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Recommended Practice

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

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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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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
Dennis Booth	Allied Aerospace, GASL Division, Force Measurement Systems
Richard Crooks	Allied Aerospace, Flight Systems Division
Robin Galway	RobGal Aerotest Consulting (Retired IAR/NRC)
Andrew Garrell	Veridian Engineering (formerly Calspan)
Don Hamilton	Institute for Aerospace Research/NRC
Steve Hatten	The Boeing Company
Mark Kammeyer	The Boeing Company
Chris Lockwood	Sverdrup Technology Inc., Ames Group
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Mat Rueger	The Boeing Company
Lew Scherer	Northrop Grumman
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Jim Thain	Institute for Aerospace Research/NRC
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Doug Voss	The Boeing Company
Jimmy Walker	Lockheed Martin LSWT
Frank Wright	The Boeing Company (Deceased)
Pat Whittaker	NASA Ames Research Center

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 affect 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.

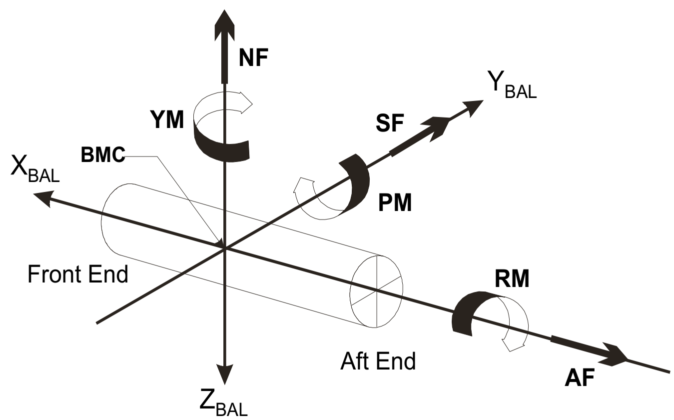


Figure 1 — Balance Axis System, Forces, and Moments

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

	Force Balance		**Moment Balance**		**Direct-Read Balance**	
Order	**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-Rread balance designs. The first is analagous 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:

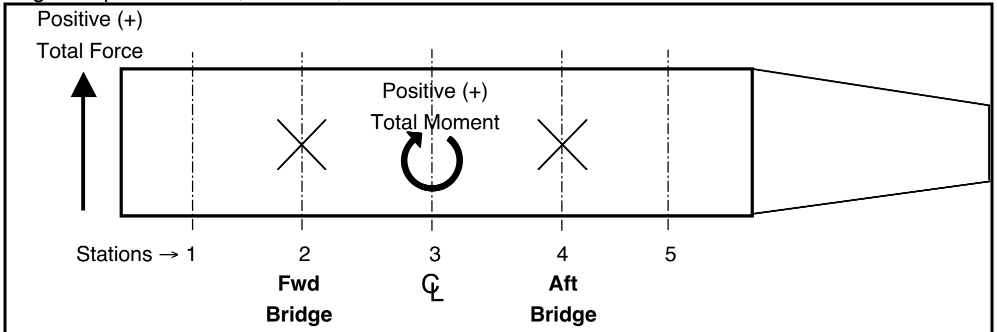
Force – Forward and aft bridges in the normal and side planes functionally respond to the equivalent force load resolved by each bridge, alternatively referred to as five force, one moment (5F/1M).

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 stilll 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:

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

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 refered 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 repesented by the equation:

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

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:

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

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 x 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 x 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 instrumention, 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 glogal 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 datsets 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 ... P), then a set of calibration coefficients is determined which satisfies the condition that the error:

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

should be a minimum for $i = 1, \ldots n$. 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:

$$R_i = a_i + \lfloor C_i \rfloor_m \{G\}_m \qquad (3.1.5)$$

where a_i is the intercept, $\lfloor C_i \rfloor_m$ 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 [ ], $\lfloor\ \rfloor$ 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: $\lfloor A \rfloor_y$ is a row matrix with y columns

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

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

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

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

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

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

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:

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

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

$$[C']_{n,m+1} = [R]_{n,P} [G']^T_{P,m+1} \left[[G'_{m+1,P}] [G']^T_{P,m+1}\right]^{-1} \tag{3.1.9}$$

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 preceeding 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 the calibration and test environments, traditionally have been ignored in balance calibration. This topic is discussed further in Section 3.5 Emerging Technologies.

- If possible the calibration load ranges should be tailored to the expected test loads, i.e. do not arbitrarily calibrate the balance to its rated loads unless there is some overriding reason for doing so. Also, it is important to ensure that the calibration loads envelope is at least as large as the anticipated test loads envelope, so as to avoid any situation where extrapolation beyond the calibrated load ranges would be required.

- Include at least a quantity of loadings with load combinations which will be representative of the test condition. For example, if the center of load in the test will be outside the balance measuring elements, that condition should be simulated in the normal force/pitching moment (and/or side force/yawing moment) combinations applied during calibration.

References 4 and 5 report on investigations into the effects of different calibration loading designs on balance calibration accuracy, while more general information on the topic of design of experiments is available from many references, of which 6 and 7 are only two examples.

It is worth noting that the above recommendations generally represent current and past practice in specifying experimental loading designs for balance calibration. While Design of Experiments (DOE) theory has sometimes been used to define orthogonal and factorial loading designs which minimize the number of loading conditions required for the calibration, many balance engineers have adopted the approach that a high degree of redundancy in the calibration loadings will minimize the effects of experimental error and provide a better result. However, the results of recent research in which experimental loading designs were defined using Modern Design of Experiments theory (MDOE), suggest that more data do not necessarily yield a better result. Rather, loading a relatively small number of selected combinations defined by the MDOE process is the key, and it is by defining what these selected combinations are that MDOE seems to hold promise for future improvements in balance calibration accuracy. The application of MDOE to balance calibration load design is discussed briefly under Emerging Technologies in Section 3.5.

Once a load design has been specified, plots of one component load versus another component load for all possible 2-component products, (15 such plots for the case of a 6-component balance), can provide a very useful tool for evaluating the design. These plots allow easy assessment of the distribution of the loads, and will show immediately if any product terms are undefined, since in this case all points would lie along the respective axes of the plot. However, to add a cautionary note, even if this display indicates a suitable distribution of finite-valued load cross products, this does not guarantee the absence of linear dependencies in the data, and consequently does not guarantee that all of the terms in the math model will be fully defined by the load design. In the event that not all coefficients are fully defined by the data, computation round-off errors often will cause the global regression process to return values for the undefined coefficients, rather than fail to produce a solution. In such cases the undefined, or ill-defined, terms in the matrix typically will have abnormally large values, and the solution should be carefully checked to ensure that the relative magnitudes of the interaction terms are reasonable. This check can be made more easily if the contribution that each matrix term makes to the appropriate component (as bridge output microvolts or load according to the units of the matrix terms) is evaluated at the maximum level of the relevant load or load product, and then expressed as a percentage of the maximum bridge output, or rated load, of the affected component. In this format, which is accomplished easily using a spreadsheet application, any terms with an abnormally large contribution will be much more obvious than they would be from an inspection of the raw coefficients. A further check on the validity of the matrix may be obtained through back-calculation of the loads contained in the calibration dataset, or more preferably by cross-calculation of additional loads applied as independent check load cases. As noted earlier, the presence of invalid terms in the calibration matrix will most probably cause the iterative load calculation to diverge even for the back-calculations, and it will almost certainly fail in any cross-calculation of check load data containing component load combinations not present in the parent dataset.

3.1.5 Frequency of Calibration

While it might be desirable to perform a complete balance calibration before every test, often this is impractical for a variety of reasons, not the least of which is the time and effort (cost) required, especially with traditional manual calibrations. To decide when a full re-calibration is necessary, a common practice is to perform check loadings of the balance before (and perhaps after) every test, and then base the decision on the ability of the currently available calibration matrix to recalculate the check loads with acceptable accuracy. Note that these check loads ideally should include some multi-component loadings typical of those to be expected in the test. If cross-calculation of these check loads indicates residual errors for each of the balance components which fall within the range of estimated uncertainties required by the test, then this normally would justify performing the test without a full re-calibration of the balance.

3.2 Matrix Determination

This section contains a description of the process used to compute a final calibration matrix. A simplified three component example illustrating this process is contained in Section 3.6 and a full six component example using all 96 terms discussed in Section 3.1.1 is available for downloading from the AIAA/GTTC website which can be reached through the AIAA website at www.aiaa.org.

The matrix determination process can begin once the calibration and zero load output data have been obtained. The make-up of the calibration load schedule is based on the knowledge and experience of the calibration engineer. Many factors influence this decision and the topic will not be addressed here. It is important however to ensure that the terms selected for inclusion in the matrix have been properly defined during calibration. This topic is discussed in more detail in Sections 3.1.4 and 4.3.

Due to the non-linear characteristics of typical balances, it is essential that all loads be computed relative to a zero-load reference state. It is this requirement which complicates what might otherwise be a straightforward curve-fitting process. Usually during balance calibration, there are loads applied to the balance that result from the setup (e.g. calibration body, weight hangers, cables, etc.), and these tare loads are typically not measured independently. This means that the total applied load relative to the zero-load reference state is not known initially, and must be found in an iterative process. This process is divided into several steps. These steps will be discussed and are shown in flow chart form in Figure 2. Note that the total applied loads also includes a portion of the weight of the balance.

There are several possible exceptions to the process outlined in Figure 2 that could be encountered. It is theoretically possible to precisely determine the weight and center of gravity for all of the required hardware used during calibration, as well as the metric portion of the balance. In this case the total applied load would be known *a priori* and no iteration would be required. A similar situation could apply in the case of some automatic balance calibration machines, where the total applied load is determined for each data point from prior knowledge of the weight and center of gravity location of the various pieces of loading hardware. Lastly, if a linear (6x6) matrix is deemed to adequately describe the behavior of a particular balance, it is necessary to know only the relative applied load. This means a strict accounting for tare loads is unnecessary, as long as the bridge outputs are used in a relative sense as well.

Some consideration needs to be given to the state of the measured data at the time the calibration matrix is determined. The process outlined here assumes that all the data are consistent with a constant excitation voltage. This could be achieved either through continuous monitoring and control of the excitation voltage, or measurement and span ratioing for each data point. Furthermore, it is assumed that the calibration dataset can be divided into a set of load series in which each load series contains a set of three or more load points; a series being defined here as a set of load points in which the tare load remains constant. The first load point of each series should be taken without any applied calibration load, but with tare loads only.

As can be seen in Figure 2 the matrix determination process consists of two independent initial steps: the determination of the initial linear matrix and the determination of the zero load outputs.

Initial Matrix Determination One of the initial steps in the process is to determine a linear matrix. In order to compute the initial linear balance matrix, it is necessary to subtract the balance outputs for the initial tare point from all subsequent load points in each load series. Without this step, the tare loads will effectively shift the data for each series, resulting in a poor estimate of the balance sensitivity. Note that only first order linear terms are used for the initial matrix. The use of higher order terms could potentially lead to convergence problems. Global regression is used to determine the initial matrix as well as all subsequent matrices. This is performed in a manner consistent with that outlined in Section 3.1.2.2.

Zero Load Outputs Another initial step in the process outlined in Figure 2 is to determine the zero load outputs for the balance. Put another way, this would correspond to the output of the balance bridges at the rated excitation voltage under a weightless condition. Since a weightless condition cannot realistically be achieved, these values are usually determined by averaging bridge outputs with the balance level in pitch, at four roll positions indexed by 90°, (e.g. 0°, 90°, 180°, and 270° of roll). It is also good practice to make one or more repeats of this group of four measurements to minimize errors in the average.

Tare Load Determination The determination of the tare loads involves an iterative process. The tare loads for a given load series are obtained through a load computation of the initial point in the series. Load computation is addressed in detail in Section 3.3. Within each load series, the tare load estimates are calculated using the current matrix and the bridge outputs for the initial points minus the zero load outputs. The tare loads for each load series are then added to the calibration loads for all points in the series. Global regressions for each component load with all of the required terms are performed using the tare adjusted calibration loads and the measured bridge outputs. The new matrix will lead to new tare loads and then the process is repeated. An intercept term is computed during the regression for each component load (in this example 3 regressions are performed). For the duration of the tare load iteration process, these intercept terms should have values close to the zero load outputs. The variation from the zero load outputs is a result of experimental and curve fit error. Note that a large deviation indicates a significant lack-of-fit problem in the process and should be investigated. The intercept terms are computed for monitoring purposes but are not used in any load calculations. The iteration process continues until the change in tare load for each load series falls below some established criteria.

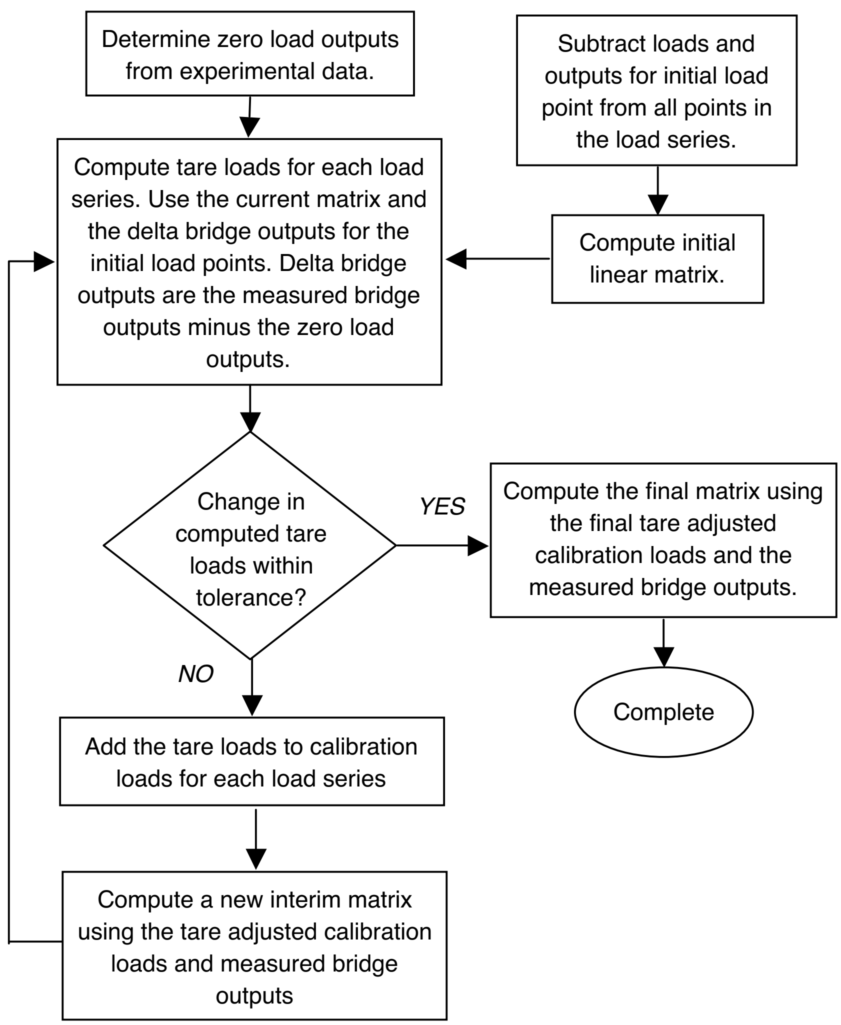


Figure 2 — Matrix Determination Process

Final Matrix Determination The final version of the balance calibration matrix is determined using the calibration loads adjusted by the final tare loads and the measured bridge outputs.

