

Recommended Practice

Calibration and Use of Internal Strain-Gage Balances with Application to Wind Tunnel Testing

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Calibration and Use of Internal Strain- Gage Balances with Application to Wind Tunnel Testing

Sponsored by

American Institute of Aeronautics and Astronautics

Abstract

This document provides a recommended method for calibration of internal strain-gage balances used in wind tunnel testing. The practices include terminology, axis system definition, balance calibration methods, matrix, and documentation. Use of this document will facilitate the exchange of information among users, suppliers, and other interested parties.

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Contents

Foreword	v
Dedication.....	vii
1 Introduction.....	1
1.1 Scope.....	1
1.2 Purpose	1
1.3 Cautions and Limitations.....	1
2 Concepts	2
2.1 Forces and Moments	2
2.2 Balance Axis System and Moment Reference Center	3
2.3 Balance Types.....	4
2.4 Designated Balance Load Capacity	6
3 Calibration	7
3.1 Calibration Process	7
3.2 Matrix Determination	16
3.3 Load Calculation Method	18
3.4 Transfer of the Calibration Result to the Test Environment	21
3.5 Emerging Technologies	22
3.6 Three-Component Balance Example	25
4 Calibration Documentation	40
4.1 Matrix File	40
4.2 Calibration Report	45
4.3 Calibration Load Envelope.....	48
4.4 Residual Load Error	51
4.5 Calibration Statistics.....	52
4.6 Facility Uncertainty.....	56
4.7 Sample Calibration Report.....	57
5 Concluding Remarks.....	61
Annex A: Glossary	62
Annex B: References	64

Tables

Table 1 — Component Load and Bridge Output Order and Terminology	4
Table 2 — Bridge Output for Force, Moment, and Direct-Read Balances.....	6
Table 3 — Measured Bridge Outputs for the Determination of the Zero Load Outputs	26

Table 4 — Calibration Loads and Bridge Outputs	26
Table 6 — Linear Matrix.....	29
Table 7 — Modified Bridge Outputs for Tare Load Calculation.....	30
Table 8 — Iteration 1 Tare Loads and Changes.....	30
Table 9 — Calibration Loads Adjusted for Iteration 1 Tare Loads	31
Table 10 — Iteration 1 Interim Matrix	32
Table 11 — Iteration 2 Tare Loads and Changes.....	33
Table 12 — Calibration Loads Adjusted for Iteration 2 Tare Loads	33
Table 13 — Iteration 2 Interim Matrix	35
Table 14 — Iteration 3 Tare Loads and Changes.....	35
Table 15 — Calibration Loads adjusted for Iteration 3 Tare Loads.....	36
Table 16 — Iteration 3 Interim Matrix	37
Table 17 — Iteration 4 Tare Loads and Changes.....	38
Table 18 — Calibration Loads Adjusted for the Final Tare Loads	38
Table 19 — Final Calibration Matrix	40
Table 20 — Contents of the Calibration Matrix File	41
Table 21 — Sample Calibration Matrix File.....	42
Table 22 — General Information for a Calibration Report.....	45
Table 23 — Balance Details for a Calibration Report.....	46
Table 24 — Calibration Details for a Calibration Report.....	47
Table 25 — Data Reduction Description for a Calibration Report.....	48
Table 26 — Back-calculated Data and Residuals	51
Table 27 — Calibration Statistical Data.....	53

Figures

Figure 1 — Balance Axis System, Forces, and Moments	3
Figure 2 — Matrix Determination Process	17
Figure 3 — Sample Load Calculation.....	20
Figure 4 — Applied Loading as Function of Database Point Number	50
Figure 5 — Normalized Calibration Loading in Two-component Load Envelope Format.....	50
Figure 6 — Load Envelope Sample for a Three Component Force Balance	50
Figure 7 — Residual Load Error and Applied Loading as Function of Load Point Number.....	54
Figure 8 — Normalized Residual Load Error and Normalized Applied Loading as Function of Load Point Number	55
Figure 9 — Histogram of Normalized Residual Load Error with Theoretical Normal Distribution Superimposed.....	56

Foreword

Internal balances are the mainstay instrument used in nearly every wind tunnel test to measure the aerodynamic loads on the test article. For the most part, each facility designs, fabricates, calibrates, and utilizes internal balances in near seclusion. However, with decreasing budgets and customers using multiple facilities, the time had arrived for collaboration on the design, use, calibration, and uncertainty estimation for internal strain-gage balances to begin. The concept of forming a working group for internal balances originated from discussions among individuals from the Arnold Engineering Development Center, the National Aeronautics and Space Administration facility at Langley Research Center, and the Boeing Commercial Airplane Group. The discussions also revealed that there was considerable skepticism concerning the willingness to share information and the ability to reach consensus among the individuals working in the area of internal balances. However, despite the skepticism, it was decided that the working group concept should go forward with the purpose of sharing information and developing recommended practices.

The Ground Testing Technical Committee (GTTC) of the American Institute of Aeronautics and Astronautics (AIAA) was asked to sponsor a working group on internal balance technology. Upon approval, the Internal Balance Technology Working Group (IBTWG) was formed under the auspices of the GTTC. The objective of the IBTWG was to share information on, and experiences with, all facets of internal balances and to develop recommended practices that would allow the facilities to work together to advance the state of the art. The working group's membership consisted primarily of individuals from organizations that calibrate and use internal balances.

One of the early issues that had to be addressed was the working group's membership. Invitations to the first meeting were made to individuals from facilities in the U.S. and Canada. However, during the time of the first meeting, several European organizations expressed an interest in participating in the working group. After considerable debate, the initial invited members agreed that achieving consensus was going to be a difficult enough task among the current members and that expanding the membership might impede the group's progress, possibly to the point of being ineffective. The initial members agreed that the current group be limited to North American participation, but would support the development of a European working group if requested. Then, once recommended practices had been developed in both groups, representatives of each group could meet to develop a mutual set of recommended practices. As of the publication date of this document, a temporary UK working group was formed; however, a European working group had yet to be formed.

The following objectives were set as goals for the working group:

1. Provide a forum for the members to share information on the methodologies and capabilities for internal strain-gage balances. (accomplished and has been very successful)
2. Recommend a calibration matrix format that can be utilized in all of the testing facilities. (accomplished)
3. Develop general guidelines for selecting a balance type and the extent of calibration necessary to meet the objectives of a particular wind tunnel test. (some discussion but not accomplished)
4. Develop a recommended balance calibration uncertainty methodology that is in agreement with existing uncertainty standards (AGARD AR-304 and AIAA S-071A-1999). (partially addressed)
5. Develop methods of accounting for weight tare adjustments (both calibration and testing) that are accepted by the members. (accomplished for calibration only)
6. Investigate new methodologies for the design, attachment, and calibration of internal balances. (not addressed)
7. Develop and publish a Recommended Practices document for internal strain-gage balance methodologies, including an adjustment methodology for thermal effects on balances.

