ICAS 2016
30th Congress of the International Council
of the Aeronautical Sciences
DCC, Daejeon, Korea ; September 25-30, 2016

A GENERALISATION OF THE MATHEMATICAL MODEL OF INTERNAL WIND TUNNEL BALANCES

Djordje Vuković*, Dijana Damljanović*
***Military Technical Institute (VTI), Ratka Resanovića 1, 11030 Beograd, Serbia**

Keywords: *wind tunnel balance, mathematical model*

Abstract

A number of designs of internal wind tunnel balance exists, each design being characterized by specific relations for combining component loads into total loads. Besides, the conventions regarding the axes systems used, the orientation of positive directions of forces and moments, and the choice of the mathematical model of internal wind tunnel balances differ from wind tunnel community to community. A concept of a generic wind tunnel balance is described, asserting that all types of internal wind tunnel balances are essentially equivalent and should be described and processed in the same way. The concept of the generic balance permits unified handling of different balance designs used in a wind tunnel facility, including non-standard balance designs, and facilitates import of balance data from laboratories with different conventions.

1 Introduction

Internal wind tunnel balances are multi-component force sensors that are used to measure aerodynamic loads on wind tunnel test objects and resolve them into axial force X, side force Y, normal force Z, rolling moment L, pitching moment M and yawing moment N, respective to a convenient axes system. Measurement is achieved by acquiring and processing the outputs from strain gauge bridges sensing the deformations of specially shaped parts of the balance subjected to load. The relation between the loads $\{F\}$ sensed by the strain gauge bridges and the increments $\{\Delta e\}$ of output signals $\{e\}$ of the bridges relative to no-load outputs $\{e_0\}$ is usually expressed as:

$$\{\Delta e\} = \{e\} - \{e_0\} = [C1]\{F\} + [C2]\{F^*\} \quad (1)$$

where $[C1]$ and $[C2]$ are the 'linear' and the 'nonlinear' part of the 'balance calibration matrix' $[C] = [C1|C2]$, and $\{F^*\}$ is the vector of 'load functions' containing simple (e.g. polynomial) functions of the members of $\{F\}$, and modelling the slightly nonlinear behaviour of a typical balance. In order to eliminate the dependence of output signals on excitation voltages, balance outputs $\{e\}$ are generally used in normalized form, i.e. the actual signals are divided by the excitation voltage so that $\{\Delta e\}$ is non-dimensional (in mV/V or V/V).

Loads $\{F\}$ are computed from Eq.(1) in a number of converging iterations i as:

$$\begin{aligned} &\{F\}_i = \left([C1]^{-1}\{\Delta e\} - [C1]^{-1}[C2]\{F^*\}_{i-1}\right) \\ &\{F\} = \lim_{i\to\infty}\{F\}_i \end{aligned} \quad (2)$$

Loads $\{F\}$ sensed by the strain gauge bridges may or may not correspond to components X, Y, Z... etc. of total loads, depending on balance design. Total loads $\{P\} = \{X,\ Y,\ Z,\ L,\ M,\ N\}^T$ are, therefore, computed from $\{F\}$ using balance-design-dependent formulae.

Because of the nature of calculation in Eq.(2), this mathematical model of the internal balance is often called 'iterative' [1]. It should be noted that some institutions use an inverse, non-iterative mathematical model of the wind tunnel balance [1] in which the dependent and independent variables are interchanged, i.e. instead of modelling the balance in the form $\{e\} = f(\{F\})$, the inverse form $\{F\} = f(\{e\})$ is used. However, the iterative model described above seems to prevail.

Equation (2) is applicable for computing the local, 'physical component' loads of any type of internal strain gauge balance, but the choice of actual nonlinear functions for the vector $\{F^*\}$ differs from institution to institution and from one balance to another. The relations for combining the physical component loads $\{F\}$ into total loads $\{P\}$ are balance-design dependent and, more-over, depend on the local conventions regarding the positive directions of forces and moments, and the axes systems used when processing wind tunnel measurements. There are many balance designs, each requiring specific formulae for combining the component loads into total loads. Besides, neither the orientations of the axes systems used, nor the conventions for positive directions of the forces and moments acting on a wind tunnel balance nor the order (sequence) of load components are universal [2]-[6]. Such differences can present a significant inconvenience to an experimenter as well as to a programmer coding wind tunnel software in an experimental or calibration facility where diverse balance types are used, especially in situations where a new balance type, heretofore not used at the site, is to be deployed, or some balance calibration data has to be imported that originated from another facility that used different conventions.

