Strain Gauge Balance Calibration And Data Reduction at NASA Langley Research Center

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Abstract

This paper will cover the standard force balance calibration and data reduction techniques used at Langley Research Center. It will cover balance axes definition, balance type, calibration instrumentation, traceability of standards to NIST, calibration loading procedures, balance calibration mathematical model, calibration data reduction techniques, balance accuracy reporting, and calibration frequency.

Balance Axes

The balance coordinate systems used for force and moment measurement at LaRC are defined as shown in Figure 1. The balance coordinate axes usually coincide with the body axes of the wind tunnel model.

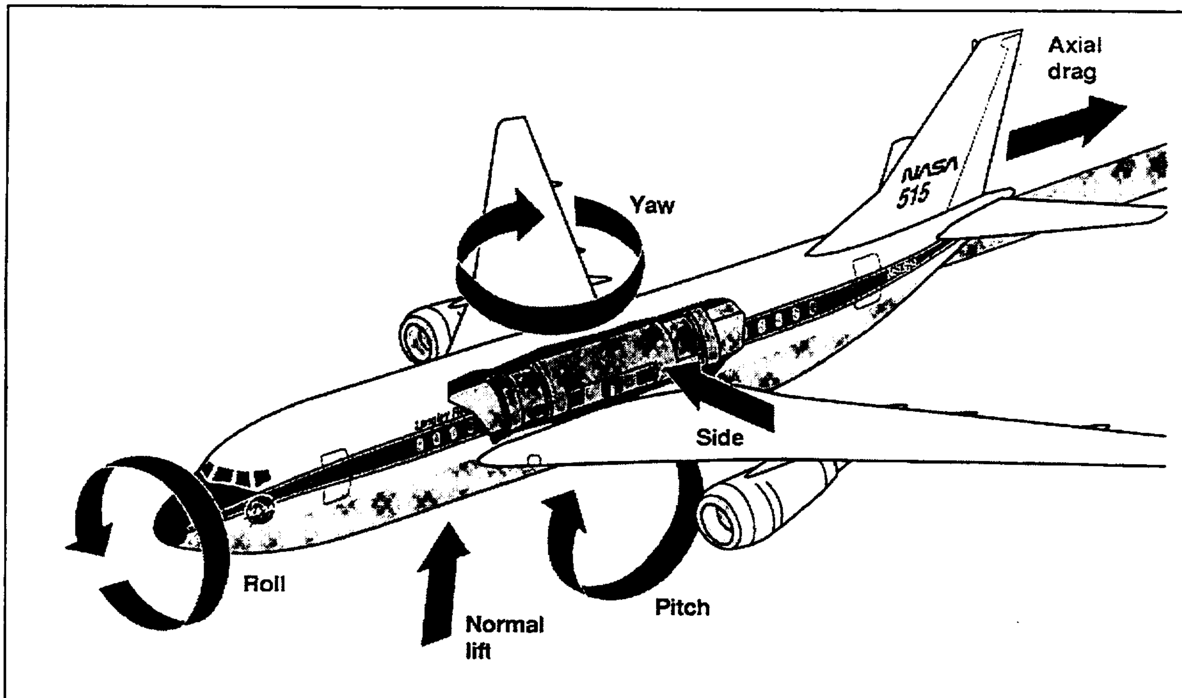

Figure 1 – Balance Axes

Balance Type

All LaRC internal strain-gage balances are custom designed to meet the load ranges, physical size, thermal environment, and accuracy requirements for given research projects. LaRC balance design philosophy is to use single piece construction techniques whenever possible. Multiple piece construction is used only in unique cases such as flow-through balances. LaRC often calibrates and uses multi-piece "Task/Able" type balances furnished by private industrial customers. LaRC also currently operates three external-balance systems and has several side-wall (semi-span) balances. Most LaRC balances are of the direct-reading type. To accommodate better thermal compensation some balances are gaged in such a manner that they require that bridge outputs must be summed and differenced. These balances are used in extreme thermal conditions such as the cryogenic environment at the National Transonic Facility (NTF).

All LaRC balances employ modulus-compensated transducer-quality strain-gages. Where extreme thermal environments are anticipated, an apparent-strain gage-matching technique patented by LaRC is used. Thermal compensation is provided by pure nickel wire placed in each balance bridge circuit to reduce temperature effects on the bridge output to less than 0.005% FS/°F. Balance temperatures and gradients are measured by means of thermocouples or RTD'S. These temperature measurements allow linear corrections to be applied for thermal sensitivity shifts and second-order corrections for apparent strain. Three types of mechanical model-to-balance attachments are employed; namely, diameter fits, expandable diameter fits, and flange fits. Mechanical balance-to-ground attachments include tapered fits, diameter fits, and flange fits.

