Check Calibration of the NASA Glenn 10- by 10-Foot Supersonic Wind Tunnel (2014 Test Entry)

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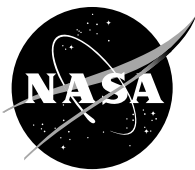
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Summary

A check calibration of the 10- by 10-Foot Supersonic Wind Tunnel (SWT) was conducted in May/June 2014 using an array of five supersonic wedge probes to verify the 1999 Calibration. This check calibration was necessary following a control systems upgrade and an integrated systems test (IST). This check calibration was required to verify the tunnel flow quality was unchanged by the control systems upgrade prior to the next test customer beginning their test entry. The previous check calibration of the tunnel occurred in 2007, prior to the Mars Science Laboratory test program. Secondary objectives of this test entry included the validation of the new Cobra data acquisition system (DAS) against the current Escort DAS and the creation of statistical process control (SPC) charts through the collection of series of repeated test points at certain predetermined tunnel parameters. The SPC charts secondary objective was not completed due to schedule constraints. It is hoped that this effort will be readdressed and completed in the near future.

Introduction

Full and check calibration tests are required to maintain confidence in the flow characteristics of any wind tunnel's test section. Establishing and routinely verifying the calibration relationships is the only way to ensure that the correct test section operating conditions are being set for a given set of facility control inputs. Without wind tunnel characterizations, including test section calibrations and flow quality tests, it is impossible to provide high-quality test data for customers. Full calibrations of the 10x10 SWT are extensive and require a large amount of time and funding to complete. As completed in 2014, check calibrations can be conducted to collect "confirmation points" of the tunnel's current test section calibration model in a much smaller time frame and for more budget friendly costs.

This paper provides a description of the check calibration performed in late May and early June 2014 in the 10x10 SWT. This check calibration was performed following an upgrade of the facility's control system. Prior to the check calibration testing, an integrated systems test (IST) was performed to verify the operability and accuracy of the new distributed process control system. The data presented in this document is from the 2014 check calibration in validation of the calibration curves produced during the 1999 full calibration.

Description of Facility

The 10- by 10-Foot Supersonic Wind Tunnel at the NASA Glenn Research Center is a continuous-flow, variable-density wind tunnel. A plan view of the tunnel loop is shown in figure 1. The facility can be operated in either a closed-loop cycle or an open-loop cycle. In the closed-loop cycle, the tunnel operates in a continuous-flow mode and the tunnel pressure level can be varied from 300 psf to 2.5 times standard atmospheric pressure (the full operating envelopes are given in ref. [1]). The facility pressure level is controlled by a vacuum system used to lower the pressure within the tunnel shell. In the open-loop cycle, the tunnel operates at atmospheric pressure and in a single-pass model where the air is brought in through the air dryer, around the circuit through the test section, and exhausted out the muffler. The open-loop cycle is used for models that introduce contaminants into the airstream, such as the combustion products from an engine test, or when the facility air heater is used. The facility operating mode is controlled by the position of a 24-ft valve. The test section elevation view is shown in figure 2. The upstream cross section of the test section is 10 feet wide by 10 feet high. The test section is 40 feet long and its walls diverge 0° 22' to a width of 10.51 feet at the downstream end, whereas its floor and ceiling are parallel.

The facility's calibrated Mach number range is 2.0 to 3.5 which can be achieved in both open-loop and closed-loop cycle. The airflow is moved through the facility by two drive systems, each consisting of a large axial-flow compressor powered by electric motors. The primary drive is used alone for Mach number conditions from 2.0 to 2.6. The primary drive is an eight stage, axial-flow compressor powered by four 41,500-hp electric motors. For Mach numbers of 2.5 and greater, both primary and secondary drive systems are used. The secondary drive is a ten-stage, axial-flow compressor driven by three 41,500-hp electric motors. Mach numbers 2.5 and 2.6 can be achieved with or without using the second drive.