The differences between representations of internal wind tunnel balances can be summed as follows:

- The default positive directions of component loads and the orientations of the axes systems differ from institution to institution.
- The formulae for the transformation of physical-components loads to total loads X, Y, Z...etc. differ from one balance type to another.
- The order (sequence) of physical components for a wind tunnel balance of a particular type differs from institution to institution.
- The choice and order (sequence) of 'load functions' used in modelling the balance differ from institution to institution and from one balance design to another.
- Physical sense of the 'load range' of a wind tunnel balance differs from manufacturer to manufacturer and from balance to balance.
- Sensitivities (signal/load ratios) of strain gauge bridges on a wind tunnel balance are influenced by the input impedance of the data acquisition system used, complicating transfers between data acquisition systems.
- Effects of temperature, pressure and similar influential variables are accounted for in various ways.

In order to minimize or eliminate these inconveniences, the concept of a 'generic wind tunnel balance' was developed over time [7]-[10], asserting that all designs of internal wind tunnel balances are, in principle, equal, should be defined in the same way and be processed using a single, generalised, algorithm, without bran-ches for specific balance types, configurations of calibration matrices and axes-systems conventions. Therefore, the processing of data acquired by a wind tunnel balance can be simplified.

The outline of the concept of a generic wind tunnel balance, as implemented at the authors' wind tunnel site is presented here.

2 Differences in representations of balances

2.1 Axes Systems Conventions

Several conventions regarding the orientation of the axes systems and the positive directions of forces and moments are in use in wind tunnel communities over the world. Weight and trust are positive in most of West-European wind tunnel practice (Fig. 1), while lift (or normal force) and drag (or axial force) are positive in the North-American practice (Fig. 2), and, besides, they are not all positive in the same directions as the coordinate axes [2]-[4].

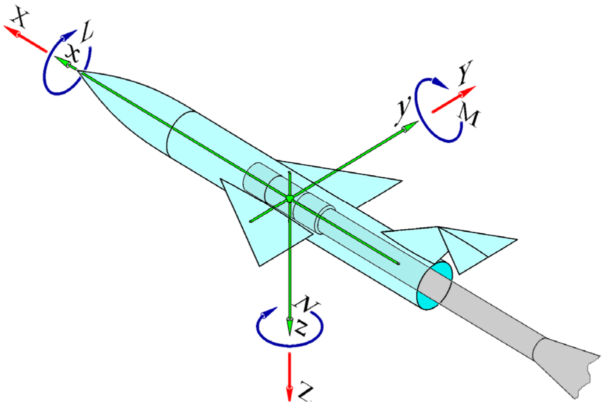

Fig. 1. Directions of axes and load components in West-European wind tunnel practice

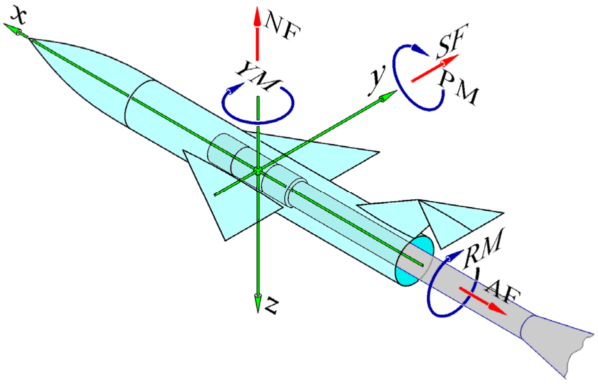

Fig. 2. Directions of axes and load components in American wind tunnel practice

In Russian wind tunnel practice, a right-handed system is used [5][6], with the Y-axis being in the direction of lift, (Fig. 3). It may be noted that the European system is mathematically consistent (right handed), while the American and Russian ones are not. Also, in some wind tunnel laboratories, e.g. [7][8], directions of forces and moments are in accordance with a mathematically consistent left-handed system.

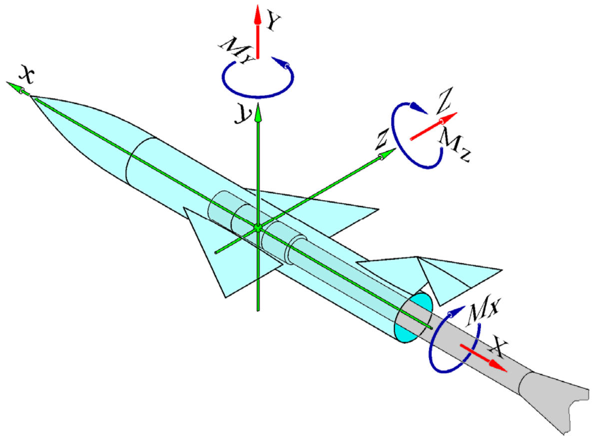

Fig. 3. Directions of axes and load components in Russian wind tunnel practice

2.2 Types of Internal Wind Tunnel Balances

According to their design, internal strain gauge balances are usually classified [1] as the ‘force’, ‘moment’ and ‘direct read’ balances, depending on whether the majority of the strain gauge bridges on the balance measure forces or moments, or a specific combination of them.

