NASA LaRC STRAIN GAGE BALANCE DESIGN CONCEPTS

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ABSTRACT

The NASA Langley Research Center (LaRC) has been designing strain-gage balances for more than fifty years. These balances have been utilized in Langley's wind tunnels, which span over a wide variety of aerodynamic test regimes, as well as other ground based test facilities and in space flight applications. As a result, the designs encompass a large array of sizes, loads, and environmental effects. Currently Langley has more than 300 balances available for its researchers. This paper will focus on the design concepts for internal sting mounted strain-gage balances. However, these techniques can be applied to all force measurement design applications. Strain-gage balance concepts that have been developed over the years including material selection, sting, model interfaces, measuring sections, fabrication, strain-gaging and calibration will be discussed.

BACKGROUND

A strain-gage balance is: *a transducer used to measure the aerodynamic loads encountered by a wind tunnel model during a wind tunnel test.* Figure 1 is a schematic of a typical strain-gage balance installation within a wind tunnel model. There are six degrees of freedom that the balance has to measure and they are depicted in figure 1 with LaRC's naming and sign convention. Although the balance's task to measure these six degrees of freedom appears simplistic, it has proven to be one of the more challenging transducer development technology areas. In addition, as the emphasis increases on improving aerodynamic performance of all types of air and spacecraft the demand for improved balances is at the forefront. This is due to the balances fundamental purpose: as the most important and critical measurement (coupled with angle-of-attack) used to determine the performance of a model undergoing aerodynamic characterization.

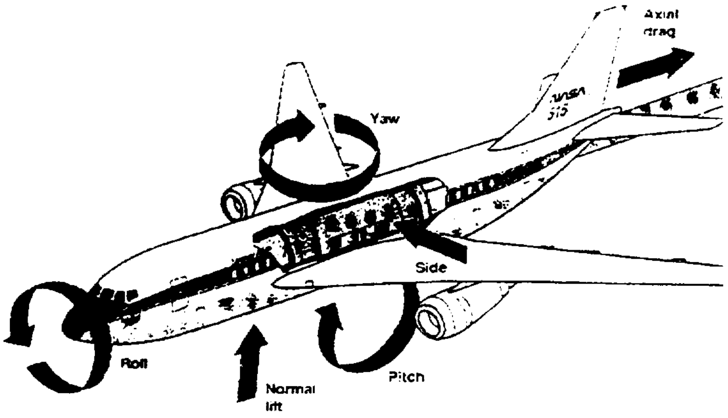


Figure 1. Strain-gage balance location in a wind tunnel model

LaRC's long history as a leader in the aerodynamic community has been in part due to its commitment to high quality transducers. Without quality instrumentation a wind tunnel test result will not be very useful. Therefore, due to its importance in aerodynamic testing results, LaRC has been designing balances and related sensors and test equipment for many years. The earliest balances were constructed out of multiple pieces of material and bolted, screwed and sometimes welded together in order to provide the measurement of six degrees of freedom necessary to characterize a test article. Figure 2 displays one of LaRC's earliest internal strain-gage balances. These multi-piece designs were state-of-the-art at the time, based on design and manufacturing techniques available, but were susceptible to problems such as hysteresis and zero shift as a result of "slop" or movement of the jointed regions. Figure 3 is a depiction of hysteresis and zero shifts that occurs during calibration of a balance.