(accomplished with the publication of this document, excluding thermal effects. Although thermal effects have a large affect on a balance, they are not included here since the existing methodologies were so diverse and there did not appear to be a time effective solution to the issue.)

Note that the objectives do not include the implementation of any recommended practices, only the development. This is a result of most of the membership not being in positions in their organizations where they can decide such issues. However, all members agreed that they would promote the implementations of the recommended practices at their facilities.

The working group made excellent progress in three areas: the exchange of information, which includes developing open communications and trust among the members; documentation of the balance technology in use at the member organizations; and the establishment of recommended practices. These efforts will benefit the wind tunnel testing community as a whole, as the recommended practices will improve understanding and communication between facilities and provide the potential to mitigate test costs, and improve the quality of test data.

The following officers and members have provided dedicated support, contributions, and leadership to the AIAA/GTTC Internal Balance Technology Working Group. Their efforts have resulted in the development of this Recommended Practice.

David Cahill	Chair, Sverdrup Technology Inc, AEDC Group
Nancy Swinford	Secretary, Lockheed Martin Space Systems Co.
Allen Arrington	Secretary, QSS Group Inc., NASA Glenn Research Center
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The AIAA Ground Testing Technical Committee (Mr. Dan Marren, Chairperson) approved the document for publication in January 2001.

The AIAA Standards Executive Council (Phil Cheney, Chairman) accepted the document for publication in September 2003.

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Dedication

The Internal Balance Technology Working Group has dedicated this Recommended Practice in the memory of Mr. Frank L. Wright, formerly of The Boeing Company. Frank was instrumental in the formation of this working group and the sharing of his wind tunnel testing experience, knowledge, and insight through his participation were instrumental in its success.

1 Introduction

1.1 Scope

This document provides a recommended method for calibration of internal strain-gage balances used in wind tunnel testing. The practices include terminology, axis system definition, balance calibration methods, matrix, and documentation. Use of this document will facilitate the exchange of information among users, suppliers, and other interested parties.

1.2 Purpose

Internal strain-gage balances are used extensively to measure the aerodynamic loads on a test article during a wind tunnel test. There has been little collaboration on internal balances; consequently, several types of balances, calibration methods, calibration matrices, tare adjustments, and uncertainty evaluations have evolved. The purpose of the group was to pool their information and experiences to enhance each other's capabilities and to develop recommended practices for the use, calibration, tare adjustment, and uncertainty evaluation of internal balances.

The acceptance and universality of a recommended practice is dependent on how well the organizations involved represent the industry. In this instance the Internal Balance Technology Working Group had membership and participation from all of the major wind tunnel facilities and aircraft developers in North America. The fact that these organizations were able to agree on the recommended practices contained in this document will provide the weight necessary to instill their adoption, not only in North America but many of the recommended practices will be adopted by organizations around the world. The members of the working group represented the following organizations:

Arnold Engineering Development Center (AEDC)	Allied Aerospace (formerly Micro Craft)
The Boeing Company	NASA Ames Research Center (ARC)
Veridian Engineering (formerly Calspan)	NASA Glenn Research Center (GRC)
Institute for Aerospace Research, Canada (IAR)	NASA Langley Research Center (LaRC)
Lockheed Martin	Northrop Grumman

This document presents the reader with a clear means of designating balance types and gage nomenclature, a concise methodology (including tare corrections) for balance calibration, the reporting of the balance calibration matrix, and for the reporting of statistical and calibration specific information. An example of the balance calibration data reduction process is available for downloading on the GTTC website. The GTTC website can be accessed via the *Technical Committees* link on the AIAA website at www.aiaa.org. This document also presents guidelines for the user in preparing a calibration load schedule and for selecting coefficients to include in the math model as well as presenting the benefits of using global regression for the computation of balance calibration coefficients. Finally, a data reduction method is presented for calculating the component loads from the bridge readings measured during a wind tunnel test.

1.3 Cautions and Limitations

The following cautions and limitations are provided as an aid in understanding and applying the recommended practices:

1. Although the working group recommends a 6x96 calibration matrix format, it is recognized that all of the terms may not be present for any single calibration. The matrix format does incorporate all the terms that are in use by the members of the working group. As noted in the text, terms should only be included in the matrix which directly correspond to loadings applied during the calibration.

2. The discussions, equations, and examples contained in this document are applicable to balances measuring from one to six component loads. Note that the primary sensitivities of any non-existent component loads (main diagonal of the first six columns) should have a value of 1 for computational purposes, and the off-diagonal terms should be 0.
3. The balance types described represent the main types in use, but it is not intended to imply that all balances may be categorized by these types.
4. The methods described here were agreed upon by all of the members of the working group to establish a common practice, but they should not be interpreted as being the only correct methods.
5. Balances exhibit non-linear behavior and therefore calibration weight tare effects cannot be ignored in the computation of a non-linear calibration matrix.
6. The reader should recognize that the normal force and the axial force directions do not coincide with the positive direction of the balance axis system as shown in Figure 1. This does not impose any difficulties in generating the calibration matrix or in using the calibration to calculate balance forces and moments. However, the fact that the normal and axial forces are rotated with respect to the balance axis system must be accounted for when rotating the forces into other axis systems.
7. The reader should note that thermal effects are very important in the calibration and use of balances even though they are not included in this document. It is widely known that changes in both the balance temperature and in the temperature gradient within the balance can have a pronounced effect on the output of the balance.

This list of cautions and limitations is not intended to be all inclusive. Additional cautions and limitation are contained throughout the remainder of this document.

2 Concepts

In the wind tunnel, measurements of the aerodynamic loads acting on the test article (model) are made using an internal strain-gage balance. Balances can be designed to measure from one to six-components of the loads, and measurement of all six components is necessary to completely define the total loads. The total loads are a combination of the aerodynamic loads, model weight, and a portion of the weight of the balance itself. A balance measures the loads by using strain-gages, arranged in a Wheatstone bridge, to measure the strain produced by the loads. A balance measuring six component loads (universally referred to as a six-component balance), will have a total of six (or more) Wheatstone bridges.

