Automation & Characterization of US Air Force Bench Top Wind Tunnels

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ABSTRACT

The United States Air Force Precision Measurement Equipment Laboratories (PMEL) calibrate over 1,000 anemometer probes per year. To facilitate a more efficient calibration process for probe-style anemometers, the Air Force Metrology and Calibration Program underwent an effort to modernize the existing PMEL bench top wind tunnels. Through a joint effort with the Department of Energy's Oak Ridge National Laboratory, the PMEL wind tunnels were improved. The improvement consists of new high accuracy sensors, automatic data acquisition, and a software-driven calibration process. As part of the wind tunnel upgrades, an uncertainty analysis was completed, laser doppler velocimeter profiling was conducted to characterize the velocities at probe locations in the wind tunnel, and pitot tube calibrations of the wind tunnel were verified. The bench top wind tunnel accuracy and repeatability has been measured for three prototype wind tunnel systems and valuable field experience has been gained with these wind tunnels at three PMELs. This paper discusses the requirements for the wind tunnel improvements along with actual implementation strategies and details. Lessons-learned from the automation, the velocity profiling, and the software-driven calibration process will also be discussed.

INTRODUCTION

The United States Air Force Metrology and Calibration (AFMETCAL) Program, headquartered in Heath OH, manages a network of over 80 individual Precision Measurement Equipment Laboratories (PMEL). The purpose of a PMEL is to calibrate test, measurement, and diagnostic equipment (TMDE). Regional PMEL's calibrate over 1,000 anemometer probes every year for United States Air Force (USAF) customers. Precise air velocity measurement is required to support a variety of workplace environmental systems and weapon maintenance systems. The regional PMEL's utilize bench-top wind tunnels as standards to perform requisite calibrations. These standards recently underwent an improvement in sensor technology and automation techniques to allow PMEL's to capitalize on modern data acquisition and computation methodologies. With AFMETCAL R&D funding, the Department of Energy's Oak Ridge National Laboratory (ORNL) developed the Wind Tunnel Automation Package

(WTAP) for deployment in regional PMEL's. The WTAP includes new high-accuracy sensors, automatic data acquisition, and a software-driven calibration process.

REQUIREMENTS

AIR VELOCITY WORKLOAD

The U.S. Air Force (USAF) utilizes anemometers for various applications. Requirements exist to measure air velocity in support of workplace environmental monitoring, weather conditions analysis, and to gather wind speed data. USAF industrial hygienists use air velocity TMDE to ensure workplace compliance with USAF Occupational, Safety, and Health regulatory standards. For example, the air velocity in room ventilation systems requires monitoring to ensure that specific air exchange rates are maintained. Other areas with such stringent requirements include paint spray booths, fume hood areas, and hospital operating rooms. Other USAF air velocity TMDE applications include the monitoring of weather conditions at remote landing strips and the measurement of wind speed during ordnance loading procedures. It is critical for anemometers to be properly calibrated to support these vital processes.

UNCERTAINTY

Manufacturers continue to tighten the uncertainty specifications in anemometer products. It is essential for USAF to maintain standards that have an appropriate Test Uncertainty Ratio (TUR) with the improved TMDE. Since some TUR's were approaching 1:1, it became necessary to upgrade the existing bench-top wind tunnels. ORNL was tasked to upgrade the wind tunnel sensors and to individually calibrate each regional PMEL wind tunnel with a Laser Doppler Velocimetry (LDV) system. With improved sensors and specific LDV calibrations, the automated wind tunnels now have a improved uncertainty limits.

WIND TUNNEL EFFICIENCY

The current process of performing anemometer calibrations consists of setting up the Test Item (TI) and manually adjusting a variable potentiometer to set individual air velocity rates. The calibration technician then manually records differential pressure, temperature, relative humidity, and barometric pressure readings. An algorithm is then used to compute standard air velocity rates from the individual parametric data for comparison with the TI. The process of manually recording data and computing air velocities is cumbersome, time consuming, and has the potential for human error. Due to the volume of anemometer workload, a more efficient wind tunnel system was required. With the Wind Tunnel Automation Package, the entire process of setting air velocity rates, acquiring raw data, and computing standard air velocity values has been automated with improved performance.