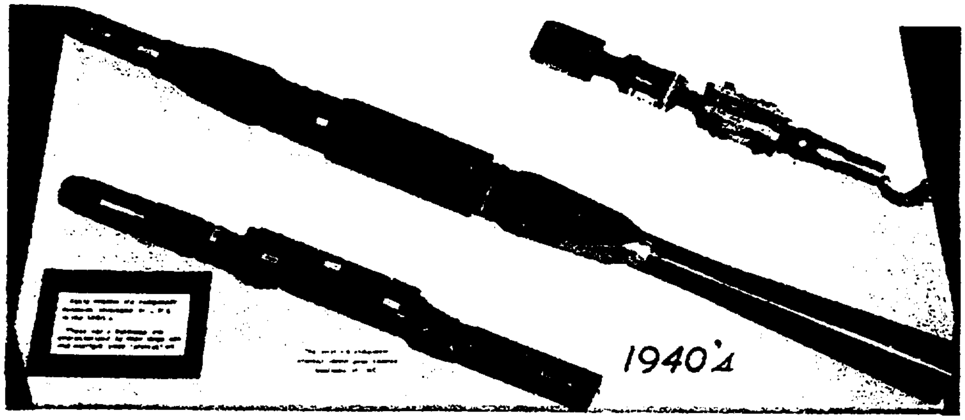


Figure 2. LaRC's First Internal Balance

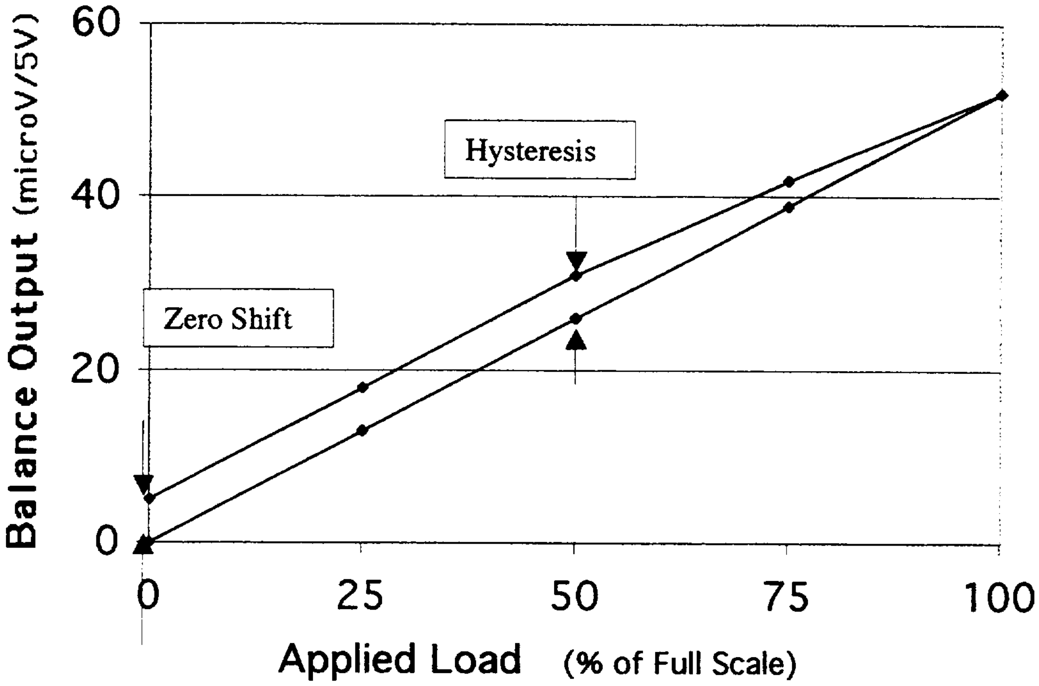


Figure 3. Example of Hysteresis and Zero Shift

One major change in the design of strain-gage balances at LaRC was the incorporation of electrical discharge machining (EDM) into the manufacturing process. This machining technique (circa 1958) allowed balance design to be a single piece of material that greatly reduced the hysteresis and zero shift issues of multi-piece designs. This is the same philosophy employed by our balance design engineers today of utilizing a single piece of material or monolithic design at all times for a quality balance.

Additional background information that has shaped the development of balances at LaRC is the environmental parameters imposed by LaRC test facilities, mainly temperature and load capacity. The major facilities at LaRC that are used for force testing have balance temperature ranges from -250°F to +250°F. In addition, the range of balance sizes is from 0.3 in to 4.5 in. in diameter with load capacities from 1 pound to 12,000 pounds of normal force. Although many of these facilities have tests that require special balances such as flow through types for powered model testing, this paper will focus on typical internal balances.

INTRODUCTION

One of the most important practices of LaRC's research staff, that is highly recommended by the balance group, is to match as closely as possible the expected loads of a test with the full scale loads of the balance. This will ensure that the maximum resolution of the instrument is obtained. Therefore, the best results from a test program will be attained from designing a balance for each particular test regime such as performance or stability and control (two balances).

As discussed in the background section, the philosophy of our balance engineers is to design the balance from a single piece of material. This is the starting point of the design and the remainder of the information is provided by the researcher preparing for a test program, or possibly by a balance engineer investigating a new design concept. Listed below are the parameters required for designing a new balance.

1. Expected loads in all six degrees of freedom
2. Location of the balance within the model
3. Maximum balance dimensions (typically given in diameter and length)
4. Environmental parameters (temperature, pressure, moisture conditions, dynamics, possible exposure to airflow or corrosive substances)
5. Interface requirements within the model (metric end of the balance) and to the support structure (non-metric end of the balance)
6. Required accuracy and resolution
7. Electrical interfaces available (data signal)
8. Data acquisition system specifications
9. Data analysis software specifications
10. Special set-up and checkout equipment

Once this information is provided the actual design can begin. The initial task is to review past designs and utilize a balance design of similar specifications. From here the balance design engineers at LaRC utilize custom software to iterate through the design and converge to the best solution. This software is based upon textbook mechanics of solids as well as LaRC developed analysis methods. Finite element analysis is beginning to be evaluated as a tool to possibly help in the areas of reducing stress concentration factors, improving thermal characteristics and optimizing the design. Reviews of the design are held with the balance group, researcher, and all personnel involved in the production of the balance to ensure a quality and timely product. The following sections will discuss in more detail the process, and technical attributes of designing LaRC strain-gage balances. Figures 4 and 5 are pictures of two LaRC balances with the main features labeled.

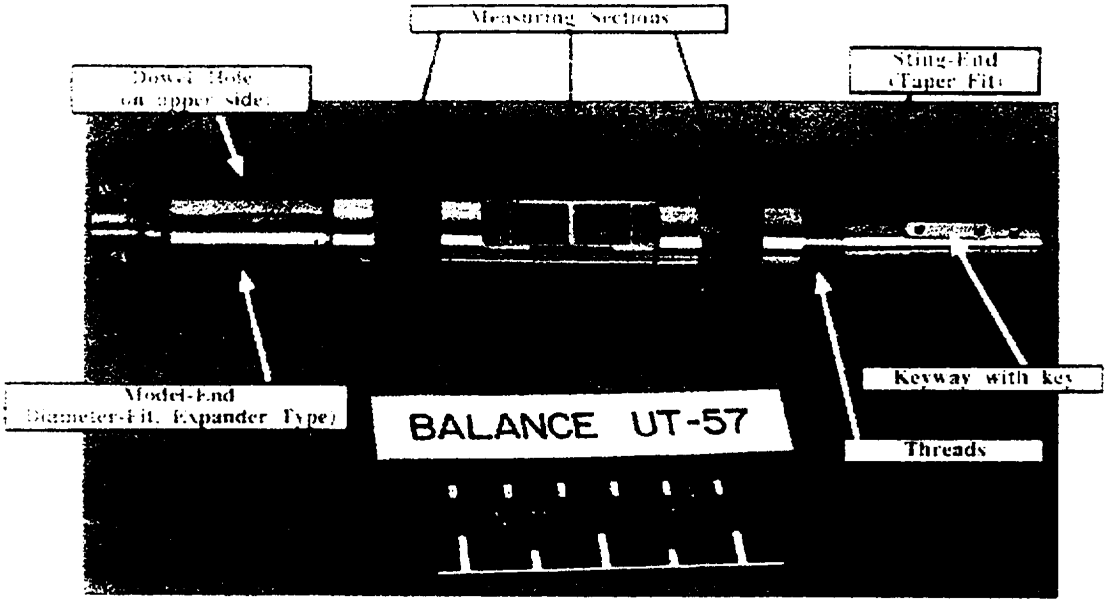


Figure 4. NASA LaRC Internal Strain-Gage Balance (Unitary Tunnel Configuration)