The test section Mach number is controlled by the mass flow generated by the drive systems and the position of the flexible-wall nozzle (flexwall). The flexwall consists of two 10-ft-high, 76-ft-long, and 1.375-in-thick stainless steel plates positioned by hydraulically operated screwjacks. The positioning system incorporates cams on a common shaft; the cams have flats that correspond to 0.1 Mach number increments. The control system for the flexwall position was improved before the 1995 calibration to allow the flexwall to be set at off-design conditions, which allows for a nearly continuous Mach number range between 2.0 and 3.5. Reference [1] describes in more detail the facility and its operation.
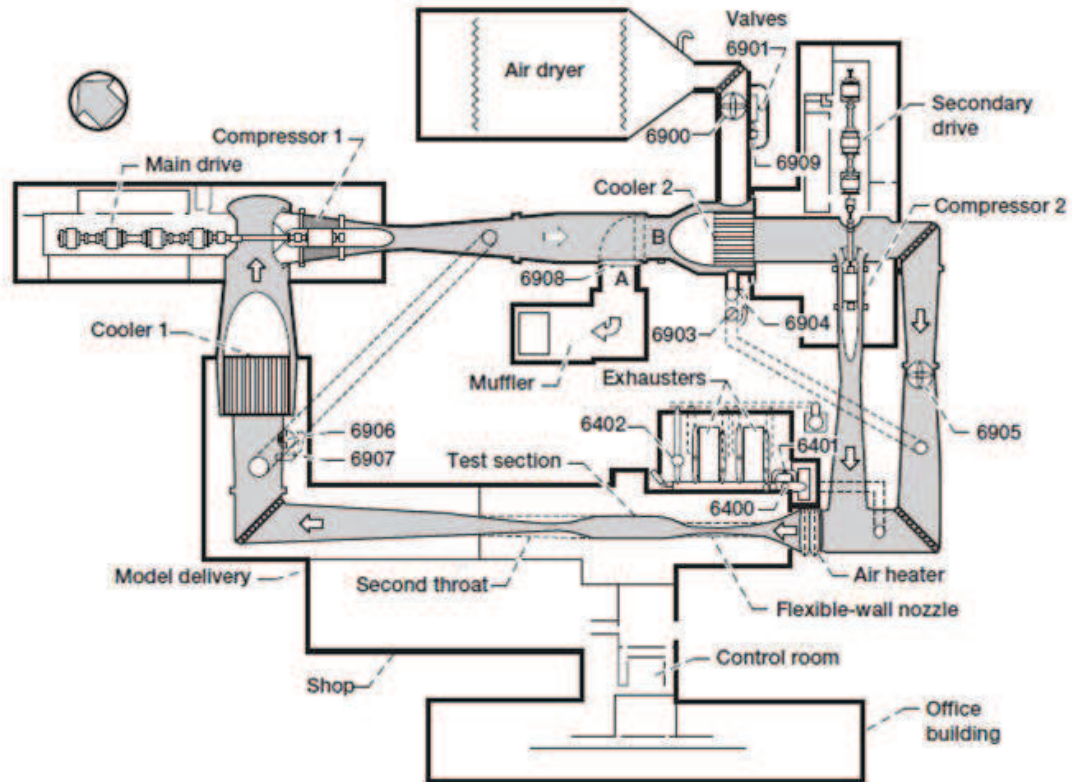
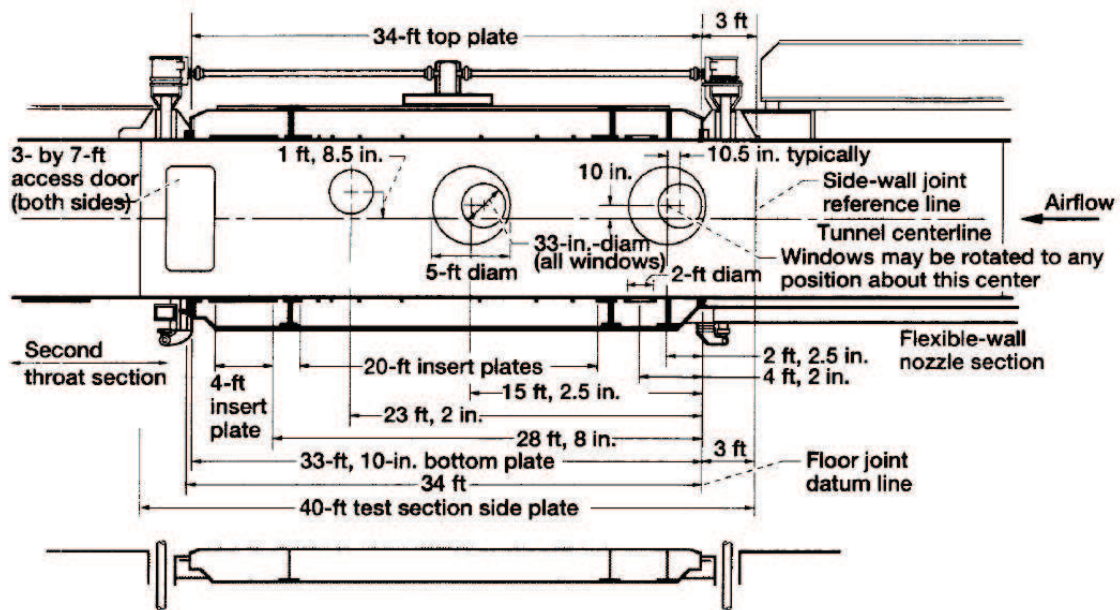Figure 1: Facility Layout of the 10- by 10-ft SWT.