The ‘direct read’ six-component internal wind tunnel balances (Fig. 4) have strain gauges positioned and wired so that the six measured loads directly correspond to components of total loads, i.e. the measured load components F_x, F_y, F_z, M_x, M_y, M_z are identical to the axial force X, side force Y, normal force Z, rolling moment L, etc. Therefore, by computing the component loads $\{F\}$ from signals using Eq.(2), total loads $\{P\}$ are immediately available:

$$\{P\} = \{F\} \tag{3}$$

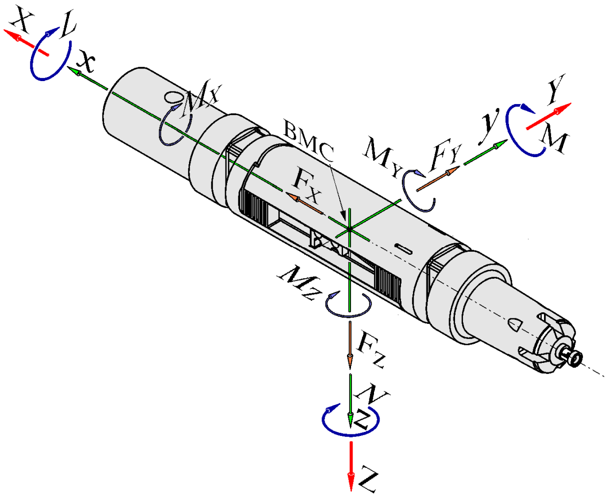

Fig. 4. Physical and total-load components of a typical monolithic direct-read balance

The ‘force’ wind tunnel balance (Fig. 5) has two sensing elements for forces F_{Z1} and F_{Z2} in the normal-force direction, two sensing elements for forces F_{Y1} and F_{Y2} in the side-force direction, one sensing element for the axial force F_X and one sensing elements for the rolling moment M_X.

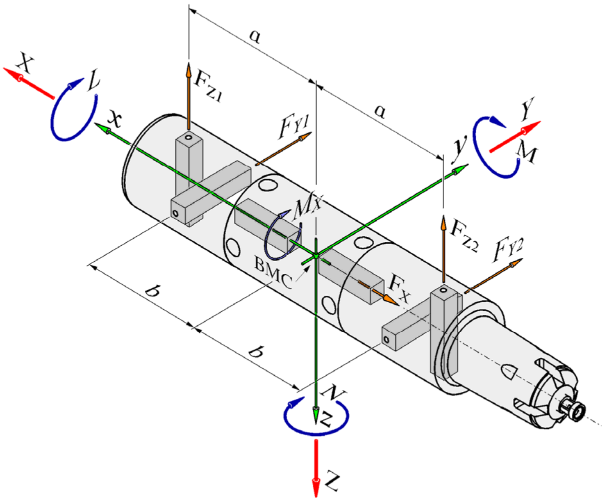

Fig. 5. Physical and total-load components of a typical Able/Task-type assembled force balance

Notable examples of the ‘force’ wind tunnel balances are the devices that were produced by the Able Corporation (formerly Task), and the orientation of their physical components follows the North-American sign conventions [1][3], Fig. 5. Total loads $\{P\}$ (e.g. according to the European practice) are computed as:

$$\begin{aligned} X &= -F_X \\ Y &= F_{Y1} + F_{Y2} \\ Z &= -F_{Z1} - F_{Z2} \\ L &= M_X \\ M &= a \cdot F_{Z1} - a \cdot F_{Z2} \\ N &= b \cdot F_{Y1} - b \cdot F_{Y2} \end{aligned} \tag{4}$$

Force balances, such as the ‘Task balance’ are often assembled from a number of individually machined parts, but can also be monolithic.