The output voltage of a balance bridge changes as a function of the strain at the bridge location produced by the applied loads. In order to convert the output voltage into a load the balance must be calibrated. The balance is calibrated by applying known loads to the balance and recording the output of the various bridges. A numerical relationship, or calibration matrix, is then determined between the applied loads and the voltages (readings) from the balance bridges. The calibration of the balance is extremely important in the use of a strain-gage balance. The measured loads can never be more accurate than the accuracy of the calibration. The methods used to calibrate a balance are much too complicated for discussion here, however, it needs to be pointed out that the equipment and techniques used to calibrate a balance greatly affect the accuracy of the loads measured by the balance.

2.1 Forces and Moments

The terminology used for the forces and moments varied from facility to facility. The recommended terminology is shown below for the applied calibration loads and loads calculated from the bridge outputs and the calibration matrix:

AF - Axial Force

RM - Rolling Moment

SF - Side Force

PM - Pitching Moment

NF - Normal Force

YM - Yawing Moment

In the United States, the units commonly used for the forces and moments are pounds (lb) and inch-pounds (in-lb), respectively, and these are the units used in this document. However, metric units, both MKS and CGS, are more commonly used in some other countries. The procedures for calibration and use of the balance are unaffected by the units chosen, but the calibration report should clearly state which system of units applies to the data presented.

2.2 Balance Axis System and Moment Reference Center

The calibration and use of a balance requires that an axis system and sign convention of the forces and moments be defined. The same axis system and sign convention were used by most of the members, while others used systems with some minor variations. The recommended balance axis system shown in Figure 1 is positioned such that its origin is at the balance moment (reference) center (BMC). The directions of the arrows indicate the positive directions for the axes, forces, and moments. Note that the sign convention for the forces does not conform to the balance axis system. This was done to conform to common practice used in conducting wind tunnel tests in North America in which the normal force is positive up and axial force positive downstream. This results in the axial and normal forces having a positive sense that is the opposite of the respective balance X and Z axes. Although the BMC may be at any location along the balance X axis, it is recommended that it be placed at the physical center of the balance for Moment and Force balance types and at the point about which both the pitching and yawing moments are resolved for a Direct-Read balance.

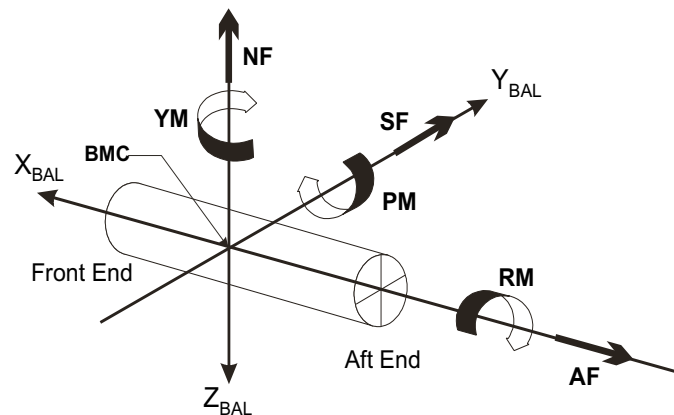


Figure 1 — Balance Axis System, Forces, and Moments

For Force and Moment types of balances, the location of the BMC relative to the bridge locations must be known in order to resolve the component loads into NF, PM, SF and YM. The bridge locations are defined as the distances from the BMC to each bridge. A positive distance indicates that a bridge is located in the positive X direction from (forward of) the BMC. The terms used to locate the bridges relative to the BMC are defined as follows:

- X_1 Distance from the BMC to the forward bridge in the normal-force plane (X - Z plane)
- X_2 Distance from the BMC to the aft bridge in the normal-force plane (X - Z plane)
- X_3 Distance from the BMC to the forward bridge in the side-force plane (X - Y plane)
- X_4 Distance from the BMC to the aft bridge in the side-force plane (X - Y plane)

For Direct-Read balances, the locations of the bridges relative to the BMC (X_1 through X_4) are normally not applicable. However, if the pitching and yawing moments were not resolved about the BMC during the calibration then, X_1 and X_3 are the respective distances from the BMC to the locations about which the pitching moment and yawing moment were resolved.

2.3 Balance Types

The terminology recommended for designating the three different types of internal balances commonly used in wind tunnel testing is as follows: Force, Moment and Direct-Read. All three balance types can resolve axial, side, and normal forces and rolling, pitching, and yawing moments. However, each balance type measures forces and moments using different mechanical structures, internal wiring, and calibration matrices.

One of the more difficult tasks of the working group was deciding on the terminology used to identify the segments of the balance which provide the balance outputs in terms of both voltages and loads. Many names were discussed including gage, component, and bridge. The final terminology is dependent on the output in terms of voltage and load. When the output is a voltage the term is bridge output. When the output is in pounds or inch-pounds (i.e. force and moment engineering units) the term is component load. The recommended order and terminology for the individual component loads and bridge outputs for the three balance types is summarized in Table 1.

Table 1 — Component Load and Bridge Output Order and Terminology

Order	Force Balance		Moment Balance		Direct-Read Balance	
	Component Load	Bridge Output	Component Load	Bridge Output	Component Load	Bridge Output
1	NF1	rNF1	PM1	rPM1	NF	rNF
2	NF2	rNF2	PM2	rPM2	PM	rPM
3	SF1	rSF1	YM1	rYM1	SF	rSF
4	SF2	rSF2	YM2	rYM2	YM	rYM
5	RM	rRM	RM	rRM	RM	rRM
6	AF	rAF	AF	rAF	AF	rAF
Notes: 1) 1 - Suffix designating the Forward bridge, if necessary 2) 2 - Suffix designating the Aft bridge, if necessary 3) r - Prefix designating bridge output in microvolts per volt excitation						

A **Force balance** resolves the applied load vector into a vector of measured component loads consisting of five forces and one moment {NF1, NF2, SF1, SF2, RM, AF}. The forward (NF1) and aft (NF2) normal force component loads are measured in the balance (X-Z) plane and used to calculate the normal force and pitching moment. Likewise, the forward (SF1) and aft (SF2) side force component loads are measured in the balance (X-Y) plane and used to calculate the side force and yawing moment. The Force balance uses a floating frame arrangement to measure the forces acting on the balance. Models attach to and transmit their loads through the outer shell. The outer shell attaches to the inner rod through load sensing elements. The loads applied to the outer shell are transmitted to the inner rod through the force sensing elements. This arrangement is sometimes referred to as a floating frame or shell balance. The aft end of the inner rod is attached to the model support system.