Figure 2: Test section elevation view of the 10- by 10-ft SWT.

Test Hardware, Instrumentation, and Data Systems

This section describes the instrumentation, test hardware, and data acquisition systems used during the check calibration of the 10- by 10-ft SWT.

5-Wedge Array

The 5-wedge array is used to provide check calibration data for supersonic operation in the 10x10 SWT. The 5-wedge array's probes are at the same vertical and horizontal location as the center five wedges on the 17-wedge array, which is used for full tunnel calibration tests. The 5-wedge array, as shown in figure 3, is a 16-in square frame that supports five supersonic wedge probes, one wedge at each corner of the frame and the fifth at the center. The number scheme for the wedges on the 5-wedge array is shown in figure 4 and is set up to be consistent with the numbering of the wedges on the 17-wedge array. The 5-wedge array is a lower strut mounted model.

The 20° half-angle wedges are instrumented with six pressure ports each: two total pressure ports, one above and below the wedge, one static pressure tap on the surface of each wedge face, and two oblique total pressure ports, each positioned to face upstream but parallel to the wedge face. Figure 5 shows the layout of the instrumentation on each wedge. Through analysis of the pressure data measured behind the shocks formed on the wedge and the total pressure ports, the local total pressure, static pressure, Mach number and one component of flow angle can be determined. To measure freestream flow angle, vertical orientation of the wedges allows for measurement of yaw angle and horizontal orientation of the wedge provides pitch flow angle measurements.

The alignment offset of each wedge relative to the tunnel centerline (span-wise centerline for yaw-offset measurement and height-wise centerline for pitch-offset measurement) is measured using a coordinate measuring machine. If the misalignment of the wedge is over a half degree offset in either direction, the wedge must be adjusted. The wedge misalignment data is used in the data reduction process to correct the final flow angularity values.

Facility Instrumentation

Figure 6 shows the locations of the tunnel bellmouth instrumentation. As shown, there are four bellmouth rakes with four total pressure probes and three thermocouples each. There are also four bellmouth wall static pressures located in the same plane as the bellmouth rakes.

Data Systems

The standard tunnel data system was used for the calibration test. The system consists of an Escort Alpha data system and electronically scanned pressure ESP system. A new data collection and on-line analysis program, D028, was written specifically for this test entry. In accordance with one of our secondary objectives, this test entry also used the new Cobra data system alongside Escort to validate the new system's performance. Each data system had its own ESP system that were set up identically, except for their location (one
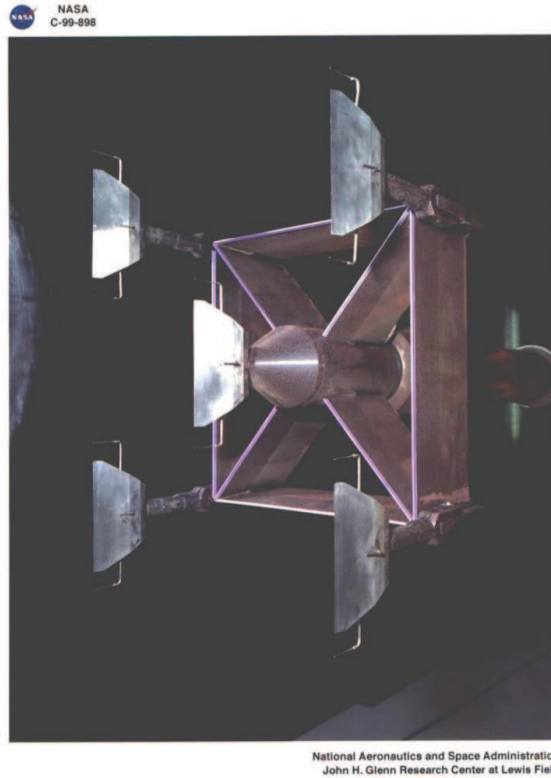
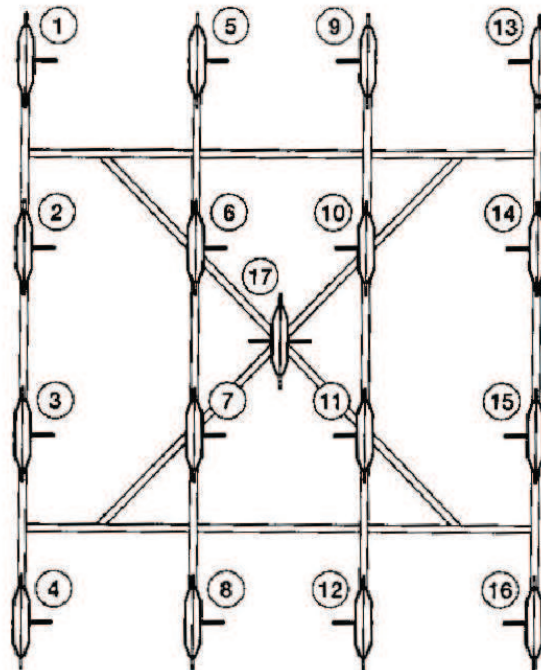Figure 3: Installation of the 5-wedge array in the 10- by 10-ft SWT test section.