The illustrative example represents results of computations using the method prescribed. It should be born in mind however, that differences in the matrix inversion process, in the iterative bridge interaction computation process and convergence criteria, and in the machine accuracy (round off error), can result in small differences in the computed tare loading at the various intermediate steps of the tare iteration. These small tare-load differences can in turn, result in small differences in the elements of the computed calibration matrix at each tare load iteration. Therefore, the user's result for the final calibration matrix obtained from the converged tare solution may not be identical to the solution provided in the example; i.e. all matrix terms may not match 'digit-for-digit'. Generally, the linear terms in the calibration matrix should be very close to the provided solution, whereas somewhat larger differences might be seen in higher order interaction terms. The included 3-component balance calibration example was verified using computer codes employed by several different facilities, and small differences were observed in some terms of the final matrix. However, the computed tare and calibration loading solution obtained by these facilities was identical to within the specified tolerance for load convergence.

It is worth noting that internal balances (like many other instruments) perform best when used as a relative measuring device. In wind tunnel testing for example, results are obtained by taking the difference between a load measured at some run condition, and a reference load condition commonly referred to as the *wind-off zero*. If the two load measurements can be made reasonably close to one another in time, then it can be assumed that many factors (e.g. temperature, amplifier gain) that can cause the balance outputs to drift, will tend to cancel out. In addition, this means that differences in curve-fit intercept or zero load output values will have only a small effect on the final computed load. The use of internal balances as a relative load measuring device is a virtually universal practice, and it is implicit in many of the techniques for balance calibration and use discussed herein.

3.3 Load Calculation Method

The method for load calculation presented here is consistent with the form of the matrix discussed in Section 3.1.1. Load determination for this matrix form is iterative in nature, but the convergence is typically very rapid.

The equation for calculating component loads from bridge outputs is derived from the calibration equation which is provided in matrix form in Eq. (3.1.6). The bridge output vector $\{R\}_n$ is replaced by $\{\Delta R\}_n$ and the intercepts $\{a\}_n$ are removed to yield:

$$\{\Delta R\}_n = [C]_{n,m} \{G\}_m \tag{3.3.1}$$

The delta bridge output vector $\{\Delta R\}_n$ is determined by substracting the zero load outputs from the bridge outputs. The intercepts $\{a\}_n$ that were determined during the development of the calibration matrix are removed because they are not used in the calculation of the component loads.

For use in data reduction, the calibration matrix $[C]_{n,m}$ is separated into two parts; the first order square matrix $[C1]_{n,n}$ that relates the bridge outputs to the component loads and an iteraction matrix $[C2]_{n,m-n}$ that relates the bridge outputs to the component load absolute values, and all non-linear combinations of the component loads and their absolute values. The load vector $\{G\}_m$ is broken into corresponding parts; $\{F\}_n$ that consists of the component loads and $\{H\}_{m-n}$ that contains the absolute value of the component loads and all non-linear combinations of the component loads and their absolute values. This results in the following:

$$\{\Delta R\}_n = [C1]_{n,n} \{F\}_n + [C2]_{n,m-n} \{H\}_{m-n} \tag{3.3.2}$$

Multiplying by the inverse of $[C1]_{n,n}$ yields:

$$[C1]^{-1}_{n,n}\{\Delta R\}_n = \{F\}_n + [C1]^{-1}_{n,n}[C2]_{n,m-n}\{H\}_{m-n} \tag{3.3.3}$$

Grouping like terms and rearranging results in the final form of the equation for the component loads:

$$\{F\}_n = [C1]^{-1}_{n,n}\left(\{\Delta R\}_n - [C2]_{n,m-n}\{H\}_{m-n}\right) \tag{3.3.4}$$

This equation is iterative because $\{H\}_{m-n}$ is a function of $\{F\}_n$. The load vector $\{F\}_n$ at iteration step t is given by:

$$\left(\{F\}_n\right)_t = [C1]^{-1}_{n,n}\left(\{\Delta R\}_n - [C2]_{n,m-n}\left(\{H\}_{m-n}\right)_t\right) \tag{3.3.5}$$

Convergence is defined by the following:

$$\{V\}_n = \left|\left(\{F\}_n\right)_t - \left(\{F\}_n\right)_{t-1}\right| < \{s\}_n \tag{3.3.6}$$

Where $\{s\}_n$ is a vector of limits set arbitrarily small.

A sample load calculation is shown in Figure 3, where the final matrix is used to compute the loads for the 2nd point in load series 5 of the example data with a convergence criteria of 0.01.

Several facilities use Eq. 3.3.5 in a slightly different form:

$$\left(\{F\}_n\right)_t = [C1]^{-1}_{n,n}\{\Delta R\}_n - [C1invC2]_{n,m-n}\left(\{H\}_{m-n}\right)_t \tag{3.3.7}$$

In this form the $[C1]^{-1}_{n,n}$ and $[C2]_{n,m-n}$ matrices have been multiplied to form a single matrix $[C1invC2]_{n,m-n}$. Forming the $[C1invC2]_{n,m-n}$ matrix eliminates the multiplication of two matrices for each iteration in the calculation of the component loads. Also, the iteration only needs to involve $[C1invC2]_{n,m-n}\left(\{H\}_{m-n}\right)_t$. A matrix constructed by including the terms from $[C1]^{-1}_{n,n}$ and $[C1invC2]_{n,m-n}$ is often referred to as the “data reduction matrix”.

Calibration Matrix

	R1	R2	R3	
[C1]	1.149328E+01	8.868524E-02	-2.161396E-02	**A**
	1.763821E-01	6.024058E+00	-5.925709E-03	**B**
	-2.037650E-02	-7.906946E-02	3.718351E+01	**C**
[C2]	-4.379940E-04	-1.992620E-05	5.735622E-04	**A^2**
	-2.109667E-06	3.225671E-05	-8.476946E-07	**B^2**
	-6.360265E-04	-1.110847E-04	1.342177E-02	**C^2**
	4.196725E-04	2.906703E-04	1.039195E-04	**A*B**
	5.289469E-09	1.924804E-04	-1.062430E-04	**A*C**
	-2.249615E-05	9.747822E-06	-6.169460E-05	**B*C**
$[C1]^{-1}$	8.702711E-02	-1.280538E-03	5.038288E-05	
	-2.548079E-03	1.660389E-01	2.497946E-05	
	4.227230E-05	3.523743E-04	2.689372E-02	

	rA	rB	rC
Bridge Output	4757.4	-737.0	2527.9
Zero Load Output	123.1	-790.5	523.7
ΔR	4634.3	53.5	2004.2

		A	B	C			
Step 1	$(F)_{t=0}$	0.00	0.00	0.00			
	H	0.00	0.00	0.00	0.00	0.00	0.00
	$\Delta R - C2\ (H)_{t=0}$	4634.3	53.5	2004.2			
	$(F)_{t=1}$	403.258	3.655	54.135			
	V	403.258	3.655	54.135			
Step 2	$(F)_{t=1}$	403.258	3.655	54.135			
	H	162617.11	13.36	2930.62	1473.87	21830.47	197.86
	$\Delta R - C2\ (H)_{t=1}$	4706.775	52.433	1873.773			
	$(F)_{t=2}$	409.563	3.339	50.631			
	V	6.305	0.316	3.504			
Step 3	$(F)_{t=2}$	409.563	3.339	50.631			
	H	167741.54	11.15	2563.52	1367.53	20736.64	169.06
	$\Delta R - C2\ (H)_{t=2}$	4708.830	52.736	1875.654			
	$(F)_{t=3}$	409.741	3.387	50.682			
	V	0.178	0.048	0.051			
Step 4	$(F)_{t=3}$	409.741	3.387	50.682			
	H	167887.49	11.47	2568.65	1387.95	20766.44	171.68
	$\Delta R - C2\ (H)_{t=3}$	4708.889	52.728	1875.503			
	$(F)_{t=4}$	409.746	3.386	50.678			
	V	0.005	0.001	0.004			

Figure 3 — Sample Load Calculation

3.4 Transfer of the Calibration Result to the Test Environment

In transferring the balance calibration to the test environment, it is necessary to address two possible sources of error. The first relates to the balance calibration reference state, and the second relates to the balance sensitivity. Both of these concerns will be discussed in detail and procedures for addressing them will be outlined.

3.4.1 The Calibration Reference Condition

The importance of the calibration load datum condition to the proper interpretation and use of any non-linear calibration result has been noted previously. Further, it has been recommended that the condition of absolute zero load (i.e. weightless) should be used as this calibration load reference condition, with the corresponding datum bridge outputs being determined from averages of the bridge outputs recorded with the balance and calibration body at roll angles indexed by 90 degrees while in a level attitude. These measured zero-load outputs then are the appropriate reference values to be subtracted from the measured bridge outputs when making back- or cross-calculations of data measured in the calibration environment. However, it is stressed that the precise values of the measured zero-load outputs are relevant only to those data that are recorded by the instrumentation in the calibration environment. For use of the balance in a different environment, (e.g. in a wind tunnel test), an independent determination of the bridge outputs corresponding to the load datum must be made in that environment. This is necessary to ensure that for any load condition encountered in the test environment, the balance will be operating at the same point on its non-linear characteristic as it would have been for the same load condition applied in the calibration environment.

Since the required weightless condition cannot be achieved experimentally in any simple way, the required datum bridge outputs, (or zero-load outputs), cannot be measured directly. Commonly the procedure used to determine them first evaluates the weight and the center of gravity of the metric mass by ‘weighing’ the model at different attitudes, and recording the bridge outputs relative to some arbitrary reference ‘zero’. This reference might, for example, be selected as the condition where the balance was level in both pitch and roll, and the test model was installed, a condition sometimes referred to in wind tunnel tests as a *wind-off zero*. As a simple example, the weight and the “X” position of the center of gravity can be determined from differences between measurements of the normal force and pitching moment made at roll angles of 0^o and 180^o. By using a more complex ‘weighing’ procedure the center of gravity may be located in three dimensions, and this information then allows the distribution of the weight among the balance components at the chosen reference condition to be calculated. The calibration matrix may then be used to convert this load vector to the corresponding bridge signals, and these values then define the output increments which are required to shift the arbitrary measurement origin to the weightless condition. It should be noted that when non-linear effects are included in the calibration math model, this process for determining the *zero-load outputs* will involve iteration, since to compute the correct loading requires knowledge of the zero load outputs, the determination of which is the objective of the process. An example of this process is illustrated in Reference 8.

3.4.2 Bridge Sensitivities

It is possible that not just the zero output datum but also the scale factor could change between the calibration and the test environments. A variety of influences that might affect the magnitude of the recorded measurement could potentially be different in the two environments. For example the effective excitation voltage at the strain gage bridges might be different for some reason. Or possibly the gains of one or more amplifiers might differ slightly from those used to perform the calibration. Consequently some form of scale factor check should be performed in the test environment so that the results may be compared to similar measurements made at the time of calibration. Any differences may then be expressed as a ratio and used to scale the output voltages. There are several commonly used methods for measuring this span ratio, each has advantages and disadvantages. The proper choice of method is strongly dependent on the data acquisition systems of both the calibration and test environment, as well as test technique.

Excitation Voltage Perhaps the most commonly encountered cause of a difference in bridge sensitivity is a difference in excitation voltage. A straightforward approach to measuring a span ratio is to precisely measure the excitation voltage at some reference point (e.g. the balance cable end) and ratio it to a measurement made at the same point during calibration. There must be no change in the wiring or connections between this reference point and the balance from the time of calibration until installation. Also, the excitation voltage used in the test environment should be very close to the value used in calibration (a span ratio of near 1) so that the self-heating of the balance is near constant. The biggest drawback of depending solely on this approach is that measuring excitation voltage provides no real check of the system sensitivity. As a result, there are other possible sources of a change in bridge sensitivity that would remain undetected, and unaccounted for.

Shunt Resistors A shunt resistor applied across one arm of the strain gage bridge is frequently used to simulate a load-induced output. In using shunt resistance measurements to check scale factor, it is assumed that when the same shunt resistance (preferably the same resistor) is applied at the same location in the circuit the resulting bridge outputs should be equal for the calibration and test environments. It is imperative for this technique that there have not been any changes in the balance wiring since calibration (e.g. increasing the cable length), and that the balance be in the same load state (e.g. bare balance upright and level) as when the shunts were applied in the calibration laboratory. While this is a frequently used technique, it has the disadvantage that the results can be quite sensitive to temperature effects, especially if the shunt resistance is applied at the end of a long copper wire harness, as is often the case.

Check Loads A third method for checking the scale factor between two environments involves duplicating some simple single component loadings in each environment and then comparing the resulting outputs from the primarily loaded bridge(s). Ideally the loads should be applied using the same calibration body and fixtures in both environments, implying that the calibration equipment should accompany the balance to the test site. For the same load condition, the outputs recorded in each environment are compared in the same manner described above. In many ways the check load approach is superior to the other two, but it depends on the ability to load the balance in the test environment in precisely the same manner and with the same accuracy as was done during calibration. Often this is not possible. Regardless of whether the span ratio is determined from check loads or another method, the use of check loads as an end-to-end system check of the balance installation is highly recommended.

While the span ratios (for each component) are often applied to the balance output (to obtain a corrected output), an alternative approach is to use them to correct the primary bridge sensitivities that correspond to the main diagonal of the calibration matrix. If the terms in each row of the calibration matrix, (i.e. those terms applying to the same balance component), are normalized by dividing each term by the primary sensitivity of that component, then the matrix terms become independent of the primary bridge sensitivities. Such a normalized matrix applies to a vector of 'nominal' loads obtained by dividing each bridge output by the corresponding bridge sensitivity. In this way any scale factor adjustments need only be applied to the individual bridge sensitivities.

3.5 Emerging Technologies

Three emerging technologies, presented in the following sections, all involve new methods for enhancing the balance calibration process. The technologies include a method for accounting for the anelasticity of the balance, the development of the calibration matrix using neural network theory, and the application of calibration loadings based on Modern Design of Experiments (MDOE). The three technologies are new enough that they could not be completely addressed by the working group prior to the publishing of this document. They are included for information and completeness only and their inclusion should not be considered as a recommendation for their use.

3.5.1 Correction for Anelasticity

As noted in Section 3.1.4, the balance output will be influenced to some extent by the order and rate of load application because of anelasticity that results in hysteresis. If the loading design includes both increasing-load and decreasing-load sequences that traverse the complete hysteresis loop, this will tend to minimize pseudo non-linear effects, which could result from curve-fitting data corresponding to a partial hysteresis loop. One can obtain a measure of anelasticity by observing change in balance output with time at constant load after having rapidly imposed a large change in load. Differences in time constants for increasing and decreasing load change cause non-linearity. Anelasticity effects can introduce errors of 0.2% or more (Ref. 3.9). The effects of rate of loading, which clearly will be very different in the calibration and test environments, traditionally have been ignored in balance calibration. However, a methodology to calibrate for anelastic effects recently has been proposed, and is presently under development (Refs. 3.9 and 3.10). The methodology proposes mathematical models for the production and relaxation phases of the time-dependent anelastic processes, and offers a means for estimating the anelastic component of the strain-gage bridge output voltage. This may then be applied as a correction to convert the measured output voltage to an equivalent balance state corresponding to anelasticity being fully relaxed. The time-dependent nature of the phenomenon would require continuous monitoring and recording of the balance bridge responses as well as time. Further work is required to develop this ‘anelasticity correction’ as a production technique, but conceptually, such a correction could reduce variance due to hysteresis and, as a by-product, also reduce non-linearity in the balance calibration.