Calibration Instrumentation

Balances are calibrated in an environmentally-controlled calibration laboratory. The calibration data are acquired using a Hewlett-Packard 3457A Digital Multimeter with ten-channel multiplexer, Option 44492. For a typical balance 5 mV full-scale output, the meter range is set to 30 mV, with an accuracy specification of 0.004% of reading + 3.65 μV. The multiplexer thermal offset specification is less than 3 μV. The data is transferred to a micro-computer (PC) using an IEEE 488 interface. For each of the six balance channels the data acquisition software acquires 50 readings at approximately 30 samples per second. To prevent corruption of the balance data by any swinging motion of the applied weights, the peak-to-peak variations of the fifty readings are monitored. If the total variation is less than ±20 μV the 50 readings are averaged; if the variation is out of tolerance, an additional fifty readings are taken on every channel and the tolerance check is repeated. If the second check fails, the calibration operator is alerted by the program to steady the weights and repeat the data point. Typically, the overall repeatability of the instrumentation system averaged over 50 data points is about 1 μVolt. LaRC employs a single 5 volt DC supply to power all six balance bridges. The input voltage leads for the six bridges are paralleled at the taper (aft end) of the balance. The input voltage is monitored for each data point. The six balance outputs are normalized to a nominal 5.000 V input voltage. The data is displayed, printed, and then stored on magnetic media for later data reduction.

Traceability of Standards to NIST

All of LaRC balance calibrations are performed using dead weight loadings. The laboratory calibration weights are checked and maintained within tolerance at least every two years. Two different weight calibration procedures are employed depending on the magnitudes of the weights. Dead weights in excess of 1,000 pounds are calibrated against Interface Gold Standard Load Cells which have overall accuracies of better than 0.01% FS (typically 0.006% nonlinearity and 0.002% hysteresis.) Every five years the load cells, and the associated power supplies and digital read-out instrumentation are sent to NIST for recalibration. Dead weights less than 1,000 pounds are calibrated on electronic scales (models Metler PC4400, Metler H51, A&-D 60, or Metler PC30.) These scales are maintained annually in the calibration laboratory with Tromner Class M and Class S mass standards. Only trained calibration technicians have access to these mass standards which are calibrated by NIST every five years.

Calibration Loading Procedures

The loading procedure for the LaRC full calibration is designed to fully determine both first and second order interactions. The procedure includes the application of all six primary loads and all two-load combinations. There are 82 loading sequences of nine loading steps each, as given in Table 1. For each sequence, loadings are applied in four equal increments to full scale and are then decremented to zero.

Assorted custom designed hardware is are used for balance calibration. The calibration equipment includes a calibration block or fixture, knife edges, symmetrical moment arms, weight hangers, and precision levels for simple gravity loadings; cables, knife edge pivoting bell cranks, and associated cable alignment equipment for the orthogonal loadings. The loading fixture, affixed to the balance metric end, is precision bored and ground to allow the use of its four orthogonal faces for balance releveling. The precision levels are Spectron electrolytic levels with a repeatability specification of 6 arc seconds. The fixture has longitudinal knife edge grooves and a screw/dowel pattern at the moment center of each face for the attachment of the moment arms. Double knife edges enable the load application point to be accurately placed to within 0.0005 inch. The orthogonal loads are applied through the use of double knife edges and a cable over a "frictionless" bell crank to a weight hanger. The alignment of the cable for orthogonal loads is obtained by first applying a gravity loading and recording the balance output on all components. The same load is then applied, and an iterative cable alignment is performed until the dead weight output is duplicated on all components, indicating that the load is now orthogonal as it was during the gravity loading. This alignment is maintained through the use of a transit and light rig to ensure that the load is kept orthogonal to the balance during the incremental loading sequence.