Figure 4: 17-Wedge Array (looking downstream). The 5-Wedge Array numbering mimics that of the 17-Wedge Array's center five wedges.

was located above and one was below the test section, with suitable elevation corrections applied to mitigate this effect), so as to allow for a one-to-one performance comparison of the data systems. The comparison of these two data sets from the two data systems will not be discussed in this document, and only data from the Escort data system will be used for the data analysis. The ESP systems use plug-in modules, each containing 32 individual transducers. On-line calibration of the ESP modules occurred approximately every two hours or at the test engineer's discretion.

During the 1999 full calibration, two configurations were used to ensure high quality data was collected from the ESP based on the pressure range of the test conditions. The first was for combinations of high Mach number settings (Mach 3.2 to 3.5) at high Reynolds numbers (2.0 million/ft to maximum achievable) to measure pressures from 0 to 45 psia. The second was for all other combinations of Mach number and Reynolds number settings to measure pressures from 0 to 30 psia. The second configuration consisted of twelve ±15-psid, 32 Port Modules (384 channels) calibrated by a 30-psia Pressure Calibration Unit (PCU). The first configuration required the replacement of five ±15-psid Modules (160 channels) with ±30-psid Modules calibrated by a 45-psia PCU. Data was acquired by both configurations below 15 psia and by the 45-psia configuration above 15 psia [2]. The team for the 2014 check calibration was unable to find enough working ±15-psid modules for the parallel set-ups of the Escort and Cobra ESP systems, therefore it was understood and accepted by the calibration team that the accuracy of the pressure readings would be relatively worse when using 30-psid modules (0.015 psi accuracy) as opposed to 15-psid modules (0.0075 psi accuracy) for this entry. The 5-wedge array used ±30-psid modules for this test entry on both Escort and Cobra. A 30-psia pressure calibration unit was used for this test entry in both the ESP systems. This has been appropriately noted for any future measurement uncertainty work.

The Escort and Cobra data systems received signals from each respective ESP system along with all steady-state analog and digital signals used, including permanent facility measurements and pertinent tunnel control parameters. Escort acquires data at a rate of 1 Hz, whereas Cobra acquires data at a minimum rate of 12.5 Hz. Each collected data reading is a 100 second cyclic reading and, during the testing process, the systems were not able to be triggered simultaneously. This required the Cobra system to be triggered "on" to collect data before Escort was triggered and "off" to stop collecting data after Escort had completed its 100 second cyclic scan. In post-processing, the time stamps will allow for comparison of the two systems' readings.
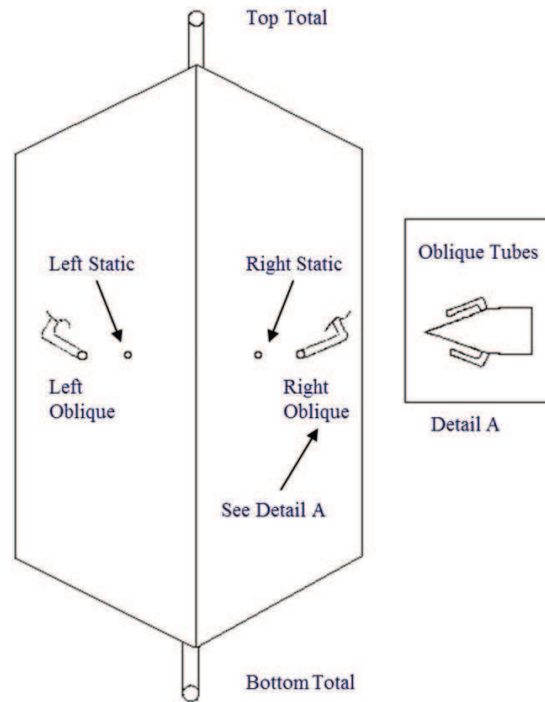
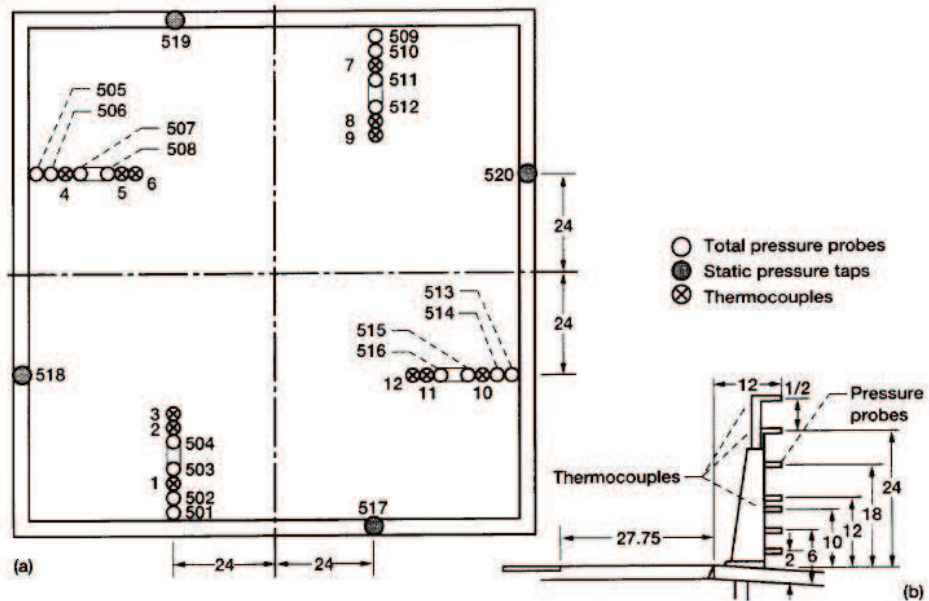Figure 5: Drawing of the instrumentation located on each wedge.