A **Moment balance** resolves the applied load vector into a vector of measured component loads consisting of five moments and one force {PM1, PM2, YM1, YM2, RM, AF}. The forward (PM1) and aft (PM2) pitching moment component loads are measured in the balance (X-Z) plane and used to calculate the normal force and pitching moment. Likewise, the forward (YM1) and aft (YM2) yawing moment component loads are measured in the balance (X-Y) plane and used to calculate the side force and yawing moment. The Moment balance uses a cantilevered beam design to measure the moments acting

on the balance. Models attach and therefore transmit their loads to the balance at the forward end of the balance while the aft end is attached to the model support system.

A **Direct-Read balance** resolves the applied load vector into a vector of measured component loads consisting of three forces and three moments {NF, PM, SF, YM, RM, AF}. A Direct-Read balance is fashioned such that the component loads are directly proportional to the bridge outputs. There are two common Direct-Read balance designs. The first is analogous to either a Force or Moment balance with changes to the wiring. By appropriately connecting pairs of strain-gages from the forward and the aft bridge locations, new bridges are formed with output proportional to total force and total moment in each plane. The second common Direct-Read balance design usually consists of a dedicated section for measuring normal and side force with strain-gages placed forward and aft on relatively short beams. Pitching and yawing moments are measured on the same beam with strain-gages located in one X-axis location similar to a Moment balance. Models attach, and therefore transmit their loads to the balance, at the forward end of the balance while the aft end is attached to the model support system.

All the balance types measure axial force and rolling moment directly. Various methods and mechanical designs are used, but for each balance type, all associated bridge outputs are proportional to the applied axial force or rolling moment. Balances typically have one or two sets of axial force and rolling moment bridges. In an optimized balance design, the strain-gages are located such that the interaction effects on the first bridge are opposite in sign to the interaction effects on the second which are wired in parallel to minimize interactions.

The Force, Moment and Direct-Read designations that the working group has adopted are based on how the balance responds under load and not necessarily on the physical design of the balance. In other words, a Moment balance that is wired to respond like a Direct-Read would be classified as a Direct-Read. The balance types become a function of how the loads in the normal (X-Z) and side (X-Y) planes are resolved. The following summarizes the distinction between each of the three different types of internal balances:

Force – Forward and aft bridges in the normal and side planes functionally respond to the equivalent force load resolved by each bridge, alternatively referred to as five force, one moment (5F/1M).

Moment – Forward and aft bridges in the normal and side planes functionally respond to the equivalent moment load resolved by each bridge, alternatively referred to as one force, five moment (1F/5M).

Direct-Read – Force and moment bridges in the normal and side planes functionally respond to applied total force and moment, respectively, alternatively referred to as three force, three moment (3F/3M).

A balance type can be identified without knowledge of its wiring simply by applying a force in either the normal or side plane, at various longitudinal stations, and observing the behavior of the sign of the bridge outputs. Table 2 summarizes the bridge output of each of the three balance types under such a load.

Table 2 — Bridge Output for Force, Moment, and Direct-Read Balances

Station	Force Balance		Moment Balance		Direct-Read Balance	
	Fwd Bridge	Aft Bridge	Fwd Bridge	Aft Bridge	Force Bridge	Moment Bridge
1, + Force	+	-	+	+	+	+
2, ↓	+	(No Output) [†]	(No Output) [†]	+	+	+
3, ↓	+	+	-	+	+	(No Output) [*]
4, ↓	(No Output) [†]	+	-	(No Output) [†]	+	-
5, ↓	-	+	-	-	+	-
1, - Force	-	+	-	-	-	-
2, ↓	-	(No Output) [†]	(No Output) [†]	-	-	-
3, ↓	-	-	+	-	-	(No Output) [*]
4, ↓	(No Output) [†]	-	+	(No Output) [†]	-	+
5, ↓	+	-	+	+	-	+
Notes: Balance is in a standard upright orientation (i.e., balance is not rolled 180° or yawed 180°). [†] Assumes load is applied at the bridge location. [*] Assumes load is applied at the electrical center of the balance.						

It is important to know the balance type prior to generating the calibration matrix using the recommended math model presented in Section 3.0. The recommended matrix incorporates terms for modeling the asymmetrical nature of a bridge output when changing the direction of the applied load. When including the effects of the sign of the applied load in the calibration matrix it is recommended that the force and moment component loads defined for the calibration matrix should be those component loads into which the balance physically resolves and measures the system of forces and moments applied to it. Thus, for a 6-component Force balance, which typically will have five force-measuring bridges and one moment bridge, the calibrating loads should be expressed in terms of the five forces and one moment measured by the balance, rather than as the generalized three forces and three moments expressed by the vector {NF, PM, SF, YM, RM, AF}. Further discussions on this are included in Section 3.0.

2.4 Designated Balance Load Capacity

It was desired that some methodology be developed that would allow for a common designation of the load capacity of a balance. Although a methodology that captures the full load range of the balance was not developed, a simple methodology, which provides the generalized capacity of the balance was agreed upon and is provided below for the three balance types. Note that the designated balance load capacity does not necessarily provide the absolute maximum loads that can be applied in any single plane. The absolute load capacities must be obtained from the custodian of the balance.

Moment and Force Balances - Maximum NF and SF with no PM or YM, maximum PM and YM with no NF or SF, with maximum AF and RM applied in both cases.

Direct-Read Balance - All bridges fully loaded simultaneously.

3 Calibration

3.1 Calibration Process

In general, calibrating any measurement device involves applying known values of the calibrating variable(s) to the device while recording the resulting sensor output(s). This process must be repeated for a sufficient number of independent conditions to allow determination of the coefficients in the math model chosen to define the device's behavior. In the context of the balances addressed in this document, the calibrating variables are the component loads in the balance axis system, and the sensor outputs are the bridge outputs. However, the precise form of the response, or whether the balance is of internal or external type, is immaterial to the calibration process.

The calibration process includes more than just the physical task of loading the balance and recording its responses. A mathematical model of the balance behavior is needed, together with a suitable mathematical process for determining the unknown coefficients in the model from the experimental data. An experimental design for the calibration loadings must be specified, one which will provide sufficient independent data to fully define the unknown coefficients in the math model selected. What constitutes an optimum (or even good) experimental loading design for a given wind tunnel test requirement is still the subject of much debate, but there is little doubt that the choice of calibration loadings can significantly influence the calibration result. The calibration process also should include some means for assessing and communicating the quality of the calibration result. Several aspects of the calibration process will be addressed in the following sections.

