PROTOTYPE OF A STIFF WIND TUNNEL BALANCE WITH SEMICONDUCTOR STRAIN GAUGES AND THERMOCOMPENSATION DONE BY SOFTWARE

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Abstract

A very stiff six-component wind tunnel balance of simple construction was produced with semiconductor strain gauges on the axial-load element and with a temperature sensor installed. Thermocompensation was performed by software, treating the temperature sensor as the seventh balance load component. Calibration of the prototype validated the concept.

1 Introduction

During the course of wind tunnel tests in the T-38 wind tunnel [1] of Vojnotehnicki institut (VTI), a need was expressed for six-component wind tunnel balances of stiffness higher than usually available in the conventional beam-type balances. It was decided to produce a prototype of such a balance, that was to be very simple and robust in shape, taking advantage of the fact that semiconductor strain gauge bridges produce acceptably large signals even at low levels of strain and can be applied to very stiff flexure elements.

Another aim of the project was to apply and test, during the calibration of the prototype balance, a general-purpose software algorithm for compensation of apparent loads caused by influences of e.g. temperature, pressurized tubing passed through the balance, inertial loads caused by the rotation of the balance on a shaft, etc. This algorithm, implemented in a flexible software tool for balance calibration named BACAL (its early development stage presented in [6]), uses the concept of a generic multi-component balance that can sense an arbitrary number of load components: external influences (temperature, etc.), measured by suitable sensors, are treated as balance "components" and processed alongside and in the same way as "real" balance load components, through the balance calibration matrix.

2 Balance Design

Mechanical design of the balance was very simple, so that it was quickly produced, which was one of the requirements in design specifications. The balance (CAD model shown in Fig.1 and photograph in Fig.2) was basically a thick-walled cylindrical tube produced of Vascomax 300 steel, with integral attachment tapers on both ends, and flat surfaces for application of strain gauges machined on two stations on the tube. It was designed so as to be geometrically compatible with an existing conventional beam-type balance (Fig.3) of comparable load range.

Semiconductor strain gauges were used only for the axial force component, while high-impedance 5 kΩ foil-type strain gauges, supplied with 21 V excitation, were used for other load components. Rough hardware thermocompensation of zero shifts was performed for all components. A temperature-sensing bridge consisting of foil-type elements was installed near the axial-force semiconductor strain gauges, and this bridge was thereafter considered to be the seventh component of the balance.

Moments reference centre of the balance was at the forward instrumented station which carried the strain gauge bridges for axial force, rolling moment, and two bending moments. For measurement of axial load this section acted as a compression-type element, with four semiconductor strain gauges arranged in two T-patterns on the opposite sides of the octagonal cross-section of the station. Two cylindrical grooves machined on the inside surface of the tube helped in creating eccentric pressure when axial load was applied, thus increasing strain at locations of semiconductor strain gauges. Eight longitudinal slits through this section reduced torsional stiffness, enabling larger-magnitude signals from the rolling moment bridge.

The rear instrumented station carried the strain gauge bridges for the remaining two bending moments.

All wiring was passed through the sting-interface taper on the rear end of the balance. A number of spare wires was also passed through the balance to facilitate connection of other instrumentation forward of the balance in a wind tunnel model.

Nominal design specifications for the prototype balance were stated as:

Diameter:	40 mm
Length:	220 mm
Axial force capacity:	1100 N
Forward bending moment capacity:	200 Nm
Rear bending moment capacity:	400 Nm
Rolling moment:	100 Nm
Temperature:	10 - 40 ^{o}C
Target accuracy:	0.2% FS