Figure 6: Instrumentation locations at bellmouth exit of 10- by 10-ft SWT.(a) View looking downstream. (b) Elevation view of bellmouth rake. (All dimensions are given in inches.)

Procedures and Test Matrix

The planned test matrix conditions to be covered by the check calibration included sweeping from Mach number 3.5 to 2.5 in 0.1 Mach number increments on 2 drives and from Mach 2.5 to 2.0 in 0.1 Mach number increments on 1 drive. All the Mach number conditions would be repeated for Reynolds numbers 2.5, 1.5, and 0.5 million/ft. The 5-wedge array was located at tunnel station 3, 31 inches downstream of the tunnel datum line. The tunnel only operated in the close-loop mode for this test entry. Table 1 shows the test matrix that was planned.

In addition to the aforementioned test condition sweeps for the check calibration, the original test matrix contained three test days' worth of series of repeat points at Mach 3.5 and Mach 3.0 at 2.5 million/ft Reynolds number. This phase of the test entry was devoted to collecting repeated points of these conditions over different time spans (short-term, near-term, and long-term) to create statistical process control charts to be included into the uncertainty analysis effort for the tunnel. The short-term, or back-to-back, repeatability would come from back-to-back 10-second intervals within a single 100-second data point at one condition. The near-term, or within-run, repeatability would come from a series of 8-10 repeats of each condition within a run where the condition would be repeated only after coming off condition first. And finally, long-term, or run-to-run, repeatability could be determined through repeating a certain series of the afore mentioned conditions then turning the tunnel off completely. Repeating this process of turning the tunnel off and on approximately 10 times and repeating the same series of test points would allow for SPC charts to be created for this time span [3]. However, due to schedule constraints, this phase of the test entry was not completed.

Table 2 shows the completed test matrix from the entire test entry. The grey regions show the test conditions, such as flexwall position and Reynolds number, that were appended to the test matrix after the beginning of the entry. Blackened regions show test conditions not conducted during this test entry, while unshaded regions represent conditions for which data was acquired. The reason that 2.5 million Reynolds number data points were not acquired for every Mach number was because the tunnel's dewpoint was outside criteria for taking data during the test entry.[1] On one run night, in particular, it was raining which made it difficult to hold the desired Reynolds number and dew point simultaneously.

Before the beginning of the test entry, the wedge misalignment measurement procedure with the coordinate measuring machine was completed. In the event of a fast-stop where a high-density shock passes over the model, the wedge misalignment measurements must be retaken to verify that the wedges have not moved considerably due to the force of the shock. This occurred one time during the test entry and measurements were recorded. Also, at the end of the test entry, the wedge offset angles were measured again. In total, the wedge misalignments were measured three times and figure 7 shows the comparison of these misalignment angles at each wedge. These misalignments are applied to the measured flow angles during post processing of the data.

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[1]The tunnel's test section calibration equations take into account the dewpoint temperature in the tunnel, however, it is desired to keep the dewpoint below -10°F during customer testing.

Reynolds Number [million/ft]	2.5	1.5	0.5	Mach Number	Number of Drives
Tunnel Station	3	3	3		
				3.5	2
				3.4	2
				3.3	2
				3.2	2
				3.1	2
				3.0	2
				2.9	2
				2.8	2
				2.7	2
				2.6	2
				2.5	2
				2.5	1
				2.4	1
				2.3	1
				2.2	1
				2.1	1
				2.0	1

Table 1: Anticipated test matrix conditions to be covered in the test entry.