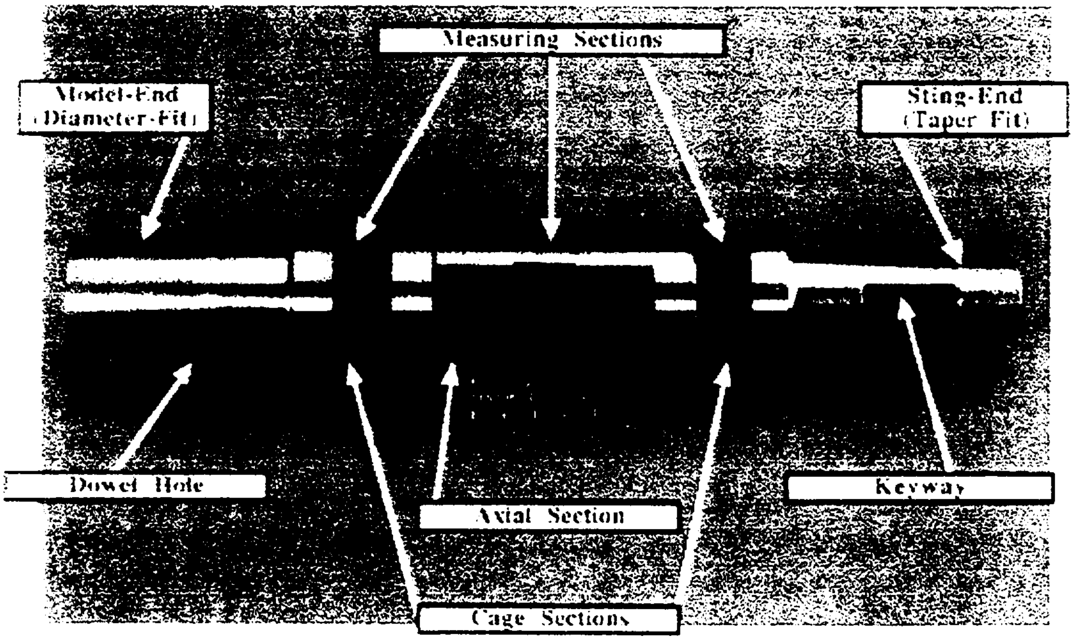


Figure 5. NASA LaRC Internal Strain-Gage Balance (NTF Configuration)

MATERIAL SELECTION

LaRC balances are fabricated from a select group of materials. They must exhibit "transducer quality" characteristics. Based on supplier generated test data and our own research programs the following materials are utilized for LaRC balances with the majority coming from the first three selections.

1. 17-4 PH or 15-5 PH stainless steel (H925; Rc = 40-42)
2. C-200 18% Ni maraging steel (H900; cryogenic applications; Rc = 41-45)
3. C-300 18% Ni maraging steel (H900; high capacity applications; Rc = 52-55)
4. 2024-T4 Aluminum
5. 7075-T6 Aluminum
6. Beryllium Copper (Be-Cu) (extreme temperature applications)

The material selection is typically determined at the outset of the balance design. Reviewing past designs and performing a few very simple diameter to load calculations the strength, toughness and hence the material required for the balance can be selected. However, there are times when some detailed analyses must be performed before final selection when a more ductile lower strength material is preferred.

Other considerations must be given to the selection process such as the environment (moisture, corrosive substances,...). In addition, strain-gage application and interaction with the material under load and test conditions must be thoroughly evaluated.

STING AND MODEL INTERFACES

The typical sting (non-metric or ground-side) interface for LaRC balances is a tapered cylinder (taper). The advantage of this design is its ease of installation especially if the model is required to be assembled to the balance prior to insertion into the sting. In addition, to the taper joint securing feature, all of these joints incorporate either a double-nut or set screw configuration for added security. The double-nut is used as the standard and set screws are employed on balances that are either: 1) too small or lack clearance for a threaded section; or 2) are required to operate cryogenically where the stress concentrations imposed by the threads are not acceptable. Also, a keyway is cut into the taper for roll load reaction. Figure 6 shows the typical configuration of tapered sting end attachments for LaRC balances. The maximum diameter of the tapers range from 0.3125 inches to 5.0 inches.

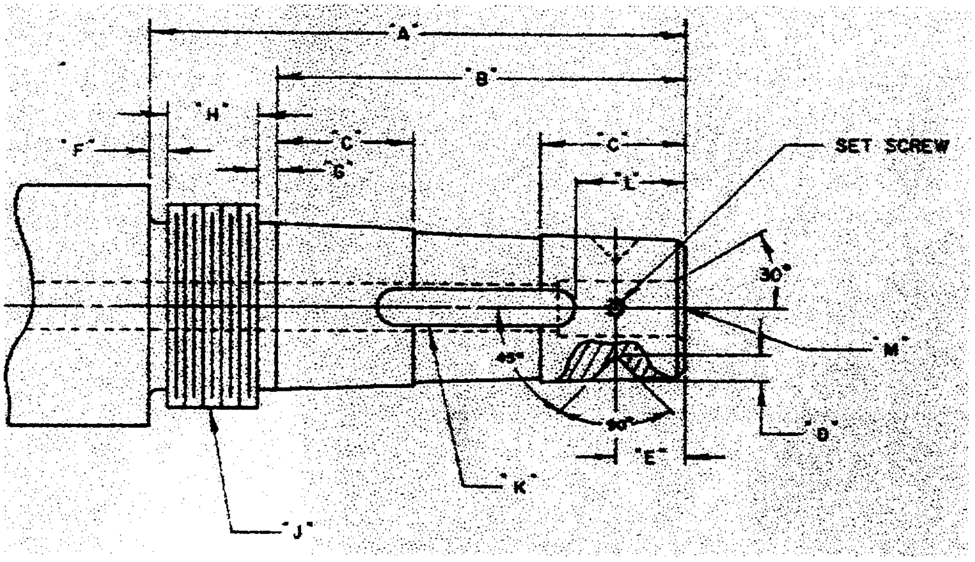


Figure 6. Balance taper (all tapers are 1inch/foot)

There are some disadvantages of the tapered sting-end attachments such as difficulty to machine to rigid specifications and maintain due to wear and high load requirements. Due to the recent increased demand on minimizing motion between balance joints, the tapered keyway design is limited. One characteristic that limits its ability to minimize roll motion is the fact that it requires some clearance for assembly because it is a sliding fit. Also, roll motion is very difficult to control when the largest securing factor is the key that is bearing on a small area.

Difficulties associated with these tapered sting-end attachments have led LaRC to utilize other methods when geometry of the balance/sting interface allows. One type is a flange fit that requires a larger diameter. The majority of semi-span balances utilize this attachment method on both the sting or support structure and model side. These joints are easier to machine, maintain and in some instance easier to assemble. Other interface designs are constantly being researched. However, implementation is a difficult aspect because of the large inventory of balances and stings.

Model interfaces are typically cylindrical fits with a location securing interference fit dowel pin. The model to balance connection is the most critical within the wind tunnel test because this fit determines the axes of the loads to be measured relative to the balance axis. If the balance is not aligned properly and the misalignment is not accounted for, errors will be present. This type of interface has the advantage of providing almost no motion between the balance and model (when properly machined and assembled). A modification of this design is the LaRC front-end expander. The front-end expander provides the same cylindrical fit but with a more adaptable design. By expanding a sleeve on the balance front-end to fit the model bore, an easier installation is provided. This expander front-end is not used for cryogenic applications or with high load to diameter ratios for performance purposes. Figure 7 shows a typical expander front-end fit design. The sizes of the expander front ends range from 0.625 to 3.1 inches.

