

A New Flow-Through Wind Tunnel Balance for Retropropulsion Testing

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Supersonic retropropulsion, or the use of retrorockets starting at supersonic conditions, is an enabling technology for large-scale human Mars lander vehicle concepts. A new flow-through balance was designed and fabricated to support an upcoming retropropulsion test campaign at the NASA Langley Unitary Plan Wind Tunnel. The balance employs membranes in place of bellows, which have historically been used, and passes the flow-through load bearing parts of the balance. Flow-through the balance is optimized via the addition of flow guides, which are manufactured as separate parts, and attached to the balance. Calibration of this new flow-through balance demonstrates that it can suitably characterize the load and pressure ranges it was designed for, which provides aero researchers a new tool to directly measure supersonic retropropulsion performance of powered descent vehicles.

I. Introduction

Current vehicle concepts for large-scale human Mars landers (~20 metric ton payloads) require powered descent with retrorockets in place of a parachute to decelerate from supersonic conditions to a soft touchdown [1–3]. Aerodynamic interference forces and moments during powered descent are not understood well enough to design a landing vehicle with high confidence using solely computational fluid dynamics modelling (CFD), an application which is still maturing for powered descent. Therefore, wind tunnel testing is required to quantify uncertainties in computational modeling and simulation. Researchers would prefer to directly measure these forces and moments using a wind tunnel balance that is designed to pass high pressure fluid internally. This is commonly referred to as a flow-through balance. However, there were no known flow-through balances that could suitably meet the objectives of this test campaign.

Existing six-component flow-through balances require the use of bellows to contain the flow. In addition, the bellows provide compliance that generally enables the balance to measure axial force [4–9]. However, the use of bellows

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in balances has been reported to introduce undesirable amounts of hysteresis. While these issues have become less prominent with the introduction of welded bellows with precision flange attachments [7], the balance design reported here sought to avoid bellows because the anticipated aerodynamic loads were low relative to typical flow-through balances and space constraints further limited their application. A five-component flow-through balance without bellows is reported in the literature [10] where a structural tube passes through the center of the balance. The tube is inconsequential to the cage section stiffness because it is located along the neutral axis of the section allowing five components of load to be measured accurately. However, this design lacks the ability to obtain sufficient axial output because the tube is too stiff in the axial direction.

In this work, a six-component single-piece flow-through wind tunnel balance is presented that replaces bellows with membranes and that passes fluid through the primary load bearing parts of the balance. The balance is also uniquely optimized for manufacturing and fluid flow. Accomplishing both objectives was achieved by using flow guides to minimize pressure losses and the speed of the flow across the balance. These guides were manufactured independently of the balance and assembled together with the balance during model build up. This balance system was designed specifically for Mars powered descent lander testing and it will provide direct measurements of the forces and moments generated by the wind tunnel models with blowing nozzles.

II. Existing Wind Tunnel Model

The wind tunnel model was originally designed and manufactured without a wind tunnel balance as shown in Figure 1. The researchers intended to approximate the aerodynamic interference forces and moments by integrating pressure taps and pressure sensitive paint on the model body (which is expected to have higher measurement uncertainty than a balance). The model (without the balance) places an emphasis on maintaining a uniform flow of the high pressure air as it passes through the model and exits the nozzles. Models 1A through 1F in Figure 1 are shown with six different nozzle configurations that will be investigated during the test campaign [11].

Given that the wind tunnel model was in a completed state, it was preferred that the incorporation of the balance require no modifications to the model or test plan. This placed constraints on the balance design including:

- 1) Balance had to mate with existing hardware.
- 2) Internal high pressure air path was previously defined.
- 3) Fluid flow path cross sectional area through balance to match or exceed cross sectional area of model nozzles.
- 4) Internal pressure of 300 psia required.
- 5) Balance to be heated up to 250°F.