3.5.2 Application of Neural Network Theory

The second alternative model represents a significant departure from the usual practice of first specifying the math model and then determining the constants in it from a regression analysis of the calibration data. Instead, a *neural network* becomes the math model with the inputs to the network consisting of the bridge outputs, and the neural network outputs being the desired component forces and moments. This work is under development and initial results, which can be found in References 3 and 11, are summarized here. Both these references study a number of one-hidden layer networks, varying in the number (2 to 15) and type (linear and tangential hyperbolic activation functions) of hidden-layer nodes. The accuracy of the balance load estimation using the neural network math model is evaluated against the load estimation accuracy using the regression analysis model of Eq. 3.1.3 of the present document. The accuracy of both math models is determined from back-calculation.

Initial work on multiple-inputs/multiple-outputs networks showed poor accuracy in the balance load estimation (Ref. 3.11). Therefore, only multiple-inputs/single-output networks are considered further in Ref. 3.4. The considered network consists of an input layer, one-hidden-layer, and a single-node output layer for each balance load component. The inputs to the network consist of the measured bridge outputs. The output of the network is the desired balance load component. For the subject balance, a total of six separate neural networks are computed: one multiple-input/one-output network for each of the six balance load components. A Levenberg-Marquardt training scheme is used to determine the weights along the node connections in the neural network model.

The analysis in Reference 11 uses two repeat calibrations of the subject balance. These two 950-point calibration databases were acquired in an automatic calibration machine. The number of inputs to the network was varied to six or twelve. The 6-input case uses the six-measured bridge outputs and the 12-input case uses the six bridge outputs plus the six squares of the bridge outputs. It is found that increasing the number of inputs from six to twelve increases the training time of the neural network substantially, while only resulting in a marginal improvement in the uncertainty in the balance load estimation. Therefore, only the six-input case is further evaluated in Reference 4.

Reference 11 also shows that including a linear activation function for one of the nodes in the hidden layer significantly reduces the training time as compared to all nodes having tangential hyperbolic activation functions without any significant decrease in the overall uncertainty of the balance load estimate.

Reference 4 uses the neural network math model and the regression analysis model to evaluate the calibration repeatability within a facility and between facilities. Calibration data from three facilities for the same subject balance are analyzed. Two facilities use dead weight loading, with one facility defining a 130-point calibration load envelope and the second facility defining a 730-point load envelope. The third facility uses an automatic calibration machine and a 130-point and 950-point load envelope. Back-calculation is used to evaluate the accuracy of the math model. The accuracy of the balance calibration process is evaluated by cross-calculation; data that are not included in the determination of the math model are used in the math model evaluation.

Reference 4 finds that neural network models should not be used for balance load estimations if only single-gage load calibration data are available. A regression analysis model should be used instead.

References 11 and 4 find that the neural network approach provides equal or more accurate results as compared to the regression math model if a calibration database with adequate single-gage and combined-gage loading is available. The lowest possible number of nodes in the hidden layer, which still provides adequate accuracy in the load estimation, should be selected to avoid over-fitting the data. A similar rule can be made with regard to the number of coefficients introduced in the regression analysis model.

A situation in which the neural network approach may prove to have an advantage is in modeling balances having redundant measurement responses, since the case where there is a different number of inputs and outputs is not amenable to treatment with the *iterative*, non-linear regression analysis model. Note that this situation can also be handled by a *non-iterative* regression analysis model.

3.5.3 Application of Modern Design of Experiments Theory

Research is being conducted in applying a "modern design of experiments" (MDOE) approach to Force balance calibration. Balance calibration can be considered an experiment in which independent variables (applied loads) are set and dependent variables (bridge outputs) are measured. A six dimensional response surface that models the bridge outputs as functions of applied load is desired. Formal experimental design techniques provide an integrated view to the Force balance calibration process. This scientific approach applies to all three major aspects of an experiment; the design of the experiment, the execution of the experiment, and the statistical analysis of the data.

Current Force balance calibration schedules increment one independent variable at a time. During this incrementing of the primary variable, all other variables are zero, or are held at a constant magnitude. This approach is referred to as one-factor-at-a-time (OFAT) experimentation. Ordering of the points within the design is based on the efficiency of the load application system and specific data analysis algorithms. Typical calibration load designs, used to derive a quadratic model, can contain over 1000 data points.

A MDOE approach deviates from the current trend of collecting massive data volume, specifying ample data to meet requirements quantified in the design but without prescribing volumes of data far in excess of this minimum. The goal is to efficiently achieve the primary objective of the calibration experiment; namely the determination of an accurate mathematical model to calculate the unknown loads from measured balance responses.

The three fundamental quality-assurance principles of MDOE are randomization, blocking, and replication (Ref. 3.12). Randomization of point ordering converts unseen systematic errors to an additional component of simple *random* error. Random error is easy to detect and also easy to correct, by replication and other means. Randomization of point ordering also increases the statistical independence of each data point in the design. This statistical independence is often assumed to exist in the current methods of balance calibration, but systematic variation can cause measurement errors to be correlated and therefore not independent of each other, as required for standard precision interval computations and other common variance estimates to be valid.

Blocking entails organizing the design into relatively short blocks of time, within which the randomization of point ordering insures stable sample means and statistical independence of measurements. While randomization defends against systematic *within-block* variation, substantial *between-block* systematic variation is also possible. For example, calibrations spanning days or weeks might involve different operators, who each use slightly different techniques, or possess somewhat different skill levels. By blocking the design, it is possible in the analysis to remove these between-block components of what would otherwise be unexplained variance.

Replication causes random errors to cancel. This includes otherwise undetectable systematic variation that is converted to random error by randomizing the point order of the loading schedule. Replication also facilitates unbiased estimates of what is called "pure error" - the error component due to ordinary chance variations in the data. These pure-error estimates are critical to evaluating the quality of the calibration model, by permitting the fit of the model to the data to be assessed objectively.

Preliminary results from a MDOE 136-point quadratic design indicate that a superior estimate of the balance calibration matrix can be obtained using these formal experimental design techniques. Typically, when a calibration matrix is applied to the same data in which it was derived, it produces a significantly lower standard deviation than its application to a set of data that contains different combinations of the independent variables. This lack of transferability indicates that the coefficients are biased toward the specific combinations of independent variables contained in the design that was used to generate the coefficients. Therefore, the estimates of standard deviation are not representative of the ability of the mathematical model to predict unknown loads throughout the entire six dimensional inference space. The cross application of a quadratic matrix derived from this MDOE 136-point design provided a stable estimate of the standard deviation of back-calculated errors when applied to other calibration designs.

The application of MDOE technology will significantly impact the Force balance calibration process. It provides a systematic method for research into better mathematical models. Ultimately, the benefit to the research community will be increased accuracy of force measurements during wind tunnel testing. Additional information on the development and application of MDOE to balance calibration can be found in References 13 and 14

3.6 Three-Component Balance Example

This section will describe in detail the process used to determine the calibration matrix. In order to ease the illustration, the data presented here are for an idealized three-component balance. This simplification involved no loss of generality, and the approach presented is equally applicable to six-component balances. Further simplification was made through the exclusion of both absolute value and third-order terms. It should be noted that a six-component example using all 96 terms discussed in Section 3.1.1 is available for downloading from the AIAA/GTTC Web site, which can be reached from www.aiaa.org.

The calibration points for this example include three load components (A, B, and C) and three outputs (r1, r2, and r3). As described in the text and illustrated here, the matrix determination process consists of four steps:

1. Determine the Zero Load Output
2. Determine the Linear Matrix
3. Tare Load Iteration Process
4. Determine the Final Calibration Matrix

The process can commence once the calibration data and zero load output measurements have been obtained. The data used for this example are shown in Tables 3 and 4. The data for the zero load outputs were measured at roll angles indexed by 90 degrees and started at a roll angle of zero. Several sets of zero load output data were obtained, and the values shown in Table 3 are the averages of the outputs for each bridge and roll angle. The balance was level in pitch during the acquisition of the data.

Table 3 — Measured Bridge Outputs for the Determination of the Zero Load Outputs

	Bridge Outputs		
Roll Angle	r1	r2	r3
0.0	143.3	-769.8	549.8
-90.0	122.8	-790.8	523.1
90.0	123.4	-789.3	524.2
180.0	102.9	-812.0	497.8

Table 4 — Calibration Loads and Bridge Outputs

		Calibration Loads			Bridge Outputs		
Series	Point	A	B	C	r1	r2	r3
1	1	0.00	0.00	0.00	143.4	-769.9	549.7
	2	0.00	0.00	25.00	141.7	-771.5	1487.5
	3	0.00	0.00	50.00	140.0	-774.5	2443.9
	4	0.00	0.00	75.00	138.1	-776.5	3415.5
	5	0.00	0.00	100.00	135.1	-779.2	4404.1
	6	0.00	0.00	75.00	138.3	-776.5	3414.6
	7	0.00	0.00	50.00	140.2	-774.6	2444.4
	8	0.00	0.00	25.00	141.7	-772.3	1487.4
	9	0.00	0.00	0.00	143.4	-770.6	550.3
2	1	0.00	0.00	0.00	145.6	-697.5	438.7
	2	0.00	400.00	0.00	216.3	1717.7	435.9
	3	0.00	800.00	0.00	286.4	4142.6	433.5
	4	0.00	1200.00	0.00	354.9	6578.6	430.6
	5	0.00	1600.00	0.00	422.9	9026.4	427.5
	6	0.00	1200.00	0.00	355.4	6579.0	431.0
	7	0.00	800.00	0.00	286.3	4143.8	433.7
	8	0.00	400.00	0.00	216.5	1717.8	436.4
	9	0.00	0.00	0.00	145.0	-697.2	438.1
3	1	0.00	0.00	0.00	235.1	-768.6	437.7
	2	200.00	0.00	0.00	2515.2	-752.0	458.9
	3	400.00	0.00	0.00	4757.3	-736.5	526.0
	4	600.00	0.00	0.00	6967.4	-722.2	637.6
	5	800.00	0.00	0.00	9144.9	-710.6	796.4
	6	600.00	0.00	0.00	6968.7	-722.7	639.3

Table 4 — Calibration Loads and Bridge Outputs (continued)

		Calibration Loads			Bridge Outputs		
Series	**Point**	**A**	**B**	**C**	**r1**	**r2**	**r3**
	7	400.00	0.00	0.00	4761.1	-736.8	525.7
	8	200.00	0.00	0.00	2514.9	-752.4	459.6
	9	0.00	0.00	0.00	253.3	-769.4	438.0
4	1	0.00	0.00	0.00	237.5	-696.2	438.3
	2	400.00	800.00	0.00	5039.8	4275.8	554.7
	3	800.00	1600.00	0.00	9970.9	9463.7	921.8
	4	400.00	800.00	0.00	5041.2	4271.6	555.7
	5	0.00	0.00	0.00	236.9	-696.3	438.0
5	1	0.00	0.00	0.00	234.7	-769.1	549.8
	2	400.00	0.00	0.00	4757.4	-737.0	2527.9
	3	800.00	0.00	100.00	9134.1	=703.9	4754.8
	4	400.00	0.00	50.00	4758.0	-737.3	2528.9
	5	0.00	0.00	0.00	234.9	-769.8	549.5
6	1	0.00	0.00	0.00	145.5	-697.9	549.1
	2	0.00	800.00	50.00	281.7	4140.6	2435.3
	3	0.00	1600.00	100.00	411.3	9017.9	4381.8
	4	0.00	800.00	50.00	281.8	4137.8	2435.7
	5	0.00	0.00	0.00	145.4	-698.0	549.1

Step 1 Linear Matrix

The next step in the matrix determination process is to determine the linear matrix. The data shown in Table 5 were determined by subtracting the calibration loads and bridge outputs for the first point in each load series from all of the points in the series. In this process the, as yet undefined, tare loads cancel and thus have no influence on the linear matrix computation.

Table 5 — Linear Matrix Data

Load Series		Calibration Loads			Bridge Outputs		
	Point	A	B	C	r1	r2	r3
1	1	0.00	0.00	0.00	0	0	0
	2	0.00	0.00	25.00	-1.7	-1.6	937.8
	3	0.00	0.00	50.00	-3.4	-4.6	1894.2
	4	0.00	0.00	75.00	-5.3	-6.6	2865.8
	5	0.00	0.00	100.00	-8.3	-9.3	3854.4
	6	0.00	0.00	75.00	-5.1	-6.6	2864.9
	7	0.00	0.00	50.00	-3.2	-4.7	1894.7
	8	0.00	0.00	25.00	-1.7	-2.4	937.7
	9	0.00	0.00	0.00	0	-0.7	0.6
2	1	0.00	0.00	0.00	0	0	0
	2	0.00	400.00	0.00	70.7	2415.2	-2.8
	3	0.00	800.00	0.00	140.8	4840.1	-5.2
	4	0.00	1200.00	0.00	209.3	7276.1	-8.1
	5	0.00	1600.00	0.00	277.3	9723.9	-11.2
	6	0.00	1200.00	0.00	209.8	7276.5	-7.7
	7	0.00	800.00	0.00	1407	4841.3	-5
	8	0.00	400.00	0.00	70.9	2415.3	-2.4
	9	0.00	0.00	0.00	-0.6	0.3	-0.6
3	1	0.00	0.00	0.00	0	0	0
	2	200.00	0.00	0.00	2280.1	16.6	21.2
	3	400.00	0.00	0.00	4522.2	32.1	88.3
	4	600.00	0.00	0.00	6723.3	46.4	199.9
	5	800.00	0.00	0.00	8908.8	58	358.7
	6	600.00	0.00	0.00	6733.6	45.9	201.6
	7	400.00	0.00	0.00	4526	31.8	88
	8	200.00	0.00	0.00	2279.8	16.2	21.7
	9	0.00	0.00	0.00	0.2	-0.8	0.3
4	1	0.00	0.00	0.00	0	0	0
	2	400.00	800.00	0.00	4802.3	4972	116.4
	3	800.00	1600.00	0.00	9733.4	10159.9	483.5
	4	400.00	800.00	0.00	4803.7	4967.8	117.4

Table 5 — Linear Matrix Data (continued)

Load Series		Calibration Loads			Bridge Outputs		
	Point	A	B	C	r1	r2	r3
	5	0.00	0.00	0.00	-0.6	-0.1	-0.3
5	1	0.00	0.00	0.00	0	0	0
	2	400.00	0.00	50.00	4522.7	32.1	1978.1
	3	800.00	0.00	100.00	8899.4	65.2	4205
	4	400.00	0.00	50.00	4523.3	31.8	1979.1
	5	0.00	0.00	0.00	0.2	-0.7	-0.3
6	1	0.00	0.00	0.00	0	0	0
	2	0.00	800.00	50.00	136.2	4838.5	1886.2
	3	0.00	1600.00	100.00	265.8	9715.8	3832.7
	4	0.00	800.00	50.00	136.3	4835.7	1886.6
	5	0.00	0.00	0.00	-0.1	-0.1	0

The linear matrix is then determined from the data in Table 5 using linear regression.