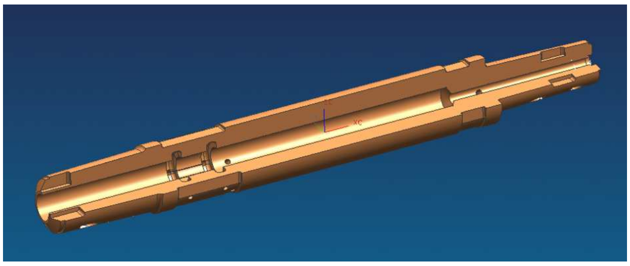

Fig. 1 CAD model of the new balance

Fig. 2 Photograph of the new balance

Fig. 3 Comparable conventional-design balance

3 Calibration

3.1 The Concept of the Generic Balance

Balance calibration and wind tunnel test balance data reduction algorithms implemented in the software used in VTI ([6], [5], [7]) are a generalization developed upon the concept presented by Galway in [2]. A common wind tunnel force balance is assumed to consists of one or several (usually three or six) load sensing elements, most often of the strain gauge type. Each element measures a single load component (either force or torque/moment). The correspondence between the balance outputs $\{e\}$ (usually electrical signals) and loads $\{F\}$ applied to these elements is contained in the calibration matrix $[C]$:

$$\{e\} = [C]\{F^{**}\} \tag{1}$$

where $\{F^{**}\} = \{1, F_1 \ldots F_n, {F_1}^2 \ldots, F_1F_2 \ldots\}^T$ is a vector of loads and load products up to the desired order (usually second or third), and including the offset term. For convenience, both the calibration matrix and the vector of load products can be divided into their zero-intercept, linear and nonlinear parts, i.e:

$$\{e\} = \{C0\} + [C1]\{F\} + [C2]\{F^*\} \quad (2)$$

where $\{C0\}$ are the terms in the calibration matrix corresponding to zero-load balance outputs $\{e_0\}$ and $[C1]$ and $[C2]$ are parts corresponding to linear and nonlinear terms respectively, so that $[C] = [\{C0\}\ [C1]\ [C2]]$. Accordingly, 1, $\{F\}$ and $\{F^*\}$ are the zero offset, linear and nonlinear parts of $\{F^{**}\}$.

Assuming the mathemathical model of the balance as in eqn. 2 above, the inverse relation between applied external loads (resolved to directions of balance components) and component outputs can be determined iteratively, from eqn.(3) below:

$$\{F\} = [C1]^{-1}\{\{e\} - \{C0\}\} - [C1]^{-1}[C2]\{F^*\} \quad (3)$$

and this is the relation that is actually used in wind tunnel data reduction to calculate balance loads from component signals.

In various types of wind tunnel balances the placements of component-load sensing elements are governed by the general design concept and also by constraints of manufacture and application. The experimenter is usually interested in reducing component loads $\{F\}$ to three components of force (e.g. R_x, R_y, R_z) and three components of moment (e.g. M_x, M_y, M_z), acting at a defined balance centre and usually aligned with geometric axes of the metric end of the balance.

An important detail in the generalization of the mathematical model of the balance is the establishment of a relation between k arbitrarily defined balance components $\{F\}$ vs. three components of total force R_x, R_y, R_z, and three components of total moment M_x, M_y, M_z.

If positions and orientations of component sensors are expressed as constants in a reference frame that is fixed to the metric end of the balance (balance deformations being acconted for by nonlinear terms in the calibration matrix), this relation can be described by a $k \times 6$ component-load transformation matrix $[S]$:

$$\left\{ \begin{array}{c} \{R\} \\ \{M\} \end{array} \right\} = \left\{ \begin{array}{c} R_x \\ R_y \\ R_z \\ M_x \\ M_y \\ M_z \end{array} \right\} = [S]\,\{F\} \quad (4)$$

The inverse relation can be expressed in the "least squares" sense as

$$\{F\} = \left[[S]^T[S]\right]^{-1}[S]^T \left\{ \begin{array}{c} \{R\} \\ \{M\} \end{array} \right\} \quad (5)$$

because matrix $[S]$ is not, in a general case, a square matrix.

Transformation matrix $[S]$ is a function of the balance geometry, i.e. of the location and orientation of "components" relative to the moments reduction centre of the balance.