SYSTEM UPGRADES

A typical conventional bench top wind tunnel is pictured in Fig. 1. The instrumentation package and PC-based data acquisition and control (DAC) system are also shown in the figure. The bench top wind tunnel is essentially a venturi with a 10cm x 10cm throat area. The geometry and honeycomb flow straighteners produce laminar flow with very little turbulent intensity (<1%). The velocity in the throat area is correlated with the square root of the pressure drop from the inlet to the throat. An LDV was used to determine the velocity at a specific position in the throat area at a specific pressure drop. Velocity probes are then placed at this location to perform an NIST-traceable calibration. The calibrated range of velocities is 0.15 meters/second (m/s) to 45 m/s. To achieve the full spectrum of velocities, it is necessary to use two nozzle plates. These plates will choke (or reduce) the flowrate traversing through the wind tunnel test section to allow generation of slower air velocity rates.

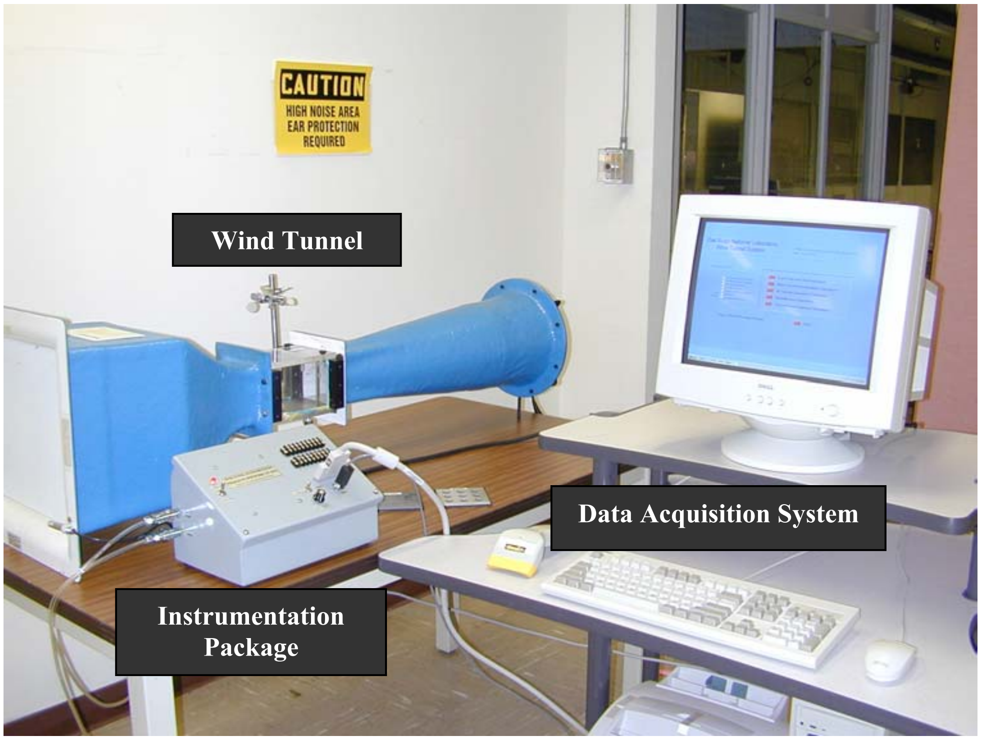

FIG. 1 BENCH TOP WIND TUNNEL, INSTRUMENTATION, AND DAC SYSTEM

INSTRUMENTATION

The main instrumentation upgrading effort included the absolute pressure transducer, the differential pressure sensor, and the temperature/relative humidity sensor. The original values and the corresponding improved uncertainties are listed in Table 1.

TABLE 1. UNCERTAINTIES OF THE BENCH TOP WT INSTRUMENTATION

PARAMETER	ORIGINAL UNCERTAINTIES	UPGRADE UNCERTAINTIES
Absolute Pressure	$\pm$0.04% FS	$\pm$0.15% Reading
Differential Pressure	$\pm$0.5% FS	$\pm$0.04% Reading
Temperature	$\pm$0.2 K	$\pm$0.1 K
Humidity	Not specified	$\pm$2.0% RH (0-90% RH)

In addition, the upgraded instrumentation is connected into a data acquisition board in a personal computer that allows the data to be archived, displayed, and manipulated. The uncertainty of the analog input board is $\pm$0.01% of reading (original system readout device was $\pm$0.25% of reading).