Table 6 — Linear Matrix

	r1	r2	r3
A	1.135007E+01	1.929592E-01	5.175871E-01
B	2.447577E-01	6.122222E+00	2.458034E-02
C	-5.592301E-01	-2.660325E-01	3.834346E+01
A^2	NA	NA	NA
B^2	NA	NA	NA
C^2	NA	NA	NA
A*B	NA	NA	NA
A*C	NA	NA	NA
B*C	NA	NA	NA
Intercepts	-10.2	-18.3	-23.6

Now that the zero outputs and linear matrix have been determined, the tare iteration process can begin.

Step 2 Zero Load Outputs

The first step is to determine the zero load outputs. The zero load outputs are the averages of the bridge outputs contained in Table 3

	r1	r2	r3
Zero Load Outputs	123.1	-790.5	523.7

Step 3 Tare Iteration Process

In order to calculate the tare loads, the bridge outputs minus the zero load outputs arfe needed for the initial point in each load series. These data are shown in Table 7.

Table 7 — Modified Bridge Outputs for Tare Load Calculation

Load Series		Modified Bridge Outputs		
	Point	r1	r2	r3
1	1	20.3	20.6	26.0
2	1	20.3	19.9	26.6
3	1	112.0	21.9	-86.0
4	1	114.4	94.3	-85.4
5	1	111.6	21.4	26.1
6	1	22.4	92.6	25.4

The iterations in the tare process are shown in the following tables. There are three tables associated with each of the first three iterations, then the data associated with the fourth iteration, then Step4, the final step, in the matrix determination process.

Tare Iteration 1

The tare loads are calculated using the bridge outputs in Table 7 and the current matrix, which for the first iteration is the linear matrix. The calculated tare loads and the change in the tare loads from the values on the previous iteration are shown in Table 8.

Table 8 — Iteration 1 Tare Loads and Changes

Load	Tare Loads		
Series	A	B	C
1	1.749	3.338	0.657
2	1.547	15.044	-2.243
3	9.684	3.170	-2.350
4	9.640	14.997	-2.342
5	9.791	3.212	0.572
6	1.679	15.100	0.634
	Changes in Tare Loads		
	A	B	C
1	1.749	3.338	0.657
2	1.547	15.044	-2.243
3	9.684	3.170	-2.350
4	9.640	14.997	-2.342
5	9.791	3.212	0.572
6	1.679	15.100	0.634

Since the changes in the tare loads are all greater than the criterion of 0.002, the tare iteration process continues. The next step in the iteration process is to adjust the calibration loads for the tare loads. These values are shown in Table 9 and are used along with the measured bridge outputs from Table 4 to determine the interim matrix shown in Table 10.

Table 9 — Calibration Loads Adjusted for Iteration 1 Tare Loads

Load Series		Tare Adjusted Calibration Loads		
	Point	A	B	C
1	1	1.749	3.338	0.657
	2	1.749	3.338	25.657
	3	1.749	3.338	50.657
	4	1.749	3.338	75.657
	5	1.749	3.338	100.657
	6	1.749	3.338	75.657
	7	1.749	3.338	50.657
	8	1.749	3.338	25.657
	9	1.749	3.338	0.657
2	1	1.547	15.044	-2.243
	2	1.547	415.044	-2.243
	3	1.547	815.044	-2.243
	4	1.547	1215.044	-2.243
	5	1.547	1615.044	-2.243
	6	1.547	1215.044	-2.243
	7	1.547	815.044	-2.243
	8	1.547	415.044	-2.243
	9	1.547	15.044	-2.243
3	1	9.684	3.17	-2.35
	2	209.684	3.17	-2.35
	3	409.684	3.17	-2.35
	4	609.684	3.17	-2.35
	5	809.684	3.17	-2.35
	6	609.684	3.17	-2.35
	7	409.684	3.17	-2.35
	8	209.684	3.17	-2.35
	9	9.684	3.17	-2.35
4	1	9.64	14.997	-2.342
	2	409.64	814.997	-2.342

Table 9 — Calibration Loads Adjusted for Iteration 1 Tare Loads (continued)

Load Series		Tare Adjusted Calibration Loads		
	Point	A	B	C
	3	809.64	1614.997	-2.342
	4	409.64	814.997	-2.342
	5	9.64	14.997	-2.342
5	1	9.791	3.212	0.572
	2	409.791	3.212	50.572
	3	809.791	3.212	100.572
	4	409.791	3.212	50.572
	5	9.791	3.212	0.572
6	1	1.679	15.1	0.634
	2	1.679	815.1	50.634
	3	1.679	1615.1	100.634
	4	1.679	815.1	50.634
	5	1.679	15.1	0.634

Table 10 — Iteration 1 Interim Matrix

	r1	r2	r3
A	1.149095E+01	9.049354E-02	-1.589335E-02
B	1.792687E-01	6.025598E+00	-9.664532E-03
C	-5.604465E-02	-1.119671E-01	3.723273E+01
A^2	-4.351618E-04	-2.205033E-05	5.660014E-04
B^2	-3.276474E-06	3.144259E-05	3.499775E-07
C^2	-3.210643E-04	1.090150E-04	1.288842E-02
A*B	4.187651E-04	2.915137E-04	1.074299E-04
A*C	-1.488618E-05	2.036665E-04	-4.653757E-05
B*C	-2.978556	1.517363E-05	-3.462190E-05
Intercepts	123.3	-789.2	525.0

Tare Iteration 2

The tare loads are calculated from the bridge outputs in Table 7 and the interim matrix shown in Table 10. The calculated tare loads and the change in the tare loads from the values on the previous iteration are shown in Table 11.

Table 11 — Iteration 2 Tare Loads and Changes

Load Series	Tare Loads		
	A	B	C
1	1.717	3.406	0.700
2	1.707	15.364	-2.280
3	9.684	3.446	-2.308
4	9.702	15.454	-2.289
5	9.664	3.418	0.704
6	1.712	15.352	0.687
	Changes in Tare Loads		
1	-0.032	0.068	0.043
2	0.160	0.320	-0.037
3	0.000	0.276	0.042
4	0.062	0.457	0.053
5	-0.127	0.206	0.132
6	0.033	0.252	0.053

Since the changes in the tare loads are all greater than the criterion of 0.002, the tare iteration process continues. The calibration loads are adjusted by the tare loads in this iteration. These values are shown Table 12 and are used along with the measured bridge outputs from Table 4 to determine the interim matrix shown in Table 13.

Table 12 — Calibration Loads Adjusted for Iteration 2 Tare Loads

Load Series	Point	Tare Adjusted Calibration Loads		
		A	B	C
1	1	1.717	3.406	0.700
	2	1.717	3.406	25.700
	3	1.717	3.406	50.700
	4	1.717	3.406	75.700
	5	1.717	3.406	100.700
	6	1.717	3.406	75.700
	7	1.717	3.406	50.700
	8	1.717	3.406	25.700
	9	1.717	3.406	0.700
2	1	1.707	15.364	-2.280
	2	1.707	415.364	-2.280
	3	1.707	815.364	-2.280
	4	1.707	1215.364	-2.280

Table 12 — Calibration Loads Adjusted for Iteration 2 Tare Loads (continued)

Load Series	Point	Tare Adjusted Calibration Loads		
		A	B	C
	5	1.707	1615.364	-2.280
	6	1.707	1215.364	-2.280
	7	1.707	815.364	-2.280
	8	1.707	415.364	-2.280
	9	1.707	15.364	-2.280
3	1	9.684	3.446	-2.308
	2	209.684	3.446	-2.308
	3	409.684	3.446	-2.308
	4	609.684	3.446	-2.308
	5	809.684	3.446	-2.308
	6	609.684	3.446	-2.308
	7	409.684	3.446	-2.308
	8	209.684	3.446	-2.308
	9	9.684	3.446	-2.308
4	1	9.702	15.454	-2.289
	2	409.702	815.454	-2.289
	3	809.702	1615.454	-2.289
	4	409.702	815.454	-2.289
	5	9.702	15.454	-2.289
5	1	9.664	3.418	0.704
	2	409.664	3.418	50.704
	3	809.664	3.418	100.704
	4	409.664	3.418	50.704
	5	9.664	3.418	0.704
6	1	1.712	15.352	0.687
	2	1.712	815.352	50.687
	3	1.712	1615.352	100.687
	4	1.712	815.352	50.687
	5	1.712	15.352	0.687

Table 13 — Iteration 2 Interim Matrix

	r1	r2	r3
A	1.149331E+01	8.881776E-02	-2.158874E-02
B	1.765082E-01	6.024134E+00	-6.101123E-03
C	-2.301365E-02	-8.164838E-01	3.718696E+01
A^2	-4.379957E-04	-2.003118E-05	5.735061E-04
B^2	-2.159698E-06	3.222678E-05	-7.751177E-07
C^2	-6.137288E-04	8.977761E-05	1.339222E-02
A*B	4.196367E-04	2.906483E-04	1.039810E-04
A*C	-6.851466E-07	1.919610E-04	-1.051381E-04
B*C	-2.285021E-05	9.481323E-06	-6.119990E-05
Intercepts	123.0	-790.7	523.6

Tare Iteration 3

The tare loads are calculated from the bridge outputs in Table 7 and the interim matrix shown in Table 13. The calculated tare loads and the change in the tare loads from the values on the previous iteration are shown in Table 14.

Table 14 — Iteration 3 Tare Loads and Changes

Load	Tare Loads		
Series	A	B	C
1	1.715	3.403	0.700
2	1.716	15.379	-2.284
3	9.690	3.461	-2.310
4	9.710	15.472	-2.292
5	9.661	3.418	0.706
6	1.714	15.353	0.686
	Changes in Tare Loads		
1	-0.002	-0.003	0.000
2	0.009	0.015	-0.004
3	0.006	0.015	-0.002
4	0.008	0.018	-0.003
5	-0.003	0.000	0.002
6	0.002	0.001	-0.001

Since the changes in the tare loads are all greater than the criterion of 0.002, the tare iteration process continues. The calibration loads are adjusted by the tare loads in this iteration. These values are shown in Table 15 and are used along with the measured bridge outputs from Table 4 to determine the interim matrix shown in Table 16.

Table 15 — Calibration Loads adjusted for Iteration 3 Tare Loads

Load Series	Point	Tare Adjusted Calibration Loads A	B	C
1	1	1.715	3.403	0.7
	2	1.715	3.403	25.7
	3	1.715	3.403	50.7
	4	1.715	3.403	75.7
	5	1.715	3.403	100.7
	6	1.715	3.403	75.7
	7	1.715	3.403	50.7
	8	1.715	3.403	25.7
	9	1.715	3.403	0.7
2	1	1.716	15.379	-2.284
	2	1.716	415.379	-2.284
	3	1.716	815.379	-2.284
	4	1.716	1215.379	-2.284
	5	1.716	1615.379	-2.284
	6	1.716	1215.379	-2.284
	7	1.716	815.379	-2.284
	8	1.716	415.379	-2.284
	9	1.716	15.379	-2.284
3	1	9.69	3.461	-2.31
	2	209.69	3.461	-2.31
	3	409.69	3.461	-2.31
	4	609.69	3.461	-2.31
	5	809.69	3.461	-2.31
	6	609.69	3.461	-2.31
	7	409.69	3.461	-2.31
	8	209.69	3.461	-2.31
	9	9.69	3.461	-2.31
4	1	9.71	15.472	-2.292
	2	409.71	815.472	-2.292
	3	809.71	1615.472	-2.292
	4	409.71	815.472	-2.292
	5	9.71	15.472	-2.292

Table 15 — Calibration Loads adjusted for Iteration 3 Tare Loads (continued)

Load Series	Point	Tare Adjusted Calibration Loads		
		A	B	C
5	1	9.661	3.418	0.706
	2	409.661	3.418	50.706
	3	809.661	3.418	100.706
	4	409.661	3.418	50.706
	5	9.661	3.418	0.706
6	1	1.714	15.353	0.686
	2	1.714	815.353	50.686
	3	1.714	1615.353	100.686
	4	1.714	815.353	50.686
	5	1.714	15.353	0.686

Table 16 — Iteration 3 Interim Matrix

	r1	r2	r3
A	1.149328E+01	8.865550E-02	-2.161381E-02
B	1.763842E-01	6.024059E+00	-5.925749E-03
C	-2.037821E-02	-7.907156E-01	3.718351E+01
A^2	-4.379957E-04	-1.992653E-05	5.735620E-04
B^2	-2.109658E-06	3.225643E-05	-8.476503E-07
C^2	-6.360083E-04	-1.110618E-04	1.342175E-02
A*B	4.196726E-04	2.906700E-04	1.039195E-04
A*C	1.695006E-08	1.924810E-04	-1.062405E-04
B*C	-2.249623E-05	9.747053E-06	-6.169293E-05
Intercepts	123.0	-790.7	523.7

Tare Iteration 3

The tare loads are calculated from the bridge outputs in Table 7 and the interim matrix shown in Table 16. The calculated tare loads and the change in the tare loads from the values on the previous iteration are shown in Table 17.

Table 17 — Iteration 4 Tare Loads and Changes

Load Series	Tare Loads		
	A	B	C
1	1.715	3.403	0.701
2	1.717	15.381	-2.285
3	9.690	3.462	-2.310
4	9.710	15.473	-2.292
5	9.661	3.418	0.706
6	1.714	15.353	0.686
Load Series	**Changes in Tare Loads**		
	A	**B**	**B**
1	0.000	0.000	0.001
2	0.001	0.002	-0.001
3	0.000	0.001	0.000
4	0.000	0.001	0.000
5	0.000	0.000	0.000
6	0.002	0.001	-0.001

Now the changes in the tare loads are all equal to or less than the criterion of).002. The tare iteration process is therefore complete.

Step 4 Final Matrix

The final step in the matrix determination process is to calculate a final matrix based on the final tare loads adjusted calibration loads. The calibration loads adjusted by the final tare loads are shown in Table 18. These adjusted loads are used along with the measured bridge outputs from Table 4 to determine the final calibration matrix, which is shown in Table 19. The matrix determination process is now complete.