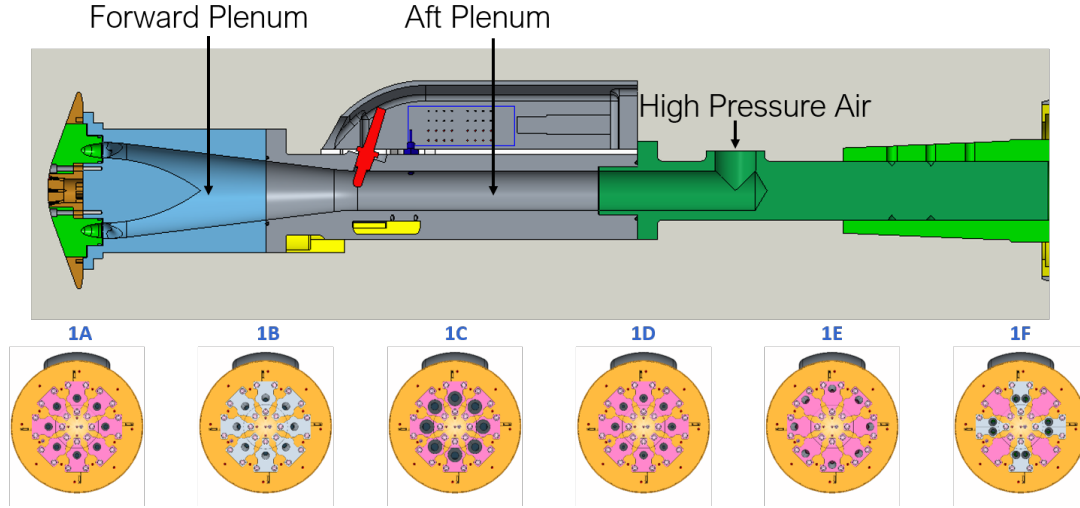


Fig. 1 Pre-existing wind tunnel model without a wind tunnel balance.

III. Balance Design

The design of this wind tunnel balance had to consider traditional transducer design objectives such as achieving desired sensitivity and acceptable stress levels while also optimizing fluid flow through the transducer. Moreover, the anticipated tunnel entry date five months from the initiation of the design of the balance necessitated a focus on design for efficient manufacturing.

A. Mechanical Design

The mechanical design of the balance was driven by the constraints outlined in Section II. In particular, the requirement that the fluid flow path cross sectional area through the balance match or exceed the cross sectional area of the model nozzles motivated the design choice that the flow path needed to pass through the primary load bearing members of the balance since these members inherently have the largest cross sectional area. Four posts were envisioned ninety degrees apart as shown in Figure 2. Two posts were oriented in the normal and pitch plane and two posts were oriented in the side and yaw plane. The two posts in the normal and pitch plane acted as the primary load bearing structure for the normal and pitch loads and the two posts in the side and yaw plane acted as the primary load bearing structure for the side and yaw loads. The posts were designed to act as beams in bending. However, these posts were inherently stiff with respect to axial force since they were in direct tension or compression. To introduce added compliance in the axial direction, circular membranes were added at the base of the posts (Figure 2 (c)). An axial measuring element was then added at the center of the balance where it is inherently shielded from the applied moments. A ring element was chosen for this purpose as one means to generate beams in bending subject to axial load. Notches were added to the area leading up to the ring to help further isolate the ring from other components of load (Figure 2 (a) and (b)). The notches also supported the measurement of normal, pitch, side, and yaw since the stress concentration in

these areas provided sufficient gage output.