Reynolds Number [million/ft]	2.5	2.4	2.3	2.0	1.5	1.0	0.5	Mach Number	Number of Drives
Tunnel Station	3	3	3	3	3	3	3		
								3.5	2
								3.4	2
								3.3	2
								3.2	2
								3.1	2
								3.0	2
								2.9	2
								2.8	2
								2.7	2
								2.6	2
								2.5	2
								2.6	1
								2.5	1
								2.4	1
								2.3	1
								2.2	1
								2.1	1
								2.0	1

■ Test condition NOT completed
☐ Test condition completed

Table 2: Completed and incomplete test conditions during the test entry. Unshaded regions represent the conditions completed during the entry, black regions represent conditions *not* completed. Grey regions represent conditions that were added to the test matrix. (Reading number 141 is not represented; at a flexwall setting of 2.6 on 2 drives, the tunnel had issues holding Reynolds number of 2.3 million/ft and the reading was taken near 2.175 million/ft.)
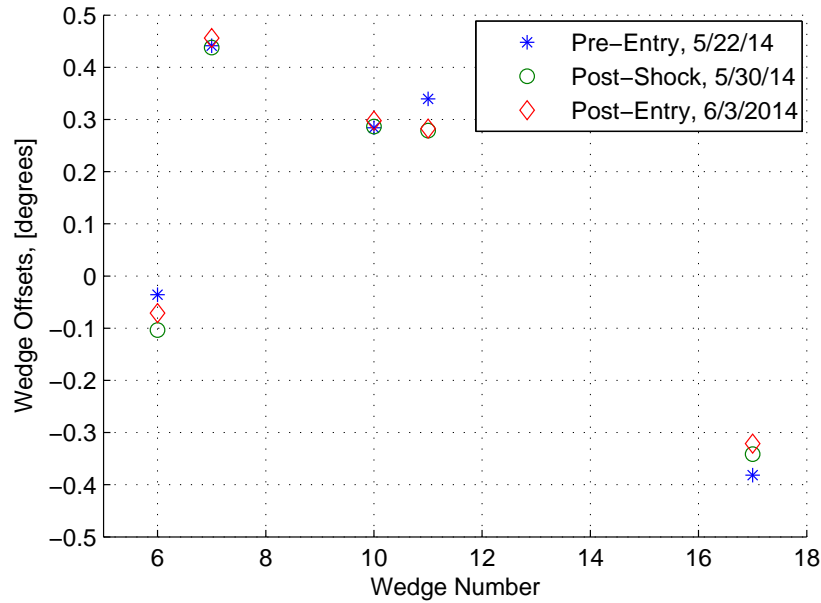
Figure 7: Wedge misalignment measurements taken by the Faro arm prior to the test entry start, after a high-density shock passed over the model, and after the end of the test entry.

Data Reduction and Analysis

A new Escort data collection program was written for this test entry, D028, that computed all freestream parameters in the test section per the calibration calculations determined during the 1999 full calibration in addition to all the freestream parameters measured locally at each wedge of the 5-wedge array. The set of test section calibration equations, known as CAL10X, calculates the test section Mach number and total pressure recovery, $P_{T,ts}/P_{T,bm}$, using the relationships derived from the previous full calibration and the following parameters:

- Number of drives in operation, DRIVE

- Axial station of the model in the test section, STATION

- Tunnel loop configuration (Aerodynamic, Propulsion, or Heater), TUNNEL

- Flexwall setting for Mach number, MWALL

- Reynolds number at the tunnel bellmouth, REBM [10^6/ft]

- Average dew point of the air in the tunnel, DPAVG [^{o}F]

For reader comprehension, further information on the equations and coefficients used in CAL10X can be found in reference [4]. Unfortunately, the current values used in the calibration equations are yet to be published from the 1999 full calibration results [2].

Discussion of Results

The main purpose of a check calibration is to verify the stability of the calibration relationships used to set the test section operating conditions. The 1999 full calibration utilized the 17-wedge array data to produce the calibration relationships now used in 10-by 10-ft SWT. The test matrix for the 2014 test entry, discussed in a previous section, was constructed to cover a similar operating range as in the 1999 full calibration, ensuring that the full operating range of the tunnel was checked in this analysis.

Figures 8 and 9 show the measured and averaged Mach number data from the center 5 wedges on the 17-wedge array and the 5-wedge array, M_{A5}, from the 1999 test entry and the 2014 test entry plotted against the calculated values of Mach number from the calibration curves, M_{ts}. The percentage change between the measured and calculated values of test section Mach number are also plotted as a function of the calculated test section Mach number. The percentage change data from the 2014 test falls completely within two standard deviations (2σ) of the 1999 percentage change data set. Therefore, with the assumption that the 1999 test entry's Mach number percentage change data set resembles a normal distribution, the Mach number calibration curves can statistically be considered to still be valid.