The ‘moment’ type of the internal balance (Fig. 6) in similar in some ways to the ‘force’ type. A six-component moment balance has two measuring elements sensing pitching moments M_{Y1} and M_{Y2}, two measuring elements sensing yawing moments M_{Z1} and M_{Z2}, one measuring element for the axial force F_X and one for the rolling moment M_X. As these balances are often of monolithic design, the measuring elements are actually instrumented sections of the balance body. Total loads $\{P\}$ are computed as:

$$\begin{aligned} X &= F_X \\ Y &= -M_{Z1}/(2b) + M_{Z2}/(2b) \\ Z &= M_{Y1}/(2a) - M_{Y2}/(2a) \\ L &= M_X \\ M &= M_{Y1}/2 + M_{Y2}/2 \\ N &= M_{Z1}/2 + M_{Z2}/2 \end{aligned} \tag{5}$$

It should be noted that the design solutions of internal wind tunnel balances are not exhausted with the three main types, e.g. ‘box’ type balances, similar to the concept shown in Fig. 7, are popular in some laboratories [11][12]. Such balances sometimes have more than six physical components. Also, a large diversity of designs, mostly dictated by the space constraints, exists of the balances for measurement of aero-dynamic loads on canards, fins, elevators, ailerons and other parts of wind tunnel models. For any of those balances, total loads are computed from measured component loads using design-specific relations.

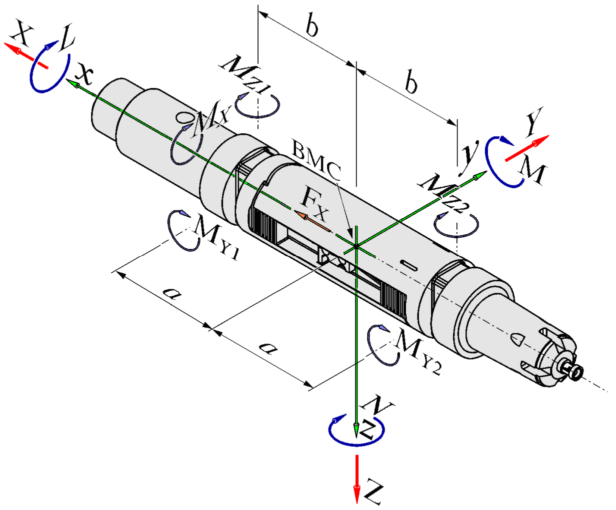

Fig. 6. Physical and total-load components of a typical monolithic moment balance

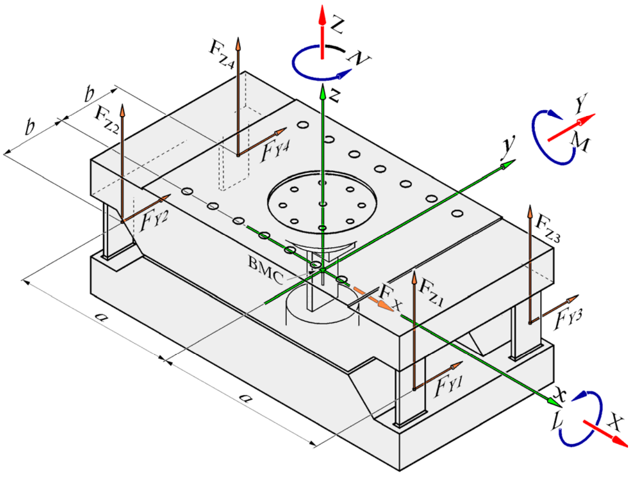

Fig. 7. **D**isposition of physical and total-load components on a nine-component box balance

2.3 Formats of the calibration matrix

Formula for computing the output a single component of a typical six-component balance can be expanded from Eq.(1) (assuming, for example, a mathematical model with second-order polynomials) as:

$$e_i = e_{0i} + \sum_{j=1}^{n} C1_{i,j} F_j + \sum_{j=1}^{n} C2_{i,j} F_j^2 + \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} C2_{i,n+\ldots} F_j F_k \tag{6}$$

In some institutions, the same model is expressed in a slightly different manner, resulting in a rearrangement of columns in the calibration matrix:

$$e_i = e_{0i} + \sum_{j=1}^{n} C1_{i,j} F_j + \sum_{j=1}^{n} \sum_{k=j}^{n} C2_{i,n+\dots} F_j F_k \quad (7)$$

Depending on the practice at a wind tunnel site and the mechanical characteristics of a particular balance, the mathematical model of the balance may be restricted to linear terms only, or else expanded with third order terms of the form F_j^3. There are also indications [13] that including the third-order terms of the forms $F_j^2F_k$ or $F_jF_kF_l$ in the model may sometimes be advantageous. For assembled balances which often exhibit an amount of bi-directionality, inclusion of modelling terms pertaining to absolute values of loads is indicated [14]. Therefore, it is obvious that there are significant variations in the content of the calibration matrices. In an attempt to achieve universality and facilitate exchange of strain-gauge-balance data, the *AIAA Recommended Practice* [1] advocates a mathematical model of a six-component balance with 96 terms per component including all the terms pertaining to F_j, $|F_j|$, F_j^2 $|F_j|F_j$, F_jF_k, $|F_j|F_k$, $F_j|F_k|$, $|F_jF_k|$, F_j^3 and $|F_j^3|$. Data for components and load products that are not modelled are to be entered as zeros. This approach, however, ignores the fact that there are balances with more than six components [9][11][12][15], and leaves no room for the mixed third-order interactions e.g. $F_j^2F_k$ or $F_jF_kF_l$.