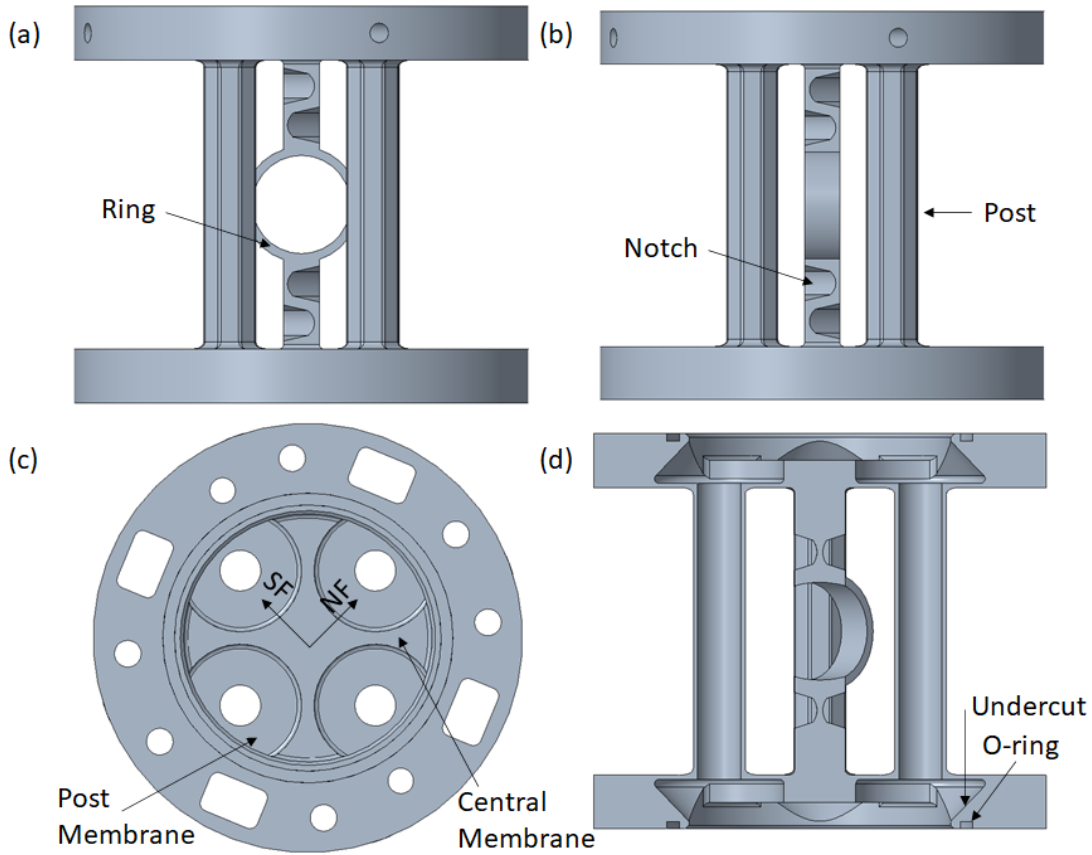


Fig. 2 Views of the balance with key features annotated.

When the balance is pressurized, the post membranes want to flex outwards and elongate the structure including the ring. This can lead to a significant axial force interaction due to applied pressure, which is undesirable. This effect was significantly curtailed by introducing the central membrane (Figure 2 (c)) which is a thinning of the center part of the bulkheads that encourages the bulkhead itself to flex outwards when subject to pressure. Balancing the bulging of the post membranes and the central membrane can significantly reduce the transfer of load to the ring element. Finite element analysis was used to optimize the central membrane thickness.

Ti-6Al-4V was chosen for the balance because it is reported to be a good spring material [12]. Moreover, in the annealed condition it provided adequate strength for this application while having a modulus of elasticity of approximately 60% of steels, which are more commonly used for balances, thus providing more strain for a given applied load. This was helpful for getting the strain levels under the gage closer to target values as manufacturing limits on wall and membrane thicknesses were approached. Ti-6Al-4V also has a coefficient of thermal expansion ($5.11 \mu\text{in/in-}^\circ\text{F}$) that closely matches the 17-4PH ($6.00 \mu\text{in/in-}^\circ\text{F}$) components to which it attaches. Given the balance's use up to 250°F , which is the maximum air temperature flowing through the model, this was desirable to minimize thermally induced

B. Flow Guide Design

Flow-through balances aim to minimize momentum tare forces that are generated as the flow passes through the balance. They also aim to minimize the pressure loss and gas speed through the balance. These goals had to be achieved using the existing forward and aft plenum components (Figure 1). The strategy for mating the balance to the existing
80 model design involved transitioning the flow from the aft plenum into the four posts of the balance using an inlet flow guide and then diffusing the flow out into the forward plenum using an exit flow guide (Figure 3).