While it is possible to calibrate the balance in such a way that application of equations (2) and (3) directly yield relations between $\{e\}$ and $\{R_x, R_y, \cdots M_z\}$, the introduction of the transformation matrix $[S]$ brings important benefits:

i) The designer is free to create $[S]$ so that it describes completely arbitrary "mathematical" positions of balance "components". However, it is convenient that they are defined close to physical locations of load sensing elements. In this way, when balance loads are calculated during a wind tunnel test data reduction, the correspondence between component loads and actual stresses in the flexure elements is simple (as has later been recommended in [3]), making it easy to check for flexure overloads, etc.

ii) A universal wind tunnel data reduction software code (or balance calibration code) can be applied to any balance, by filling the matrix $[S]$ with appropriate data. This is a more flexible approach than the one recommended in [3] which identifies particular cases of algorithms only for some most common balance configurations.

iii) If a need arises for uncommon orientation of the directions of nominal balance axes in some special application, this can easily be defined through $[S]$.

Further generalization is possible when it is realized that "total loads" in eqn. (4) need not be restricted to three components of force and three components of moment, and that the number of component loads need not be restricted to six. Additional measurable factors $\{F_w\}$ that influence balance output signals of one or more components can be considered as "component loads" (i.e. members of $\{F\}$) alongside the "real" components. Influences $\{F_w\}$ can be measured by appropriate transducers (e.g. a pressure transducer, a thermocouple, etc.) which may be located on the balance body or elsewhere in a wind tunnel model. Most common influences of such kind may be e.g:
- ambient temperature (or temperature of balance body or balance body regions);
- pressure in a gas supply passed through the balance to the model;
- rotation rate of a balance mounted on a rotating shaft.

If a balance measures k actual components of loads and there are m measured additional influences, signals $\{e_{w1} \ldots e_{wm}\}$ from m additional transducers can be concatenated with vector $\{e\}$ to form an extended vector of signals $\{e_e\}$, and corresponding load products $F_{w1} \ldots F_{wm} \ldots {F_{w1}}^2 \ldots F_1 F_{w1} \ldots F_k F_{wm}$ included into vector $\{F^{**}\}$ to form extended loads-product vector $\{{F_e}^{**}\}$. The interaction of additional influences with the balance is simply modelled by the same equation (2) as above:

$$\{e_e\} = [C_e]\{{F_e}^{**}\} \tag{6}$$

except that the balance is now considered to have $k+m$ components.

A vector $\{W\}$ of one or several additional "total loads" can also be formed, usually identical to $\{F_w\}$, and equation (4) can be expanded to

$$\left\{ \begin{array}{c} \{R\} \\ \{M\} \\ \{W\} \end{array} \right\} = [S_e]\ \{F\} \tag{7}$$

Additional influences affect the outputs of balance components through changes in zero offsets and changes in sensitivity. The generalization presented above permits modelling of these interactions with linear, second- or third-degree terms (depending on the capabilities of the calibration software). This is considered to be adequate.

The presented concept also permits simple modelling of interactions of actual balance loads onto sensors measuring external influences, e.g. on the prototype balance a foil-type resistive themperature sensor was used that, being essentialy a strain-gauge, was slighly sensitive to strains at the positions where it was cemented onto the balance body. Influence of balance loads on the output from this sensor was determined during the calibration at the same time as influence of temperature onto outputs from component load bridges.

3.2 Calibration with Composite Loads

Since approx. year 1985, the preferred method used in VTI for calibration of multi-component wind tunnel balance has been by loading a balance with "composite loads", i.e. loading more than one component simultaneously, in a proportional manner, by a conveniently directed single force acting at a known point on the metric end of the balance. Sequences of such loadings applied to a number of points having precisely known positions on the calibration body attached to the balance constitute a load set from which a calibration matrix can be obtained.