AUTOMATION

To increase the efficiency and accuracy of the calibration process, the entire measurement process was automated via a personal computer, remote blower control, and software-driven calibration. This includes automatically acquiring data from the instrumentation (absolute pressure (P), differential pressure (dP), air temperature (T), and relative humidity (RH)), converting this data to an air velocity, displaying the information, and archiving the calibration data (Fig. 2).

In addition to automatically recording, displaying, and archiving the calibration data, the system has the capability to check for up-to-date instrumentation calibration, converts the data to selected engineering units, and stores pertinent calibration information such as serial numbers, operator, time and date, as well as any operator comments.

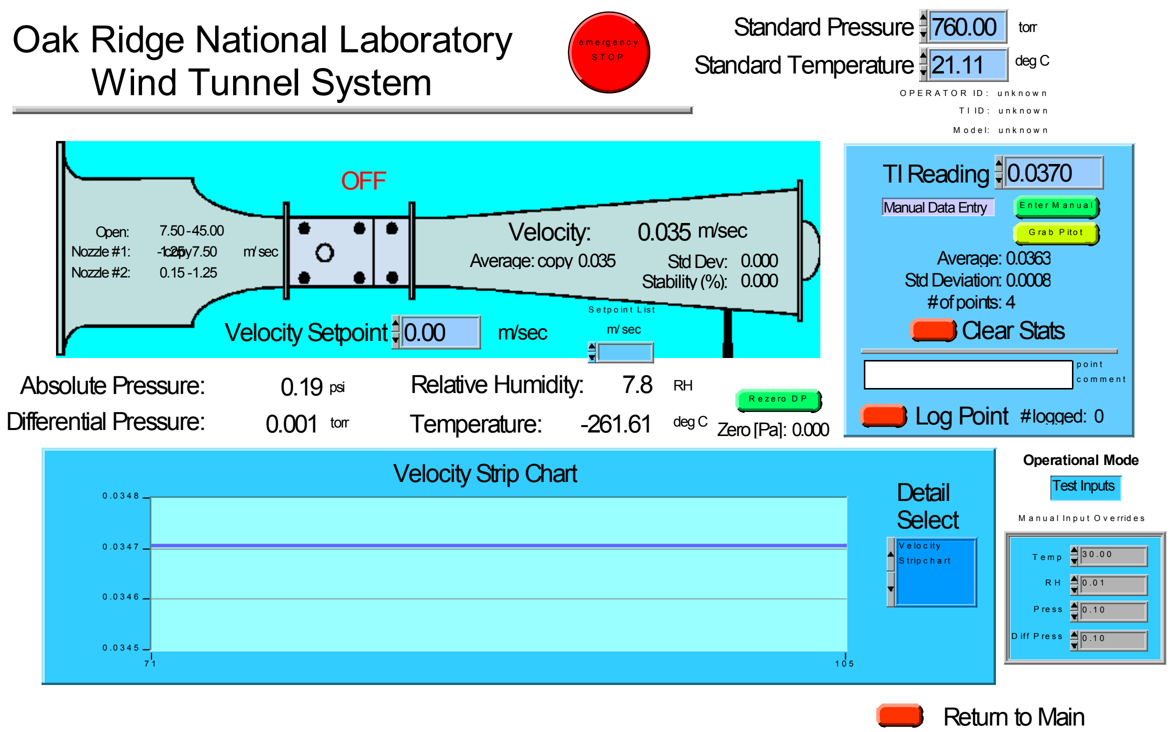

FIG. 2 WIND TUNNEL AUTOMATION DISPLAY

Finally, the operator can input a velocity setpoint, which in turn generates a computer command for the WTAP to automatically control the velocity in the wind tunnel at the desired setpoint. Once the data at this point has been taken, a new setpoint can be entered to proceed to the next calibration setpoint. Templates lists of setpoints, specific to a flow instrument model, may be used to allow single button stepping through calibration points.

DISPLAYS, REPORTS, AND ARCHIVING

The computerized DAC has several graphical displays for the operator to use. These displays include real-time data plots, averaged data, and archived data for pressure, differential pressure, temperature, humidity, and velocity. The DAC will also create reports for calibration purposes, diagnostics, or for recalling previous calibration runs. The DAC system will store calibration data via user selected file names. This data can be recalled for historical trending information, comparisons between calibration runs, and evaluation or quality control needs.