Table 18 — Calibration Loads Adjusted for the Final Tare Loads

Load Series	Point	Tare Adjusted Calibration Loads		
		A	B	C
1	1	1.715	3.403	0.701
	2	1.715	3.403	25.701
	3	1.715	3.403	50.701
	4	1.715	3.403	75.701
	5	1.715	3.403	100.701
	6	1.715	3.403	75.701
	7	1.715	3.403	50.701
	8	1.715	3.403	25.701
	9	1.715	3.403	0.701

Table 18 — Calibration Loads Adjusted for the Final Tare Loads (continued)

Load Series	Point	Tare Adjusted Calibration Loads		
		A	B	C
2	1	1.717	15.381	-2.285
	2	1.717	415.381	-2.285
	3	1.717	815.381	-2.285
	4	1.717	1215.381	-2.285
	5	1.717	1615.381	-2.285
	6	1.717	1215.381	-2.285
	7	1.717	815.381	-2.285
	8	1.717	415.381	-2.285
	9	1.717	15.381	-2.285
3	1	9.69	3.462	-2.31
	2	209.69	3.462	-2.31
	3	409.69	3.462	-2.31
	4	609.69	3.462	-2.31
	5	809.69	3.462	-2.31
	6	609.69	3.462	-2.31
	7	409.69	3.462	-2.31
	8	209.69	3.462	-2.31
	9	9.69	3.462	-2.31
4	1	9.71	15.473	-2.292
	2	409.71	815.473	-2.292
	3	809.71	1615.473	-2.292
	4	409.71	815.473	-2.292
	5	9.71	15.473	-2.292
5	1	9.661	3.418	0.706
	2	409.661	3.418	50.706
	3	809.661	3.418	100.706
	4	409.661	3.418	50.706
	5	9.661	3.418	0.706
6	1	-1.714	-15.353	-0.686
	2	-1.714	784.647	49.314
	3	-1.714	1584.647	99.314
	4	-1.714	784.647	49.314
	5	-1.714	-15.353	-0.686

Table 19 — Final Calibration Matrix

	r1	r2	r3
A	1.149327E+01	8.867369E-02	-2.160496E-02
B	1.763771E-01	6.024053E+00	-5.916313E-03
C	-2.016247E-02	-7.885715E-02	3.718323E+01
A^2	-4.379893E-04	-1.991730E-05	5.735552E-04
B^2	-2.106897E-06	3.225855E-05	-8.515281E-07
C^2	-6.378172E-04	-1.128533E-04	1.342405E-02
A*B	4.196750E-04	2.906722E-04	1.039160E-04
A*C	6.736297E-08	1.925309E-04	-1.062996E-04
B*C	-2.246933E-05	9.772504E-06	-6.172310E-05
Intercepts	123.0	-790.7	523.7

4 Calibration Documentation

Use of a balance requires information describing the balance and its calibration. For instance, a user may need to know the limitations of the calibration for proper balance selection to meet a customer's test objectives. One item that must be known is how the balance was connected to the instrumentation in the calibration laboratory. In spite of this, balance users oftentimes are not involved with a calibration and consequently do not have first hand knowledge of the balance. Therefore, adequate documentation of the balance and its calibration is essential. This is even more important if the balance is to be loaned to another facility. The following sections give descriptions of the type of documentation that should accompany a balance and its calibration.

4.1 Matrix File

The matrix file is a comma-delimited ASCII text file that will be used to transmit the calibration matrix and the information necessary for its use. The contents and order of the file are described in Table 20. Except for item number 12, each item in Table 20 is a line of information contained in the Matrix File. Item 12 is the calibration matrix and is to be transmitted in transposed form using the following formats:

- Include labels for each column and row
- Coefficients in E14.6 format (b±#.######E±##)

An example of a calibration matrix is shown in Table 21 and is described in further detail in Sections 3.1 and 3.2. The example calibration matrix is presented for a Moment balance, a matrix for the other balance types would have the same appearance and information; only the nomenclature for the row and column headings would change. Note that the first six rows are labeled with the nomenclature for the component loads and a designation consisting of the component number from Table 1. The remaining rows are only labeled using the component number or combinations of component numbers. For example; the 1.1 designation means component 1 squared, 3.4 means component 3 multiplied by component 4, I3.5I means the absolute value of component 3 multiplied by component 5, and 4.I5I means component 4 multiplied by the absolute value of component 5. Although the component nomenclature will vary for the first six rows, depending on the balance type, the nomenclature for the remaining 90 rows is constant and does not vary with balance type.

Table 20 — Contents of the Calibration Matrix File

No.	Item	Description
1	Calibration Facility / Data Analysis	The name of the facility performing the calibration and the data analysis (may be the same or different facilities).
2	Calibration Number	Alphanumeric designation of the balance calibration assigned by the originating facility
3	Balance Identification	Alphanumeric designation of the balance (e.g., 1.5” MK-XXI M)
4	Balance Type	Force, Moment, or Direct-Read *see Section 2.3 for more details*
5	Calibration Date	DAY/MONTH/YEAR (DD/MM/YYYY)
6	Convergence Criteria	The maximum allowable difference between calculated loads from successive iterations through the matrix equations, indicates that the matrix iteration has adequately arrived at or converged on a solution, *see Section 3.3 for more details*
7	Maximum Rated Loads	Maximum designated load for each balance component, in lbs & in-lbs, (See Section 2.4 for guidelines and details.)
8	Calibration Temperature	Average balance temperature at time of calibration; it could correspond to ambient or room temperature, a direct measurement of temperature in the balance (via temperature sensors in the balance) or the temperature to which the balance is heated or cooled, in °F
9	Temperature Correction Constants	Coefficients used in an algorithm to correct for thermal effects (not including thermal gradients) on the balance
10	BMC to Gage Distances (X_1, X_2, X_3, X_4)	X_1, X_2, X_3, X_4 are distances, in inches, of the BMC (Balance Moment Center) from each balance gage, (See Section 2.2 for more detail.)
11	Additional Comments	Any additional comments which may aid in the use of the matrix file and its contents (particularly concerning the calibration matrix), including calibration matrix input and output units
12	Calibration Matrix	6 by 96 matrix coefficients generated from the balance calibration, (See Section 3.1.1 for more detail.)

Table 21 — Sample Calibration Matrix File

AEDC MT&L Cal Lab / AEDC
9001
4.00-Y-36-090
Moment
9/3/1998
1.000E-06*(Max. Rated Loads)
2000.0, 2000.0, 2000.0, 2000.0, 100.0, 50.0
72
0.0, 0.0, 0.0, 0.0, 0.0, 0.0
3.1392, -3.8828, 3.1415, -3.8942
Comments, Units

Col. No.	Row ID	rPM1	rPM2	rYM1	rYM2	rRM	rAF
1	PM1	0.000000E+00	0.000000E+00,	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
2	PM2	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
3	YM1	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
4	YM2	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
5	RM	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
6	AF	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
7	l1l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
8	l2l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
9	l3l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
10	l4l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
11	l5l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
12	l6l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
13	1.1	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
14	2.2	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
15	3.3	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
16	4.4	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
17	5.5	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
18	6.6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
19	1.l1l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
20	2.l2l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
21	3.l3l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00

Table 21 — Sample Calibration Matrix File (continued)

Col. No.	Row ID	rPM1	rPM2	rYM1	rYM2	rRM	rAF
22	4.l4l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
23	5.l5l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
24	6.l6l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+0	00.000000E+00
25	1.2	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
26	1.3	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
27	1.4	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
28	1.5	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
29	1.6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
30	2.3	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
31	2.4	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
32	2.5	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
33	2.6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
34	3.4	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
35	3.5	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
36	3.6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
37	4.5	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
38	4.6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
39	5.6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
40	l1.2l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
41	l1.3l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
42	l1.4l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
43	l1.5l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
44	l1.6l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
45	l2.3l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
46	l2.4	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
47	l2.5l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
48	l2.6l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
49	l3.4l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
50	l3.5l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
51	l3.6l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
52	l4.5l	l0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
53	l4.6l	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00

Table 21 — Sample Calibration Matrix File (continued)

Col. No.	Row ID	rPM1	rPM2	rYM1	rYM2	rRM	rAF
54	I5.6I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
55	1.I2I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
56	1.I3I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
57	1.I4I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
58	1.I5I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
59	1.I6I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
60	2.I3I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
61	2.I4I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
62	2.I5I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
63	2.I6I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
64	3.I4I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
65	3.I5I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
66	3.I6I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
67	4.I5I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
68	4.I6I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
69	5.I6I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
70	I1I.2	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
71	I1I.3	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
72	I1I.4	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
73	I1I.5	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
74	I1I.6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
75	I2I.3	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
76	I2I.4	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
77	I2I.5	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
78	I2I.6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
79	I3I.4	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
80	I3I.5	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
81	I3I.6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
82	I4I.5	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
83	I4I.6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
84	I5I.6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
85	1.1.1	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00

Table 21 — Sample Calibration Matrix File (continued)

Col. No.	Row ID	rPM1	rPM2	rYM1	rYM2	rRM	rAF
86	2.2.2	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
87	3.3.3	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
88	4.4.4	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
89	5.5.5	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
90	6.6.6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
91	I1.1.1I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
92	I2.2.2I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
93	I3.3.3I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
94	I4.4.4I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
95	I5.5.5I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
96	I6.6.6I	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00

4.2 Calibration Report

The calibration matrix file provides only the information absolutely necessary to use the calibration matrix and does not contain additional information vital to the use of the balance. A calibration report, containing the additional information on the calibration process, results, and other pertinent information, should be prepared and provided with the calibration matrix and data. The information to be included in a calibration report is described below in Tables 22 through 25 and is grouped into four areas: a) General Information, b) Balance Details, c) Calibration Details, and d) Data Reduction. This report need not contain the information in the exact order, or be organized in the manner that is reported here. However, it is important that all listed information be addressed at some point in the calibration report. A sample calibration report is shown in Section 4.7.

Table 22 — General Information for a Calibration Report

Item	Description
Facility Designation	A standardized alphanumeric designation which uniquely identifies the Calibration/ Wind Tunnel facility where the balance calibration was performed
Calibration Number	Alphanumeric designation of the balance calibration assigned by the originating facility
Balance Identification	Alphanumeric designation of the balance (e.g., 1.5” MK-XXI M)
Balance Type	Force, Moment, or Direct-Read see Section 2.3 for more details
Name of Calibration Contact	Name of the person or persons responsible for the balance and its calibration
Additional Comments	Any additional comments which may aid the wind tunnel facility’s utilization of the balance, such as the inclusion of tare corrections

Table 23 — Balance Details for a Calibration Report

Item	Description
Balance Manufacturer	Name of balance manufacturer (e.g., Able (Task), MM&T, MicroCraft, etc.)
Balance Sketch	Sketch or illustration of the balance with dimensions such as diameter(s), length, pin location(s), taper dimensions, gage locations, BMC location, etc.
Load Rhombus Sketch	A two dimensional graphical sketch illustrating the allowable load ranges of the balance, usually plotting applied force versus applied moment
Safety Factors & Basis	Assigned safety factor of the balance and an explanation of the basis for that factor (e.g., based on a ratio of ultimate material strength and maximum-allowed stress level when all balance components loaded simultaneously)
Material Type	Material used in balance manufacture (e.g., Vascomax, 17-4ph Stainless, etc.)
Zero Load Output & Explanation	Balance signal output at no-load (bare balance) and a description of how it is defined (e.g., an average of the bare balance output at roll angles of 0°, 90°, 180°, and 270°)
Is a Dummy Balance Available	Indication if a dummy balance of the same size and dimensions as the “live” balance, is available
Attachment Methodology	Description of the method the balance attaches to the calibration body (or model center body) and support sting (e.g., Taper, clutch face, sleeve, etc.)
Wires per Bridge	Number of wires per balance bridge
Wiring Diagram	A schematic of the bridge wiring including identification of power, signal, sense, and/or shunt lines and their wire colors
Wire Color Code	Colors of wires and their identification (i.e., ± powers, ± signals, etc.) for each balance bridge or pin connector assignment
Gage Resistance	Resistance(s) of Gages used for each balance bridge, in ohms
Bridge Resistance	Total resistance of each bridge, identifying resistance across ±Power and ±Signal (two numbers) and where these outputs were obtained (e.g., at the end of the cables), in ohms
Balance Excitation Range	The allowable excitation supply range for each balance bridge, in volts or milliamps
Connector Type	Identification of connector types on the end of the balance cables (e.g., plugs, pins, bare wires)

Table 23 — Balance Details for a Calibration Report (continued)

Item	Description
Gage Manufacturer	Manufacturer of the gage(s) used in the balance (e.g., Micro-Measurements)
Gage Type	Type of gage(s) (e.g., foil, semi-conductor)
Type of Temperature Sensors	Description of the type of temperature sensors in the balance (e.g., I-C thermocouple, RTD, Thermistor) and their locations inside the balance

Table 24 — Calibration Details for a Calibration Report

Item	Description
Calibration Date	Date at which the calibration was performed
Balance Calibration Type	A description of type or scope of calibration performed on the balance whether it be one component, two component, multiple component loadings, or other types of loadings, also indicating whether the calibration was performed manually or on an automatic calibration machine and what equipment was used
Which Bridges are used	Indication of which bridges were used (if the balance has extra bridges) and the order in which they were assigned (i.e., as they are assigned in the calibration matrix)
Pin Location	If balance was pinned, provide a description of how the balance was held during the calibration and location, measured in inches from some known reference point on the balance
Calibration Body Identification	The facility’s alphanumeric designation of the calibration body used in the calibration
Calibration Temperature	Average balance temperature at time of calibration: it could correspond to ambient or room temperature, a direct measurement of temperature in the balance (via temperature sensors in the balance) or the temperature to which the balance is heated or cooled, in units of °F
± Maximum Calibration Loads	Maximum positive and negative loads applied to each balance component during the calibration, in lbs & in-lbs
± Maximum Calibration Bridge Output	Maximum positive and negative output for each bridge during the calibration
Excitation Supply	Nominal excitation(s) supplied to each balance bridge during the calibration, in volts or milliamps
Shunts and where used	The resistance(s), in ohms, of the shunts used on the balance and where those shunts were applied (e.g., at end of balance cable and across what bridge legs)

Table 24 — Calibration Details for a Calibration Report (continued)

Item	Description
Shunt Output	Bridge output when shunt is applied
Balance Statistics	The mean, standard deviation, minimum, and maximum of the residual load errors. The residual load errors are defined as the difference between back-calculated and applied loads through the calibration matrix (See Sections 4.4 and 4.5 for more details.) Include information on how many data points were used and if applicable, the normalizing value(s) (e.g., balance design loads)

Table 25 — Data Reduction Description for a Calibration Report

Item	Description
X_1, X_2, X_3, X_4 Distances	X_1, X_2, X_3, X_4 are distances, in inches, from the BMC to each balance gage, (See Section 2.2 for more detail.)
BMC (Balance Moment Center)	Longitudinal point along the X axis of the balance about which all moment loads are resolved, indicating a distance from some known reference (e.g., front face of the balance) in inches, include an illustration
Primary Constants	The slopes or sensitivities of each balance component, in microvolt/EU @ one-volt excitation (EU = Engineering units)
Balance Deflection Constants	Relationship(s) of balance deflection to applied load, in °/EU (Engineering units)
Temperature Correction Scheme	Provide temperature correction algorithm and constants for the balance
Calibration Matrix	6 x 96 matrix coefficients generated from the balance calibration, (See Section 3.1 for more detail.)
Convergence Criteria	The maximum allowable difference between calculated loads from successive iterations through the matrix equations, indicates that the matrix iteration has adequately arrived at or converged on a solution, (See Section 3.3 for more detail.)