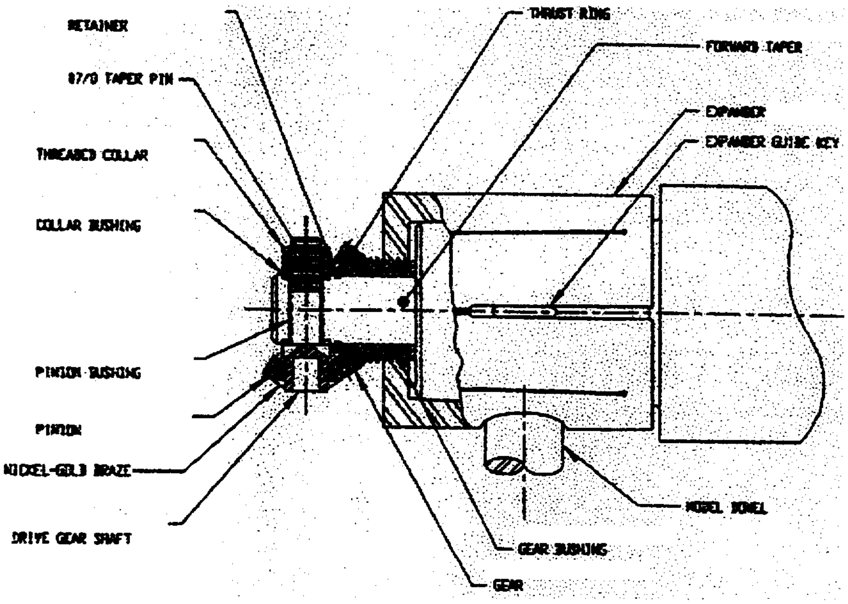


Figure 7. Typical expander front-end

There are some difficulties associated with these designs. Machining is very critical in the areas of roundness and cylindricity as well as true position of the dowel hole. Assembly is critical, can cause wear and requires a detailed procedure. In conclusion, alternative methods are being researched and designs such as the flange-type mentioned above are utilized when possible.

MEASURING SECTIONS

The measuring sections are strain-gaged areas of the balance that have been optimized for a given balance design based on the full scale load of the balance. There are typically three sections, one for measuring axial force and two for measuring the other five components. A typical NTF balance is shown in figure 8 with the measuring sections labeled. Classical strength of materials and internally generated analysis techniques are utilized to optimize the design of the balance measuring sections. Finite element analysis is being evaluated for use in final optimization and in some cases may be utilized for thermal predictions. The target design criteria is 1 to 1.5 milliVolts output voltage per Volt of input or excitation voltage. The equation below shows how this output voltage translates into strain (or stress) on the balance. Therefore, an iterative process is performed to produce this magnitude of strain-gage output while maintaining a safe level of strain on the balance when all six components of load are applied simultaneously. The ultimate goal is to produce a balance that contains strain gages strategically located that are sensitive to the desired measurement and insensitive to all others. This is achieved through design and proper strain-gage location as well as bridge wiring techniques.

$$\text{Strain} = \frac{(\text{Bridge Output Voltage (Volts)})}{(\text{Bridge Input Voltage (Volts)} * \text{Gage Factor of strain gages})}$$

Note: This is for a four-arm active strain-gage Wheatstone bridge configuration

The axial section design is centered on producing a target output voltage to assure adequate measurement resolution while minimizing interaction effects (outputs from the axial strain-gage bridge caused by the other five components). The features noted in figure 8 are the measuring beam (axial slotted-T beam) which is the strain-gaged beam, and the flex beams. This configuration provides the following benefits and many more: 1) Locates the measuring beam as close to the centerline of the balance as possible to minimize moment loading effects; 2) Utilizes the slotted configuration to provide a single bending beam effect and reduce the beams strain due to a normal force loading; 3) Reduces the loads transferred to the measuring beam by having flex beams on either side for support.

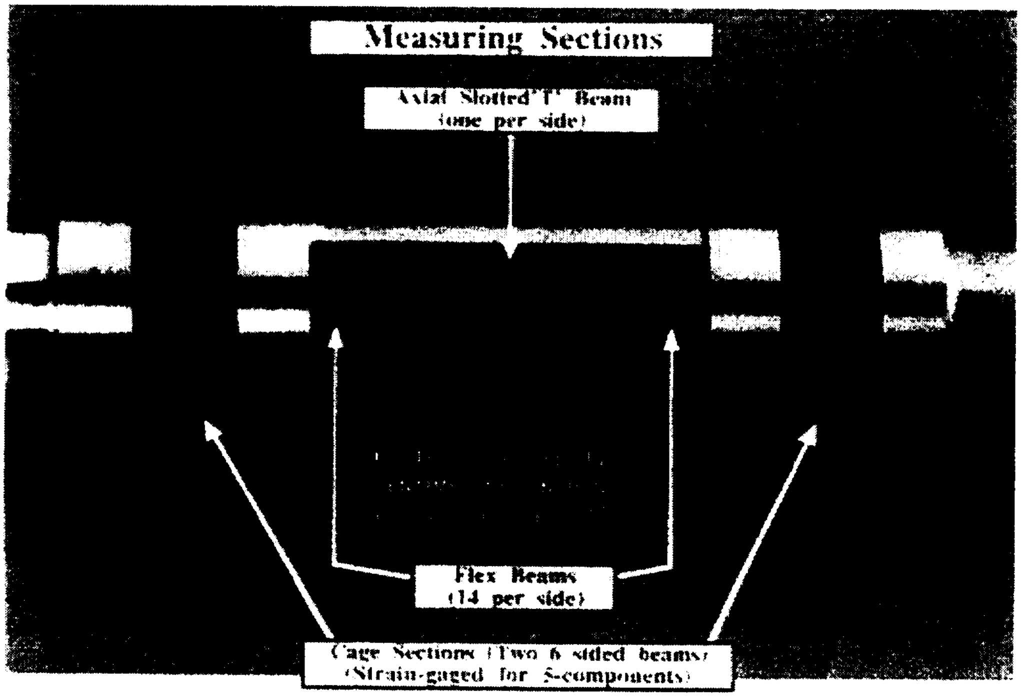
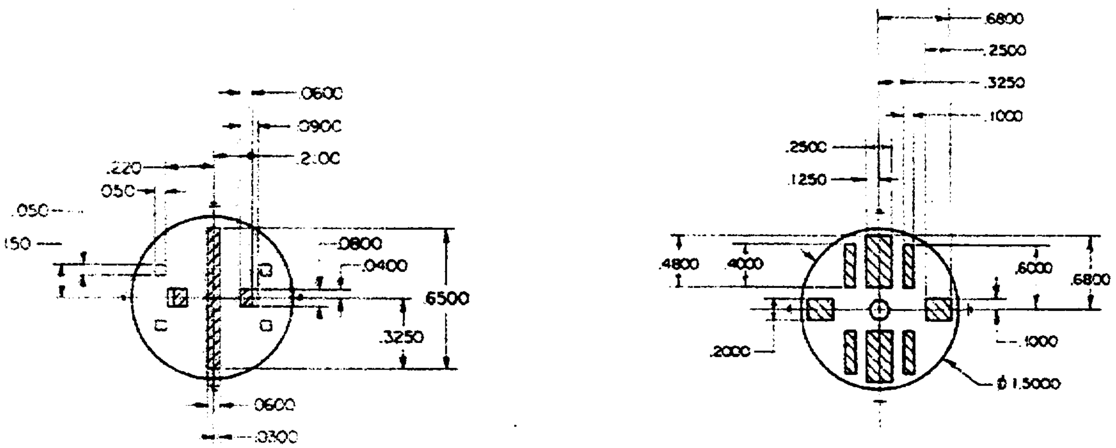