3.1.1 Math Model

While one of the objectives in design of strain-gage balances is to minimize interactions between bridges, i.e. the unwanted bridge output resulting from a load applied to a different bridge, it is generally not possible to eliminate them completely. Such interactions may be classified as either 'linear' or 'non-linear'. The linear terms typically result from such things as construction variations (manufacturing tolerances and misalignments arising during assembly of multi-part balances), improper positioning and alignment of the strain-gages, variations of gage factor, etc. The non-linear terms are attributable to misalignments resulting from the complex deflections which occur when the balance is loaded. In cases where the design loads are relatively large in relation to the size of the balance these non-linear effects will be more significant, and it becomes important that the chosen math model adequately represents these effects in order to achieve the desired test measurement accuracy.

The math model recommended by the members of the AIAA/GTTC Internal Balance Technology Working Group is based upon a representation of the strain-gage bridge signals as polynomial functions of the component loads. This general form of math model has been widely accepted in the wind tunnel balance community for many years, (e.g. see Ref. 3.1), and was employed, in some form or other, within the organizations of all working group members. In its most common form, the model assumes the electrical output reading from the strain-gage bridge for the i^{th} component (R_i) to be related to the applied single and two-component loads (F_j, F_k) by a second order polynomial function of the form:

$$R_i = a_i + \sum_{j=1}^n b_{i,j} F_j + \sum_{j=1}^n \sum_{k=j}^n c_{i,j,k} F_j F_k \quad (3.1.1)$$

where 'n' is the number of component loads measured by the balance, and the intercept term a_i represents the output from the i^{th} bridge when all loads (F) are zero relative to the *calibration load datum*.

The concept of the *calibration load datum* is crucial to the proper interpretation and use of any *non-linear* calibration result, since the coefficients obtained from non-linear curve fits of the calibration data will apply only to the particular load datum defined for the calibration. Therefore, when the balance is used in a different environment, e.g. the wind tunnel, the correct reference condition must be established; i.e. values of the bridge outputs corresponding to the *calibration load datum* must be determined using the local measurement system. The precise load condition chosen as the load datum during calibration is immaterial, provided that the *same* condition is used in all environments. However, to facilitate the use of calibration constants having different values for positive and negative loads, it is recommended that the condition of *absolute zero load* (Ref. 3.2) be selected as the load datum.

In the event that the *calibration load datum* is defined to be absolute zero load, the intercept term a_i will represent the output of the i^{th} bridge at absolute zero load, as measured relative to the defined *electrical output datum*. Provided that the bridge outputs have been recorded without zero suppression, a_i then defines what is commonly referred to as the bridge zero load output, also referred to as the bridge natural zero. However, note that the precise value of a_i determined from regression analysis of the calibration data is specific to the calibration measurement system, and a reading recorded at the same zero load condition when using different instrumentation will not necessarily be the same. Thus the actual value of the intercept term determined from regression analysis of the calibration data is not significant, since an equivalent value, (i.e. that which corresponds to the *calibration load datum* condition), must be determined when the balance is used with a different measurement system. What is important is that the intercept term should be included in the regression, since to exclude it would be equivalent to forcing the curve fit to pass through zero output. Omission of a_i would have little effect on the curvefit provided that zero suppression was employed when the data were recorded, but in the absence of zero suppression the intercept term must be included in order to obtain the best fit to the experimental data. For this reason it is recommended that the intercept term should *always* be included. The choice of whether to use, or not use, zero suppression when recording the bridge outputs typically will depend on the preferences and normal practices within each facility, but inclusion of the intercept term in the regression ensures that the end result will be the same regardless of whether or not the zeros are suppressed.

Some users of the basic model of Eq. 3.1.1 prefer to extend it to include cubic terms for the primary component loads in order to provide better modelling of the load/output characteristic over the full positive-to-negative load range. This extended model is represented by the equation:

$$R_i = a_i + \sum_{j=1}^n b_{i,j} F_j + \sum_{j=1}^n \sum_{k=j}^n c_{i,j,k} F_j F_k + \sum_{j=1}^n d_{i,j} F_j^3 \quad (3.1.2)$$

in which the calibration coefficients can be classified as:

- 'offset', i.e. a_i
- 'linear', i.e. $b_{i,j}$ for $j = 1, n$
- 'load squared', i.e. $c_{i,j,k}$ for $j = 1, n$
- 'load second order cross product', i.e. $c_{i,j,k}$ for $j = 1, n$ and $k = (j+1), n$
- 'load cubed', i.e. $d_{i,j}$ for $j = 1, n$

For an 'n'-component balance the number of calibration coefficients in each of these classifications is $[n]$, $[n]$, $[n(n-1)/2]$ and $[n]$ respectively, for a total of $[n(n+5)/2]$ coefficients in the equation for each bridge output, excluding the offset term a_i . Thus, a 6-component balance would have 33 calibration coefficients in the equation for each bridge output, and the calibration matrix would be of size (6 x 33).

However, it is not uncommon for the load/output relationship of balances, especially those of multi-piece design, to exhibit some dependency on the sign of the strain in the measuring elements. This asymmetry results in the need to determine and use different calibration coefficients according to the sign of the force

or moment acting on the bridge, in order to achieve the best accuracy from the balance. Rather than defining separate calibration coefficients for positive load and negative load and then selecting from these to suit the particular combination of signs in a given instance, this asymmetric load behavior can be modelled effectively by an extension of the basic math model to include terms combining the component loads with their absolute values. If the math model of equation 3.1.2 is extended to include the 'sign of load' effect for all coefficients, the equation becomes:

$$\begin{aligned}
 R_i = & a_i + \sum_{j=1}^n b1_{i,j} F_j + \sum_{j=1}^n b2_{i,j} |F_j| + \sum_{j=1}^n c1_{i,j} F_j^2 + \sum_{j=1}^n c2_{i,j} F_j |F_j| + \\
 & \sum_{j=1}^n \sum_{k=j+1}^n c3_{i,j,k} F_j F_k + \sum_{j=1}^n \sum_{k=j+1}^n c4_{i,j,k} |F_j F_k| + \sum_{j=1}^n \sum_{k=j+1}^n c5_{i,j,k} F_j |F_k| + \\
 & \sum_{j=1}^n \sum_{k=j+1}^n c6_{i,j,k} |F_j| F_k + \sum_{j=1}^n d1_{i,j} F_j^3 + \sum_{j=1}^n d2_{i,j} |F_j^3|
 \end{aligned} \quad (3.1.3)$$

For an 'n' component balance this model defines a total of $[2n(n+2)]$ calibration coefficients for each bridge, (excluding the offset term a_i), i.e. 96 coefficients per bridge for a 6-component balance, corresponding to a (6×96) calibration matrix. This calibration matrix defines the strain-gage bridge output in terms of the known applied component loads, and consequently the inverse procedure of calculating the component loads from the bridge outputs will be iterative, unless only the $b1_{i,j}$ linear terms are present. For this reason this math model is generally referred to as the *iterative model*, for which the linear, quadratic and cubic terms in the calibration matrix have units of *Bridge Output per Engineering Unit (EU)*, EU^2 and EU^3 respectively. This document recommends that the bridge output be expressed as "microvolts normalized to 1-volt excitation" to provide a common standard for interchange of the balance calibration.

