Development of the NTF-117S Semi-Span Balance

Keith C. Lynn[1]
NASA Langley Research Center, Hampton, Virginia, 23681

A new high-capacity semi-span force and moment balance has recently been developed for use at the National Transonic Facility at the NASA Langley Research Center. This new semi-span balance provides the NTF a new measurement capability that will support testing of semi-span test models at transonic high-lift testing regimes. Future testing utilizing this new balance capability will include active circulation control and propulsion simulation testing of semi-span transonic wing models. The NTF has recently implemented a new high-pressure air delivery station that will provide both high and low mass flow pressure lines that are routed out to the semi-span models via a set high/low pressure bellows that are indirectly linked to the metric end of the NTF-117S balance. A new check-load stand is currently being developed to provide the NTF with an in-house capability that will allow for performing check-loads on the NTF-117S balance in order to determine the pressure tare affects on the overall performance of the balance. An experimental design is being developed that will allow for experimentally assessing the static pressure tare affects on the balance performance.

Nomenclature

AF = Axial Force (lb)
AOA = Angle of Attack
AMS = Angle Measurement System
NASA = National Aeronautics and Space Administration
NF = Normal Force (lb)
NTF = National Transonic Facility
PM = Pitch Moment (in-lb)
RM = Roll Moment (in-lb)
SF = Side Force (lb)
SMSS = Sidewall Model Support System
YM = Yaw Moment (in-lb)

I. Introduction

In order to determine the aerodynamic loads that a wind tunnel model encounters during wind tunnel testing, the fundamental instrument used to directly measure these loads is known as a force balance. The force balance is a force transducer that is capable of providing high-precision measurements of forces and moments, in six degrees of freedom. The underlying purpose of performing wind tunnel tests is to use a scaled test model, and test its performance characteristics (with different model configurations) in an environment that closely simulates 'true' flight conditions, so that these performance estimates can be transferred over to the design of full-scale aircraft. In order to accurately determine these model performance characteristics, it is crucial that a measurement device be used during the wind tunnel test that is capable of accurately/precisely measuring the aerodynamic loads encountered by the test model.

Typically there are two types of balances; internal and external. Internally mounted balances are mounted internal to the wind tunnel model during the testing process. Externally mounted balances, typically referred to as semi-span balances, are mounted external to the wind tunnel model being tested. Semi-span balances are used to test semi-span test models, as shown in Figure 1 below (5.2% 777 semi-span test model, tested at the NTF facility at

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[1] Mechanical Engineer, Aeronautics Systems Engineering Branch, Mail Stop 238, Member AIAA.

NASA Langley Research Center). The recent increase in the need for semi-span balances is directly linked to the advantages/benefits that semi-span model testing provides over full-span model testing. Semi-span model testing provides an increased Reynolds number capability by simply increasing the overall size of the model, allows for higher model fidelity, reduction in aero-elastic effects during testing, and provides a substantial reduction in the costs associated with model fabrication.[1-5] It is also significantly easier to route pressure out to a semi-span model than it is to route the pressure up through a sting, and bridging over an internal force balance. Since most semi-span tests are not concerned with measuring aerodynamic side forces, routing low/high pressure in line with the side force vector presents less repeatability issues than when trying to route the pressure in-line with the axial force measurement component of the typical internal force balance. When providing a pressure source out to a full-span model, the pressure is routed through a series of pressure bellows that are directly in-line with the axial force vector of the force balance, thus increasing the likelihood that the pressure tare effects could impact the performance (accuracy, repeatability) of the internal balance.

While there are significant advantages to semi-span model testing, there are also several factors that present disadvantages. These disadvantages include increased negative impacts due to tunnel wall interference,[3,5] interaction of air-flow over the semi-span model with the tunnel wall boundary layer,[3,5,6] and thermal stability issues that are observed by the externally mounted semi-span force balances. While each of these impacts negatively impacts data accuracy, a significant amount of research has been performed to determine proper corrective measures to reduce the impacts on the accuracy of the test data.

With the demand for performing semi-span wind tunnel testing on the rise, the demand to provide highly accurate and precise semi-span force balances has increased. This report is going to go into detail on the design and calibration of a new semi-span balance developed for use at the NTF at NASA LaRC, and will also provide detail on the upcoming wind tunnel tests that will utilize this new measurement capability. The upcoming tests that will utilize this new balance will also be using an new high-pressure air delivery station that will be used to route this high-pressure air flow out to the semi-span models for testing circulation control and simulated propulsion capabilities. This high-pressure air is delivered from the air delivery station to the semi-span model through a concentric set of pressure bellows, which are indirectly linked to the metric end of the balance. With the addition of these bellows to the system, a new check-load stand design will also be discussed that will enable the NTF to characterize the effects of the pressurized bellows on the performance/behavior of the semi-span balance.

5.2% 777 semi-span model in the NTF
NASA Langley Research Center 5/3/2000 Image # EL-2000-00153

Figure 1. 5.2% 777 Semi-Span Test at NTF (NASA Langley Research Center)

II. Balance Development

A. Test Facility

The NTF is a large cryogenic, high-pressure, closed-circuit wind tunnel facility that was developed in the 1970's due to the increased need for a facility that was capable of providing high Reynolds number testing capabilities.[7,8] The need for this high Reynolds number capability allows for simulating full-scale aircraft operating conditions. The NTF is a unique test facility in that it allows for testing both full-span and semi-span test models, using either air or cryogenic nitrogen as the test gas. The original motivation for developing the NTF was spawned during the 1960's from a discussion during an Advisory Group for Aerospace Research and Development (AGARD) specialists meeting on transonic aerodynamics.[8] It was decided at this meeting that the United States lacked adequate theoretical methods and experimental wind tunnel testing facilities for predicting aircraft flight characteristics at high Reynolds numbers for both military combat and commercial aircraft. Construction of the NTF began in 1975, and the facility was first opened up for operation in 1982.

The NTF is a close-circuit fan-driven facility, with a test section that measures 8.2' x 8.2' x 25', and has both slotted floors and ceilings (to help prevent any near-sonic flow 'choking' effects). The facility has operating conditions of 15-125psia and +150°F to -260°F, with a Mach number capability ranging from 0.2-1.2. In order to test at cryogenic temperatures, liquid nitrogen (LN2) is injected into the tunnel directly up-stream of the fan and this liquid nitrogen evaporates resulting in a cool down as a result of the heat of vaporization and latent heat. By testing with liquid nitrogen as the test medium, the resulting increased Reynolds number capability is achieved through reducing the kinematic viscosity and increasing the density of the air stream.[6] When testing in air, the heat is removed from the tunnel by an upstream water-cooled heat exchanger.

As mentioned previously, the NTF has the capability of testing both full and semi-span wind tunnel models. In order to conduct semi-span model tests, the semi-span model is supported in the tunnel by the SMSS. Before mechanically attaching the model to the SMSS, a segment of the test section wall is removed so that the SMSS can be installed behind the test section. Once the SMSS is attached to its appropriate structure behind the tunnel wall, the removed test section wall is re-installed. The center of the SMSS (and semi-span balance) is located 13 feet aft of the plane where the test section begins. When the semi-span model is mounted, it is mechanically joined to the semi-span balance by fastening it to the SMSS top-hat adapter. During model installation a stand-off is place in between the test section wall and the model, to help reduce any negative effects between the interaction of the sidewall boundary layer and the performance of the semi-span model.