Figure 8. NASA LaRC NTF Balance Measuring Sections

The cage sections take on many different configurations based on the loads to be measured and the ratios of the six components. Figure 9 shows some various designs optimized for the loadings listed. The same philosophy for the axial section holds for these sections, that sensitivity is maximized while interactions are minimized. The typical cross sections of the beams are rectangular. However, notched beams as well as stress riser beams are employed to increase sensitivity when necessary. Other techniques are considered during the design such as stiffening end shoulders which transition the beams to other section of the balance (the model or sting attachment sections) to minimize nonlineraities.



SECTION AA
SCALE 2/1

SECTION AA
SCALE 1/1

Balance Loads

Normal Force	50 lbs (220 N)	800 lbs (3,560 N)
Axial Force	10 lbs (45 N)	60 lbs (270 N)
Pitch Moment	100 in-lbs (11 Nm)	2,000 in-lbs (225 N)
Roll Moment	10 in-lbs (1 Nm)	800 in-lbs (90 Nm)
Yaw Moment	15 in-lbs (1.7 Nm)	1,000 in-lbs (110 Nm)
Side Force	15 lbs (65 N)	400 lbs (1,780 N)

Figure 9. Cage Sections

FABRICATION

The fabrication of LaRC balances is a delicate process requiring high precision and patience. Since the balance is constructed from a single piece of material, it is a series process that relies heavily on the Electrical Discharge Machining (EDM) technique (reference 1) and can be separated into the following phases.

- The material certification phase is used to certify the material and ensure it does not contain voids over a pre-determined size for fatigue and fracture requirements. The material undergoes a material certification and an ultrasonic inspection, which is detailed in NASA TM 84625.
- The preliminary machining phase consists of conventional machine shop operations such as turning, milling and grinding. An in process quality assurance (QA) inspection is completed on the balance prior to sending it to step 3, heat treatment, to ensure proper sizing before proceeding.
- The heat treatment phase involves heat treating the material to vendor specifications as listed in the material selection chart. A heat treat certification is issued as well as a hardness test (performed utilizing the Rockwell C scale).
- The final phase of machining is in the EDM process. This consists of wire and plunge type EDM machines. The wire is utilized as much as possible in cutting flats and through holes (typically in the cage sections and on the outline of the axial section). Figure 10 shows a balance in the plunge EDM. Tolerances for the measuring beams are on the order of 0.0005 inches to 0.0002 inches. Therefore, this machining process is very time consuming and critical. The method of either the wire or plunge EDM

requires multiple stages of machining to maintain the tight tolerances and to minimize the EDM effects on the material which are known to reduce the fatigue life. Consequently, there are typically three phases of cutting with the EDM. One is called rough, which gets within approximately 0.050 in of the final dimensions and is performed with the machine in a fast cut mode. The final two steps are called finishing which are performed at much lower cut rates for control as stated above.

- In the QA phase, inspections are performed to tolerances in the range of 0.0002 inches, which require specialized measurement tools and procedures to ensure the measurements are performed correctly. The combination of a coordinate measuring machine (CMM), precision height gages, bore gages, ring, plug and taper gages are typically utilized. This is the final check before proceeding to strain-gaging and is critical for evaluating the final product. A report of actual dimensions verses designed is generated and any deviations noted for review. An internal LaRC document titled "Standardized Model Support System Assembly" lists typical manufacturing fit tolerances and procedures for inspections.

Figure 10. Balance in "plunge type" EDM Machine

Strain-Gaging

Once the balance has completed the final QA inspection it moves into strain-gaging. This step in the production of a balance is very critical to the final performance.

Due to the attention to detail required, usually an experienced technician is required (>5 years experience in transducer quality gaging).

The strain-gaging or wiring diagram, which details the strain-gage layout on the balance, is reviewed by the engineer and strain-gage technician for any possible improvements. The balance undergoes a complete microscopic examination for sharp edges, surface imperfections, and any other areas that may influence the gaging procedures. Reference 2 details the gaging procedures utilized at NASA LaRC. Listed below are typical strain-gages, adhesives, moisture protections and associated materials.

- Strain gages: C-891113-A or B (Micro-Measurements), 350 ohm gages
- Adhesive: M-BOND 610 (Micro-Measurements)
- Moisture Protection: GageCoat 8 (JP Technologies); M-COAT B (Micro-Measurements)
- Solder: 361A (Micro-Measurements)
- Wire: stranded silver-clad copper wire with Teflon insulation (AWG#30 to 44)
- Temperature sensors: type J and T thermocouples, EL-700T (Hy-Cal) platinum resistance temperature detectors

For harsh environments such as elevated temperatures or excessive moisture other techniques are applied and detailed in reference 2.

Following the installation of the strain-gages, a QA inspection is performed to ensure proper location and alignment. The strain-gages are then wired into a bridge configuration as shown in figure 11.