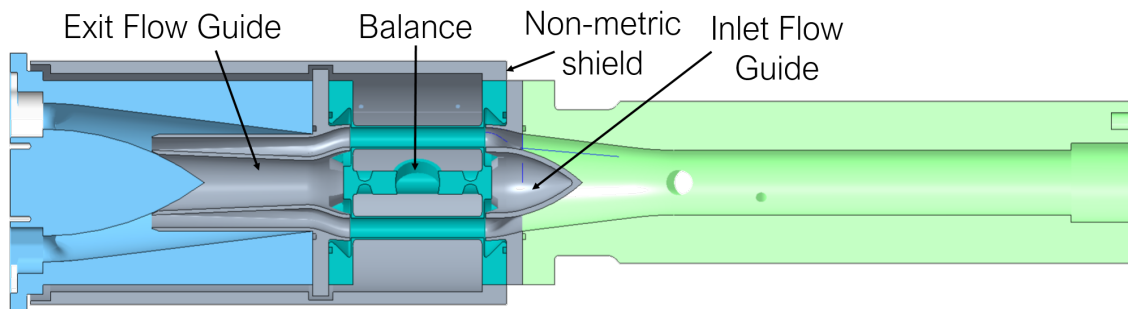


Fig. 3 Wind tunnel model showing balance, flow guides, and non-metric shield.

Computational fluid dynamics simulations were used to help design the flow guides. The final design used an ogive on the inlet flow adapter to transition the flow into the balance and then gradually diffused the flow into the forward plenum to better distribute the flow prior to reaching the nozzles. Figure 4 shows a simulation of the expected
85 pressure loss throughout the entire model system for representative conditions. Results from the simulation indicate pressure losses across the balance itself are expected to be close to zero and average pressure losses between the forward and aft plenums are expected to be several percent. The near zero pressure loss across the balance is consistent with expectations given the balance's smooth straight tubes and marks an improvement over traditional bellow based designs which typically have flow turning features [13].

90 C. Design for Manufacturing

With the anticipated tunnel entry date five months in advance of the balance design process, extra attention was paid to designing the balance for manufacturing. Conventional subtractive manufacturing methods were preferred to manufacture the balance, but an additive manufacturing route was also pursued to maximize that likelihood that a balance would be ready for the wind tunnel entry.

95 The posts were intentionally designed as octagons to enable subtractive manufacturing via computer numerical control (CNC) machining. The ring is also oriented to enable maximum access for CNC tooling with respect to the four posts (Figure 2 (b)). Finally, an undercut was employed that allowed access to the membranes for machining while also

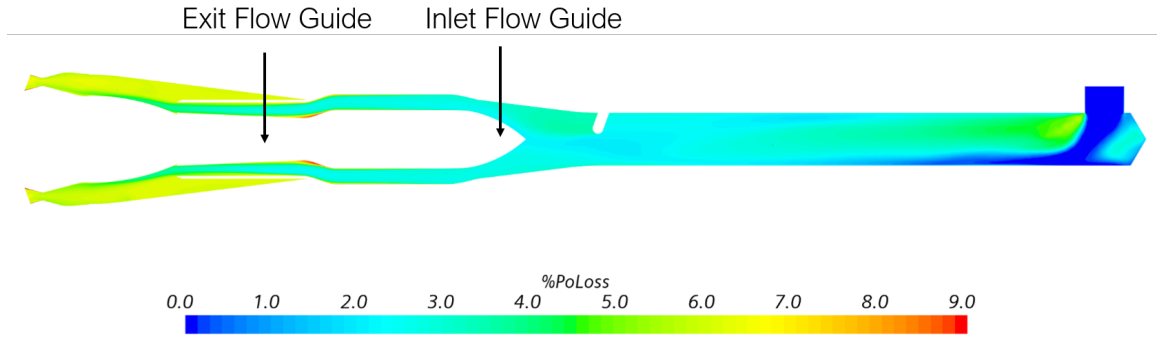


Fig. 4 Computational fluid dynamics simulation of the percentage pressure loss across the model system including the balance.

enabling the pre-existing O-ring groove to pass over top of the membrane (Figure 2 (d)).