B. Cryogenic Testing

The NTF has the capability to perform wind tunnel tests in both air and cryogenic nitrogen operating conditions. As the operating temperature within the test section begind to approach cryogenic temperatures, the thermal behavior of both the model and balance are affected by thermal characteristics of the system. The semi-span balances are located within the SMSS, which is a self-contained unit that houses the balance, the drive mechanisms that pitch the model to vary angle of attack, and all other instrumentation/wiring that is used during the test. The existing SMSS is contained behind the test section wall, but the operating temperature within the tunnel affects all elements internal to the SMSS. The inherent design of any semi-span model requires that the model be attached to it's support mechanism such that reflection plane of the model is as close to the test section wall as it can be, without creating a parallel load path (fouling the model against the test section wall). With this design, naturally a finite gap will exist between the model and the test section wall which can provide an opening for cold airflow to pass through, which will cause temperature gradients both within the SMSS and between the SMSS and the attached model.

In previous years the facility has conducted a very thorough investigation was conducted on the SMSS and the NTF-114S semi-span balance behavior/performance, with all experimental tests directly relating to issues associated with thermal gradients that were discovered within the system as a result of cryogenic operating conditions.[3] A series of different configuration modifications were made to the SMSS in an attempt to reduce theses gradient effects, such that the measurement accuracy of the balance was within an acceptable range. Some of these SMSS configuration modifications included[3]:

1. Adding a labyrinth seal between the model fuselage (metric) and the model standoff (non-metric)
2. The balance cavity was sealed, to decrease/eliminate airflow of gas through the SMSS (See Figure 3a)
3. Non-fouling seals were added between the balance and top-hat model adapter
4. New cover shields were added to NTF-114S balance, to help block flow through balance (See Figure 3b)
5. Balance thermal compensation tolerances were tightened in order to reduce the result apparent strain effects
6. Nitrogen purge system was added to internal SMSS cavity to help stabilize SMSS and balance temperatures
7. Heaters added that surround the exterior of the NTF-114S balance, to implement the "hot-balance" concept

At the conclusion of these tests, all of the above modifications were made in order to decrease the observed balance temperature gradients. One of the main conclusions from these series of tests was that during test operations, it is best to utilize the "hot-balance" concept, where heaters surrounding the balance are used to keep the balance at an elevated temperature (relative to the tunnel conditions) of around 70-80°F. By maintaining the balance at an elevated temperature, it can be monitored and controlled such that the internal gradients can be maintained at a minimum during the duration of the test.

C. NTF-117S Balance Design

In recent years the NTF has devoted a considerable amount of effort in developing its semi-span model testing capability[1-3,5]. The increased interest in semi-span testing at the NTF has sparked the development of new balance design requirements, which in turn resulted in the development of new semi-span balances capable of measuring the aerodynamic loads on these semi-span test models. Initially, a single semi-span balance was designed (NTF-114S) that had a NF measurement capability of 6,100 lb. The NTF-114S semi-span balance has traditionally been used primarily for high-Reynolds number testing for low-speed high-lift model configurations.[2] As new semi-span model configurations and testing technologies continue to be developed that will require testing at high-speed transonic testing regimes, the required NF measurement capability needed at these testing conditions surpasses the capability of the existing NTF-114S balance. The limited measurement capability of the existing NTF-114S semi-span balance prompted the development of the new NTF-117S balance, which has a NF measurement capability (12,000 lb) that nearly doubles that of the NTF-114S. Table 1 below compares the design loads for both the NTF-114S and NTF-117S, to show the increase in measurement capability as a result of the development of the new NTF-117S balance.

Table 1. Current NTF Semi-Span Balance Capabilities

	NF (lb)	AF (lb)	PM (in-lb)	RM (in-lb)	YM (in-lb)
NTF-114S	6,100	1,300	70,000	353,800	75,400
NTF-117S	12,000	1,800	90,000	670,000	100,000

The NTF-117S is a monolithic 5-component left-wing semi-span balance (no SF measurement component), made of titanium-strengthened high strength 18% nickel maraging steel (VascoMax T-200), which has been heat treated to the H900 condition (heat treat to 900°F for 6 hours, air cooled to room temperature). The VascoMax T-200 H900 heat treated material condition provides a Rockwell C hardness value of 41-45, and results in nominal strength values of $\sigma_{ultimate}$= 214 ksi, σ_{yield}= 209 ksi. The balance has an overall outer diameter of 16.0", and a total length of 25.75" (see Figure 2 below for all critical dimensions), and weighs approximately 900 lbs. Both the metric and non-metric interfaces have bolted type flanges.

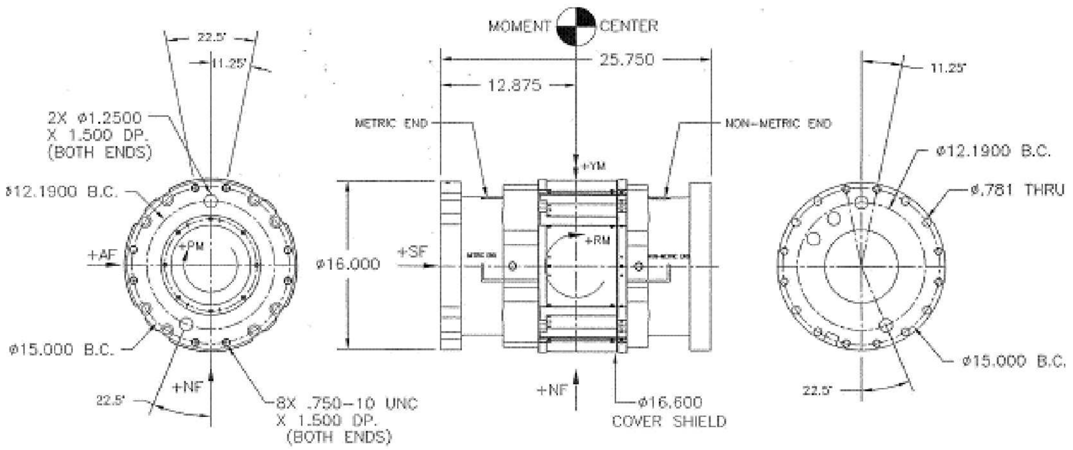


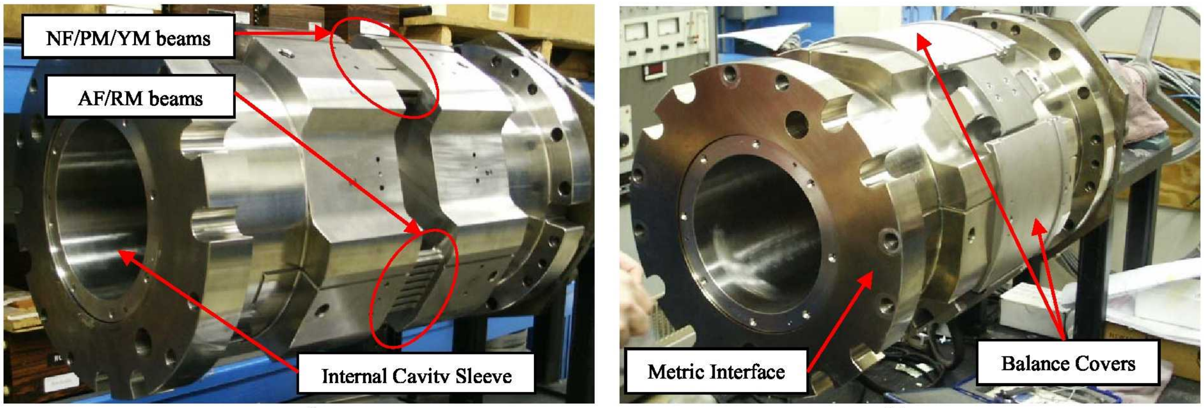
Figure 2. NTF-117S Critical Dimensions

The balance was designed and fabricated in the late 1990's by Triumph Aerospace, and when fabrication was completed the available funding for the balance development was eliminated, forcing the un-instrumented balance to sit unused for nearly 10 years. A series of upcoming tests to be performed at NTF (to be discussed in further sections) needing to utilize a semi-span balance with design loads matching the capability of the NTF-117S prompted revitalizing the balance, and completing its development. In late 2008 the balance was delivered to Modern Machine & Tool for it to be instrumented (strain gages, PRT's, AOA measurement system) and calibrated.