2.4 Definition of full-scale loads

Each wind tunnel balance is designed having in mind certain maximum permissible loads, or its 'full-scale loads', beyond which the accuracy of the measurements and the structural safety of the balance would be compromised. During a wind tunnel test or during the calibration of a wind tunnel balance, measured loads must be monitored and checked against the permissible loads. The meaning of the 'full-scale loads' may differ, however, from manufacturer to manufacturer and from one balance design to another. Two concepts are in general use: defining the load envelope of the balance in terms of maximum values of simultaneously acting component loads or 'combined loads' (often presented graphically as the 'load trapeze'), and defining the load envelope in terms of maximum values of single loads (presented graphically as the 'load rhombus', Fig. 8) [2]. Neither of these approaches may be always adequate to represent the load limits of critical points on a wind tunnel balance. Besides, the full scale loads can be expressed either as maximums of total loads $\{P\}$ or as maximums of the physical-component loads $\{F\}$. These variations in the representations of full-scale loads in balance manufacturer's data are an inconvenience when it is necessary to monitor measured loads for overload. The issue is further complicated by the fact that the inventories of balance repositories do not always state whether the listed balance data represent combined or single- load limits.

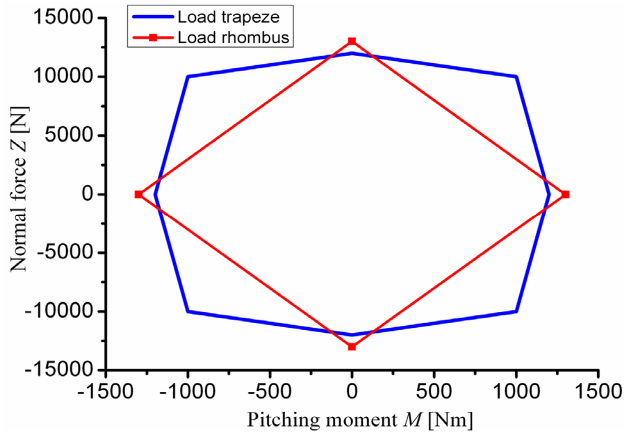

Fig. 8. Load envelopes of two wind tunnel balances defined by similar values of maximum combined loads (load trapeze) and maximum single loads (load rhombus). Actual load capacities of the two balances are quite different

2.5 Influence of the data acquisition system

Because strain-gauge bridges are devices with relatively high output impedances, sensitivities (signal/load ratios) of balance components are influenced by the input impedance of the data acquisition system used, sometimes complicating transfers between the calibration and wind-tunnel data acquisition systems. This effect is especially pronounced if a balance having high-impedance (e.g. 1 kΩ or 5 kΩ) strain gauge bridges (used in some high-stiffness internal balances), and calibrated on a high-input-impedance data acquisition system is connected to a low-input-impedance data acquisition system. Some older data acquisition systems may have input impedances as low as 10 MΩ and if a 5 kΩ strain gauge bridge is connected to such system, the drop of sensitivity is about 0.05% FS, which is of the same order of magnitude as the accuracy of a typical internal balance, and is usually unacceptable.

3 The ‘generic wind tunnel balance’ concept

The concept of a generic internal wind tunnel balance, developed over time at authors’ wind tunnel site, incorporates several ideas, some of them already known and used in diverse institutions. The concerted use of the incorporated concepts, however, permits an abstraction of wind tunnel balances when they are to be handled by the data processing software. The main components of the generic wind tunnel balance concept are:

- The use of load transformation matrices for computation of total loads from physical-component loads, eliminating the dependency on balance types, as wall as on axes-system and component-directions conventions.
- Generalization of the concept of ‘component loads’, permitting the use of additional influencing variables, such as e.g. temperature, pressure, rotation rate, etc. in the balance calibration matrix.
- Normalization of the calibration matrix by primary sensitivities, of the physical components, facilitating data transfers from one data acquisition system to another.
- Handling of the balance calibration matrix in a self-descriptive format that offers greater flexibility and eliminates dependence on facility conventions.
- Generalization of the definition of overload constraints in a way that permits the load-rhombus and the load trapeze conventions for full scale loads, as well as additional constraints, facilitating detection of balance overloads during data processing.