One of the primary design decisions to enable manufacturing the balance efficiently was to fabricate the geometries that were to guide the flow into and out of the balance as separate parts. The flow guide geometries were complex and were not well suited to subtractive fabrication methods. Thus, by separating their fabrication from the balance and focusing only on how they interface with the balance, more design flexibility was afforded. In particular, this fabrication choice freed up space on the forward and aft ends of the balance enabling access for conventional tooling to machine the membranes and holes through the posts (Figure 2 (c)).

D. Integration with Model

Figure 3 shows the balance and flow guides integrated into the pre-existing wind tunnel model. The balance is inserted between the forward and aft plenums with the inlet flow guide directing flow from the aft plenum into the balance and with the exit flow guide transitioning the flow from the balance into the forward plenum. The flow guides and balance are separated by a 0.010 inch gap to prevent fouling. Also, shown is a non-metric shield that extends from the non-metric end of the balance to just aft of the forward end of the model. The shield was added to transfer all aerodynamic forces that are being imparted aft of the heat shield on the model to the non-metric end of the balance so they will not be included in the aerodynamic forces measured by the balance. The non-metric shield was also designed such that it acts as a secondary containment system for the model system.

IV. Manufacturing

Only three months were available before the balance was anticipated to be needed in the wind tunnel when the manufacturing process began. As a result, several manufacturing paths were pursued in parallel to increase the likelihood of meeting the test entry date. The costs and lead times for this balance are emphasized here because they stand in sharp contrast to the \$100K cost and lead time of approximately one year expected for a typical wind tunnel balance [14].

Five conventional fabrication vendors were contacted regarding balance fabrication. Two of the vendors did not bid the job due to technical complexity. One shop did not bid due to concerns about meeting the delivery date. Two of the vendors did provide quotes with drastically different estimates of \$5K and \$43K. Both had anticipated lead times of approximately five weeks.

Two additive manufacturing vendors were also approached to manufacture the balance. One vendor quoted a \$9K purchase price with a seven week lead time. The other quoted \$15K with a lead time of ten weeks. These costs and lead times include hot isostatic pressing of the balance along with an X-ray tomography scan. The lead times could be reduced by several weeks if these additional processing and inspection steps were not requested.

Additive manufacturing was used to manufacture the inlet and exit flow guides. These parts were particularly well suited for additive manufacturing due to their complicated geometries and high structural safety factors.

Both the additively manufactured balances and flow guides required surface finishing upon receipt. A commercial chemically accelerated vibratory polishing process [15] was performed on all the components. Surface finishes were taken from a starting roughness of 500 to $32\text{ }\mu\text{in}$ average roughness (Ra) following polishing. Images of both the inlet and exit flow guides following polishing are shown in Figure 5 (a) and (b). The surface contour of the inlet flow guide was also characterized using an optical comparator (Figure 5 (c)). The surface contour of the flow guide appears as a shadow in the image and is shown relative to the specified contour (black line). With the exception of the apex of the flow guide, the surface contour follows the specified contour within approximately two thousandths of an inch.