When the balance was initially designed in 1999, the design requirements included the following:

1. Conform to the stress criteria defined in the NASA Langley Research Center "Wind-Tunnel Model Systems Criteria" document LPR1710.15
2. Design for an operating temperature range from -40°F to 150°F ('mild' cryogenic conditions)
3. Minimum Spring Constants:
    a. NF – 6,000,000 lb/in
    b. AF – 600,000 lb/in
    c. PM – 4,500,000 in-lb/deg
    d. RM – 25,000,000 in-lb/deg
    e. YM – 20,000,000 in-lb/deg
4. Minimum Full-Scale gage outputs:
    a. NF – 1,200 μV/V
    b. AF – 1,200 μV/V
    c. PM – 1,200 μV/V
    d. RM – 1,200 μV/V
    e. YM – 400 μV/V

The balance was designed using beam relations/equations to compute the resultant loads and maximum stress values in each of the measurement flexure beams. This balance was designed to have a total of 22 measurement flexure beams; 8 for NF/PM/YM & 14 for AF/RM, as shown in Figure 3 below. The high stiffness requirements imposed on the design of the balance were unique for this balance, and were based directly on the method of assembling the balance into the SMSS. As mentioned in an earlier section, when a semi-span model is attached to the balance there is a non-metric standoff that is placed between the model and the test section wall. There is also a non-fouling labyrinth seal between the model and the test section wall, which is used to decrease air flow from the tunnel free stream into the internal cavity of the SMSS. Both of these gaps are as small as possible in order to minimize thermal gradient effects, therefore the torsional stiffness requirement for the pitching moment of the balance was increased so that the gap distances could be maintained during aerodynamic testing.[8]



a) b)

Figure 3. NTF-117S Semi-Span Balance, a) w/o external balance covers, b) w/ external balance covers

As seen in Figure 3 above, the balance has flange type mounting interfaces on both the metric and non-metric interfaces, which allow for rigidly attaching the non-metric end of the balance to the SMSS, and the metric end of the balance to the semi-span model (with a thermal insulation disk located between the balance and top-hat, to decrease thermal gradient effects). The balance was designed with an 8.0" diameter hole down its centerline, which accommodates all of the wiring and instrumentation that is routed between the semi-span model and the data acquisition system. As will be discussed in a later section, for future tests the hole down the centerline of the balance will be used as a passage way to route high-pressure air lines from the NTF high-pressure air-station, out to the semi-span models (via a concentric set of pressure tubes/bellows).

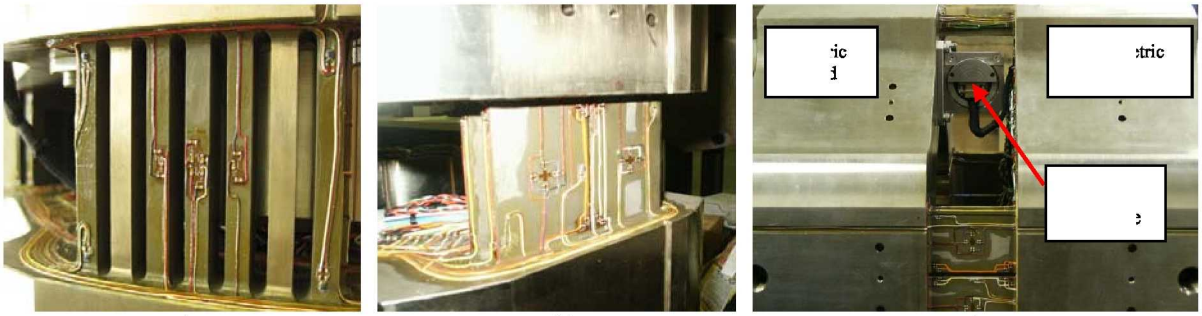
D. Balance Instrumentation

The NTF-117S balance was instrumented with double-bridged primary and secondary bridges, using a total of 80 C-891113-A (Micro-Measurements) 350-ohm strain gages. Each primary and secondary bridge was instrumented with a double-bridge configuration to aid in decreasing both interaction and thermal gradient effects. Each of the primary and secondary bridges are individually powered with a parallel wiring scheme (common voltage), where each of the 5 bridges are excited with a common 5V power source, and the voltage is both monitored and sensed locally at the balance main terminal. Using this common voltage excitation method allows for reducing the number or wires required that run between the balance and the data acquisition system (a total of 32 wires required for both the primary and secondary bridges). Advantages of this common voltage scheme are; it allows for reducing the total number of required wires, any changes in the wiring resistance does not change the measured data, and only one power supply needs to be set and monitored for each of the primary and secondary bridges. Disadvantages of using this common voltage excitation scheme include troubleshooting issues, as each of the bridges being operated from the common source are not electrically separated, and any grounding issues that arise are difficult to trace because the issue occurs with all bridges.

One issue that must be carefully investigated when dealing with a balance that will be used in cryogenic operating conditions is that the balance instrumentation must be protected from possible moisture that could build-up on the surface of the balance instrumentation. Although moisture management has been investigated at the NTF, and the tunnel monitors/controls the levels of particulate moisture in the tunnel[2], the likelihood that moisture build-up on balance instrumentation will occur must be accounted for during the design process. In order to properly install strain gages on a balance to be used in cryogenic operating conditions, a standard set of installation procedures have been established at NASA Langley Research Center which have been implemented and experimentally verified to both protect the instrumentation from moisture, and reduce the effects of moisture on the resultant force/moment data. An abbreviated subset of the critical procedure steps used to properly instrument the NTF-117S balance for use at the NTF is as follows[10]:

1. Perform gage matching process[11], to select a set of strain gages whose thermal response characteristics are similar. The gages that are selected based on similar thermal response behaviors are then used to compose a measurement bridge within the balance.
2. Degrease the entire balance using a vapor degreasing solvent rinse.
3. Rinse balance with ethyl alcohol.
4. Mask areas to be instrumented, and micro-sandblast areas using 50 micron AL_2O_3 (after sandblasting, remove abrasive powder with dry shop air).
5. Repeat degreasing and rinse operations.
6. Apply all strain gages (typically C-891113-A or –B) using M-BOND 610 adhesive.
7. Perform several cure cycles to ensure gages are properly adhered.
8. Wire up strain gages to balance terminals using interconnecting wiring and jumper wire; typically AWG#32 (7 strands of 40AWG silver-clad copper wire, with etched non-extruded Teflon insulation).
9. Perform initial electrical checks (resistance leakage to ground, electrical zeroes, shunting, and hand loading of balance to ensure proper performance and output polarity).
10. Perform thermal soaking cycles.
11. Perform initial apparent strain correction runs (for the NTF-117S balance, the apparent strain correction process differs from most NTF balances in that the balance is kept at an elevated temperature, approximately 80°F, during test operation. Therefore the NTF-117S apparent strain correction runs were performed between 80°F-180°F).
12. Install 2 coats of moisture-proofing (typically M-Coat B) over all strain gage solder dots, gage jumpers, solder joints, axial differential compensation wire, and all un-insulated wire.
13. Perform final apparent strain runs (80°F-180°F).

In addition to the strain gage instrumentation, a total of 32 PRT's (type EL-700T) were installed on the balance in order to monitor the temperature profile of the balance during testing. The PRT's were distributed throughout the balance such that both the global temperature profile can be observed, as well as being able to measure the local temperatures near the strain gage locations. The installation of the PRT's is performed using the EA-934 (Hysol) adhesive, to adhere the PRT to the metallic surfaces near the strain gage locations. The balance also has an on-board AOA measurement package, which provides an absolute reference of the balance and model pitch attitude (angle-of-attack) during testing. This AOA was operational during the calibration of the balance, and was used to compare the pitch deflection measurements from the AMS (which was mounted to the calibration hardware during the duration of the calibration). The difference in the pitch measurement between the AOA and AMS packages provides an estimate of the pitch deflections induced on the balance and calibration hardware as a result of the applied calibration loads. Figure 4 below shows some of the instrumentation (strain gages, AOA package) installed on the NTF-117S balance.