Since this form of the math model encompassed all of the variants in use by the organizations represented in the working group, the matrix representing all of the terms implicit in this model has been recommended as the standard form for the exchange of balance calibration results between organizations. Further, to realize the full advantages of this standardization, it is recommended that each organization's balance data reduction software should be capable of using the calibration matrix in this standard form. However, it is stressed that this recommendation does not imply that all of the terms in the full math model must be defined, (or even *should* be defined), in the calibration of any given balance. It is good engineering practice to design the balance calibration to meet the objectives of the intended test, and if these objectives can be realized using a less complex calibration, (which omits selected terms from the full model), then additional calibration effort (and cost) is not justified. (However, note that if the calibration is to be used in multiple tests, or is intended to validate balance performance over a wide load range, then the calibration must be designed to satisfy the objectives of the most stringent application.)

Complete definition of all of the terms in this bi-directional load math model requires a very extensive loading design, and a 'full' calibration of a 6-component balance becomes a difficult and time-consuming task when using conventional (manual) deadweight calibration techniques. Such a calibration is greatly facilitated by use of an automatic balance calibration machine, of which there are several designs currently in use around the world, with others in development. As noted above, it is not mandatory that all terms in this full math model be determined, and the complexity of a manual calibration may be reduced considerably by eliminating terms of lesser significance to the test application. For example, one possible simplifying abbreviation of the math model might involve exclusion of some or all of those terms associated with bridges not expected to be loaded significantly in the proposed test. Another option might be to ignore any sign-dependent effects for all 2-component load cross-product terms, since much of the effort in a 'full' calibration is devoted to properly defining these asymmetric load terms. For a 6-component balance this would leave only 15 of the possible 60 terms in this category, reducing the size of the calibration matrix to (6×51) , in which all but 15 of the terms are defined by the relatively simply-applied single-component calibration loadings - a much more practical model for manual calibrations.

Ultimately it is the content of the calibration dataset (the experimental loading design) that will determine the permissible math model, and any terms which are undefined by the data must be eliminated from the computation process. In cases where the full math model is abbreviated, the size of the calibration matrix either may be defined to match the chosen model, or alternatively the calibration coefficients for the abbreviated model may be stored in their appropriate locations in the general (6 x 96) matrix, with the unused elements being set to zero. The working group has recommended this latter alternative to facilitate the exchange of balance calibration information in a common form. However, note that if the number of components is less than 6, the primary sensitivity elements for non-existent components must be set to unity rather than zero, since it must be possible to invert the square matrix which is composed of only the linear terms.

It should also be noted that it may not always be appropriate to include all of the terms shown in the general math model, even though there may be sufficient independent calibration loading data available to define them mathematically. Always it should be recognized that there are dangers inherent in *over-fitting* experimental data. Often adding extra terms in a curve fit may appear to improve the modelling *within the parent dataset*, (e.g. fitting a cubic to only 4 data points yields zero error *at those points*), but the resultant model may perform poorly with different data. In general it is best to include in the math model only those terms for which there is some underlying physical reasoning. In particular, when the linear and quadratic asymmetric load terms are included there is an argument to be made for elimination of the cubic terms, since their primary purpose is to provide better modelling of the balance's behavior *over the full range of loads, from negative to positive*. Since the presence of the asymmetric load terms effectively separates the positive load and negative load behavior, the cubic terms should perhaps not be included unless the bridge outputs exhibit definite evidence of cubic behavior *for a particular direction of loading*.

3.1.1.1 Other Math Models

While this document recommends use of the math model described above, two other models are discussed briefly for the sake of completeness. The first of these is very similar to the recommended model differing only in the choice made for the independent variable, while the second uses the quite different approach of applying neural network methodology to the problem.

The recommended math model expresses the bridge outputs as polynomial functions of the component forces and moments and so, as noted previously, the inverse procedure of calculating the component loads from the measured bridge outputs requires an iterative computation procedure, unless the calibration matrix contains only the $b1_{ij}$ linear terms and can be inverted. In order to make the load computation a direct (non-iterative) procedure, some people in the balance community advocate a math model which expresses the component forces and moments as polynomial functions of the bridge outputs. In this model it is the bridge outputs which are defined to be the independent variables, and the component forces and moments to be the dependent variables. There is an ongoing debate as to which of these two models is 'correct'. While it is indisputable that the two do not yield the same result, it has been shown through comparisons made with real calibration data that the differences are small, and it is probably true to say that they are insignificant in an engineering sense for typical balances in use today. The reasoning behind the working group's decision to recommend the so-called *iterative calibration math model* is discussed below.

The principle of least squares is commonly employed in curve-fitting experimental calibration data to the chosen math model and in this process, as it is usually applied, the independent variable is assumed to be infallible and the dependent variable(s) fallible. While no experimental measurement is ever without error, the objective in any instrument calibration is to ensure that the value of the calibrating variable, (force, moment, pressure, temperature, etc.) is known with an uncertainty (estimate of the error) which is several times smaller than the uncertainty of the instrument being calibrated. When calibrating strain gage balances, it is the applied loads which are the independent calibration variables whose values are known, albeit not with zero uncertainty since this is not possible in experimentation. These applied loads cause stresses and strains throughout the balance structure, and the strain at the location of each strain

gage bridge produces an electrical output from the Wheatstone bridge that is proportional to the magnitude of the strain. The bridge outputs therefore are *dependent* on the calibrating loads, and become the dependent variables in the regression. The calibration loads, while not without error, most closely approximate the condition of infallibility assumed for the independent variable in the regression procedure as it is usually applied.