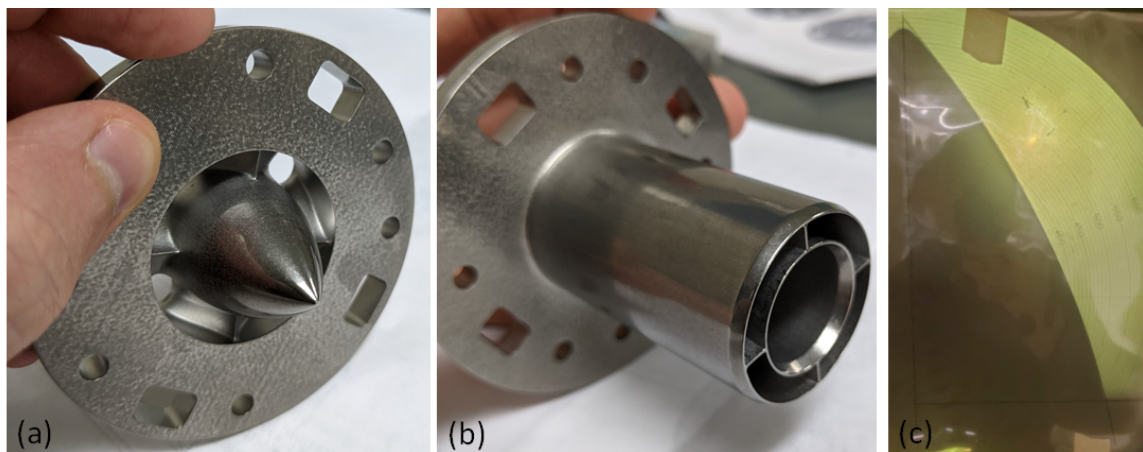


Fig. 5 Photos of (a) inlet flow guide and (b) exit flow guides. (c) Optical comparator image of the inlet flow device ogive profile relative to the specified profile (black line).

Of the multiple balances that were purchased, one of the conventionally manufactured balances was chosen for strain gage installation and wind tunnel use. Strain gages were applied to the balance using standard procedures [16].

V. Balance Calibration

The calibration plan for this balance placed an emphasis on expediency given that only two to three weeks were expected before the balance was needed in the wind tunnel. So, the initial calibration was kept to a series of primary long arm loadings [17] at room temperature to enable the estimation of the linear and pure quadratic terms of a second order model. Two and three-component short-arm loadings (i.e. loading at points on the fixture) were also performed on the axial end plate by introducing load points offset from the centerline such that pitch and/or yaw could be loaded in combination with axial. Axial loadings were emphasized because of the importance of axial for the wind tunnel test.

The response of the balance was modeled using a subset of a second-degree polynomial. The model included coefficient estimates for all primary and quadratic terms however, the interaction coefficients were limited to AFxPM, AFxYM, and PMxYM (AF=axial force, PM=pitching moment, and YM=yawing moment) based on the calibration design.

Table 1 lists the full scale outputs of the balance based on the calibration results. Axial and roll stand out for their low outputs relative to the other components. The axial bridge was designed for $300 \mu\text{V/V}$ output and the lower output in practice is expected to be attributable to the post membrane thickness being larger than the specified tolerance. The oversizing is likely due to the vendor being conservative on the thickness. Due to time constraints, it was not brought into tolerance. Roll output was not a primary focus of the design based on the objectives of the test campaign and therefore the expected output was less than $100 \mu\text{V/V}$.

Table 1 Full scale outputs ($\mu\text{V/V}$) for the balance.

Component:	Normal	Axial	Pitch	Roll	Yaw	Side
Output ($\mu\text{V/V}$):	1168	203	573	53	553	1010

The accuracy of each component of load is shown in Table 2. The accuracy is defined as two standard deviations of the residuals between the model estimated outputs and those measured experimentally, and it is expressed as a percentage of the full scale output for each component. Axial and roll again stand out for accuracies that are larger than the other components of load. Much of this can be attributed to the low full scale outputs of axial and roll. However, axial was observed to have 0.6% of the full scale error attributable to hysteresis and zero shift. While relatively large as a percentage of full scale, the hysteresis and zero shift equate to $1.2 \mu\text{V/V}$ which is not uncommon for balances. The axial force bridge exhibited more temperature sensitivity than the other bridges, so it is hypothesized that temperature sensitivity may have played a role in the hysteresis and zero shift though definitive explanations remain under investigation.