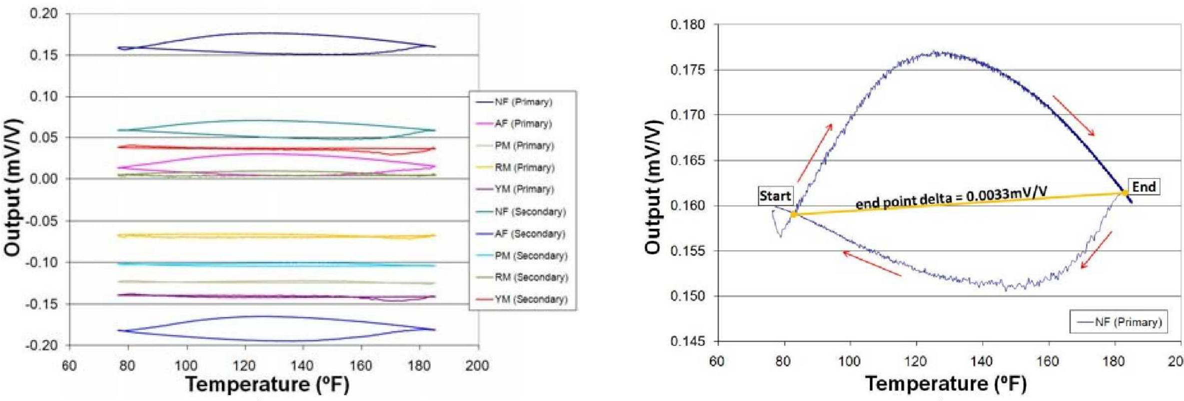
a) b) c)

Figure 4. a) AF/RM flexure beams, b) NF/PM/YM flexure beams, c) on-board AOA measurement package

E. Thermal Compensation

After all of the above instrumentation was installed on the balance, steps 11-13 from the previous section were performed in order to thermally compensate the balance strain gages. The purpose of performing this compensation process is to minimize the apparent strain output of the measurement bridges due to steady state temperature changes. Before taking any corrective measures to compensate the measurement bridges, the first steps that are taken in order to reduce any thermal effects begin in the initial design phase of the balance.[9] During the design of the balance, the strain gage locations are selected strategically in order to both increase the maximum measurement sensitivity, and to aid in reducing the magnitude of the resultant thermal interaction effects. After the gage locations are selected, the next step in minimizing the resultant apparent strain outputs are performed during the gage matching process, where the gages that compose a single bridge are selected such that each of the bridges have similar thermal response behaviors.

After the strain gages are installed, the balance is cycled through its expected operating temperature range, and the electrical zeroes for each measurement bridge are recorded. As the balance is cycled through some temperature range, the strain gages themselves contract and expand, which results in an output from the bridges which is observed to be an apparent strain. For NASA Langley balances, the resulting apparent strain output curves are recorded and plotted for each of the bridges. In order to compensate each of the bridges, sections of temperature sensitive wire (typically nickel or silver-clad wire) are placed within the appropriate legs of the bridges to help counteract the output response of the bridge to any temperature changes.[12]



a) b)

Figure 5. a) NTF-117S Primary & Secondary apparent strain curves, b) Primary NF apparent strain curve

Typically for NASA Langley balances, when the balance is cycled to measure its resultant apparent strain output, the resulting outputs are non-symmetric loops (as shown in Figure 5 above). Figure 5a plots the final apparent strain output loops for each of the 10 bridges on the NTF-117S, and Figure 5b plots the loop data for the primary NF bridge (both plots are for a temperature range of 80°F to 180°F). It can be seen from these figures that the response output from nearly all of the bridges show some level of hysteresis, where the apparent strain output differs depending on whether the balance is being heated up or cooled down. This is typical for nearly all balances, thus when performing the apparent strain thermal compensation the corrections do not attempt to correct for the changes in the electrical zero between any discrete temperatures. The corrective measures that are taken to compensate all NASA Langley balances are performed by looking at the difference in the electrical zero output at the start and end points (80°F and 180°F), and the typical requirement is that each bridge must be compensated such that the maximum delta between the end points is less than 0.003 mV/V. Note the end-point difference for the apparent strain curve of the primary NF component for the NTF-117S balance (shown in Figure 5), which resulted in a difference of 0.0033 mV/V. Each of the apparent strain corrected values for all primary and secondary measurement bridges are shown in Table 2.

Table 2. NTF-117S Apparent Strain Corrected end point differences

Apparent Strain End Point Deltas					
Primary Bridge	NF (mV/V)	AF (mV/V)	PM (mV/V)	RM (mV/V)	YM (mV/V)
	0.00334	0.00071	0.00270	0.00010	0.00280
Secondary Bridge	NF (mV/V)	AF (mV/V)	PM (mV/V)	RM (mV/V)	YM (mV/V)
	0.00046	0.00129	0.00203	0.00047	0.00361

F. Balance Calibration

The most critical portion of thno probe balance design process is the balance calibration, which is the process by which known loads are applied to the balance and the measured responses from each of the measurement bridges are recorded. The purpose of performing a balance calibration is to develop a mathematical model that characterizes the behavior/performance of the balance, so that this mathematical model can be used to estimate the aerodynamic loads imparted on the balance during the wind tunnel test. As a general procedure, when calibrating a force balance a set of pre-determined independent variables (applied calibration loads) are applied to the balance, and the resulting dependent variables (electrical output response of each measurement bridge) are recorded. The range of the calibration loads applied to the balance during the calibration process defines the 'design space'. Historically, the load schedule used to calibrate a balance (which defines the load combinations and the order that they are to be performed) has been a standardized process that is the same for all balance types. NASA Langley's traditional method for calibrating any balance is to use a full 2nd order mathematical model (6 linear main-effect terms, 15 non-two-factor interactions and 6 pure quadratic terms) to represent the functional relationship between the applied calibration loads and the bridge response voltages.[13]

The multivariate polynomial equation for the full 2nd calibration model created for each of the balances responses is:

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 \qquad (1)$$

For the NTF-117S balance calibration, k would be the number of independent variables (k = 5), x_i*'s* are the *ith* independent variable, and the β's represent the calibration coefficients determined from a linear regression procedure. The calibration coefficients are included within a calibration matrix, which is essentially a curve-fit to the calibration data.

The calibration of the NTF-117S force balance involved applying different load combinations to the balance with dead weights (shown in Figure 6), where these dead weights are applied to precisely defined load points on the balance calibration hardware. The balance is supported on the non-metric end by mechanically grounding it to a calibration stand, which supports the balance during the application of all calibration loads. The calibration stand has actuators that allow for re-leveling the balance in both pitch and roll after each load is applied, to ensure that applied loads are orthogonal with the balance coordinate system before the data acquisition system collects the data for that load point. For the calibration of the NTF-117S balance, 62 different loading sequences were performed, with each sequence containing 5 increments (0 load, 50% load, 100% load, 50% load, 0 load). Of these 62 different loading sequences, combinations of single and multi-component loading were applied to the balance, providing a total of 310 data points to be used for building the mathematical calibration model. All loadings were performed at a nominal ambient room temperature. The calibration loads are transferred through a configuration of double knife-edge decoupling devices, which are used to minimize coupling of unwanted moments on the balance during calibration. With most manual calibration systems, there are limitations that prevent being able to apply pure moments during the calibration. In order to simulate applying pure moments, the long-arm calibration technique is used where all moments are applied to the balance by applying small magnitude loads to calibration arms that are relatively long. This process helps minimize inaccuracies, and helps isolate the interaction effects.[12]

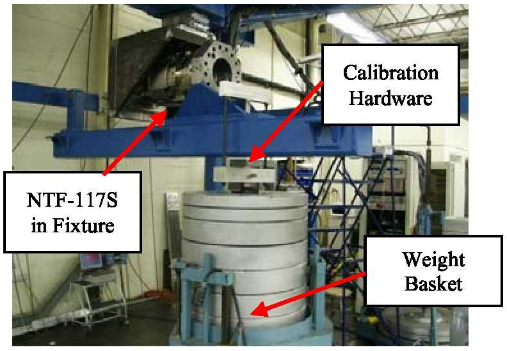


Figure 6. NTF-117S Calibration Configuration

The 62 different load sequences used to calibrate the balance were selected to enable for exploring the entire design space capability of the balance, with the full-scale capability of each load component being explored. The load combinations explored during the duration of the calibration are depicted in Figure 7 below. These plots show the different load combinations that were explored, revealing how the load combinations were dispersed for each of the load measurement components.