While the lower uncertainty of the calibrating load as compared to the balance responses is relatively easy to justify in the context of traditional deadweight balance calibrations, this becomes less obvious when the calibrating loads (however applied) are measured by load cells, as is the case with the increasingly numerous automatic or semi-automatic calibration machines. In these situations the calibrating loads are themselves measured by secondary instrumentation, which also must be calibrated and has its own error sources, and the assumption of 'infallibility' for the measured forces and moments seems less rigorous. In this situation the mathematically correct approach would be to use a regression analysis formulation which assumes error in both the dependent and independent variables. However, the working group members are not aware of any instance of this technique having been applied to global regression involving six independent and six dependent variables.

An added reason for the recommendation that the *iterative* model be used lies in the fact that the presence of invalid coefficients, (i.e. those which are undefined by the calibration data but for which a value is obtained as a result of round-off error in the global regression computation), will likely cause the iterative solution to fail, thus drawing attention to the problem. However, with the *non-iterative* math model such invalid coefficients often will pass undetected in a back-calculation of the parent dataset, but can lead to incorrect results in later use of the balance with different data which may be difficult to detect.

The second alternative model involves application of neural network theory to balance calibration and is discussed in Section 3.5.2 Application of Neural Network Theory.

3.1.2 Calibration Matrix Derivation

There are two procedures commonly used to derive the balance calibration matrix from the calibration data. The first, a piece-wise curve-fitting process (Ref. 3.1), has long been the traditional approach in many organizations, but the method imposes restrictions (see below) on the experimental loading design which make it unsuitable for application to data obtained in automatic calibration machines. The second procedure, which utilizes global regression, is free of these restrictions and is the recommended method. A brief description of both methods is given below, and an example of the application of the global regression method to a 3-component balance calibration is described later in Section 3.2 Matrix Determination Example. A comparison of these two approaches was made, using simulated 'calibration data' for a 3-component balance which was derived by superimposing random error on the exact data computed from an initial matrix which defined 'truth'. The results, based on comparison of the residual errors obtained from cross-calculations performed with datasets having different random error seeds, showed the errors to be smaller and more consistent when using the global regression method.

3.1.2.1 Piece-wise Curve-fitting

This procedure requires that the experimental loading design be structured such that all components are first loaded singly with an appropriate number of incremental loads, and then the same sequences are repeated in combination with a constant secondary load on each of the other components, one component at a time. The procedure also requires that the loading design be restricted to loading a maximum of two components, one with varying loads while the other is held constant. This latter condition makes it unsuitable for analysis of calibration data which have been acquired using an automatic balance calibration machine, (of which an increasing number are now in use), since with most of these machines it is impractical to achieve the condition of *precisely zero force or moment* on the non-loaded components. The data reduction process involves fitting second or third order polynomials to the data from each of the loading sequences. For the single-load cases the coefficients of the first, second and third degree terms yield the required linear, quadratic and cubic primary and interaction coefficients in the calibration matrix. The second order cross-product coefficients are determined from the slope of a

straight-line curve fit of the first order coefficients (slopes) found from the initial curve fits, versus the level of the constant secondary load (with the single-load cases equating to a constant secondary load of zero). These straight-line curve fits must be made for each primary/secondary load combination to determine all of the cross-product interaction coefficients. This procedure is described in a paper by Cook (Ref. 3.1), and consequently is sometimes referred to as Cook's method.

3.1.2.2 Global Regression

The recommended procedure utilizes least squares global regression to determine the coefficients in the defined functional relationship between the given applied component forces and moments and the bridge outputs. In this case the *mathematical process* places no restrictions on the experimental loading design, other than that it must provide sufficient linearly independent information to solve for all of the unknown coefficients in the math model. That is to say, there is no requirement for a specific structure in the calibration loading data, nor for the condition that there be no more than two simultaneous non-zero loads, as is the case with Cook's procedure. The procedure therefore is suitable for analysis of data from automatic balance calibration machines. Should the calibration loadings include data for cases with three or more components loaded simultaneously, then the regression process will provide a solution which fits these data (in a least squares sense) to the prescribed math model, although this (normally) would not include cross-product terms involving more than two components. However, it is important to note that in practice the experimental loading design can have a significant influence on the calibration result. For example, the measured bridge outputs may be influenced by the order and rate of load application as a result of anelasticity (hysteresis) effects. The selection of load ranges, and the particular combinations of multiple loads, will influence the deflections within the balance, and thus the interaction effects.

In the global regression process the unknown coefficients for each of the 'n' components in the math model of Eq. 3.1.3 are determined, by the method of least squares, such that the sum of the squares of the deviations between the calculated and measured outputs will be a minimum for the calibration dataset. If in this dataset there are P sets of F_i with P sets of corresponding R_i , (denoted by $F_{i,p}$ and $R_{i,p}$ where $p = 1 \dots P$), then a set of calibration coefficients is determined which satisfies the condition that the error:

$$e_i = \sum_{p=1}^P \left(a_i + \sum_{j=1}^n b1_{i,j} F_{j,p} + \sum_{j=1}^n b2_{i,j} |F_{j,p}| + \sum_{j=1}^n c1_{i,j} F_{j,p}^2 + \sum_{j=1}^n c2_{i,j} F_{j,p} |F_{j,p}| + \right. \\ \left. \sum_{j=1}^n \sum_{k=j+1}^n c3_{i,j,k} F_{j,p} F_{k,p} + \sum_{j=1}^n \sum_{k=j+1}^n c4_{i,j,k} |F_{j,p} F_{k,p}| + \sum_{j=1}^n \sum_{k=j+1}^n c5_{i,j,k} F_{j,p} |F_{k,p}| + \right. \\ \left. \sum_{j=1}^n \sum_{k=j+1}^n c6_{i,j,k} |F_{j,p}| F_{k,p} + \sum_{j=1}^n d1_{i,j} F_{j,p}^3 + \sum_{j=1}^n d2_{i,j} |F_{j,p}^3| - R_{i,p} \right)^2 \quad (3.1.4)$$

should be a minimum for $i = 1, \dots, n$. The standard least squares solution involves partial differentiation of each of the e_i with respect to each of the coefficients, and equating the resulting expressions to zero to form the normal equations, which may then be solved for the unknown coefficients, including the intercept term a_i .

The math model of the balance response (Eq. 3.1.3) for bridge output R_i can be written in matrix format as:

$$R_i = a_i + [C_i]_m \{G\}_m \quad (3.1.5)$$

where a_i is the intercept, $[C_i]_m$ is a row matrix comprised of the i^{th} row of the calibration matrix, and $\{G\}_m$ is a column matrix comprised of the component loads, component load absolute values, and all non-linear combinations of the component loads and their absolute values as shown in Eq. (3.1.3).