4.3 Calibration Load Envelope

The calibration report should include a description of the applied load envelope during the balance calibration. This description should mention the total number of data points making up the calibration database, the type of loading (single-component, two-component, or multi-component loading) applied during the calibration, and the number of load points in each of these calibration database subsets. The various component loadings should be described in some detail. Alternatively, the load schedule could be shown in graphical form by plotting the loading on each balance component as a function of database point number. An example of such a plot is shown in Figure 3, which presents the calibration load data of the example case given in Figure 2.

The sample calibration database shown in Figure 3 contains 42 load points. Single-component loading is applied to each of the three balance components with 9 load points per load cycle for a total of 27 single-component load points. Two-component loading is applied to each two-component combination with 5 load points per load cycle for a total of 15 two-component load points.

Review of Figure 3 shows that single component loading was applied to each component; component A: points 19-27; component B: points 10-18; and component C: points 1-9. Two-component loading was applied by loading the two selected components to 50% and 100% of the maximum component loading. For example, points 28-33 of Figure 3 show that a 50% and 100% maximum loading was applied to components A and B. Similarly, points 38-42 show a 50% and 100% maximum loading on components B and C.

Displaying the calibration data in the form of a two-component plot is a good way to indicate to the balance user the type of two-component loading that was applied to the balance. Such a two-component plot for each possible component combination is shown in Figure 4, where the loading has been normalized by the maximum applied calibration loading on each component. The left most plot in Figure 4 shows that the loading on component A was cycled from zero to maximum loading, while the loading on component B was held constant at a zero loading. This subplot also shows that component B was loaded from zero to maximum loading while component A was held constant at zero loading. Finally, the data points on the 45 degree lines indicate that 50% and 100% simultaneous loading was applied to the A and B component. The middle sub-plot in Figure 4 shows that the same type of single and combined loading was applied to components A and C, whereas the right most plot in Figure 4 shows that this type of loading on components B and C. In addition, the two-component load envelope plots can be used as a tool in the selection of calibration coefficients.

Care should be exercised in that linear dependencies may exist in the data although the two-component envelope plots may suggest otherwise. For example, a load envelope for a three component Force balance is shown in Figure 5 (note that this data set is different than that shown in Figure 3). Based on this load envelope, the user may be tempted to compute NF1*RM and NF2*RM. Although it is not obvious from the load envelope plots, there may be linear dependencies in the NF1 and NF2 data when considering their cross product terms with rolling moment, RM. Typically, a roll moment is introduced by placing the balance x-axis in the horizontal plane and applying the loading in the y-z plane through the balance center, but with a horizontal offset from the balance x-axis. With the balance x-z-plane being the vertical plane, a vertical loading in the y-z-plane will result in a simultaneous loading of NF1, NF2, and RM. In this loading scheme, the NF1 and NF2 loads are linearly dependent. Therefore, separate data do not exist for the NF1*RM and the NF2*RM load combinations (i.e., no independent variation of NF1 or NF2 occurred while RM varied). In this case, only one of the two cross-component terms, NF1*RM or NF2*RM, can be computed. However, if the combinations loading of NF1 with RM and NF2 with RM are obtained independently by a different loading scheme, then both cross-component terms could be computed.

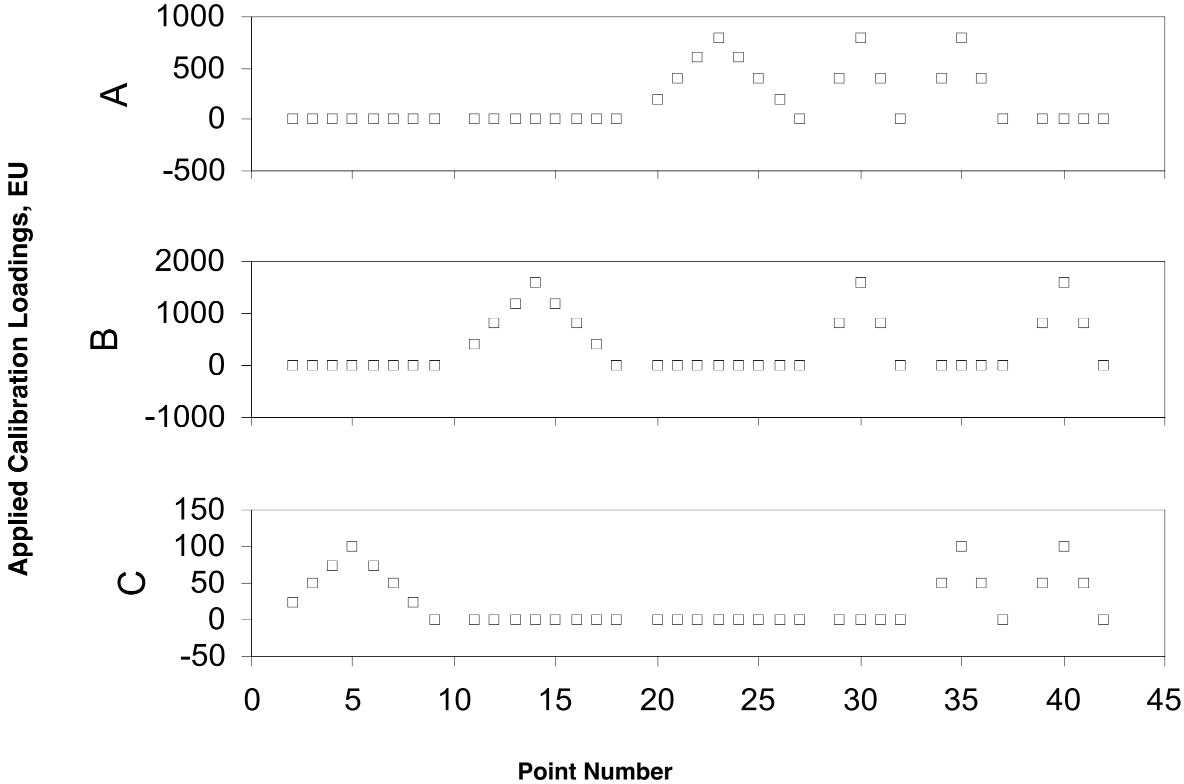


Figure 4 — Applied Loading as Function of Database Point Number

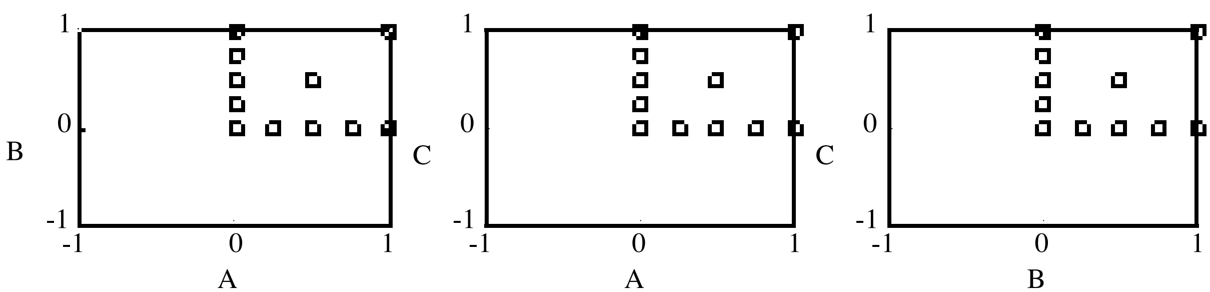


Figure 5 — Normalized Calibration Loading in Two-component Load Envelope Format

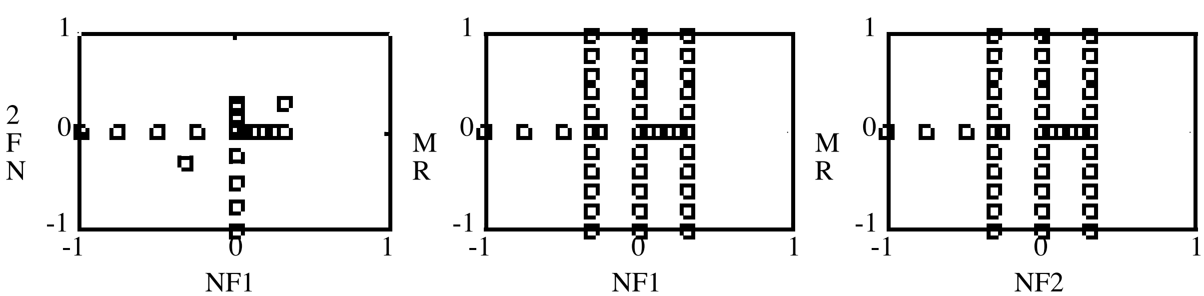


Figure 6 — Load Envelope Sample for a Three-Component Force Balance

4.4 Residual Load Error

The calibration matrix should be used to compute (or estimate) the balance loading from the bridge output. This estimated calibration loading is referred to as the back-calculated loading. The residual load error, defined as the difference between the estimated balance loading and the applied loading, should be determined for each calibration point. The back-calculated loads and residuals for the three-component example provided in Section 3.6 are shown in Table 27. The residual error of the back-calculated calibration loading is a measure of how well the assumed math model, represented by the calibration matrix, is able to fit the calibration data. The experimentally determined zero load outputs terms are used when estimating the back-calculated residual load errors. Note however that the values of the zero load output terms established during the calibration are never relevant to load computations outside the calibration. Instead, the bridge outputs corresponding to the load datum used in the calibration, ideally zero absolute load, must be re-established from measurements made using the test environment instrumentation. (See Section 3.4.1.)

Table 26 — Back-calculated Data and Residuals

Load		Total Applied Loads			Back-calculated Loads			Residual Loads		
Series	Point	A	B	C	A	B	C	A	B	C
1	2	1.715	3.403	25.701	1.647	3.477	25.684	-0.068	0.073	-0.017
	3	1.715	3.403	50.701	1.651	3.341	50.715	-0.064	-0.063	0.014
	4	1.715	3.403	75.701	1.704	3.392	75.705	-0.011	-0.011	0.004
	5	1.715	3.403	100.701	1.733	3.352	100.700	0.017	-0.051	0.000
	6	1.715	3.403	75.701	1.721	3.392	75.682	0.006	-0.011	-0.019
	7	1.715	3.403	50.701	1.669	3.324	50.728	-0.046	-0.079	0.027
	8	1.715	3.403	25.701	1.649	3.344	25.681	-0.066	-0.059	-0.019
	9	1.715	3.403	0.701	1.717	3.287	0.717	0.002	-0.116	0.016
2	2	1.717	415.381	-2.285	1.735	415.352	-2.296	0.018	-0.029	-0.011
	3	1.717	815.381	-2.285	1.760	815.220	-2.289	0.043	-0.161	-0.004
	4	1.717	1215.381	-2.285	1.705	1215.221	-2.288	-0.012	-0.160	-0.003
	5	1.717	1615.381	-2.285	1.663	1615.464	-2.285	-0.054	0.083	0.000
	6	1.717	1215.381	-2.285	1.746	1215.284	-2.277	0.029	-0.097	0.007
	7	1.717	815.381	-2.285	1.749	815.418	-2.283	0.032	0.037	0.001
	8	1.717	415.381	-2.285	1.752	415.368	-2.285	0.035	-0.013	0.000
	9	1.717	15.381	-2.285	1.664	15.431	-2.301	-0.053	0.050	-0.016
3	2	209.690	3.462	-2.310	209.725	3.400	-2.304	0.034	-0.062	0.006
	3	409.690	3.462	-2.310	409.493	3.423	-2.295	-0.198	-0.039	0.016
	4	609.690	3.462	-2.310	609.528	3.506	-2.325	-0.163	0.044	-0.015
	5	809.690	3.462	-2.310	809.797	3.408	-2.325	0.107	-0.054	-0.015
	6	609.690	3.462	-2.310	609.649	3.424	-2.281	-0.041	-0.038	0.029
	7	409.690	3.462	-2.310	409.835	3.370	-2.307	0.145	-0.092	0.003
	8	209.690	3.462	-2.310	209.700	3.335	-2.290	0.009	-0.127	0.020

Table 26 — Back-calculated Data and Residuals (continued)

Load Series	Point	Total Applied Loads A	Total Applied Loads B	Total Applied Loads C	Back-calculated Loads A	Back-calculated Loads B	Back-calculated Loads C	Residual Loads A	Residual Loads B	Residual Loads C
	9	9.690	3.462	-2.310	9.710	3.329	-2.302	0.020	-0.133	0.008
4	2	409.711	815.474	-2.293	409.575	815.853	-2.312	-0.135	0.379	-0.020
	3	809.711	1615.474	-2.293	809.732	1615.404	-2.289	0.022	-0.070	0.004
	4	409.711	815.474	-2.293	409.718	815.168	-2.287	0.007	-0.306	0.006
	5	9.711	15.474	-2.293	9.659	15.458	-2.301	-0.052	-0.016	-0.008
5	2	409.661	3.418	50.706	409.746	3.385	50.678	0.084	-0.033	-0.028
	3	809.661	3.418	100.706	809.589	3.395	100.715	-0.072	-0.023	0.009
	4	409.661	3.418	50.706	409.801	3.336	50.703	0.140	-0.082	-0.003
	5	9.661	3.418	0.706	9.680	3.301	0.698	0.019	-0.117	-0.008
6	2	1.714	815.353	50.686	1.668	815.558	50.693	-0.045	0.206	0.007
	3	1.714	1615.353	100.686	1.721	1615.313	100.680	0.007	-0.040	-0.006
	4	1.714	815.353	50.686	1.684	815.097	50.704	-0.030	-0.256	0.017
	5	1.714	15.353	0.686	1.705	15.336	0.686	-0.008	-0.016	0.000

4.5 Calibration Statistics

A number of statistical measures should be included in the calibration report to aid the balance user in quantifying the uncertainty in the balance load estimation. The mean, the standard deviation, the minimum, and maximum of the residual load errors should be provided in the calibration data report. Table 27 shows the suggested statistical quantities for the sample database, which is previously reported in Figure 2. The same type of statistical information should be calculated and reported for any check loading that may be applied to the balance.

It should be noted that the initial points in each load series of Table 21 are not included in the residual error results of Table 26 and are therefore not included in computing the statistics of Table 27. These initial points are used to compute the tare loads on the balance for each load series. In computing statistics to evaluate the fit, these initial data points should not be included because they do not bring any independent information to the process. The result of this is that the degrees-of-freedom in the overall curve-fit process have been reduced by the number of load series in the calibration database.

It is suggested that the residual load error for each component be shown graphically as a function of the point number in the balance calibration data. The applied calibration loading could also be presented in the same figure. This graphical depiction of the applied loading and residual load error allows the balance user to quickly obtain a measure of the uncertainty in the load estimation due to uncertainty introduced by the curve fit math model. An example of such a residual load error plot is shown in Figure 7. The initial load point for each series, which are equivalent to calibration points 1, 10, 19, 28, 33, and 38, have been omitted from the residual error plots in Figure 7. The top three sub-plots of Figure 7 show the residual load error as the back-calculated loading minus the applied loading for the three balance components. A positive residual error therefore indicates that the back-calculated loading is greater than the applied loading, while an underestimation of the applied loading will result in a negative residual error in Figure 7. The bottom three sub-plots of Figure 7 show the applied calibration loading for each of the three balance components.