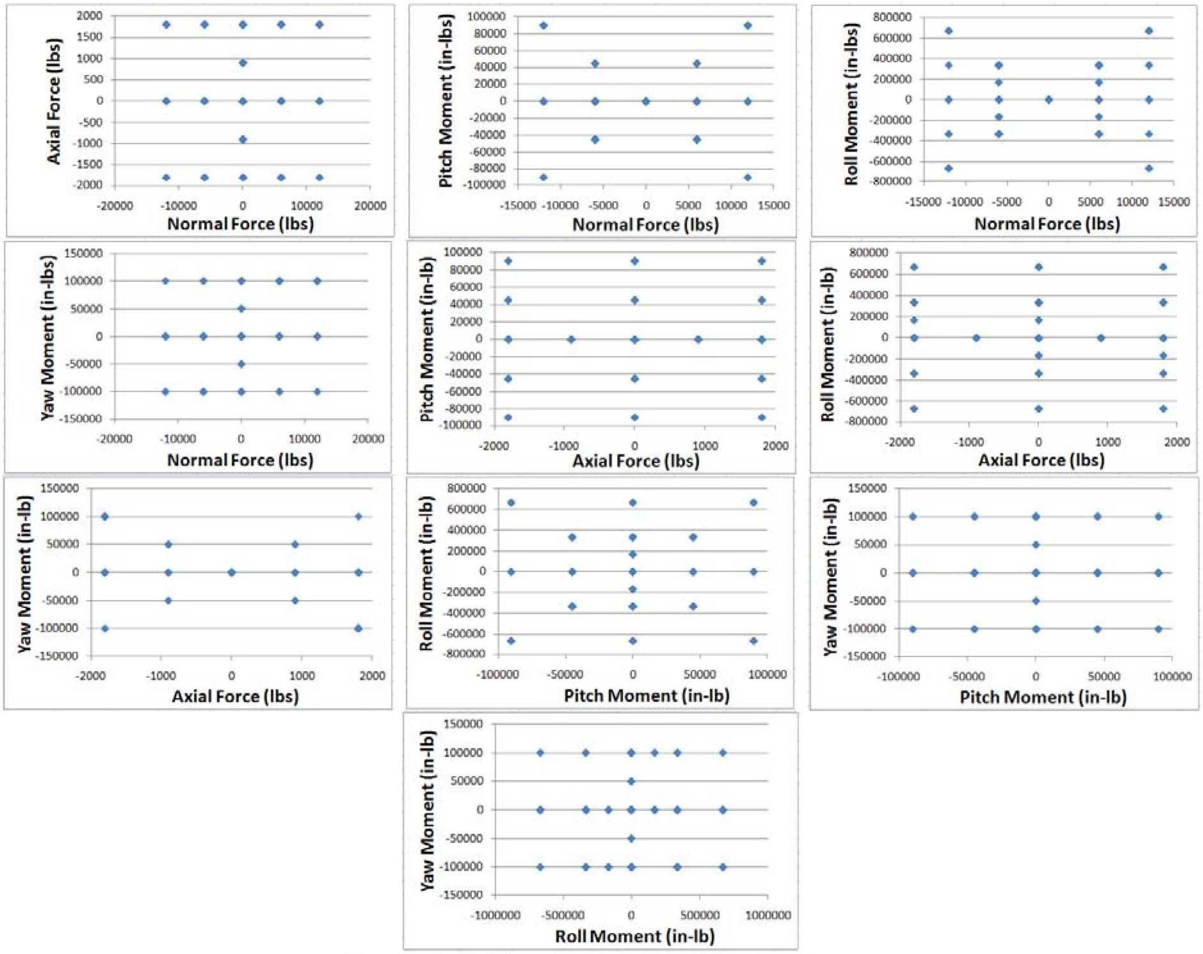


Figure 6. Calibration load combination plots

After each of the 310 calibratin loads were completed (over the course of 5 weeks), all of the data points were reduced using a least-squares linear regression technique to produce the resulting calibration coefficients. Once the calibration coefficients were computed from the data reduction process, the calibration model for each of the balance responses was used to back-calculate the response residuals (error in the prediction capability of the calibraiton models). The process of computing the back-calculated residuals is as follows:

1. Compute the calibration model for each of the balance responses (NF, AF, PM, RM, YM)
2. Using this model and the output responses form the calibration, compute the predicted applied loads
3. The residual error is the difference between the applied load and the predicted load
4. Compute the 2-sigma standard deviation of the residuals, which yields the resultant % full-scale accuracy for the measurement component

By using the calibration models to back-calculate the residuals for the calibration data points, the % full-scale accuracies for each measurement component are computed. The calibration residuals and the resulting measurement accuracy is used to assess the associated measurement accuracy and uncertainty of the balance. There are 3 main sources of uncertainty associated with the calibration; 1) calibration model that is created from the calibration data, 2) the measurement repeatability of the balance, and 3) the uncertainty of the calibration system (hardware, data system) used during the calibration. The back-calculated residuals, expressed in terms of the % full-scale loads, are shown in Figure 7 below for the NTF-117S primary bridge. As seen from the figure below, all of the individually computed residual values are less than 0.5% full-scale.

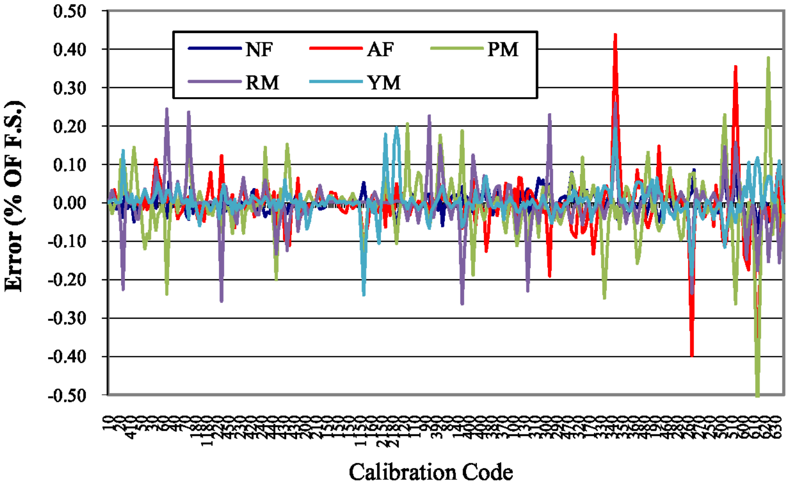


Figure 7. NTF-117S error plot for each measurement component

At the conclusion of the calibration, after the calibration model is created and the back-calculated residuals are computed, the final accuracy (as % of full-scale) is reported back to the researcher, along with the expected full-scale voltage output and the linear sensitivity constants. The final calibration accuracies and full-scale outputs are provided shown below in Tables 3 & 4, and the calibration interaction coefficients for each measurement component are contained within Table 5.