This method, outlined in [2] and further developed in [6] has lately become known as the "Single Vector Calibration" [4]. Since 1997, a generalized calibration method has been used, applied though BACAL software, that permits more than one composite-load vector to be applied (currently, number of applied vectors has been arbitrarily limited in BACAL software to three, and number of balance components to eight, mostly in order to keep data-entry screen forms manageable).

The composite-loads calibration method is particularily suited to the generalized balance concept presented above. One load vector applied in a calibration run can be the actual load (i.e. force), while the other can be an external influence like e.g. ambent temperature or pressure. Loading cases can be formed where only the first vector (i.e. force) is applied and varied, or only the second one (i.e. temperature is varied), or both vectors are varied simultaneously. Calibration software decomposes all applied loads into corresponding component loads using relation (5), and calculates a calibration matrix by global fitting over complete datasets from a number of load cases, as recommended in [3].

As the number of load cases required to determine a "full" second- or third-order calibration matrix for a balance with additional components defined (e.g. a seven- or eight-component balance) can become very large, it is essential that the calibration software permits a selection of a subset of calibration matrix terms that are to be calculated for any particular balance component. E.g. in the prototype stiff balance with semiconductor strain gauges on the axial force element, load-product terms that include temperatue "loads" were calculated in BACAL only for combinations of temperature vs. axial force variations, temperature influences on foil-type elements for other components being much smaller and satisfactorily compensated in hardware.

3.3 Calibration of the Prototype Balance

Simple design of the balance resulted in poor separation of components. This was not considered as a significant drawback, because it was felt that elaborate balance designs which provide good separation of components are at least partially a legacy from the time when computer power available for processing balance data was by several orders of magnitude less than it is today; it was proposed that a design with poor separation of components can perform in a satisfactory way if a calibration matrix with a sufficient number of higher-order terms can be determined from a loading set that mimicks the loads expected in a wind tunnel test. The composite-loads calibration method, implemented in BACAL was applied to this end.

As a measure of the "goodness" of a wind tunnel balance, VTI uses the criterion for a state-of-the-art balance, established some years ago by AEDC; namely, to have standard deviations of the errors, computed from the back-calculated calibration data, of approximately 0.05 % of full range load for each component under all combinations of loadings. The term "accuracy" is also used, as more intuitive than standard deviation, defined as three times this standard deviation (for each component respectively, and expressed as percentage of nominal full range load for the particular component). Target "accuracy" for the prototype balance was 0.2 %.

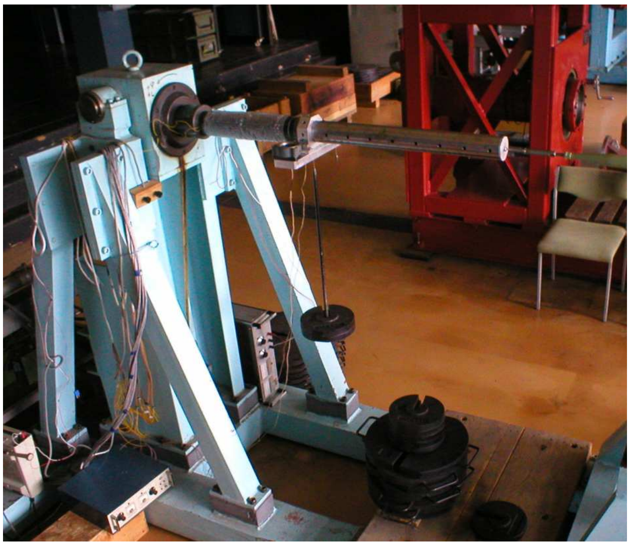

Fig. 4 Balance on the calibration rig

Prototype balance was calibrated (Fig.4) on one of the standard calibration rigs in the balance calibration laboratory of VTI. Balance was kept on the frame with main axis horizontal, and rotated in roll at 45° intervals to obtain diverse combinations of component loads by applyine external loads in the vertical plane only. Balance was automatically leveled using hydraulic actuators on the calibration rig. A cylindrical calibration body was attached to the balance, and a slider bar fixed by a pin to any of a number precisely known locations on the body. Calibration body permitted application of loads only in positions forward of the balance reference point, because the calibration was performed to suit the requirements of a particular wind tunnel test in which such configuration of loads was expected. Forces normal to the main axis were applied by weights hanging on plates attached at precisely known locations on the slider. Forces along the main balance axis were applied by converting, by the use of a rocking triangular frame, vertical loads created by weights into horizontal loads acting along the axis. Temperature of the balance body near