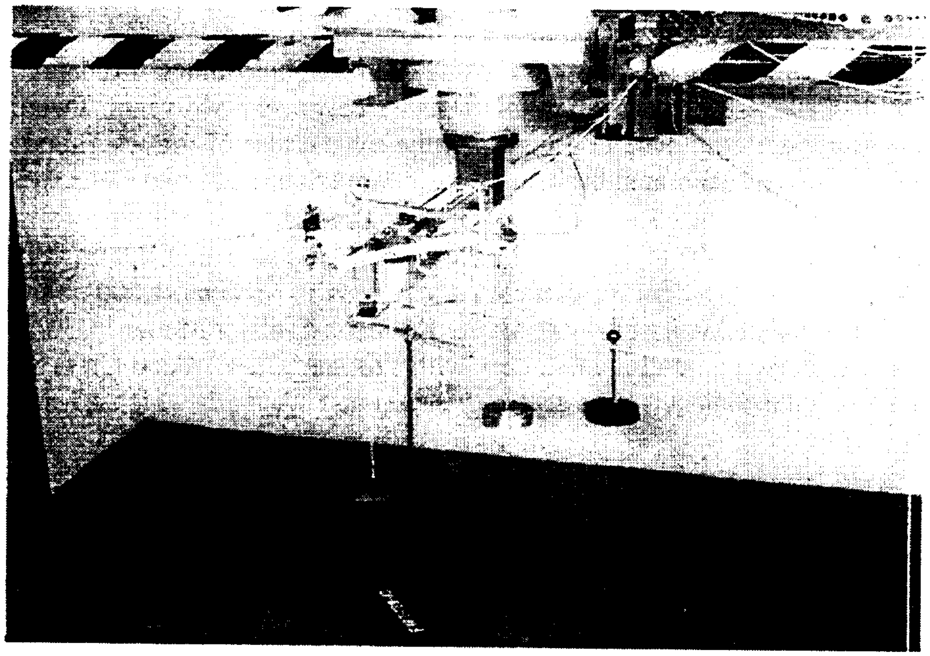

Figure 2. Multicomponent Loading

Balance Calibration Mathematical Model

The term "calibration mathematical model" used at LaRC denotes the multivariate polynomial which represents the functional relationship between the applied loads and die observed strain-gage bridge output voltages of the aerodynamic balance. The form of the polynomial model is specified by the following:

1) The physical parameters selected as independent and dependent variables including forces and moments, and output voltages;
2) The order (degree) of the polynomial;
3) The interaction terms, including quadratic terms and cross-product terms;
4) The rectangular array of muitivariate polynomial coefficients ordered into a matrix format, typically 6 x 27; and
5) The direction of the model, i.e., the choice of independent and dependent variables.

The traditional *forward* model, used at LaRC, characterizes the true physical process in which the independent variables, i.e., the applied loads, produce strains within the balance measuring beams, which in turn manifest voltage variations in the corresponding bonded strain-gage bridges, thereby producing the observed dependent variables, i.e., the output voltages, which vary as functions of applied loads. The forward model has been also designated as the *iterative model*. Computation of the applied loads corresponding to the observed voltage outputs requires iterative inversion of the system of nonlinear multivariate polynomial equations.

The forward mathematical model used at LaRC is a second order muitivariate polynomial function f of the six force-moment components including six linear terms, six quadratic terms, and 15 cross terms. The coefficients of these terms are established by the calibration procedure described in Section G entitled "Calibration Data Reduction Techniques." Function f is continuous everywhere with continuous partial derivatives. A theorem from advanced calculus shows that a unique inverse function f′ does exist in some open region R about the solution, provided that the Jacobian matrix of f is nonsingular. Moreover, f′ is also continuous with continuous partial derivatives in region R. One cannot find, in general, a closed-form algebraic expression for f′ in terms of radicals or elementary functions.

Calibration Data Reduction Techniques

The loading procedure of LaRC balances allows data reduction to be performed by grouping the loadings to break out the data necessary to compute each sensitivity and interaction. There are 27 groupings which are arranged into sets of sensitivities, linear interactions, quadratic terms, and cross terms respectively. For each grouping, the corresponding coefficient for each component is obtained by second-order least-squares estimation. In most instances the interactions are linear and the initial loads do not adversely affect the computation of the interaction. However, corrections for initial loads are made on the quadratic interactions. The resultant 6 by 27 matrix of coefficients is normalized with respect to the corresponding full scale loads of each component and a standard format print-out and standard format electronic data file is made and stored for the users of force balances at LaRC. The calibration data reduction computations are performed on personal computers.

Balance Accuracy Reporting Method

The calibration of wind tunnel balances at LaRC is a lengthy and labor-intensive process requiring fixture leveling, cable alignment, and dead weight application at each of 738 loading steps. The first description of strain gage balance calibration methods at LaRC was reported in 1956, followed by a refinement of these methods reported in 1964. These two reports described the rationale for including all first and second order interaction coefficients for accurate balance characterization and devised a comprehensive calibration procedure to individually estimate each of the coefficients. This calibration procedure was also valuable in identifying error sources in balance design, strain gage installation, and inaccurate calibration load application. The 1964 reference also presents a scalar iterative data reduction method, which was upgraded by a more efficient muitivariable iterative matrix technique in 1972.