CHARACTERIZATION OF WIND TUNNEL

UNCERTAINTY ANALYSIS

A generalized uncertainty analysis was used to determine the sensitivity of the various parameters that affect the wind tunnel performance. The Bernoulli's Equation may be written as (initially discounting losses and assuming the density is constant over the limited pressure drop occurring within the system.)

$$\frac{P_1 - P_2}{\rho} \approx \frac{1}{2}\left[V_2^2 - V_1^2\right] \qquad (1)$$

Where P_1=upstream pressure
P_2=throat pressure
ρ=density
V_1=upstream velocity
V_2=throat velocity

Using continuity and substituting β = (throat diam, d)/(inlet diam, D), yields

$$V_2 = \frac{\sqrt{2}}{\sqrt{1-\beta^4}} \frac{1}{\sqrt{\rho}} \sqrt{\Delta P} \qquad (2)$$

Where ΔP=pressure drop, upstream minus throat pressures

and ρ is a function of pressure, temperature, and relative humidity. This velocity expression may be evaluated using the standard expression for measurement uncertainty to produce the sensitivity coefficients for the input quantities P, dP, T, and RH[2].

$$u_c^2(v) = \left[\frac{\partial V}{\partial P}\right]^2 u_P^2 + \left[\frac{\partial V}{\partial \Delta P}\right]^2 u_{\Delta P}^2 + \left[\frac{\partial V}{\partial T}\right]^2 u_T^2 + \left[\frac{\partial V}{\partial RH}\right]^2 u_{RH}^2 \qquad (3)$$

Where u = uncertainty, u_c is the total velocity uncertainty, and [term] is the sensitivity coefficient.

This analysis showed that the dP measurement is the most significant contributor to the uncertainty, followed by the pressure measurement. The T and RH measurements had only slight contributions to the uncertainty; however, all parameters were included in the analysis.

In practice, however, the upgraded dP transducer calibrated much better than manufacturer's specification at the low end, i.e. to within 0.04% of reading as opposed to .01% of full scale. This calibration was accomplished using a cross-floated dead weight testing scheme to provide accurate standard differential pressures from 0 to 5 torr. Currently, however, field standards for differential pressure (i.e. Hooke Gages) do not provide for calibration to this level of uncertainty. Calibration with these field standards provides a 0.005 torr uncertainty in the differential pressure measurement, which is an uncertainty greater than the manufacturer's specification for the differential pressure unit. Using this higher uncertainty value for the differential pressure measurement results in an increase in static uncertainty throughout the wind tunnel's range of use, as indicated in Fig 3.

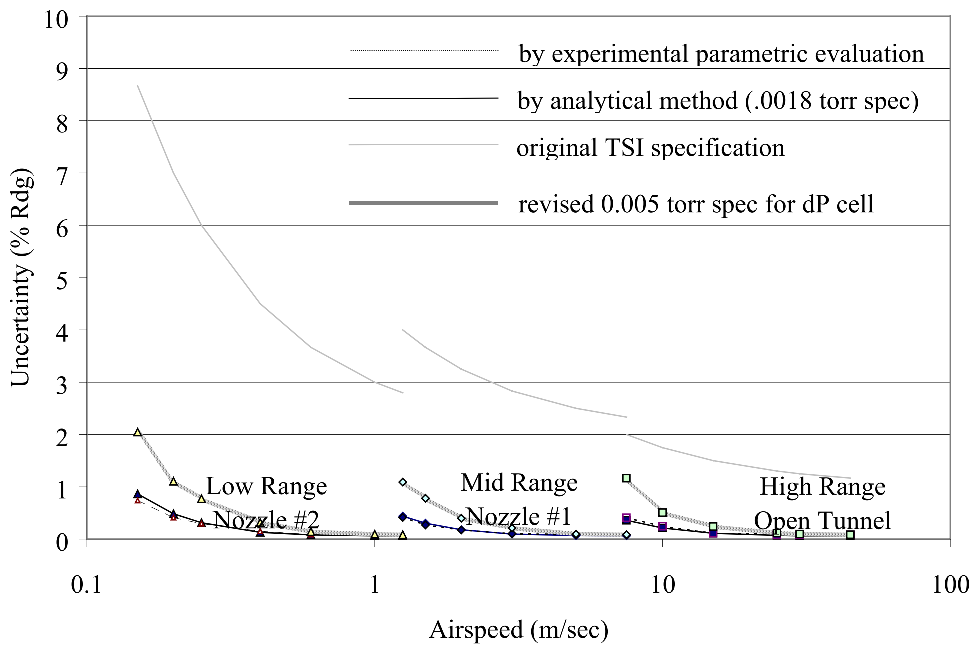

FIG. 3 STATIC UNCERTAINTY OF WTAP

Overall uncertainty of the upgraded WTAP is the combined uncertainties contributed by the static uncertainties of the instrumentation package, turbulence within the wind tunnel (as determined by laser doppler measurements throughout the velocity range), standard velocity measurement contributions (pitot and LDV systems), and curve-fit bias errors in correcting the wind tunnel velocity. The overall WTAP uncertainty was calculated over the full range of flows, as shown in Table 2.