Normalizing the balance loading, the balance load error and the various statistical measurements will aid in quantifying the relative magnitude of the uncertainty in the load estimation for the various balance components. The normalization loading could be the balance component capacity, the maximum loading due to calibration weights, or the maximum applied loading including calibration weight tares. The normalization loading used in this example is the maximum applied calibration loading, excluding the calibration tare weight. The normalization loading for each balance component should be clearly stated in the calibration report and in this case are included in Table 27. The statistical measurements in normalized format are also included in Table 27 for the three-component example.

The residual errors for each balance component are divided by that component's normalization loading to arrive at the normalized residual load error. The normalized residual loading typically is reported in percent of the normalization loading. A sample of the normalized load error plot is shown in Figure 8. The top three sub-plots of Figure 8 show the normalized residual error of estimated loading minus applied loading in percent of the normalization loading and the bottom three sub-plots show the applied loading in percent of the normalization loading for each of the three balance components.

Presenting the results in graphical format as shown in Figures 7 and 8 illustrates more clearly any deficiency of the curve fit model, represented by the calibration matrix, in estimating the calibration loadings.

Table 27 — Calibration Statistical Data

	A	B	C
Engineering Units			
Standard deviation	0.072	0.117	0.014
Average residual	-0.010	-0.041	0.000
Maximum residual	0.145	0.379	0.029
Minimum residual	-0.198	-0.306	-0.028
Normalization loading in Engineering Units			
Normalization loading, EU	800	1600	100
In percent of normalization loading			
Standard deviation	0.009%	0.007%	0.014%
Average residual	0.001%	0.002%	0.000%
Maximum residual	0.018%	0.024%	0.029%
Minimum residual	-0.024%	-0.023%	-0.028%

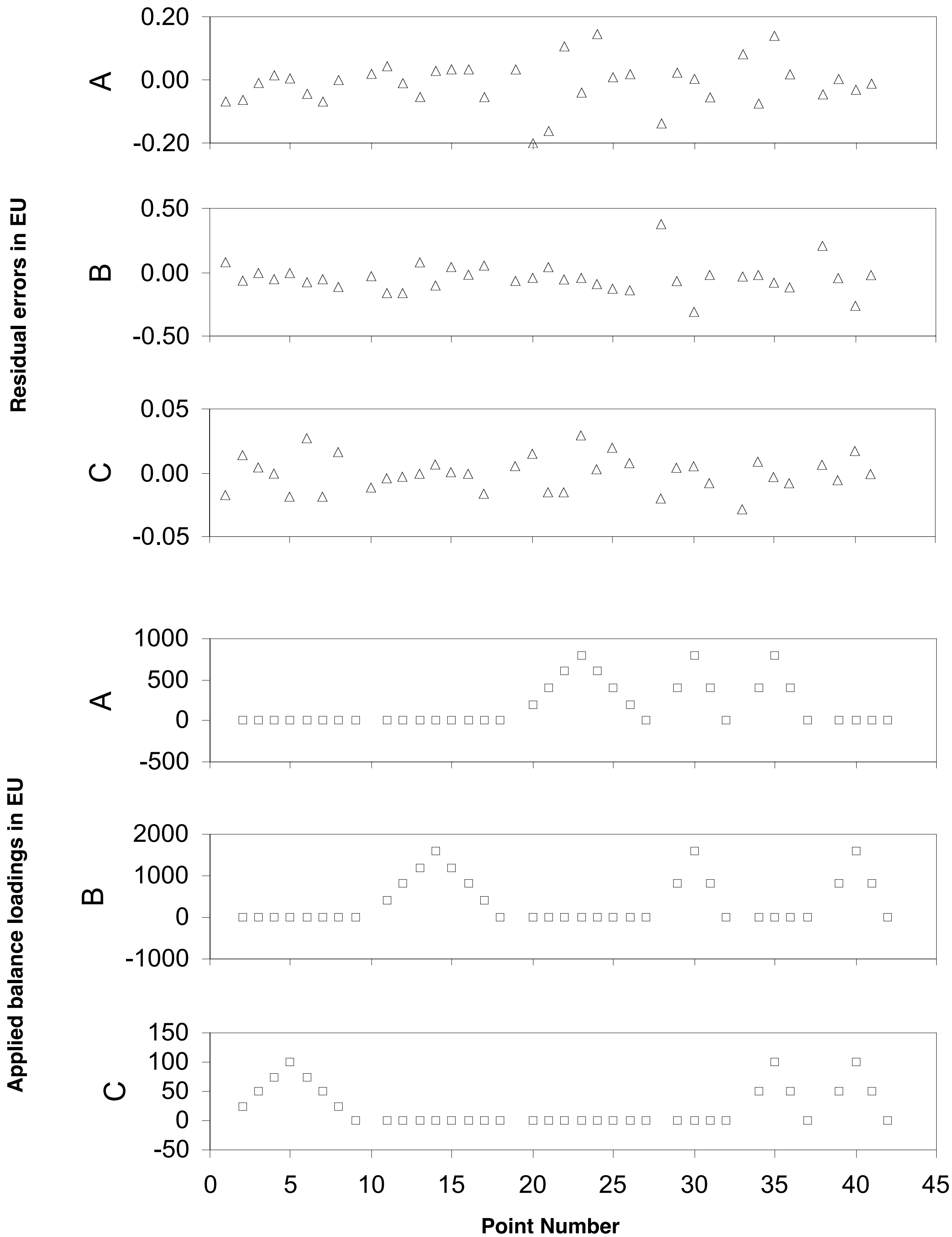


Figure 7 — Residual Load Error and Applied Loading as Function of Load Point Number

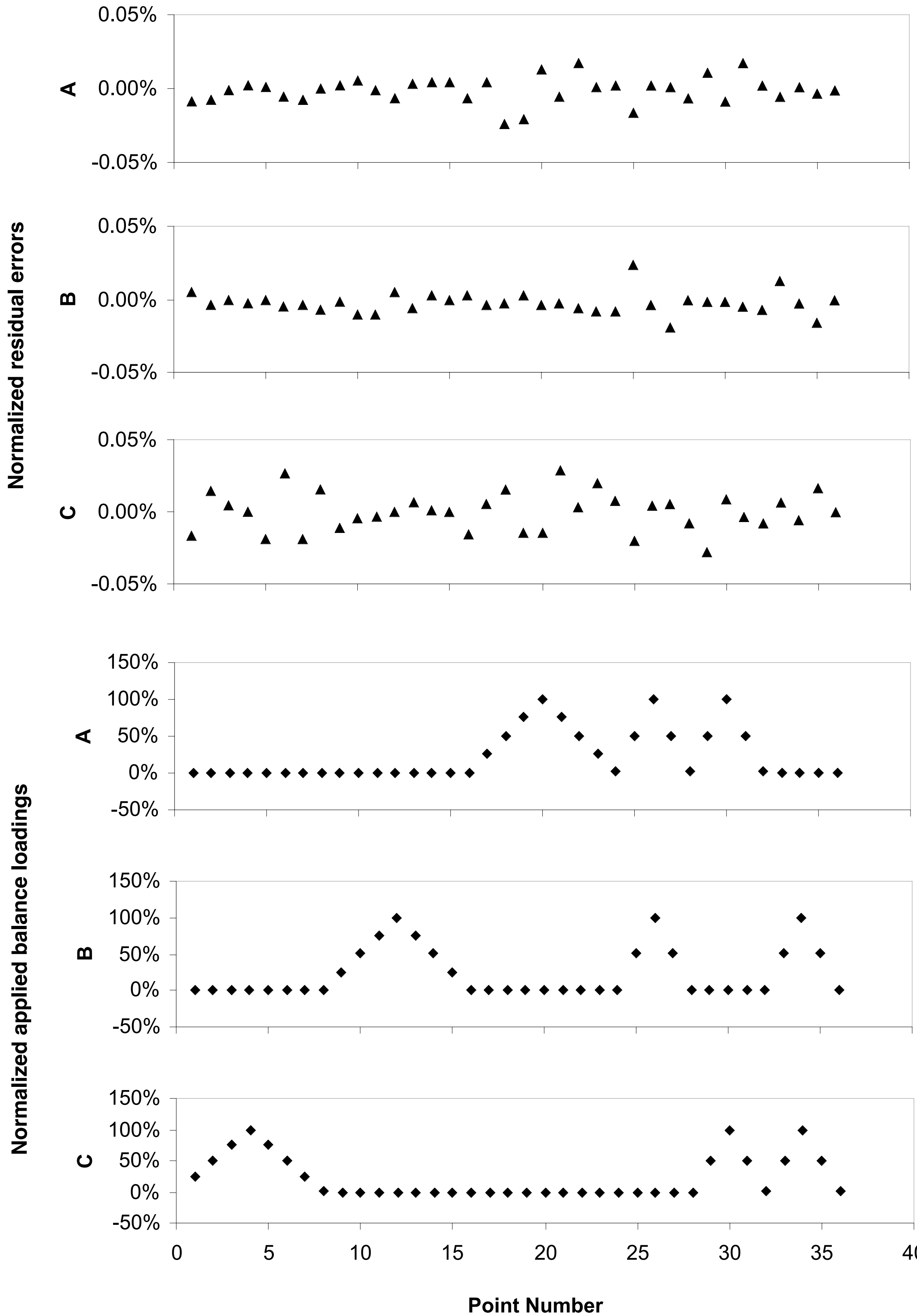


Figure 8 — Normalized Residual Load Error and Normalized Applied Loading as Function of Load Point Number

Some additional insight into the uncertainty of the balance load estimate might be gained by plotting a histogram of the load error distribution. Such a plot is shown in Figure 9, which also shows the normal distribution as computed from the standard deviation of the normalized residual load error.

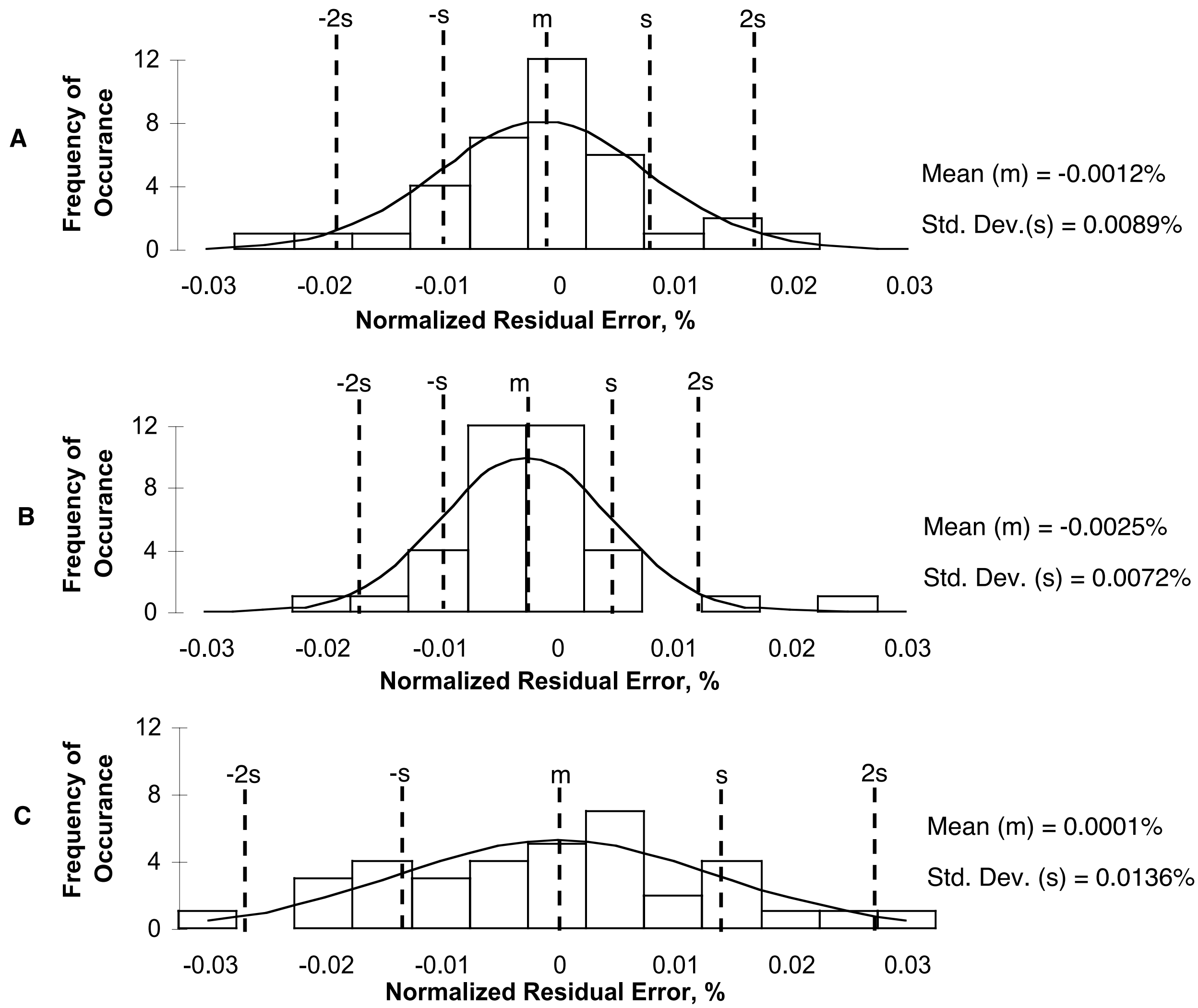


Figure 9 — Histogram of Normalized Residual Load Error with Theoretical Normal Distribution Superimposed

4.6 Facility Uncertainty

All the statistics mentioned in the previous section pertain to how accurately the calibration matrix fits the calibration data. The inherent assumption is that the applied loading is known exactly and the bridge output includes only a random error. However, the overall accuracy of the balance load measurements is also affected by uncertainty in the overall balance calibration process. These so-called facility effects are introduced through uncertainty in the applied load vector and also through systematic error in the bridge outputs. Performing repeat calibrations on a balance will aid in quantifying some of the facility uncertainties in the balance load estimation. Ideally, in order to exercise as many sources of error as possible, the balance should be removed from, and re-installed into, the calibration facility prior to each repeat calibration. The residual load error obtained from calibration cross-calculations can help provide a measurement of these facility uncertainties. The balance load cross-calculation is defined as the process of estimating the loading corresponding to the bridge output in calibration dataset A, using the calibration matrix derived from data in calibration dataset B.