The concept of proof loadings in which multiple loads are simultaneously applied was reported in the 1956 report as a means to verify balance accuracy. The overall accuracy of the balance was cited in the 1964 reference as the worst-case error among all components from the proof loadings. In 1993 an alternative method for reporting balance accuracy was developed which cites the accuracy of each of the six balance components. Each accuracy term is computed as two standard deviations of the residuals of all the 738 loading obtained during the calibration, expressed as a percentage of the full-scale load of the corresponding component. A sample error plot is included in Figure 3.

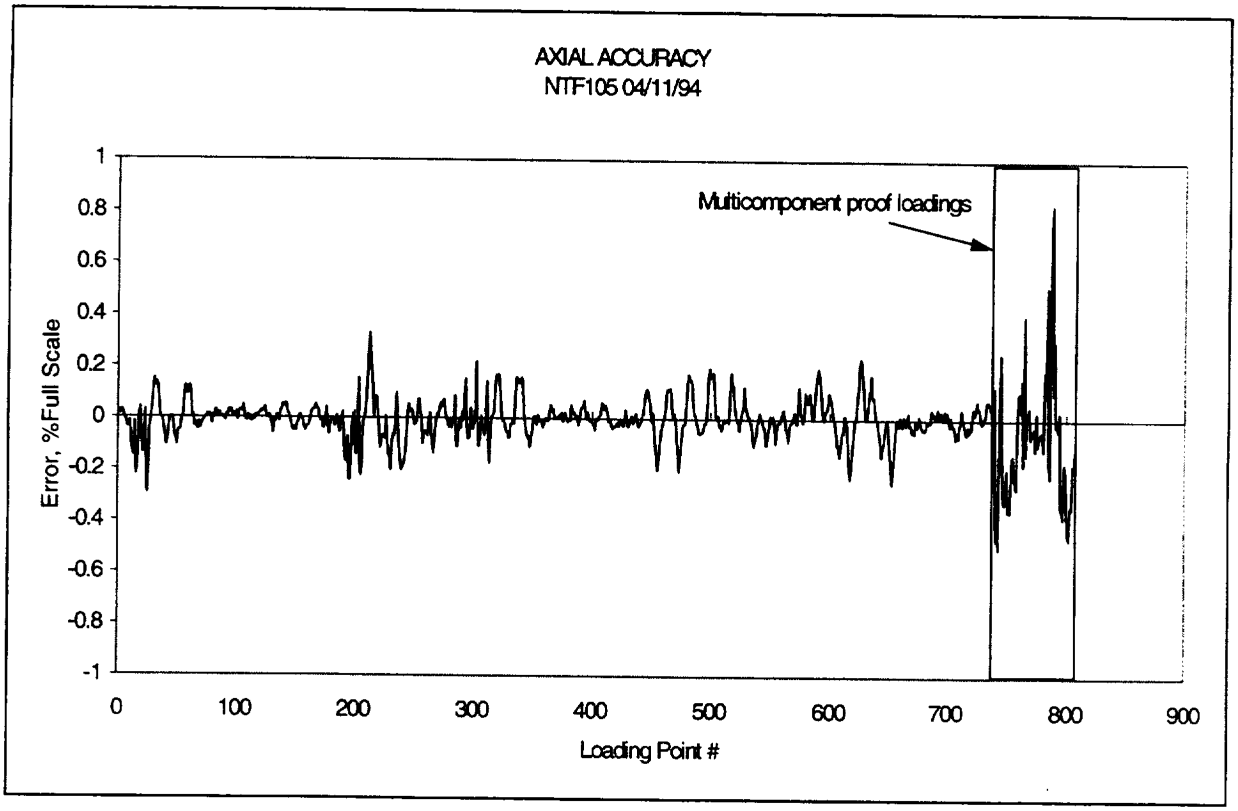

Figure 3. Error Plot

An effort is underway at LaRC to develop a new technique to ascertain the uncertainties of the forces and moments measured by the balance. This technique is an enhanced improvement over the existing procedure in which accuracies were cited as percentages of the full scale loads. It allows error bands to be quoted for each computed force and moment as functions of the actual measurands. The new method has been verified using data obtained from calibration.