3.1 Use of the calibration matrix

Relations Eq.(3)-(5) lend themselves well to matrix representation, as shown in Eq.(8) for the ‘direct-read’ balance and Eq.(9) for the ‘force’ balance. Similar matrix representations of the relations between the physical-component loads and total loads can be easily formed for the ‘moment’ balance as well as for any other balance type with arbitrary number of physical components.

$$\begin{Bmatrix} X \\ Y \\ Z \\ L \\ M \\ N \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{Bmatrix} F_X \\ F_Y \\ F_Z \\ M_X \\ M_Y \\ M_Z \end{Bmatrix} \tag{8}$$

$$\begin{Bmatrix} X \\ Y \\ Z \\ L \\ M \\ N \end{Bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ -1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ a & -a & 0 & 0 & 0 & 0 \\ 0 & 0 & b & -b & 0 & 0 \end{bmatrix} \cdot \begin{Bmatrix} F_{Z1} \\ F_{Z2} \\ F_{Y1} \\ F_{Y1} \\ M_X \\ F_X \end{Bmatrix} \tag{9}$$

In a general case, instead of using balance-design-specific formulae like in Eq.(3)-(5), the relation between the physical-components loads of any balance type is expressed as:

$$\{P\} = [S]\{F\} \tag{10}$$

where $[S]$ is the user-defined load-transformation matrix [10] describing the geometry and type of the balance. The inverse computation of component loads from total loads is made using the Moore-Penrose pseudoinverse $[S]^+$ of the transformation matrix. Either the right pseudo-inverse (12) or the left pseudoinverse (11) is used, depending on whether the number of elements of $\{F\}$ is greater than the number of elements in $\{P\}$ or not. In most cases, the use of the left pseudoinverse is appropriate.

$$[S]^{+} = [S]^{T} \cdot \left[[S] \cdot [S]^{T} \right]^{-1} \qquad (11)$$

$$[S]^{+} = \left[[S]^{T} \cdot [S] \right]^{-1} \cdot [S]^{T} \qquad (12)$$

There is a number of benefits from using a load transformation matrix instead of balance-design-particular relations, the most important being:

- An identical wind tunnel data-reduction algorithm (or a balance-calibration algorithm) and computer code can be used for any design of internal multi-component or single-component balance, making the 'type' of the balance, as defined in [1], practically irrelevant.
- As recommended [1][16], any wind tunnel balance, including unorthodox designs, can be calibrated in its 'native' load format, without constraints related to limitations in data processing
- Transfer of balance calibration data or the balances themselves between wind tunnel communities using different axis and sign conventions is facilitated. The calibration matrix and the sequence of physical components can be kept in the source format and only the transformation matrix is to be rearranged to suit the local conventions
- A balance can be deployed conforming to local conventions while retaining the manufacturer-defined sequence and positive directions of components, so that original documentation, manufacturer's colour-coding of cabling, illustrations, etc. can remain relevant.

3.2 Generalization of the concept of load

Traditionally, the calibration matrix of a wind tunnel balance described only the relation between the electrical outputs of the balance and the forces and moments acting on it. For some time, however, the practice of including in the calibration matrix the coefficients pertaining to additional variables that may influence bridge outputs, such as temperature or pressure, has been becoming more and more common [9][15][17].

Therefore, the vectors of total loads $\{P\}$ has to be expanded, containing not only the three forces and three moments X, Y, Z, L, M, N but also an arbitrary number of additional variables, e.g. U, V… etc. The inclusion of additional variables is facilitated by the use of the load transformation matrix [10] which allows easy separation of the additional variables from the actual forces and moments.

3.3 Normalization of the calibration matrix

Coefficients in the calibration matrix $[C]$ of a wind tunnel balance are not non-dimensional, and have the units of 'output per unit of load', 'output per unit of load squared' etc. Therefore the complete calibration matrix is applicable only when the balance is used with a data acquisition system having identical conversion factors as the one used in calibration. This may not be the case when the wind tunnel data acquisition system has input impedance different from the calibration system.