The matrix notation used in this document is as follows; the $[]$, $[]$ and $\{ \}$ brackets denote rectangular, row, and column matrices respectively and the subscript(s) denote the number of rows and/or columns contained in the matrix.

For example: $[A]_y$ is a row matrix with y columns

$\{B\}_x$ is a column matrix with x rows

$[C]_{x,y}$ is a rectangular matrix with x rows and y columns

Equation 3.1.5 can be expanded to include all of the 'n' bridge outputs:

$$\{R\}_n = \{a\}_n + [C]_{n,m} \{G\}_m \quad (3.1.6)$$

Equation (3.1.6) can be further expanded to include all the individual calibration loadings (P):

$$[R]_{n,P} = [a]_{n,P} + [C]_{n,m} [G]_{m,P} \quad (3.1.7)$$

Where $[a]_{n,P}$ results from multiplying $\{a\}_n$ by a unity row matrix of size P and is comprised of P identical columns each equal to $\{a\}_n$.

In the solution process the intercept terms are included into the calibration matrix, $[C]_{n,m}$, as the first column in the extended calibration matrix, $[C']_{n,m+1}$. Correspondingly, a row of unity values must be included in the calibration loads matrix $[G]_{m,P}$ as the first row in the extended calibration load matrix $[G']_{m+1,P}$ so that the equation to be solved becomes:

$$[R]_{n,P} = [C']_{n,m+1} [G']_{m+1,P} \quad (3.1.8)$$

The extended calibration matrix is obtained from solution of the matrix equation:

$$[C']_{n,m+1} = [R]_{n,P} [G']_{m+1,P}^T [G']_{m+1,P} [G']_{m+1,P}^T]^{-1} \quad (3.1.9)$$

Equation (3.1.9) is implicit in the regression analysis techniques that are used to determine the calibration matrix.

3.1.3 Definition of Force and Moment Components for Calibration

The recommended calibration math model incorporates terms which are dependent upon the signs of the component forces and moments, in order to provide better modelling of the asymmetric nature of the load/output relationship often present in strain-gage balances. This type of behavior usually is most apparent in multi-piece Force balances, but even one-piece Moment balances often show reduced residual errors in back- and cross-calculations when this expanded math model is used. (When one considers that bi-directional calibration coefficients commonly are employed even for single component load cells, the benefit derived from their use in the case of multi-component balances perhaps should not be unexpected.)

However, when a distinction is to be made between the signs of the forces and moments it is necessary to examine which forces or moments are responsible for any asymmetry in the bridge outputs. Consider the case of a typical Force balance in which force-measuring elements at two axial locations in the normal force plane are used to resolve the total normal force and total pitching moment applied to the balance. Clearly any asymmetric behavior in the bridge outputs is related to the signs of the forward and aft normal forces, rather than to the signs of the total force and total moment applied to the balance. The sign of the total force or total moment cannot uniquely define the signs of the component forces, since a given sign of either total force or total moment can result from three of the four possible combinations of the signs of the component forces. Since all terms in the recommended *iterative* math model are expressed as functions of the balance components implicitly defined by the calibration matrix, (i.e. the vector of

calibrating forces and moments), it follows that these should also be the component forces and moments if asymmetric load effects are to be applied correctly.

Therefore, *when the effects of sign of load are to be included in the calibration math model*, it is recommended that the force and moment components defined for the calibration matrix should be those components into which the balance physically resolves and measures the system of forces and moments applied to it. Thus, for a 6-component Force balance, which typically will have five force components and one moment component, the calibrating forces and moments should be expressed in terms of the five forces and one moment measured by the balance, rather than as the generalized three forces and three moments expressed by the vector {NF, PM, SF, YM, RM, AF}. Reference 3 uses the very descriptive terminology (5F/1M) and (3F/3M) to distinguish between these two forms of the force and moment vector. A similar argument applies in the case of a six-component Moment balance, for which the equivalent terminology would be 1F/5M.

As described in Section 2.3 Balance Types, one type of Direct-Read balance has bridges corresponding to the total force and total moment which are derived by appropriately connecting pairs of strain-gages from the forward and aft bridge locations. If this is viewed as being analogous to the digital summation and differencing of the forward and aft bridge outputs of a Force balance, then the preceding argument might suggest that the use of asymmetric load terms may not be appropriate for Direct-Read balances. However, so far as the working group members are aware this hypothesis has not been investigated experimentally. Indeed, since direct-read balances are most often based on one-piece, Moment balance designs, for which any effects of sign of load are usually small, it may be that asymmetric load terms are unnecessary for such balances in any event. As noted previously, it is generally best to include in the math model only those terms for which there is some underlying physical reasoning, and hence it is suggested that asymmetric load terms should be used with Direct-Read balances only if the calibration result indicates improved performance when they are included.

3.1.4 Experimental Loading Design

The experimental design of the calibration loadings may have a significant influence on the performance of the resulting calibration matrix, yet how to define these loadings to give the optimum result in a given circumstance is probably the least well understood element of the entire balance calibration process. Often a loading design established at some time in the past continues to be used, principally because "it has always been done this way", or perhaps because the data reduction process relies on that particular loading structure. Generally the choice of the number and type of loadings is based on basic principles, in addition to engineering experience and judgement. The principles include:

- The loading design must provide sufficient, *linearly independent*, information to fully define all of the unknown coefficients in the math model to be used. Depending on the particular balance and the accuracy required in its intended application, it may not be necessary to include all of the 2-load cross-product terms, and elimination of some of these can significantly simplify the physical loading process in manual calibrations. For example, if little or no side force, yawing and rolling moments are expected in the test environment, then it would be reasonable to eliminate from the loading design any cases which are aimed at defining cross-products including these components.
- The loads should be well distributed across the calibration range to avoid any undesired weighting of the curve-fit; for example acquiring a large number of zero-load data points will add extra weight to this condition. (By extension, the load distribution also may be used to impart some specific weighting to the curve-fit if this is desired.)
- As a result of anelasticity (hysteresis) effects, the measured strain-gage bridge responses will be influenced to some extent by the order and rate of load application. The loading design should include both increasing-load and decreasing-load sequences which traverse the complete hysteresis loop, as this will tend to minimize pseudo non-linear effects which could result from curve-fitting data corresponding to a partial loop. Any effects of rate of loading, which clearly will be very different in