Table 3. Primary Bridge calibration results

	Component	Calibration Load Range	Full Scale Output (mV/V)	Sensitivity Constant (lb/mV/V)	Accuracy %F.S. (2-sigma)
Primary Bridge	NF	-12000 to 12000 lb	1.332	9010.86	***0.05***
	AF	-1800 to 1800 lb	1.224	1470.4	***0.14***
	PM	-90000 to 90000 in-lb	1.734	51900.06	***0.16***
	RM	-669000 to 669000 in-lb	1.873	357224.4	***0.12***
	YM	-100350 to 100350 in-lb	0.291	345046.5	***0.09***

Table 4. Secondary Bridge calibration results

Secondary Bridge	Component	Calibration Load Range	Full Scale Output (mV/V)	Sensitivity Constant (lb/mV/V)	Accuracy %F.S. (2-sigma)
	NF	-12000 to 12000 lb	1.363	8803.72	***0.09***
	AF	-1800 to 1800 lb	1.226	1467.67	***0.13***
	PM	-90000 to 90000 in-lb	1.436	62687.1	***0.16***
	RM	-669000 to 669000 in-lb	1.885	354977.8	***0.12***
	YM	-100350 to 100350 in-lb	0.289	347772.5	***0.10***

Table 5. Balance Calibration Interaction Coefficients

		NF	AF	PM	RM	YM
Linear Interaction Coefficients	Normal	1.000E+00	1.945E-04	-5.059E-02	1.019E-01	4.978E-02
	Axial	8.785E-02	1.000E+00	-2.355E-03	-3.283E-01	1.946E+00
	Pitch	2.599E-04	-7.279E-05	1.000E+00	-8.616E-03	-8.346E-03
	Roll	2.995E-04	-7.596E-07	-7.458E-05	1.000E+00	-1.781E-03
	YM	-4.396E-05	-1.057E-04	5.724E-05	-2.044E-03	1.000E+00
	SF	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Non-Linear Interaction Coefficients	Normal x Normal	-7.047E-09	-1.052E-09	-7.727E-08	-8.679E-10	1.271E-08
	Normal x Axial	-4.088E-08	-4.626E-09	1.881E-06	-4.440E-07	4.854E-07
	Normal x Pitch	1.646E-06	2.016E-09	-8.011E-09	-3.506E-08	1.177E-08
	Normal X Roll	-4.862E-10	5.288E-11	-2.069E-09	-5.292E-09	6.506E-09
	Normal x Yaw	-8.550E-10	-1.385E-10	2.159E-07	-3.622E-09	1.719E-08
	Normal x Side	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
	Axial x Axial	1.071E-07	-3.756E-08	-2.769E-06	-2.598E-06	4.124E-06
	Axial x Pitch	-1.712E-08	3.698E-09	9.437E-08	3.186E-07	1.069E-07
	Axial x Roll	2.799E-10	1.168E-10	7.486E-07	-8.580E-08	-1.415E-08
	Axial x Yaw	-1.734E-10	1.612E-09	2.418E-08	-5.368E-07	-2.297E-08
	Axial x Side	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
	Pitch x Pitch	-1.661E-10	-1.010E-11	-2.140E-09	2.333E-09	-1.303E-09
	Pitch x Roll	1.610E-10	2.287E-09	2.401E-10	-5.148E-10	2.230E-09
	Pitch x Yaw	2.065E-09	1.601E-10	3.182E-09	1.172E-08	1.602E-09
	Pitch x Side	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
	Roll x Roll	6.315E-13	3.689E-12	5.725E-11	7.285E-11	-1.048E-10
	Roll x Yaw	-5.178E-11	1.068E-11	-6.451E-09	-1.711E-09	2.455E-10
	Roll x Side	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
	Yaw x Yaw	1.522E-10	-3.876E-11	1.278E-10	-2.635E-09	-3.340E-09
	Yaw x Side	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
	Side x Side	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00

III. Future Testing and Check-Load Stand Development

G. Future Flow Control/Propulsion Simulation Testing

An area of research that has shown increased interest in the aircraft research field is that of active flow control. Active flow control research has shown promise in its ability to increase aerodynamic performance of existing conventional aircraft designs, as well as leading to the development of non-conventional aircraft designs.[14] There are many varieties of active flow control, but the one technique that is of interest for upcoming tests at the NTF that will utilize the NTF-117S balance is the area of circulation control. The concept of circulation control works by increasing the velocity of the airflow over the leading edge and/or trailing edge of a wing using high-pressure air that is ejected out of a set of blowing slots. Increasing the momentum of the airflow over the wing by introducing this high-pressure air allows for increasing the resulting lifting capability of the wing, which is critical during both takeoff and landing of any aircraft (research has also shown that circulation control techniques can assist in both drag reduction and simplified maneuvering systems during transonic cruise test conditions[15]). The circulation control testing community has been pushing forward building their aerodynamic database, but one area of research that has not

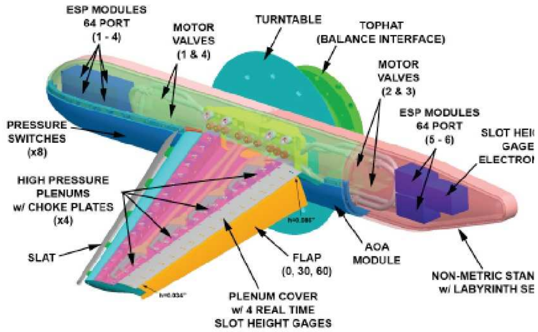


Figure 8: NTF Transonic circulation control & propulsion simulation semi-span model design

been published is circulation control data at actual flight Reynolds numbers, which limits the scalability of the techniques.[14]

Another area of research that is currently being tested in conjunction with the active circulation control technique is that of propulsion simulation. This concept is a technique that is used to simulate the thrust of full-scale aircraft jet engines by ejecting high-pressure (and high mass-flow) air out of simulated jet engines on the test model.

Upcoming semi-span model tests at the NTF will be implementing both circulation flow control and propulsion simulation capabilities on a transonic wing design. The model was designed to allow testing both capabilities (active flow control and propulsion simulation) for both low speed high-lift conditions, as well as transonic cruise flight conditions. The design for the new NTF transonic wind design is depicted in Figure 8. The figure shows both the internal configuration of the pressure system that is routed throughout the fuselage/wing, and the mounting interface between the model and the semi-span balance. The model was designed to allow testing flexibility, in that nearly all of the different model testing configurations can be adjusted by adding/removing components that are mechanically fastened to the structure of the wing. During the design of the wing several features were designed into the system that will allow for testing other flow control techniques in the future (for instance, additional passageways have been integrated into the structure of the wing that will allow flow control testing of the leading edge).

H. NTF Air Station Development

Recent facility modifications at the NTF have incorporated a high-pressure air station, which is capable of providing high-pressure air to semi-span models that are mounted to the metric end of the SMSS's internal semi-span force balances. In order to route this high-pressure air out to the semi-span model, the NTF air station was designed as a dual flow air delivery system capable of providing two independently controlled air lines to the semi-span model via a set of concentric air lines. These dual air lines are coupled to the semi-span model via a concentric set of bellows (low & high mass flows), and a model interface choke plate. Both the high and low flow legs of the system can provide up to 1200 psig capability. The high mass-flow leg of the system is capable of providing 0.1-20.0 lbm/sec of air flow, while the low mass-flow leg is capable of providing 0.1-8.0 lbm/sec directly to the model. The air delivery station provides continuous flow of dry air to the semi-span model (5-micron filter on high flow leg, 1-micron filter on the low flow leg). A fast acting model over-pressure protection system has been integrated, which will automatically isolate and vent the wind tunnel model, to protect the model in the event of a pressure spike within the system.