TABLE 2. OVERALL UNCERTAINTY OF BENCH TOP WIND TUNNELS

CALIBRATED RANGE	WTAP UNCERTAINTY	ORIGINAL WT UNCERTAINTY	NOZZLE PLATE
0.15 to 0.3 m/s (30-60 fpm)	2.5% of reading	8.6 to 5.3% of reading	#2
0.3 to 1.25 m/s (60-250 fpm)	1.5% of reading	5.3 to 2.8% of reading	#2
1.25 to 3 m/s (250-600 fpm)	1.75% of reading	4 to 2.8% of reading	#1
3 to 7.5 m/s (600-1500 fpm)	1.5% of reading	2.8 to 2.3% of reading	#1
7.5 to 10 m/s (1500-2000 fpm)	1.5% of reading	2.0 to 1.75% of reading	Open
10 to 45 m/s (2000-9000 fpm)	1.0% of reading	1.75 to 1.15% of reading	Open

The uncertainty of the original wind tunnel is also shown in Table 2. The WTAP has significantly lower uncertainty in all velocity ranges.

VELOCITY PROFILING AND PROBE LOCATION

Using the LDV, velocities throughout the measurement volume were measured and velocity profiles characterized. The most significant finding was that there is significant flow development occurring with axial travel into the measurement volume. The velocity profile increases as much as 1-2% per 10 millimeter (mm) of travel along the horizontal axis toward the nozzle plate location (Figs. 4 & 5). This finding indicates that profiles must be taken into account if the wind tunnels are going to be used at improved accuracy levels.

Nozzle Plate #2, dP=5.40 in. w.c.

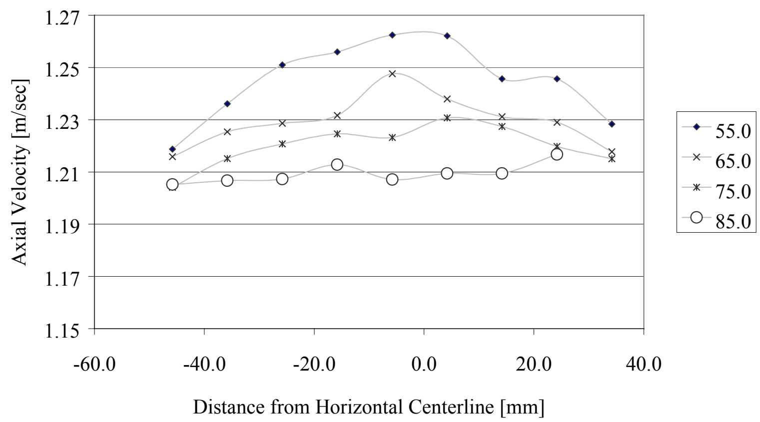

FIG. 4 SUPERIMPOSED VERTICAL PROFILES. NOTE, the recommended manufacturers' position of 85 mm from nozzle plate provides a relatively flat profile (w.c. = water column).

Nozzle Plate #1, dP=4.55 in. w.c.

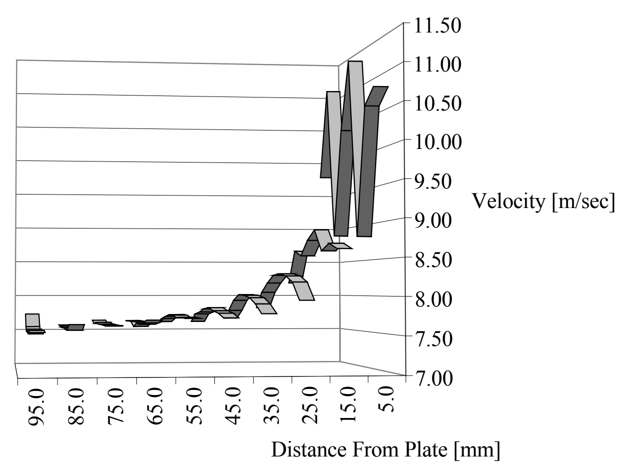

FIG. 5 VERTICAL PROFILES AT THE HORIZONTAL CENTERLINE OF FLOW. NOTE, the change in profile across the wind tunnel and the increase in velocity as the nozzle plate is approached.