LaRC maintains an active balance inventory of over 250 internal strain-gage balances. A two-year calibration update is recommended by the force measurement group. However, complete calibrations are lengthy and labor intensive, and it is not feasible to recalibrate each balance every two years. The frequency of calibration at LaRC is based on the balance usage rate and the needs of the researchers. Frequently used balances are recalibrated on a two-year calibration update cycle. Other balances are recalibrated at user request. Balances are also be recalibrated at the discretion of the staff of the force measurement group as the calibration schedule permits. All new balances receive full calibration. A full calibration consists of the application of 738 dead weight loads in two categories: primary and secondary loadings over all six components to establish the balance sensitivity and interaction coefficients. The calibration coefficients are next validated by application of 123 proof loadings with three to six components loaded simultaneously at 50% and FS levels. Users are furnished a calibration report detailing the balance specifications, wiring codes, calibration coefficients, accuracies, deflections, and other pertinent data. Update recalibrations, which include primary component loadings only, are conducted routinely following the complete calibration.

Table 1

PRECISION DEAD WEIGHT CALIBRATION LOADING SCHEDULE
(LOADING ORDER IS TYPICAL BUT NOT REQUIRED)
LOADING AT EACH CODE IS IN 1/4 FULL SCALE INCREMENTS
TO FULL SCALE AND BACK DOWN TO ZERO LOAD

CODE	PRIMARY LOAD	AUXILIARY #1	AUXILIARY #2	AUXILIARY #3
10	AXIAL			
20	NORMAL			
30	PITCH	NORMAL		
1030	- PITCH	NORMAL		
1040	- ROLL	NORMAL		
40	ROLL	NORMAL		
50	-NORMAL			
1060	- PITCH	-NORMAL		
60	PITCH	-NORMAL		
70	ROLL	-NORMAL		
1070	- ROLL	-NORMAL		
80	SIDE			
90	YAW	SIDE		
1090	- YAW	SIDE		
100	- SIDE			
1110	- YAW	- SIDE		
110	YAW	- SIDE		
120	ROLL	- SIDE		
1120	- ROLL	- SIDE		
130	ROLL	- SIDE		
1130	- ROLL	- SIDE		
1140	- YAW	ROLL	- SIDE	
140	YAW	ROLL	- SIDE	
1150	- YAW	- ROLL	- SIDE	
150	YAW	- ROLL	- SIDE	
1160	- YAW	- SIDE		
160	YAW	- SIDE		
170	YAW	SIDE		
1170	- YAW	SIDE		
1180	- ROLL	SIDE		
180	ROLL	SIDE		
1190	- ROLL	SIDE		
190	ROLL	SIDE		
200	YAW	ROLL	SIDE	
1200	- YAW	ROLL	SIDE	
210	YAW	- ROLL	SIDE	
1210	- YAW	- ROLL	SIDE	
220	PITCH	NORMAL		
1220	- PITCH	NORMAL		
1230	- ROLL	NORMAL		
230	ROLL	NORMAL		
240	PITCH	ROLL	NORMAL	
1240	- PITCH	ROLL	NORMAL	
250	PITCH	- ROLL	NORMAL	
1250	- PITCH	- ROLL	NORMAL	
1260	- PITCH	-NORMAL		

Table 1 (Cont)

60	PITCH	-NORMAL		
270	ROLL	-NORMAL		
1270	- ROLL	-NORMAL		
1280	- PITCH	ROLL	-NORMAL	
280	PITCH	ROLL	-NORMAL	
1290	- PITCH	- ROLL	-NORMAL	
290	PITCH	- ROLL	-NORMAL	
1300	- PITCH	AXIAL	-NORMAL	
300	PITCH	AXIAL	-NORMAL	
310	ROLL	AXIAL	-NORMAL	
1310	- ROLL	AXIAL	-NORMAL	
320	-NORMAL	AXIAL		
330	NORMAL	AXIAL		
340	PITCH	AXIAL	NORMAL	
1340	- PITCH	AXIAL	NORMAL	
1350	- ROLL	AXIAL	NORMAL	
350	ROLL	AXIAL	NORMAL	
360	SIDE	AXIAL		
370	YAW	AXIAL	SIDE	
1370	- YAW	AXIAL	SIDE	
1380	- YAW	AXIAL	- SIDE	
380	YAW	AXIAL	- SIDE	
390	- SIDE	AXIAL		
400	NORMAL	SIDE		
420	NORMAL	YAW	SIDE	
430	PITCH	SIDE	NORMAL	
1430	- PITCH	SIDE	NORMAL	
440	PITCH	YAW	SIDE	NORMAL
1440	- PITCH	YAW	SIDE	NORMAL
460	-NORMAL	SIDE		
470	-NORMAL	YAW	SIDE	
1490	- PITCH	SIDE	-NORMAL	
490	PITCH	SIDE	-NORMAL	
1510	- PITCH	YAW	SIDE	-NORMAL
510	PITCH	YAW	SIDE	-NORMAL
1010	- AXIAL			

Table 1. Calibration Loading Schedule