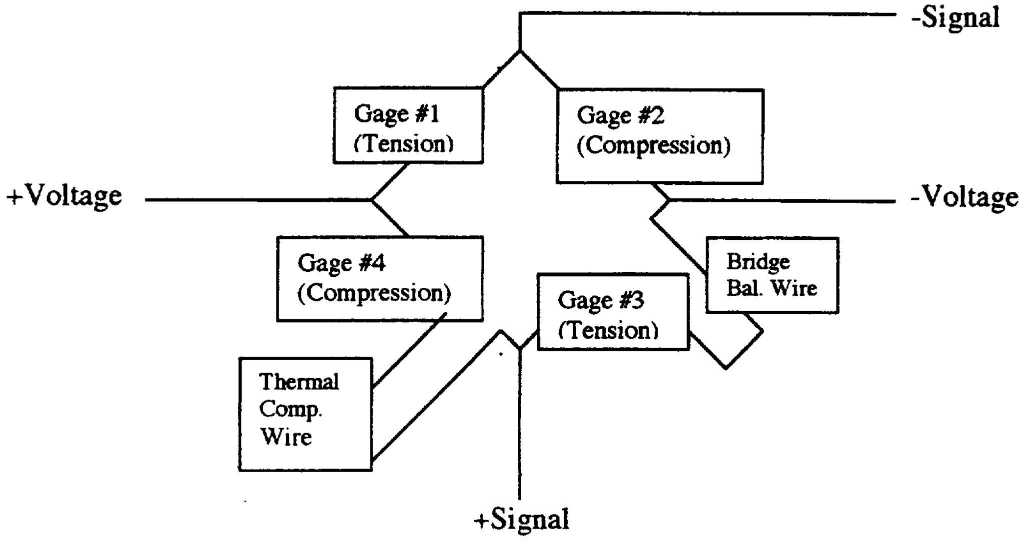


Figure 11. Wheatstone bridge configuration

The bridges must be zero balanced within 0.4 mV/V using Manganin wire to offset the resistance difference between the gages. The balance bridges go through temperature compensation to minimize the output due to steady state temperature changes. Nickel (and silver-clad copper) wire is placed in the bridge (see figure 11) to counteract the response of the bridge to temperature change in a constant load condition. Figure 12 shows a typical temperature run for a balance to be used in a conventional tunnel (80°F to 180°F to 80°F) and the accepted tolerance. Additional sensors are installed on the balance as needed for monitoring temperature. A list of standard temperature sensors is in the bullet list above. When possible, the lead wires are in twisted pairs, signal and power, with a shield to ensure minimum interference and an outer protective sleeving is installed that is nylon or fiberglass. Once the strain-gage bridge wiring is completed, the balance is temperature cycled through its expected operational temperature range plus 50°F where possible. This ensures that all of the wiring has been relieved.

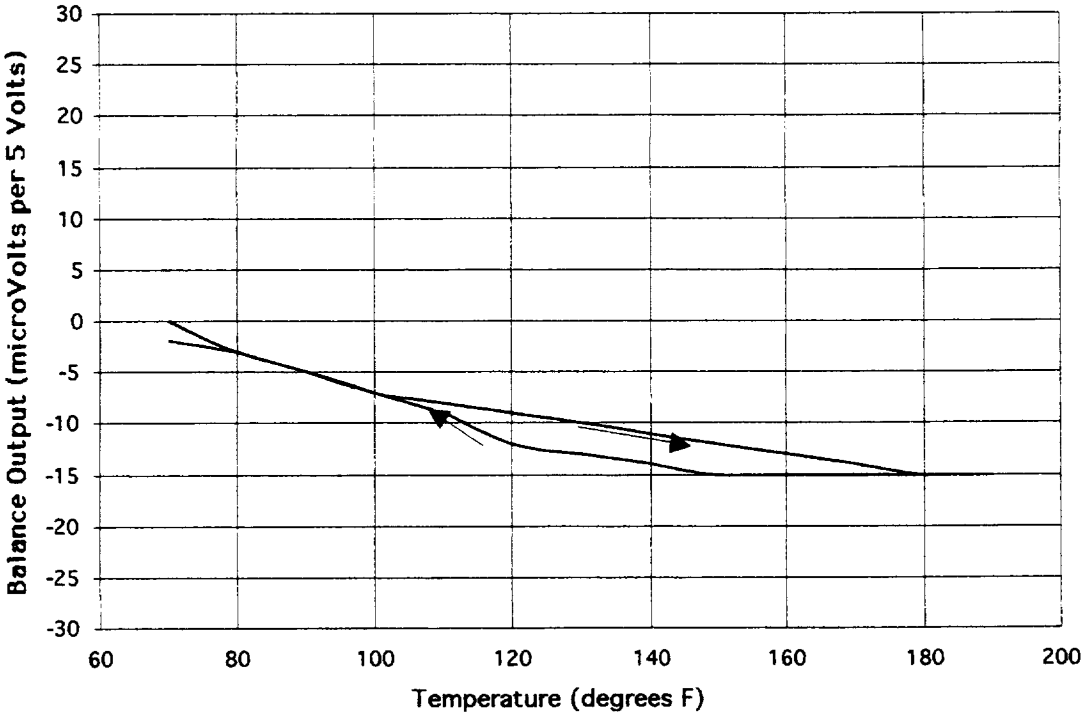


Figure 12. Balance temperature compensation run (test)

Calibration

Balance calibration is the final major step before delivery to the customer. The methods utilized are critical to characterizing the balance and the data is the only deliverable other than the balance itself. The best calibration is achieved when the balance is subjected to the same environmental conditions in the calibration laboratory as the research facility or wind tunnel where the balance will be used. Currently the majority of balances are calibrated at room temperature and to full scale balance loads. While this approach has been acceptable in the past, certain applications, such as cryogenic, have required more in depth calibration at simulated tunnel conditions to improve accuracy. This section will briefly discuss LaRC's current calibration techniques and touch on future developments. References 3, 4, 5 and 6 discuss these techniques in more detail.

LaRC's traditional calibration approach is to use the 6x27 (matrix) second order iterative math model (illustrated below) to characterize a balance.

Balance output (θ) = $k_{1,1}F_N + k_{1,2}F_A + k_{1,3}M_Y + \ldots + k_{1,6}F_Y + k_{1,7}F_{N\wedge2} + k_{1,8}F_NF_A + k_{1,9}F_NM_Y + \ldots k_{1,27}F_{Y\wedge2}$

This equation is rearranged, for each component, to present the form utilized to convert balance output to engineering units.