Table 2 Accuracy of each component expressed as a percent of full scale.

Component:	Normal	Axial	Pitch	Roll	Yaw	Side
Accuracy (% of F.S.):	0.2	1.0	0.3	0.8	0.3	0.2

A. Pressure Effects

The wind tunnel model system was instrumented with a pressure transducer just aft of the balance. Thus, by calibrating the balance for pressure effects (unloaded zero and sensitivity corrections) a math model should be able to correct for pressure effects in the wind tunnel. A deadweight tester was used to apply pressure to the balance throughout testing.

An incremental pressurization of the balance (under no external load) was performed first to better understand the influence of pressure on the axial force response (Figure 6) and determine whether modifications to the central membrane were required. As indicated in the figure, the axial force output due to pressure is non-linear. A math model with linear and quadratic pressure terms (dashed line in Figure 6) captures the response. The $40 \mu\text{V/V}$ axial output at 300 psig internal pressure was considered reasonable and thus no changes to the central membrane were pursued.

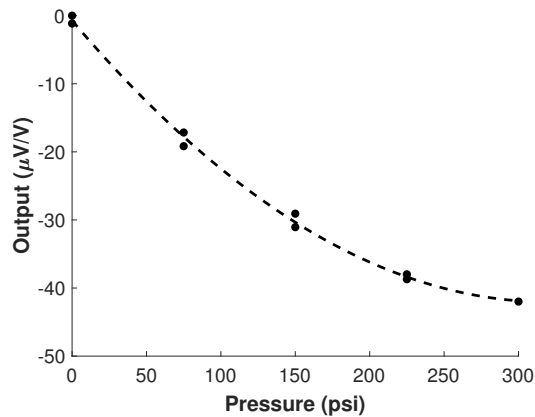


Fig. 6 Axial force output measured with incremented pressure.

Next, the balance was loaded while applying internal pressure. Specifically, the balance was pressurized to 300 psig and all primary loadings were repeated. Axial force loadings were also performed at 100 and 200 psig to develop a more thorough understanding of the influence of pressure on the axial force sensitivity.

Table 3 lists the pressure corrections for all the components expressed as a percentage of full scale effect at 300 psig. All components with the exception of roll have a sizable pressure correction. Roll is likely less sensitive to pressure because it is the only component located on the posts of the balance whereas all other components are located on or adjacent to the center ring. Normal and side force were expected to exhibit similar pressure response given the similarity in their gaging strategies and full scale outputs, which is consistent with the experimental results. The same was true of the pitch and yaw response.

Table 3 Sensitivity correction expressed as a % of full scale effect due to 300 psi pressurization of the balance.

Component:	Normal	Axial	Pitch	Roll	Yaw	Side
Sensitivity Correction (% of F.S.):	-0.9	-3.8	-2.5	0.0	-2.3	-1.2

A subset of a second-degree polynomial was again fit to the whole data set (loadings with and without pressure applied). However, this time pressure was added as a factor to be fit as part of the model. The change in the unloaded zero due to pressure for each component was modeled with a linear and quadratic pressure term. The sensitivity correction of each component due to pressure was modeled with a linear term and reflected the shifts shown in Table 3. Using this math model, the accuracy of each component of load is shown in Table 4.

Table 4 Accuracy of each component expressed as a percent of full scale considering pressure effects.

Component:	Normal	Axial	Pitch	Roll	Yaw	Side
Accuracy (% of F.S.):	0.2	1.0	0.3	0.7	0.3	0.3

The accuracies reported here are nearly identical to the accuracies reported without the pressure loadings (beginning of Section V). This suggests that the math model including pressure terms is adequately capturing the behavior of the balance in response to applied pressure.