Figures 10 and 11 show the relationship between the calculated and measured total pressure recovery from the 1999 and 2014 test entries. The total pressure recovery measured at the 5-wedge array and the center 5 wedges of the 17-wedge array are referenced to sixteen bellmouth total pressures, averaged, and output as $P_{PT,bm,A5}$, and the calculated test section total pressure recovery is denoted as $P_{PT,bm}$. When juxtaposing figures 10 and 11, 95.5% of the total pressure recovery percent change data from the 2014 test falls within two standard deviations (2σ) of the 1999 percentage change data for total pressure recovery. Assuming the total pressure recovery percentage change data set from 1999 resembles a normal distribution, the total pressure recovery calibration curves can statistically be considered to still be valid.
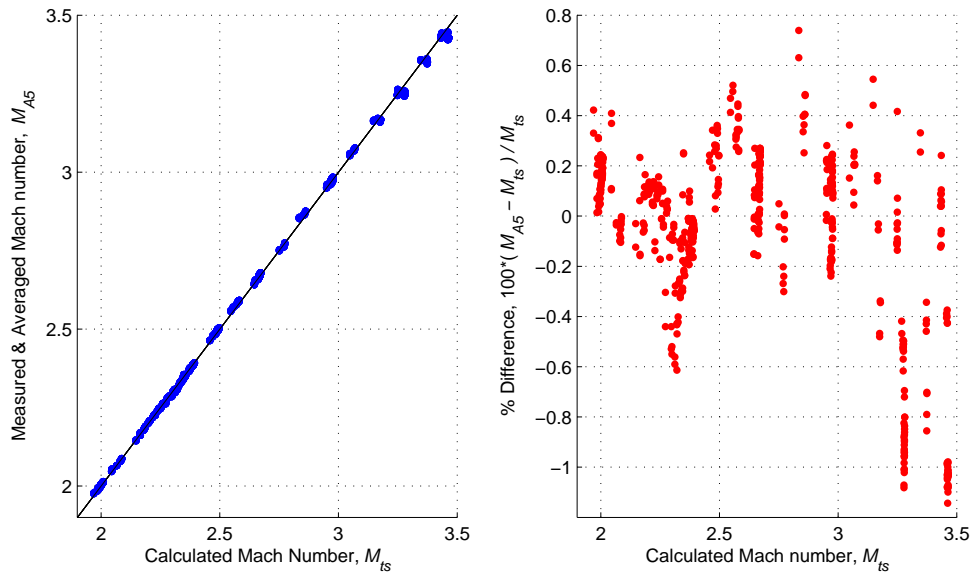
Figure 8: Comparing the calibration relationships in CAL10X with the averaged data from the center 5 wedges on the 17-wedge array for Mach number from the 1999 test entry.
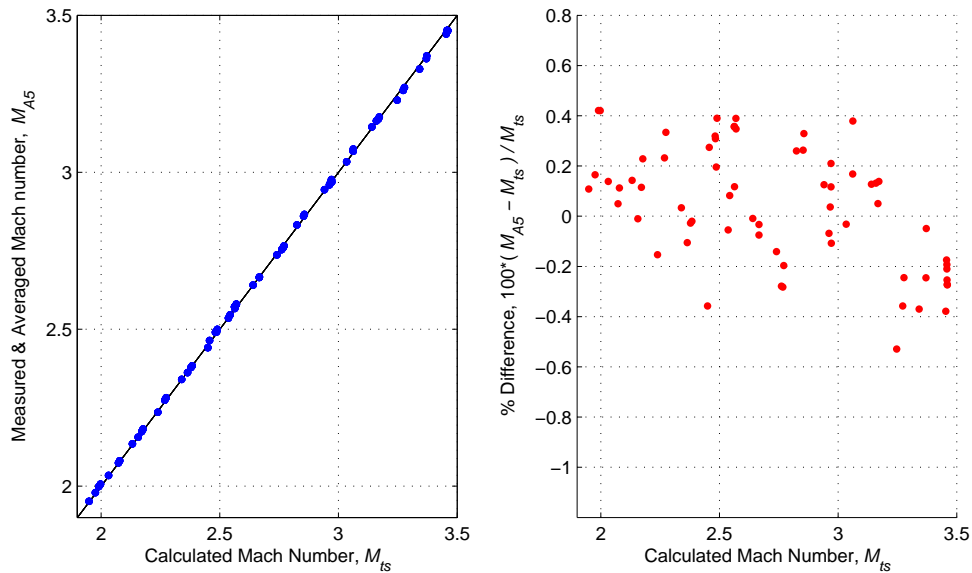