4.7 Sample Calibration Report

Sample Calibration

Facility: VTWT

Calibration Number:2000-53

Balance: MK-VID

Contact: John Doe

Report Date: October 3rd, 2000

Balance **:**

Type: Force

Designation: MK-VID

Manufacturer: Able (Task)

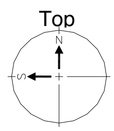
No. of Components: 6

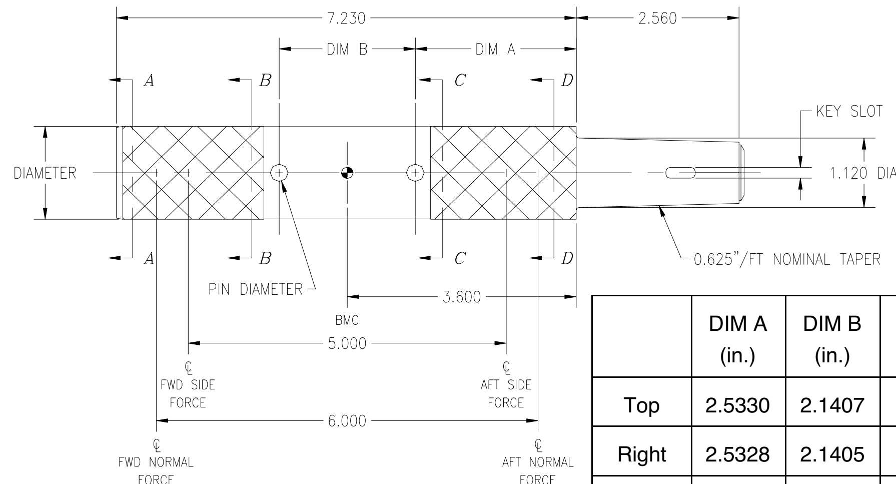
Material Type: 17-4, 43-40 Steel

Attach. Method: Taper to Sting, Pin to Model

Dummy Balance: Yes

Safety Factor(s): Ultimate 2.6, Yield 2.0 when all components loaded simultaneously

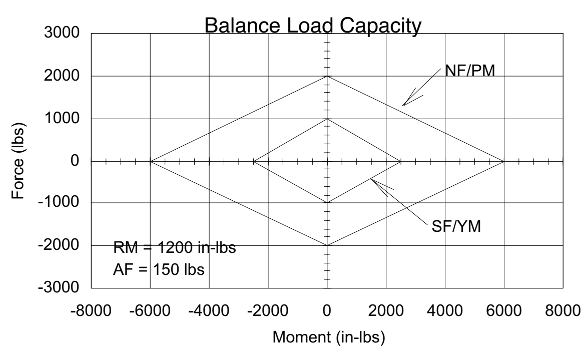




	DIM A (in.)	DIM B (in.)	Key Slot (in.)
Top	2.5330	2.1407	0.1719
Right	2.5328	2.1405	0.1719
Bottom	2.5330	2.1399	0.1719
Left	2.5333	2.1408	0.1719

	Diameter (in.)
Sect A-A Top	1.4994
Sect A-A Side	1.4997
Sect B-B Top	1.4998
Sect B-B Side	1.4999
Sect C-C Top	1.4999
Sect C-C Side	1.4999
Sect D-D Top	1.4998
Sect D-D Side	1.4994

	Pin Diameter (in.)
Top Fwd	0.2663
Top Aft	0.2663
Right Fwd	0.2663
Right Aft	0.2663
Bottom Fwd	0.2663
Bottom Aft	0.2663
Left Fwd	0.2663
Left Aft	0.2663



Additional Comments

None.

Sample Calibration

Facility: VTWT

Calibration Number:2000-53

Balance: MK-VID

Contact: John Doe

Report Date: October 3rd, 2000

<u>Balance Description (Concluded)</u>:

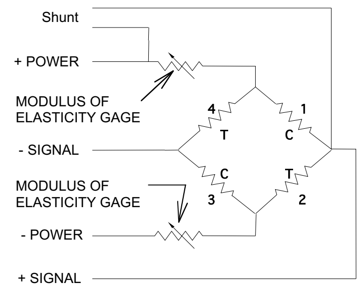
Wires per Bridge: 6

Connector Type: All Bare Wire

Gage Type(s): All foil, epoxy bonded

Gage Manufacturer(s): All Micro-Measurements

Gage Resistance(s): All 120 W



Wiring Diagram

Bridge Characteristics & Wire Color Code

	Bridge	NF1	NF2	SF1	SF2	RM†	AF†
	Zero Load Output* (mV)	-0.336	0.281	0.147	0.388	-1.350	-0.112
	Across ± Power	120 Ω	120 Ω	120 Ω	120 Ω	60 Ω	60 Ω
	Across ± Signal	120 Ω	120 Ω	120 Ω	120 Ω	60 Ω	60 Ω
	Excitation Range	12V	12V	12V	12V	12V	12V
Wire Color Code	+ Power	White	White	White	White	White	White
	- Power	Black	Black	Black	Black	Black	Black
	+Signal	Red	Red	Red	Red	Red	Red
	-Signal	Green	Green	Green	Green	Green	Green
	+Shunt	White	White	White	White	White	White
	-Shunt	Brown	Red	Orange	Yellow	Blk/White	Blue

* Zero Load Output is an average of bare balance readings at roll angles of 0°, 90°, 180°, 270°

† Composed of two complete bridges wired together in parallel, internally to the balance

Negative Shunt color identifies bridge cable

Temperature Sensors: I-C Thermocouples

Number & Location: 4 Total Forward & aft, Inner Rod Forward & aft, Outer Shell

Additional Comments

All bridges are compensated for effects of Young's Modulus change with temperature over a range of 60° → 160°F.

Sample Calibration

Facility: VTWT

Contact: John Doe

Calibration Number:2000-53

Report Date: October 3, 2000

Balance: MK-VID

Calibration

Date Calibration Performed: September 18, 2000

Calibration Type: Single component loads in both the positive & negative directions applied at each bridge. NF1/NF2 and SF1/SF2 combinations also, via loadings at balance centerline. All loads applied manually.

Bridges Used: NF1, NF2, SF1, SF2, RM, AF

Pin Location: Bottom, Fwd

Calibration Body: 1.5-in #2

Calibration Temperature: 70°F (Ambient)

Calibration Specifics

Bridge	Excitation Supply (V)	Shunts* (k Ω)	Shunt Output (mV)	Max Calibration Loads		Max Calibration Bridge Output (mV)	
				Positive	Negative	Positive	Negative
NF1	6	26	6.410	980 lbs	-980 lbs	6.5534	-6.4872
NF2	6	24	6.914	980 lbs	-980 lbs	6.8970	-6.8128
SF1	6	22	7.535	560 lbs	-560 lbs	7.5514	-7.2624
SF2	6	22	7.545	560 lbs	-560 lbs	7.8105	-7.5722
RM	6	17	4.555	880 in-lbs	-880 in-lbs	5.1190	-5.1222
AF	6	46	1.680	110 lbs	-110 lbs	1.7411	-1.7364

* Applied directly at balance bridges using shunt lines (see page 2 for wiring diagram)

Calibration Statistics

Component	NF1	NF2	SF1	SF2	RM	AF
FS (Max Design Loads)	1000 lbs	1000 lbs	500 lbs	500 lbs	1200 in-lbs	150 lbs
Average Error (%FS)	-0.012	-0.012	-0.017	-0.035	-0.009	-0.002
1σ Std. Deviation (%FS)	0.066	0.057	0.082	0.109	0.029	0.096

* Average errors and standard deviations are based on 169 load points and include residual errors from both the primary & interaction loads

Additional Comments

None.

Pg. 3 of 4

Sample Calibration

Facility: VTWT

Contact: John Doe

Calibration Number:2000-53

Report Date: October 3, 2000

Balance: MK-VID

Data

BMC Location: 3.600 inches from Balance aft face (see illustration on page 1)

Gage Distances from BMC (inches):

X_1= 3.000

X_2= 3.000

X_3= 2.50

X_4= 2.500

Primary Constants:

NF1: 6.6421 mV/lbs
NF2: 6.9950 mV/lbs
SF1: 13.1919 mV/lbs
SF2: 13.7132 mV/lbs
RM: 5.8210 mV/in-lbs
AF: 15.8084 mV/lbs

Balance Deflection Constants:

NF: 0.000384 °/lb
PM: 0.000128 °/in-lb
SF: 0.000333 °/lb
YM: 0.000130 °/in-lb
RM: 0.001022 °/in-lb

Temperature Correction Algorithm & Constants: Valid from 70 → 120 °F

$T_{K_{NF1}}$ = 0.00005152 / °F

$T_{K_{NF2}}$ = - 0.00000567 / °F

$T_{K_{SF1}}$ = 0.00004088 / °F

$T_{K_{SF2}}$ = - 0.00011962 / °F

$T_{K_{RM}}$ = - 0.00003924 / °F

$T_{K_{AF}}$ = 0.00012988 / °F

$$rX = {rX_u}\Big/\left[1 + \Delta T\left(T_{K_x}\right)\right] \qquad \Delta T = \overline{T}_{Bal} - 70$$

Where,

rX_u Uncorrected bridge output

$\overline{T}_{Bal}$ Average of balance thermocouple readings, °F

T_{K_x} Temperature correction constants

rX Corrected bridge output

Calibration Matrix:

		rNF1,	rNF2,	rSF1,	rSF2,	rRM,	rAF
1,	"1(NF1)",	6.642090E-03,	-3.947846E-04,	-4.310451E-06,	-2.489590E-05,	-1.011338E-05,	5.876804E-05
2,	"2(NF2)",	-6.900304E-05,	6.995008E-03,	8.726036E-06,	-5.868996E-05,	1.259534E-06,	-1.519455E-05
3,	"3(SF1)",	-2.306594E-05,	2.289632E-05,	1.319192E-02,	1.158038E-04,	3.563955E-05,	2.952495E-06
4,	"4(SF2)",	2.298114E-05,	8.375216E-06,	3.623796E-05,	1.371318E-02,	9.284032E-06,	3.804768E-06
5,	"5(RM)",	-8.977273E-07,	4.875000E-06,	2.424432E-05,	5.507955E-05,	5.821034E-03,	-5.993750E-05
6,	"6(AF)",	1.712121E-05,	-1.783422E-05,	-1.651515E-05,	1.409091E-05,	-9.000000E-05,	1.580835E-02
7,	"I1I",	3.802692E-05,	2.009664E-05,	1.256830E-05,	4.940587E-06,	-1.378285E-05,	-5.259137E-06
8,	"I2I",	2.152877E-05,	3.518322E-05,	-3.885011E-06,	-2.154673E-05,	-7.326453E-06,	-5.269959E-06
9,	"I3I",	8.957281E-06,	-4.898018E-06,	2.253849E-04,	-3.092212E-05,	-6.372977E-06,	1.429592E-06
10,	"I4I",	-5.028108E-06,	3.811397E-06,	-1.278071E-05,	1.632094E-04,	-1.091031E-05,	-1.370733E-06
11,	"I5I",	9.356252E-06,	5.689797E-06,	1.403128E-05,	3.651107E-06,	5.842618E-07,	7.065312E-06
12,	"I6I",	-1.697319E-05,	2.949515E-05,	4.254564E-05,	7.884929E-05,	5.287954E-06,	1.712853E-05

All other constants set to zero, See Matrix File

Convergence Criteria: 0.00001(lbs or in-lbs) for each component

Additional Comments

None.

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5 Concluding Remarks

The AIAA/GTTC Internal Balance Technology Working Group was formed primarily to provide a means of developing standards and fostering communication between North American organizations that calibrate and use internal balances. The goals of the working group were to continue to foster open communications, and develop recommended practices for internal balance design and fabrication, calibration (including required loadings), usage, uncertainty estimation, and reporting. In the six years since its formation, the working group made excellent progress, particularly with increased communication between member organizations and in the establishment of several key recommended practices regarding the terminology and calibration of internal balances. This document formally documents all of the recommended practices adopted by the working group. The results of the working group will benefit the wind tunnel test community as a whole by improving understanding through the use of a common terminology and communications between the participating facilities. The data quality and interpretation of data between facilities should also be enhanced for these same reasons.

Work on other issues, such as; an alternative calibration matrix and matrix generation methodology, techniques for correcting balance data for temperature and anelastic effects, and determining what calibration loads are required to generate the desired calibration matrix and its related accuracy will not be accomplished as a part of the working group. With the publishing of this document the working group will no longer exist as an AIAA/GTTC sponsored working group. However, it is anticipated that an *ad-hoc* group, consisting of the member facilities, will continue to work in a collaborative manner.

Annex A: Glossary

Back-calculation The application of a calibration matrix to calculate calibration loads which were used to develop the matrix.

Bi-directionality A characteristic of some balances in which the bridge sensitivity is dependent on the sign of load.

BMC Balance moment reference center. The single point about which the balance forces and moments are resolved.

Bridge A four arm or Wheatstone bridge circuit. The standard method of wiring four or more strain gages together to measure a single load component.

Calibration Matrix A matrix of curve-fit coefficients resulting from balance calibration that relates the outputs on the balance bridges to the load components. The matrix recommended in this document contains 6 rows and 96 columns, and the coefficients relate the bridge outputs to the component loads.

Component A single force or moment with specific directionality and point of application.

Cross-calculation The application of a calibration matrix to calculate calibration load points which were not used to develop the matrix.

Curve-fit Matrix See **Calibration Matrix**

Data Reduction Matrix A modified form of the Calibration Matrix in which consists of the inverted [C1] matrix and the $[C1]^{-1}$ and [C2] matrices have been multiplied together. This 6x96 matrix is minimizes the computations necessary to compute the component loads.

Direct-Read Balance A balance whose components are made up of 3 forces and 3 moments, and for which the strain-gage bridge responses are directly proportional to these forces and moments.

Dummy Balance A machined part designed to match the external dimensions of a specific balance, but with no load measurement capability.

Electrical Center Location on a Force or a Moment balance, where the *magnitude* of the electrical outputs from either the normal force or side force bridge pairs (e.g. rNF1 and rNF2) is equal. For a Direct-Read balance, the electrical center corresponds with the location on the balance where the electrical output of the moment bridge becomes zero for a force applied at that point.

Electrical Output Datum The outputs of the balance bridges that correspond to the load datum. Equivalent to Natural Zeros when load datum is zero absolute load.

Force Balance A balance whose components are made up of 5 forces and 1 moment

Gage Typically a single strain gage. May also refer to a set of strain gages wired in a bridge.

Iterative Math Model Math model expressing the bridge outputs as functions of the applied loads, implying that the independent variable in the curve fit is the applied loads. An iterative procedure is required to determine the loads from bridge outputs.

Load Datum The specific load condition that defines a calibration origin. Recommended to correspond to zero absolute load.

Load Rhombus A plot relating one balance component to another on which the maximum rated loads have been defined.

Maximum Rated Loads The maximum component loads under which the balance was designed to operate.

Moment Balance A balance whose components are made up of 5 moments and 1 force.

Multiple Gage Loading A calibration load applied to two or more components simultaneously.

Natural Zeros See **Zero Load Outputs**

Non-iterative Math Model Math model expressing the applied loads as a function of the bridge outputs, implying that the independent variable in the curve fit is the bridge outputs. Loads are determined explicitly from bridge outputs.

Residual or Residual Load Error The difference between a load resulting from back calculation and the actual applied load. Typically computed minus applied.

Shunt A resistor placed across one arm of a bridge to yield a precise output.

Single Gage Loading A calibration load applied to a single component.

Tare or Tare Load Any load present on the balance during calibration that has not been independently determined. Also, the load on the balance resulting from the model weight.

Wind-off Zero A term sometimes used to refer to readings taken at a “Wind-off” reference condition during a wind tunnel test. Frequently, the reference condition would correspond to the model level in pitch and roll.

Zero Load Outputs The outputs of the balance bridges at a specified excitation that would result from a weightless condition.

Zero Suppression The electrical adjustment of the balance outputs to zero voltage at some reference load condition.

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