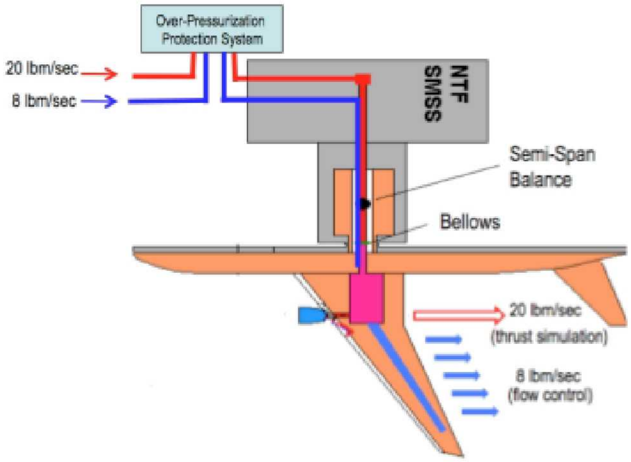
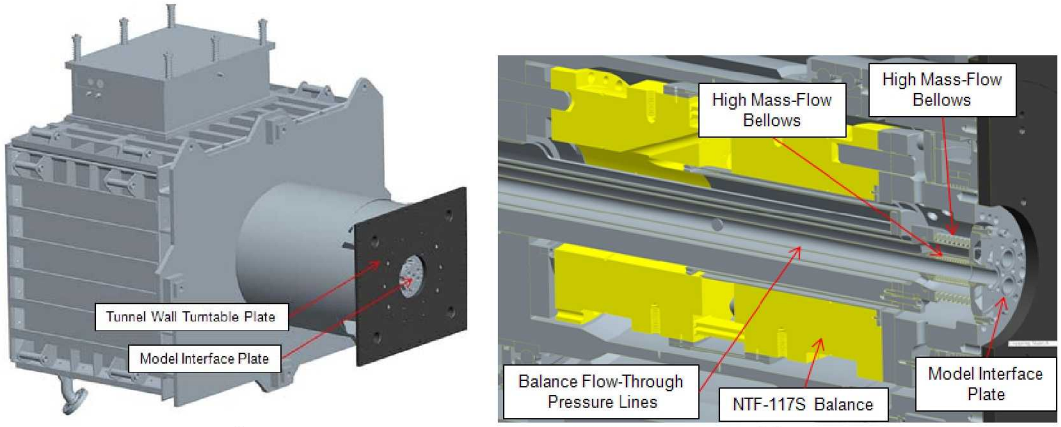


Figure 9. Schematic of new high-pressure air being routed out to semi-span model mounted to internal semi-span balance in SMSS

Semi-span models interface with the SMSS by mechanical joining the model to both the model interface plate, and the top-hat. The top-hat is bolted directly to the semi-span balance; therefore the balance and pressure bellows set are directly linked to each other through the model interface attachment. As a result of the pressure bellows and balance be mechanically linked, any associated stiffness that the bellows has in either the pressurized or un-pressurized state can impact the performance by adding in interference effects due to both pressure and momentum tare effects. See Figure 10 below, which shows the internal configuration of the SMSS and all important components for the scope of this report. The newly incorporate air lines that are routed through the internal cavity of the balance are joined to the internal turn-table pitching mechanism, which allows the entire system (balance, model, internal instrumentation tube, pressure lines, etc) to rotate as a single unit.

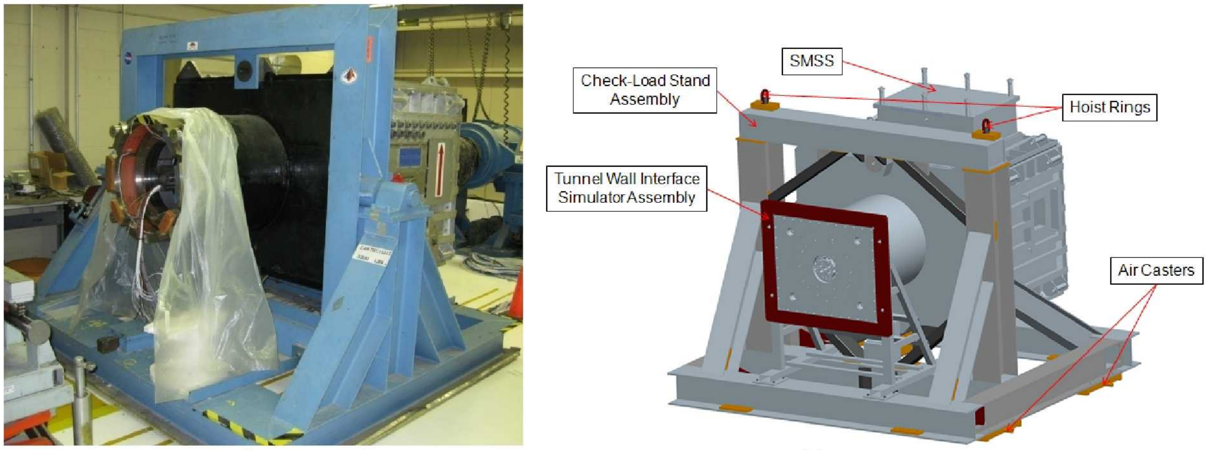


a) **b)**

Figure 10. a) NTF SMSS, b) Cross sectional view of SMSS showing NTF-117S balance, bellows configuration, and model attachment/interface plate

I. Check-Load Stand Design & Development

The purpose of this portion of the project was to design and develop a load frame for the National Transonic Facility (NTF) that is capable of supporting the facilities SMSS, such that the internal semi-span balances can be check-loaded to their full-scale design loads. An existing structure is currently used at the NTF for transporting the SMSS around the facility, from the model build-up bays to the tunnel entrance. This existing blue frame structure (shown in Figure 11a) was only designed as frame to support the weight of the SMSS, and was not designed to support any type of loading. This new frame (shown in Figure 11b) will provide the NTF an in-house capability that will allow for performing check-loads on the SMSS's internal semi-span balances, and can also be used to perform intermittent calibrations on the semi-span balance. The new stand has also been designed such that the stand can be used to transport the SMSS around the facility, via 4 air casters that are mounted to the base of the check-load stand.



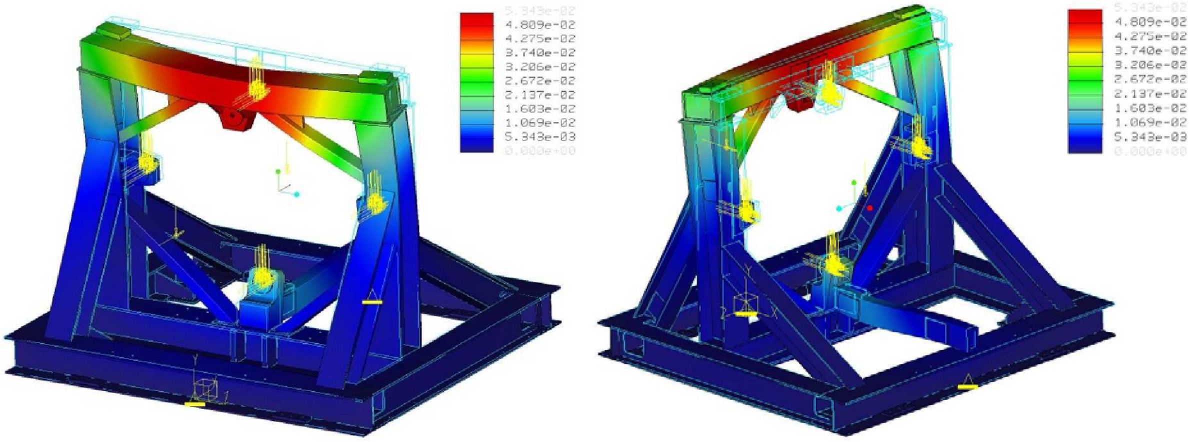
a) **b)**

Figure 11. a) Existing NTF SMSS transport cart, b) New NTF SMSS check-load stand

The presence of the newly incorporated air station and pressure bellows will potentially affect the performance of the internal semi-span balances. While the stiffness of the bellows has been calculated to be insignificant (less than 0.5% of the stiffness of the balance), the significance of their impact needs to be investigated. The measurement repeatability of the balance with these pressurized bellows effects will also be investigated. In order to determine these pressure tare effects, this new SMSS check-load stand has been designed such that it can support loading of balances that far surpasses the maximum normal force capability of NTF's highest capacity semi-span balance, which is the NTF-117S. The NTF-117S semi-span balance has a maximum full-scale normal force capability of 12,000lb, which is nearly double that of the NTF-114S semi-span balance. Therefore, when the new check-load stand was designed, one requirement was that it needed to be able to support no less than a 12,000lb normal force loading to cover the range of both existing NTF semi-span balances.

