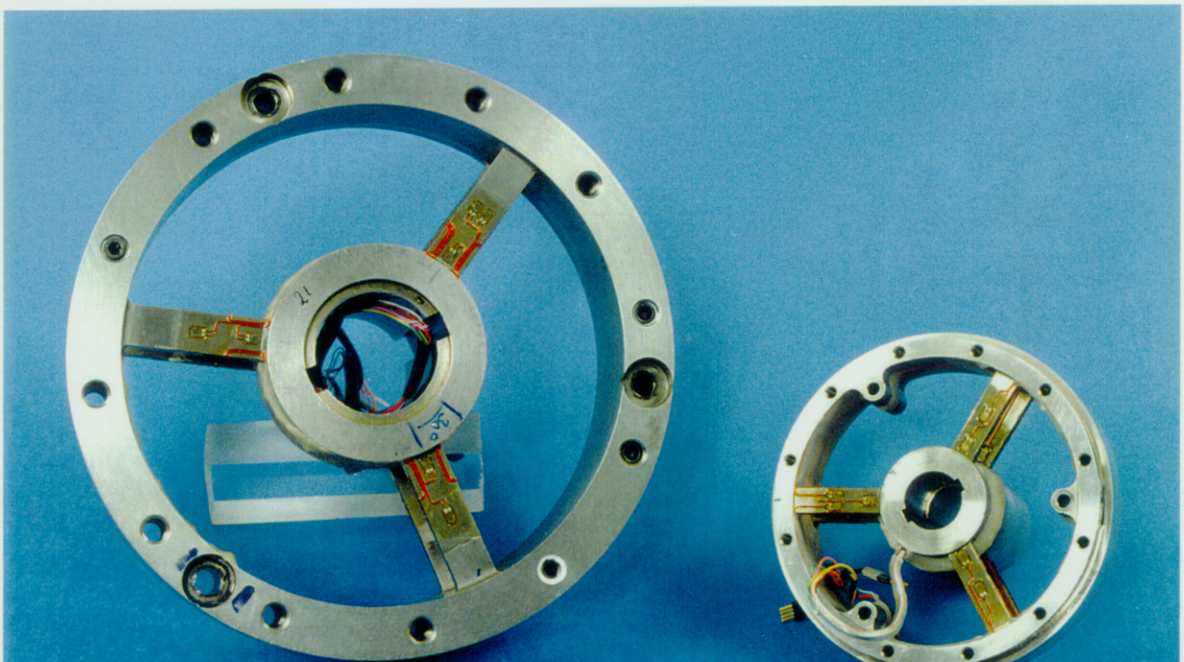

Figure 5 Compact rotary balances

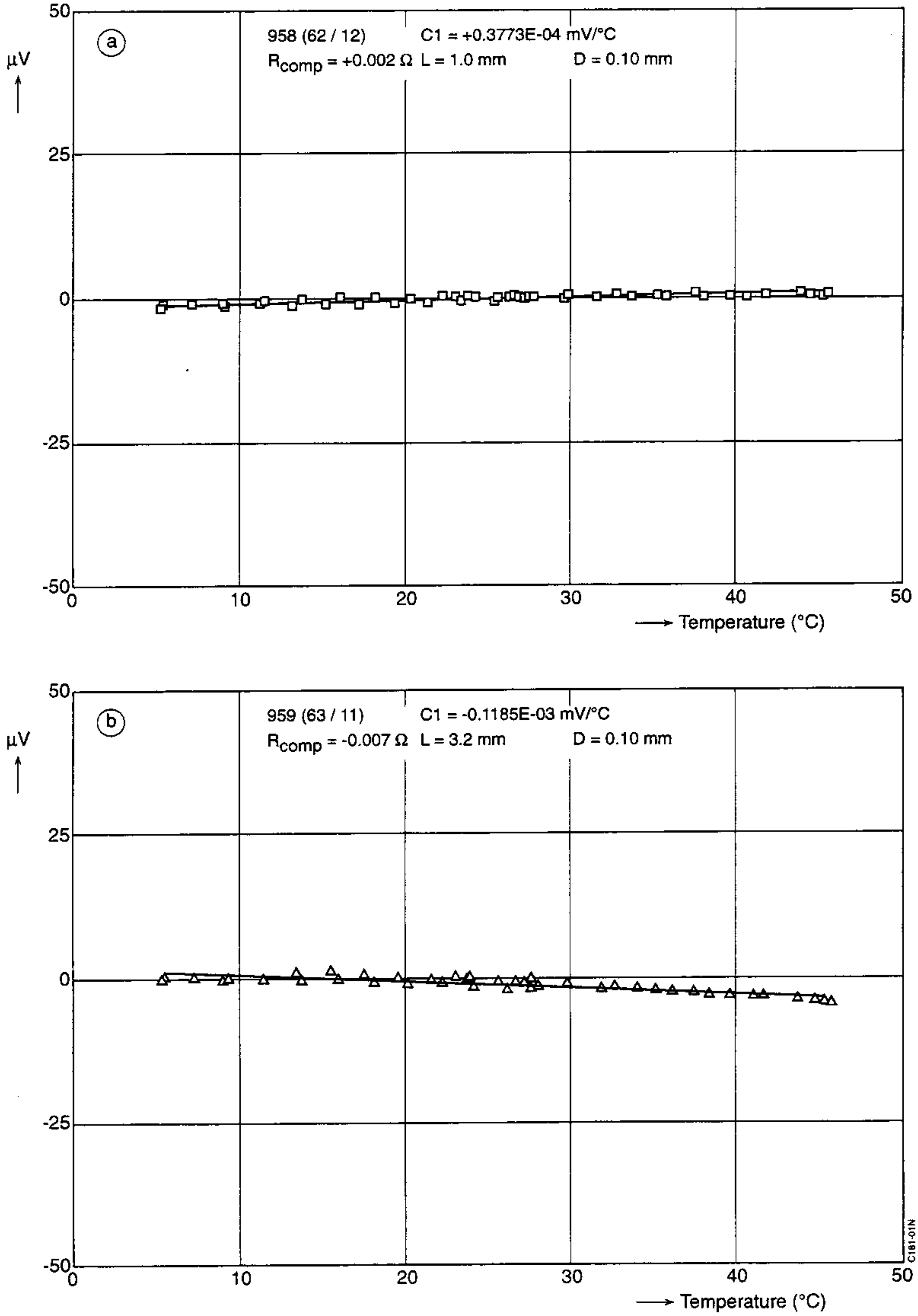

Figure 6 Typical compensation results of a temperature run