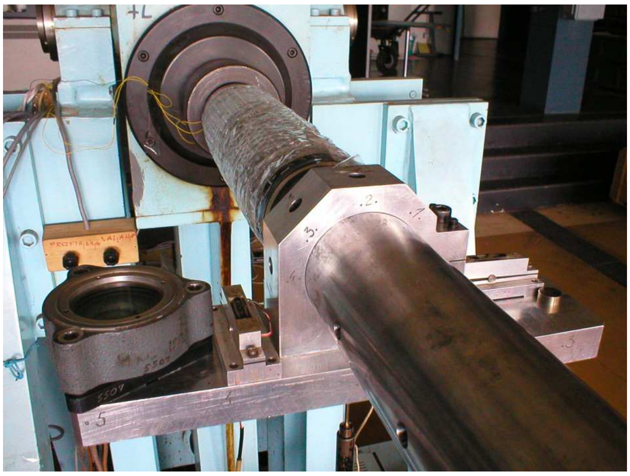

Fig. 5 Heating chamber around the balance

the axial-force strain gauge bridge was treated as an additional load vector and measured by a reference J-type thermocouple cemented to balance body. Temperature was varied either by slowly varying ambient temperature, or by encasing the balance in a thermally insulated heated chamber (Fig.5) over the balance and part of the calibration body.

Calibration dataset consisted of about 200 "load cases" (orientations and/or combinations of load vectors) at different temperatures, with at least five load magnitudes in each load case. Data were taken both when increasing and decreasing loads, so that at least 10 datapoints (each containing about 200 samples per component) were taken for each load case. Calibration matrix with nonlinear terms up to the 3^{rd} order was calculated in BACAL using global regression over the complete calibration data set. Iterative computation of the calibration matrix converged to a correct solution, although more slowly than usual, requiring more than a thousand iterations instead of several hundred iterations commonly needed when computing matrices for six-component balances.