B. Temperature Effects

The air used to flow through the balance and nozzles is expected to have a total temperature of no more than 250°F. This necessitated the characterization of the balance at elevated temperatures. Specifically, the sensitivity correction as a function of temperature was sought. This was achieved by mounting the balance in an oven (Figure 7) and performing an initial loading at room temperature, and then heating the balance and loading hardware overnight in the oven until a uniform temperature of approximately 200°F was reached (extrapolation beyond 200°F will be used if required). At this point, the loading was repeated. Then, the balance was cooled to room temperature and the loading was repeated. Comparing output differences at room temperature and 200°F produced sensitivity correction estimates. Thermal sensitivity corrections were determined for all components except rolling moment.

Table 5 lists the temperature corrections for all the components expressed as a percentage of full scale effect based on heating the balance from room temperature to approximately 200°F (approximately 130°F temperature rise). Much like the pressure data, normal and side forces are observed to have similar sensitivity corrections. The same was true for pitch and yaw.

Table 5 Sensitivity correction expressed as a % of full scale effect due to 130°F temperature rise of the balance.

Component:	Normal	Axial	Pitch	Yaw	Side
Sensitivity Correction (% of F.S.):	0.3	1.2	1.8	1.7	0.4

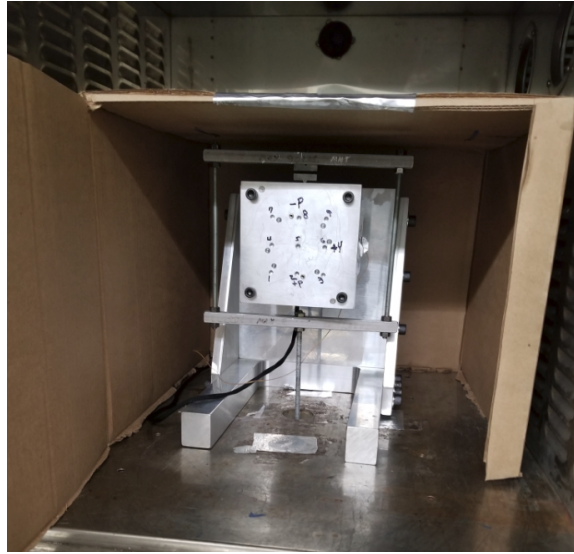


Fig. 7 Photo of the balance mounted in the oven with hanger exiting through the oven floor to allow for the application of load.

VI. Conclusion

This work demonstrates a new flow-through balance that is well suited for supersonic retropropulsion measurements. The balance departs from previous flow-through balances in several respects including the use of membranes in place of bellows, the use of flow guides to optimize fluid flow into and out of the balance, and the flow of fluid through the flexures of the balance versus around. This design is also unique for its fast production time—requiring just five weeks to fabricate and eight weeks to strain gage and calibrate.

Calibration of the balance at room temperature and pressure revealed a full scale axial output that was lower than targeted, but sufficient output for normal, pitch, yaw, and side were measured. The low axial output contributed to less accuracy (approximately 1%) than is typically expected for a single piece balance. However, the axial force bridge was particularly sensitive to temperature fluctuations, so this was believed to be another contributing factor. Increasing axial force output can be achieved in future designs and fabrication refinements, and it is not an inherent limitation of the design concept, rather it was accepted to meet the tunnel schedule. Furthermore, we designed for low axial force output due to uncertainty in the tunnel loads for this first, direct measurement.

The calibration of the balance also included characterizing pressure and temperature effects. A 300 psig pressurization and heating to 200°F each generally resulted in a 1-2% sensitivity correction for all components though an increase in pressure stiffened the balance and an increase in temperature decreased the stiffness. Overall, the accuracy of the balance did not change when comparing loadings with and without pressure applied, which suggests that the proposed math model is adequately capturing the balance's response to pressure.

This balance provides a much needed tool for researchers investigating powered descent at supersonic speeds and

the design is expected to be used as the basis for a family of balances to support this ongoing testing need. Future wind tunnel model designs will benefit from incorporating the balance earlier in the design process to further optimize the internal high pressure air flow path.

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