$F_N = (F_N)_u - (K_{1,2}F_A + K_{1,3}M_Y + \ldots + K_{1,6}F_Y + K_{1,7}F_{N\wedge2} + K_{1,8}F_NF_A + K_{1,9}F_NM_Y + \ldots K_{1,27}F_{Y\wedge2})$

or

Corrected Balance Load = Uncorrected Load (output*sensitivity) - Σ(interaction effects)

Where, F_N is normal force, F_A is axial force, M_Y is pitching moment, and F_Y is side force.

It is assumed that a balance has all of the possible first and second order interaction terms prior to calibration. Therefore, the loading schedule is tailored around this approach and contains 729 loading points with three proof loadings (2 three component and one six component loading to verify the matrix generated from the calibration data). The accuracy of the balance is determined by statistically analyzing back calculated errors using two standard deviation as the result. The balances are calibrated in manual dead weight stands (figure 13 displays a dead weight stand during calibration). LaRC has a variety of stands ranging from a normal force capacity of 3,000 pounds to 20,000 pounds. All loadings are transferred to the balance through a double-knife edge arrangement to minimize unwanted moments and to ensure accurate locations. All applied moment loadings are generated using the long arm technique (whenever possible) to minimize inaccuracies in the position of the load and isolate interaction effects. After each loading, the balance is releveled before data is acquired. When a pure gravity load can not be achieved, for example, loading normal force and side force simultaneously, cable loads are applied (cable refers to what is used to transfer the load in a plane perpendicular to gravity). Also, these cable loads are applied over a bell crank (LaRC developed) as opposed to a pulley. The bell cranks minimize the frictional effects that are commonly found in pulleys. The loading or calibration hardware such as fixtures, moment arms and adapters are precision machined to state-of-the-art tolerances since this equipment is used for ensuring proper balance performance.

Figure 13 is a typical balance calibration set-up. The data acquisition system is made up primarily of a digital voltmeter with a custom written software operation system. The results of a calibration are the sensitivities and interactions for all six components. In some cases temperature loadings are performed to characterize the balance's behavior in those environments. Resistive strip heaters and liquid nitrogen are utilized for varying balance temperature during calibration. Figure 14 is a cover sheet and interaction sheet from the results of a balance calibration. The full report contains other balance related information including all of the interaction terms.

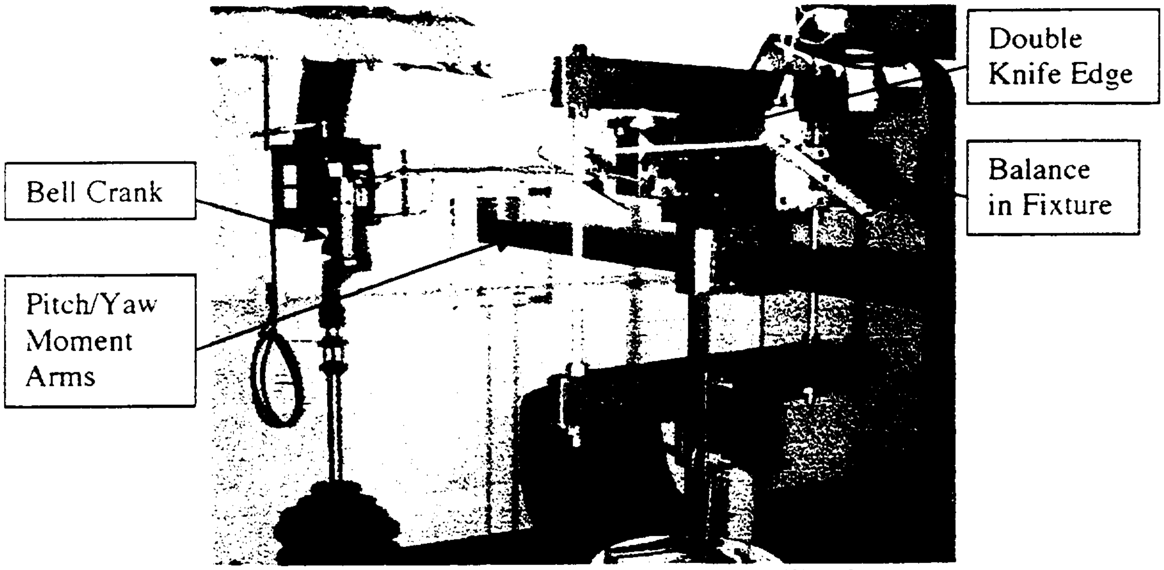
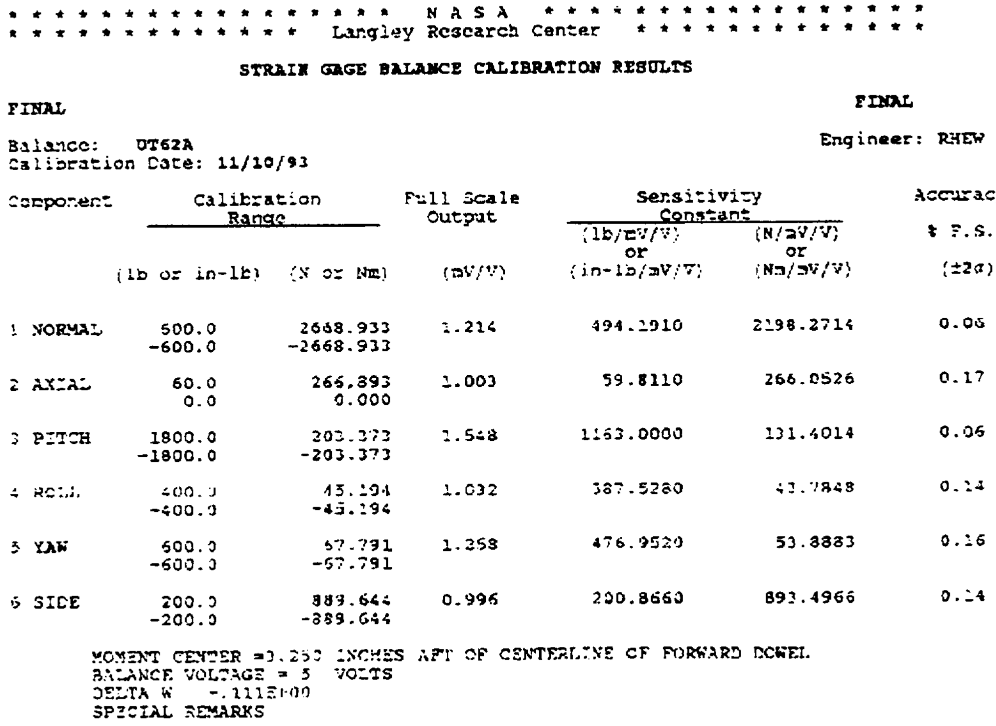