Figure 9: Comparing the calibration relationships in CAL10X with the averaged 5-wedge array data for Mach number from the 2014 test entry.
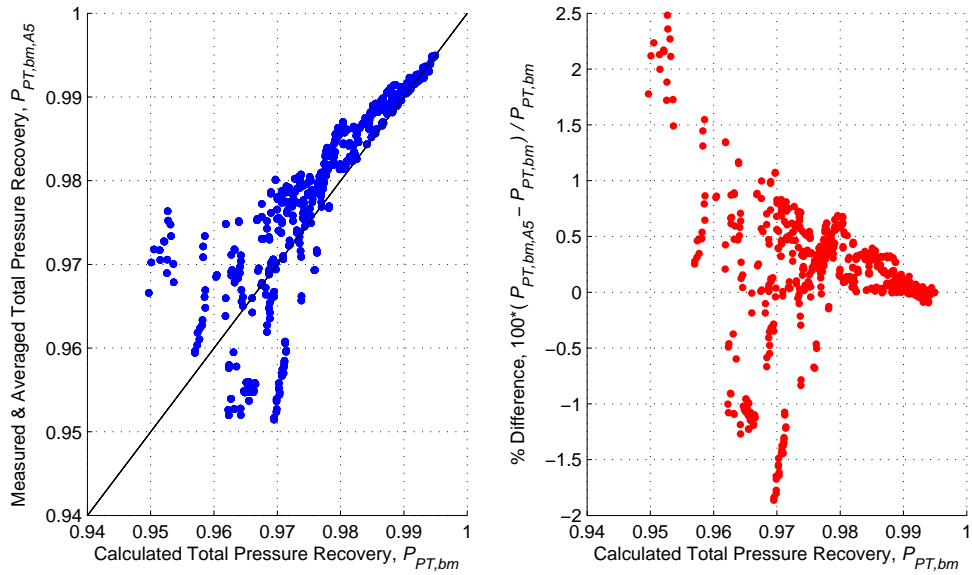
Figure 10: Comparing the calibration relationships in CAL10X with the averaged data from the center 5 wedges on the 17-wedge array for total pressure recovery from the 1999 test entry.
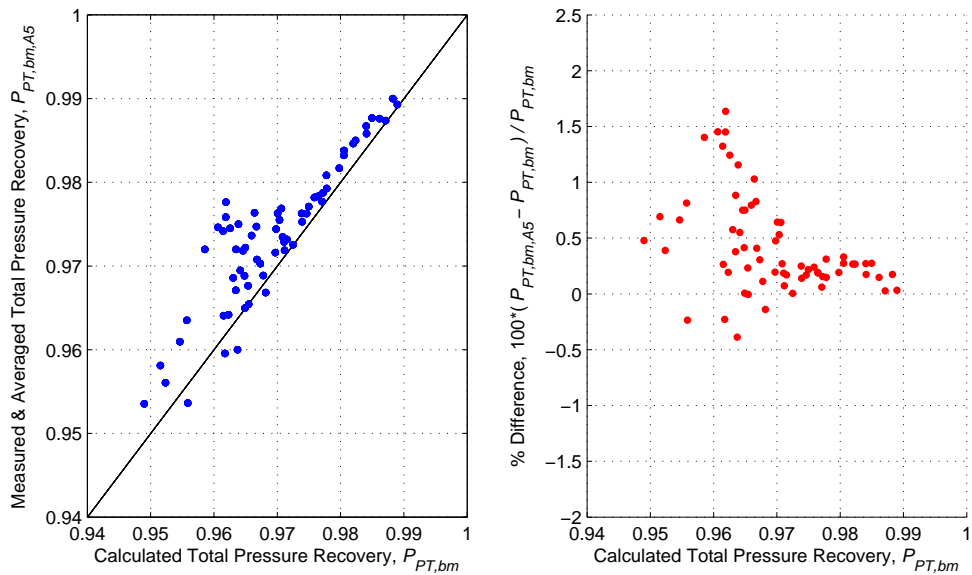

Figure 11: Comparing the calibration relationships in CAL10X with the averaged 5-wedge array data for total pressure recovery from the 2014 test entry.

Concluding Remarks

There were three goals for this check calibration effort. The first, validation of the CAL10X calibration curves, was completed and the curves were shown to still be valid. The second, the validation of the Cobra data acquisition system's performance against Escort's data, is still in progress and Cobra's performance during this entry will be documented separately. The third goal, creation of statistical process control charts, was not able to be completed due to scheduling constraints. In the future, the calibration team hopes to perform the SPC charting exercise at the earliest opportunity when there is sufficient time and funding available.

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