Rather than having to re-specify the complete calibration matrix to account for the changes in sensitivity because of the characteristics of the data acquisition systems, a 'normalized' form of the calibration matrix is used [16], in which the coefficients in $[C]$ are expressed as ratios of the 'primary sensitivities' of physical components. The primary sensitivities are the diagonal elements in the linear part $[C1]$ of the calibration matrix and the normalization is achieved by division of the coefficients for each component by the primary sensitivity of that component. This corresponds to the pre-multiplication of the calibration matrix $[C]$ by a diagonal matrix $[D]$ composed of the reciprocals of the primary sensitivities. The resulting matrix $[X]$ of relative interactions is obtained as:

$$[X] = [X1 \mid X2] = [D][C1 \mid C2] \qquad (13)$$

where only the elements of $[D]$ are dependent on the data acquisition system and $[X]$ have universal application. Adjustment of a calibration matrix to the input impedance of a particular data acquisition system consists of multiplying only the members of $[D]$ with the ratios $1+R/R_i$ where R is the bridge impedance and R_i is the input impedance of the data acquisition system. As the number of elements in [D] is equal to just the number of balance components, while the number of elements in [C] can amount to several hundreds. The effort and the possibility of errors are reduced. The equations Eq.(1) and Eq.(2) then become:

$$\{\Delta e\} = [D]^{-1}[C1]\{F\} + [D]^{-1}[C2]\{F^*\} \tag{14}$$

$$\begin{aligned} \{F\}_i &= \left([X1]^{-1}[D]\{\Delta e\} - [X1]^{-1}[X2]\{F^*\}_{i-1}\right) \\ \{F\} &= \lim_{i\to\infty}\{F\}_i \end{aligned} \tag{15}$$

3.4 Self-descriptive calibration matrix format

In an attempt to generalize the format of the calibration matrix, a course different from that advocated in [1] was taken. Instead of trying to define an encompassing format that would include all possible forms of load functions and the maximum possible number of balance components, a self-descriptive 'compacted' format of the calibration matrix was created containing only the data for the components and load functions that are actually used.

A 'generic' form of the load-functions vector {F^{**}} was defined, concatenated from vectors of loads {F} and load products {F^*}. An auxiliary matrix [Q] that accompanies the calibration matrix [C] (actually, the matrices [D] and [X], because the normalized format is used) is created, manually or automatically, when the calibration matrix is defined, having three rows and the number of columns identical to the number of columns in the calibration matrix.

Each column in [Q] contains the indices (1 to n) of balance components contributing in the load functions for the corresponding column of the calibration matrix. Indices –1 to –n can be used for absolute values of component loads. An intermediate vector {f} is formed during the computation, containing the values of component loads and absolute values of components loads, and also a term equal to unity. Instead of handling the diverse sequences of elements in {F} and {F^*} (like in Eq.(6)(7)) by different branches of software code, universally defined elements of {F^{**}} have a generalized form:

$$F_j^{**} = \prod_{k=1}^{3} f_{Q_{k,j}} \tag{16}$$

Therefore, the auxiliary matrix of component indices [Q] effectively describes the meaning of columns in the calibration matrix and any form of the mathematical representation of the balance that includes the polynomial terms up to the third order can be modelled.

Admittedly, the 'generic' model of the load-functions vector defining the form of the calibration matrix appears more complex than the 96-coefficients-per-component 'all-encompassing' model advocated in [1]. However, after repeatedly encountering the requirement to add new branches in the data-reduction software code at the authors' wind tunnel site in order to accommodate previously unused types of terms in the calibration matrix, or to extend the number of balance components beyond the traditional six, it was found that the new form of the mathematical model was more flexible and is expected to satisfy all requirements for a considerable time in the future.

3.5 Generalization of overload constraints

Load range of a balance, which is important in checking for overloads, is defined for each physical component. This is not sufficient, however, if critical overload of a balance can occur at locations other than at instrumented flexures. Therefore, a system of constraints similar to the one presented in [18] is used. A load-constraints matrix [L] is defined, that can define an arbitrary number of overload constraints. Elements in [L] are defined so that the matrix product:

$$\{O\} = [L]\{P\} \tag{17}$$

indicates overload if the absolute value of any member of {O} is greater than unity. Therefore, each row in [L] defines one constraint that is a linear combination of the contributions of components of total loads {P}. In this way either the 'maximum combined loads' or the 'maximum single loads', or a combination thereof, can be defined, as appropriate for a particular balance.

4 Conclusions

It was observed that different types of wind tunnel balances are treated as distinct cases in data processing and that significant variations exist between conventions related to wind tunnel balances from different manufacturers or in different wind tunnel laboratories. At the authors' wind tunnel site, wind tunnel balancers of different makes are in use, including some very specific designs of panel-force balances. In an effort to facilitate the manipulation by software of balance data from different sources and/or pertaining to various balance designs, the concept of a 'generic wind tunnel balance' was gradually developed over time, asserting that all designs and types of internal wind tunnel balances are equal, should be defined in the same way and be processed using an identical algorithm. The concept incorporates the use of component-loads transformation matrices, self-descriptive form of the calibration matrix, expansion of the calibration matrix to include additional influential variables, normalization of the calibration matrix and generalization of the full-scale-load constraints and creates an abstraction of the balance that can be processed without regard to peculiarities of various balance designs. As experience has shown, it has significantly facilitated the use of internal balances of various types at the site and simplified the maintenance and further development of the balance-calibration and data-reduction software.