The stand was designed using Pro/ENGINEER Wildfire 3.0, and all individual components were assembled to build the completed stand model as shown in Figure 11b above. The newly designed check-load stand is a welded assembly structure primarily composed of structural steel I-beams (ASTM A992) that provide the stand the load bearing capability to serve as a load frame for performing check-loads on the SMSS's internal semi-span force balances. To help increase the stiffness and strength capability of the load frame, gussets and doubler plates (ASTM A36 & ASTM A514 Grade A) were added at certain locations (determined iteratively through the FEA process to be discussed in the next section). A series of rectangular box beams (ASTM A500 Grade C) were added in the inner frame structure to help decrease deflection of the mounting brackets when the load stand is being loaded under the designed loading conditions.

The design criteria requirements identified for this project were established in accordance with method 2 of LPR 1710.15, with a minimum factor of safety (FoS) of 2.0, calculated on yield. For this project, all analysis was conducted using Mechanica, the finite element analysis (FEA) solver embedded in Pro/ENGINEER. All FEA analysis on the CAD model was conducted using assuming ¼" fillet welded joints for the connection of all assembly components. The deformed FEA model is shown in Figure 15 below. It is evident from the deformation model shown that the applied NF is the dominant load, as when the NF is applied at point 43.0" away from the SMSS to stand interface, the resulting moment that is created is causing a large torsional load to be carried by the upper box beam and mounting flange. The light blue outline profile shows the un-deformed model, and the 3-D geometry (as shown) is the model deformed as a result of all 3 combined loads. The maximum deflection within the model during the worst case loading condition is 0.053", which occurs as the upper mounting flange is deflected due to the torsional load it sees as a result of the resultant pitching moment caused by the NF check-load.



a) **b)**

Figure 11. FEA Deformed Model, a) front view, b) rear view

The maximum von Mises Stress values and resulting FoS for each of the 12 regions of highest stress concentration are shown in Table 6 below. As seen from the table, the maximum von Mises stress values and FoS are computed for the full-scale load of the check-load stand (27,000 lb NF). Since the maximum balance capability that the NTF currently has is the NTF-117S balance, the immediate need for the stand is to be used while check-loading this balance. As seen from the table below, the FoS for both loading situations fall above the minimum requirements (minimum FoS of 2.0, computed on yield) that were established using LPR 1710.15.

In order to secure the stand during while using it to check-load the internal SMSS semi-span balances, the facility floor at the NTF will need to be reinforced so that its load bearing capability will be able to support loading of the semi-span balances. An analysis study has been conducted by contractor engineers at NASA Langley to determine what modifications will be necessary in order to secure and support the stand during loading.

Table 6: Check-Load Stand FEA FoS Results Table

Location	Material Yield Strength	Stress @ 27K NF	FOS @ 27K
1	36	15.1	2.38
2	50	20.1	2.49
3	65	22.3	2.91
4	36	17.8	2.02
5	65	23.4	2.78
6	65	22.9	2.84
7	36	15.7	2.29
8	36	13.4	2.69
9	50	16.5	3.03
10	50	24.4	2.05
11	50	19.4	2.58
12	50	16.5	3.03

J. Pressure Tare Calibration

As discussed, the integration of the new air delivery station and the pressure bellows that will be directly linked to the metric end of the NTF-117S semi-span balance will present more variables into the system that can impact the performance of the balance. In order to determine the significance of these pressure tare effects on the performance/accuracy of the NTF-117S balance, a load schedule is being designed that will involve performing a set of check-loads on the balance. This check-load process will involve varying the combination of 7 factors (applied NF, AF, PM, RM, YM, and static pressures applied to both legs of the air delivery system) in order to collect a set of data points that can be used as confirmation points, to predict the response of the calibration matrix/model. The data points obtained from this set of check-loads will be collected, and the original calibration math model will be used to predict how well it can predict the applied loads. Confirmation points are typically used within balance calibration, as a subset of the calibration load schedule, where the confirmation points are not used to build the calibration model, but are used to test the prediction "robustness" of the calibration model.[16]

The new check-load stand detailed in the previous section is currently in the process of being fabricated and assembled, and has an anticipated delivery date of July 27, 2010. Once the stand is delivered to the facility for use, and once the SMSS becomes available the first pressure tare calibration will be performed. The calibration hardware to be used during the pressure tare check-loading process is still being design, and the specific design details of the calibration hardware will dictate the exact load combinations that can be performed. Once the calibration hardware design is complete, a detailed load schedule for the pressure tare check-loads will be developed and available for release.

IV. Conclusion

A new semi-span measurement capability has been designed that will allow the NTF to test high-lift semi-span model configurations, increasing the previous capability by nearly double. The new NTF-117S balance has been designed, instrumented and calibrated to optimize the sensitivity and reduce the presence of interaction influences. The calibration of the balance resulted in % of full-scale accuracies less than 0.20% for all 5 load measurement components.

Upcoming tests at the NTF will be the first to use the new NTF-117S balance, as well as the new NTF air delivery station that will provide high-pressure air to the semi-span models, for testing both circulation control and simulated propulsion techniques. In order to check-out the NTF-117S balance for these tests, a new check-load stand has been designed that will allow the facility to check-load the balance before the SMSS is delivered from the model build-up bay to the tunnel test section. This new capability will allow for assessing any fouling issues prior to the final model build-up, as well as assessing the impacts of the pressure bellows on the performance/accuracy of the NTF-117S balance.

Acknowledgments

The author would like to express sincere appreciation to the group of personnel, both NASA and contractors, who contributed to the development of this new measurement capability. The scope of this project required open lines of communication and cooperation amongst many organizations/contractors in order to successfully complete the development of both the new semi-span balance, and the check-load stand capability. The many personnel involved contributed to the mechanical design, fabrication, instrumentation, calibration, and overall engineering expertise required in order to provide NASA with a new semi-span measurement capability for the NTF. The project has been supported and funded by the National Force Measurement Technology Capability (NFMTC).

The author would like to recognize the following individuals (and organizations) for their critical contributions in their respective expertise domains: Ray Rhew for mentoring the author on all things balance related, Dennis Booth and Dave King for their efforts in the original design and fabrication of the NTF-117S balance, Kevin Bloxom & Robert Bondurant for instrumenting the balance, Wes Vellines for his efforts in performing the balance calibration, Jeff Cox for his efforts in overseeing the balance calibration and data reduction, Dr. Greg Jones and Dr. William Milholen for their expertise with both semi-span model testing and the development of the new circulation control model that will be the first test at NTF using the NTF-117S balance, Matt Stearman for his manufacturing/welding expertise in the development of the new NTF SMSS check-load stand, and Frank Beltinck for being a valuable source of knowledge for both the SMSS and NTF operations.

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