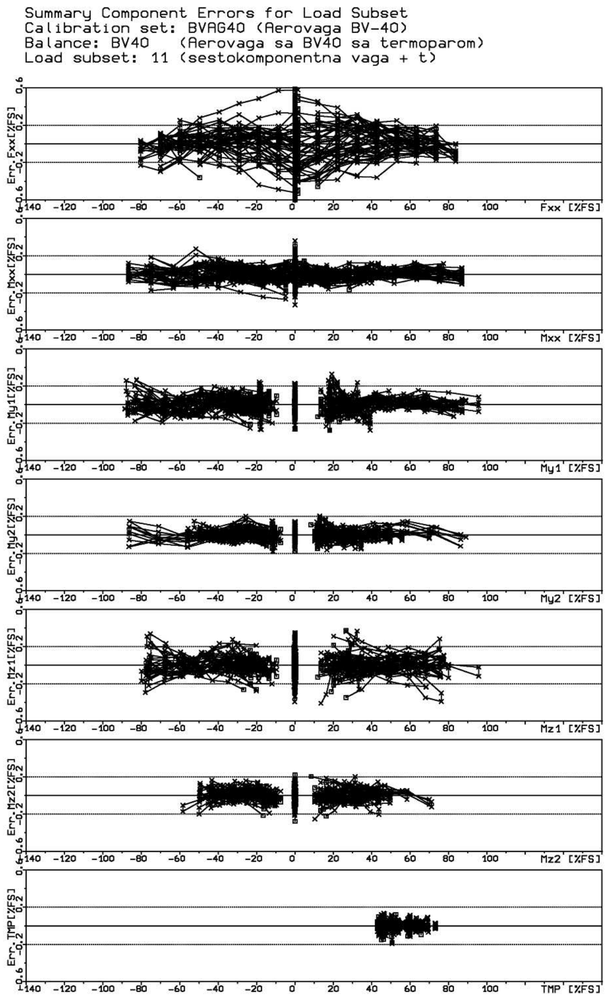

Fig. 6 Plot of error residuals in balance checkout

Error residuals from a checkout using the calculated calibration matrix on the complete set of calibration load cases are displayed for all seven components on a BACAL summary plot shown in Fig.6 (dotted lines parallel to abscissae on each plot mark 0.2% target accuracy). Standard deviations of error residuals for all components except the axial force were in the range 0.03%FS to 0.08% FS, while on the axial force it was about 0.18% FS, maximum error on this component being about 0.58% FS. When the same data were processed without taking into account the seventh balance component (the temperature sensor), i.e. when the balance was treated as a common six-component balance, maximum error on the axial force component was about 2.4% FS. It was noted that significant errors on the axial force component were completely due to hysteresis when large bending moments were applied. In load cases with pure axial loads the accuracy of cca. 0.2% FS was obtained on this component, in spite of very stiff flexure element and relatively low output signal level.

4 Conclusions

Results of the calibration showed that, using the generalized composite-load method, the prototype balance could be calibrated close to the required level of accuracy in the tested range of ambient temperatures. High-impedance foil strain gauges on bending / rolling moments components produced large FS output signals that could easily be handled by the standard wind tunnel data acquisition system. Axial force element with semiconductor strain gauges, although extremely rigid, proved very accurate when measuring axial loads and produced an acceptably large FS output signal of about 11 mV. A significant amount of hysteresis was experienced in several instances on this bridge when large bending moments were applied, degrading its accuracy to about 0.6 % FS. At first this was completely attributed to creep and local thermal effects, but, as the problem was not repeatable and occured only in some of otherwise similar load cases, a large part of the hysteresis was finally tracked to the calibration body and load-pan attachments that were found not to be machined to the desired level of precision. Deflections of the balance under load were less than 50 % of those on the comparable conventional beam balance.

The balance did not meet the design requirements regarding the accuracy of the measurement of the axial force component. However, as the nominal load capacity of 1100 N for this component was, in fact, arbitrarily declared, the actual safe-load capacity being several times larger, and as the large errors observed on this component conicided not with the loading of the component itself, but with the maximum bending moments on the forward instrumented station, the nominal load range for the axial force component was re-declared to 4500 N and it is considered that the balance is completely usable in wind tunnel test configurations requiring measurements of large axial loads, e.g. in some parachute tests, in high-Mach-number tests experiencing large transient loads, or when the device is to be used as a pole balance, supporting an aircraft model on a vertical strut. A recalibration of the balance within the anvelope of the re-declared load range will be performed at the first opportunity.

It was concluded that, with appropriate calibration tools available, a practical balance like the described prototype can be easily produced tailored to certain wind tunnel test requirements, without needing to design and machine the sophisticated flexure cages and other similar elements usually present on beam-type balances.

The concept of the generic multi-component balance and treatment of temperature as an additional balance component was shown to be practical. Implementation allowed modelling of temperature-induced component zero shifts with 3^{rd} degree polynomials, and sensitivity changes with 2^{nd} degree polynomials which appeared to be sufficient. Temperature-induced errors were reduced by the software compensation to about 25 % of those obtained without it. Sensitivity of the foil-type temperature sensor to strains caused by actual loads was automatically accounted for, through interaction terms in the calibration matrix. With several temperature sensors strategically placed on the balance, the algorithm should be capable of handling effects of temperature gradients. An important feature of the generic balance concept is that it can be included into existing wind tunnel data reduction software with minimum modifications (by redimensioning some arrays) and does not require dedicated code for handling particular situations like e.g. influences of temperature or pressure.

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