Figure 13. Balance dead weight stand calibration



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STRAIN GAGE BALANCE CALIBRATION RESULTS

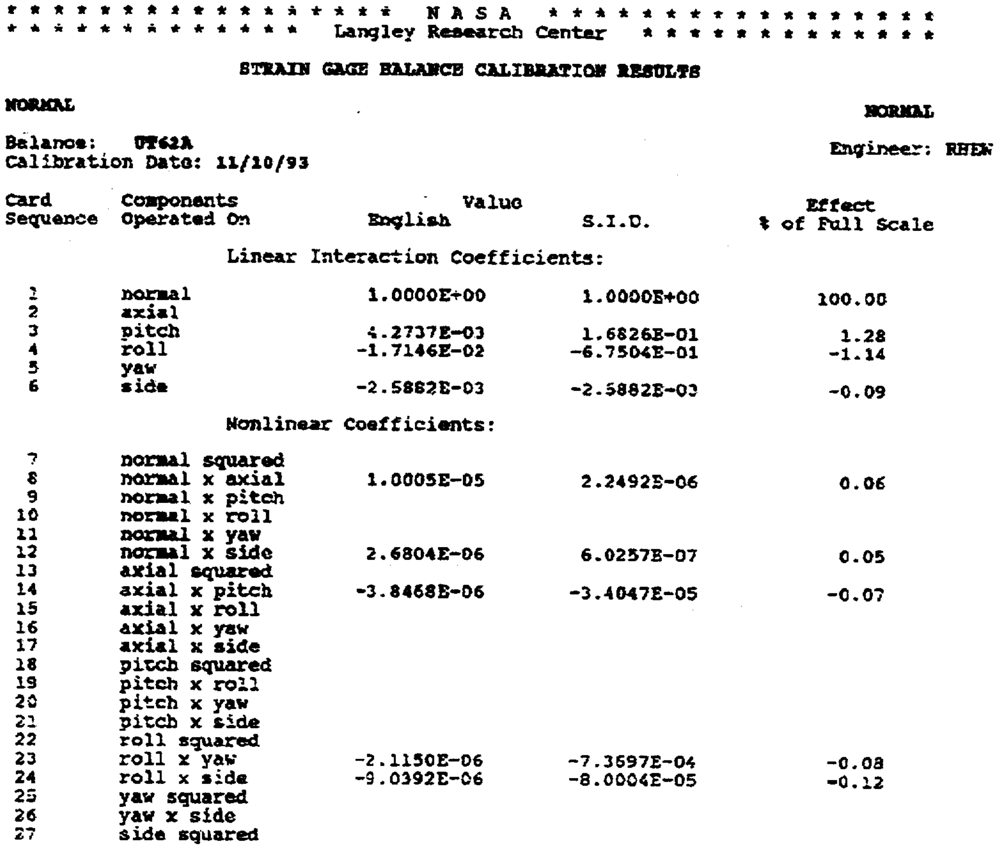
FINAL **FINAL**

Balance: UT62A
Calibration Date: 11/10/93
Engineer: RHEW

Component	Calibration Range		Full Scale Output	Sensitivity Constant		Accuracy
	(lb or in-lb)	(N or Nm)	(mV/V)	(lb/mV/V) or (in-lb/mV/V)	(N/mV/V) or (Nm/mV/V)	% F.S. (±2σ)
1 NORMAL	500.0 -600.0	2668.933 -2668.933	1.214	494.2910	2198.2714	0.06
2 AXIAL	60.0 0.0	266,893 0.000	1.003	59.8110	266.0526	0.17
3 PITCH	1800.0 -1800.0	203.373 -203.373	1.548	1163.0000	131.4014	0.06
4 ROLL	400.0 -400.0	45.194 -45.194	1.032	387.5280	43.7848	0.14
5 YAW	600.0 -600.0	67.791 -67.791	1.258	476.9520	53.8883	0.16
6 SIDE	200.0 -200.0	889.644 -889.644	0.996	200.8660	893.4966	0.14

MOMENT CENTER =3.250 INCHES AFT OF CENTERLINE OF FORWARD DOWEL
BALANCE VOLTAGE = 5 VOLTS
DELTA W -.1111E+00
SPECIAL REMARKS

Figure 14. Calibration cover sheet example



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                     STRAIN GAGE BALANCE CALIBRATION RESULTS

NORMAL                                                                      NORMAL

Balance:    UT62A                                                   Engineer: RHEW
Calibration Date: 11/10/93

Card      Components                  Value                              Effect
Sequence  Operated On          English           S.I.D.             % of Full Scale

                    Linear Interaction Coefficients:

  1       normal               1.0000E+00        1.0000E+00             100.00
  2       axial
  3       pitch                4.2737E-03        1.6826E-01               1.28
  4       roll                -1.7146E-02       -6.7504E-01              -1.14
  5       yaw
  6       side                -2.5882E-03       -2.5882E-03              -0.09

                    Nonlinear Coefficients:

  7       normal squared
  8       normal x axial       1.0005E-05        2.2492E-06               0.06
  9       normal x pitch
 10       normal x roll
 11       normal x yaw
 12       normal x side        2.6804E-06        6.0257E-07               0.05
 13       axial squared
 14       axial x pitch       -3.8468E-06       -3.4047E-05              -0.07
 15       axial x roll
 16       axial x yaw
 17       axial x side
 18       pitch squared
 19       pitch x roll
 20       pitch x yaw
 21       pitch x side
 22       roll squared
 23       roll x yaw          -2.1150E-06       -7.3697E-04              -0.08
 24       roll x side         -9.0392E-06       -8.0004E-05              -0.12
 25       yaw squared
 26       yaw x side
 27       side squared
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Figure 15. Calibration interaction sheet example

Recent advances in automatic balance calibration system technology have caused LaRC to review these techniques in more detail. These systems allow balances to be efficiently calibrated in the expected load and temperature environment of the wind tunnel and thus provide the best calibration.

Summary

NASA LaRC strain-gage balance design concepts have been discussed from initial balance request information to final calibration. All of these areas must be considered during balance design to produce a state-of-the-art balance. However, once a balance is delivered to the customer another process must be executed. This process involves consultation, troubleshooting and maintenance to ensure the balance is used and maintained properly. There are current projects underway or under review to make technological advances in each of the disciplines covered.

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