References

[1] AIAA/GTCC Internal Balance Technology Working Group. *Recommended practice - Calibration and use of internal strain-gage balances with application to wind tunnel testing*, AIAA-R-091-2003, American Institute of Aeronautics and Astronautics, Reston, US, 2003.

[2] Hufnagel K and Schewe G. *Force and Moment Measurement* in: Tropea, C., Yarin, A.L., and Foss, J.F., (Ed.): *Springer handbook of experimental fluid mechanics*, Springer-Verlag, Berlin – Heidelberg, Chap.8, pp. 563-616, 2007.

[3] AIAA/GTCC Internal Balance Technology Working Group: *Guide, nomenclature and axis systems for aerodynamic wind tunnel testing*, AIAA-G-129-2012, American Institute of Aeronautics and Astronautics, Reston, US, 2012.

[4] Wright J. *A compilation of aerodynamic nomenclature and axes systems*, NOLR 1241, US Naval Ordnance Laboratory, White Oak, Silver Spring, US, 1962.

[5] Chugunov G.P, Gorbushin A.R, Kuleshov A.Ye, Petronevich V.V, Sudakova I.A, Tikhomirov V.I, Volobuyev V.S. Two methods for calibration of strain gauge balances using the TsAGI 6GS-20 balance calibration machine, *8th International Symposium on Strain Gauge Balances*, Lucerne, Switzerland, 2012.

[6] Krasnov N.F. *Aerodynamics*, Mir Publishers, Moscow, 2012.

[7] Vuković Dj. Generalization of data reduction routines for model attitude, force and moment measurements in the wind tunnels of the aeronautical institute Žarkovo, *ICAS Proceedings 1996: 20th Congress of the International Council of the Aeronautical Sciences*, Sorrento, Italy, pp. 825-833, 1996.

[8] Philipsen I. and Zhai J. Comparative study of strain-gauge balance calibration procedures using the balance calibration machine**,** AIAA-2007-143, *Proceedings of the 45th AIAA Aerospace Sciences Meeting*, Reno, US, 2007.

[9] Vuković Dj, Samardžić M. and Vitić, A. prototype of a stiff wind tunnel balance with semiconductor strain gauges and thermo-compensation done by software, *26th Congress of the International Council of the Aeronautical Sciences*, Anchorage, US, Paper ICAS2008-P2.9, 2008.

[10] Vuković Đ. and Damljanović D. On the use of load-transformation matrices when working with internal wind tunnel balances, *FME Transactions*, No. 43, pp 21-29, 2015.

[11] *Strain gauge balances for high loads***,** Brochure 04.10/1500, RUAG Aviation, Emmen, Switzerland, 2010.

[12] Zimmermann C, Häberli W. and Monkewitz M. Mono-bloc balance for high loads, *Proceedings of the 5th International Symposium on Strain Gauge Balances*, Modane, France, 2006.

[13] Rhew R. and Parker P.A. Wind tunnel balance calibration: are 1,000,000 data points enough, *10th International Symposium on Strain Gauge Balances,* Mianyang, China, 2016.

[14] Johnson T.H, Parker P.A and Landman D. Calibration designs for non-monolithic wind tunnel force balances. *7th International Symposium on Strain-Gauge Balances*. NASA Langley, 2010.

[15] Lynn K.C, Commo S.A, Johnson T.H and Parker P.A. Thermal and pressure characterization of a wind tunnel force balance using the single vector system. *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Aerospace Sciences Meetings*, Orlando, Florida, US, AIAA-2011-950, 2011.

[16] Galway R.D. *A Comparison of methods for calibration and use of multi-Component strain-gauge*

Wind tunnel balances. National Aeronautical Establishment, Ottawa, Aeronautical Report LR-600, 1980.

[17] Boot D. and Ulbrich N. Calibration and data analysis of the MC-130 air balance, *8th International Symposium on Strain Gauge Balances,* Lucerne, Switzerland, 2016.

[18] Alons H.J. and Wright M.C.N. *Two cryogenic NLR balances for the ETW twin sting rig*, National Aerospace laboratory NLR, NLR-TP-2004-149, 2004.

5 Contact Author Email Address

mailto:vdjole@sbb.rs

Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.