NOZZLE PLATE INSTALLATION EFFECTS

The impact of improperly installing the restriction nozzle plates was investigated by using a repeatable velocity probe and by correctly and incorrectly (backwards) plate installment. The effect of the way the plates were installed was evaluated throughout the lower and midrange velocities. The data indicated an error of 20-25% across the entire low and mid range points. This sizable effect would be noticed on a recalibration unless the sensor happened to be "off" by the same 20-25% error.

CALIBRATION OF THE BENCH TOP WIND TUNNEL

The upgraded wind tunnel system was compared to a NIST-calibrated pitot tube and a laser doppler velocimeter. The pitot tube was used at the upper range of velocities produced by the wind tunnel. The LDV was used primarily at the low end and it was also used at some velocities in the upper range of the wind tunnel for comparison to the pitot tube results.

PITOT TUBE CALIBRATION

The wind tunnel-determined velocity was compared to a NIST-calibrated pitot tube over a range of velocities from 8 m/s to 45 m/s. The first three upgraded wind tunnels' comparisons are shown in Fig 6. The data is presented as the difference between the wind tunnel-determined value and the pitot tube value as a percent of reading error and the wind tunnel velocity setpoint. The agreement of the wind tunnel with the NIST-calibrated pitot tube is well within the expected uncertainty of the WTAP.

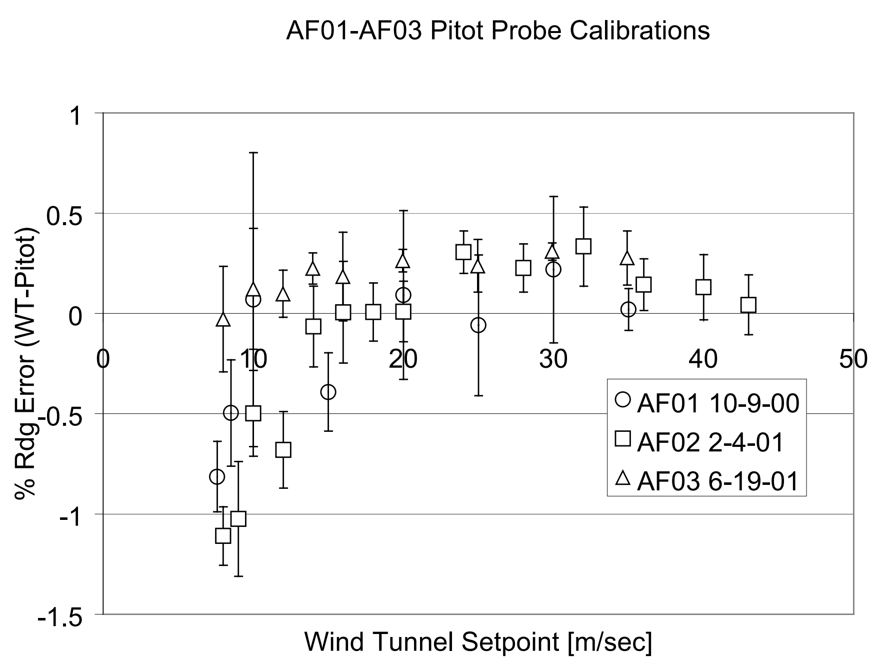

FIG. 6 COMPARISON OF UPGRADED WT & NIST-CALIBRATED PITOT TUBE VELOCITIES

LASER DOPPLER VELOCIMETER CALIBRATION

The ORNL LDV geometric uncertainty was determined from NIST-traceable dimensional measurements and LDV system geometry to be ±0.2%[1]. Additional uncertainties from the LDV's signal conditioning and statistical variations were quantified against the NIST-calibrated pitot tube. Because of the excellent agreement between the pitot tube and LDV at the higher velocities, the LDV was used as a transfer standard to the low velocity range. The LDV data versus the wind tunnel measurements are illustrated in Fig 7. The data in Fig. 7 shows the error to be less than ±1.5% of reading for velocities < 3m/s and less than 1% over the rest of the velocity range, which is well within the WTAP's specifications.

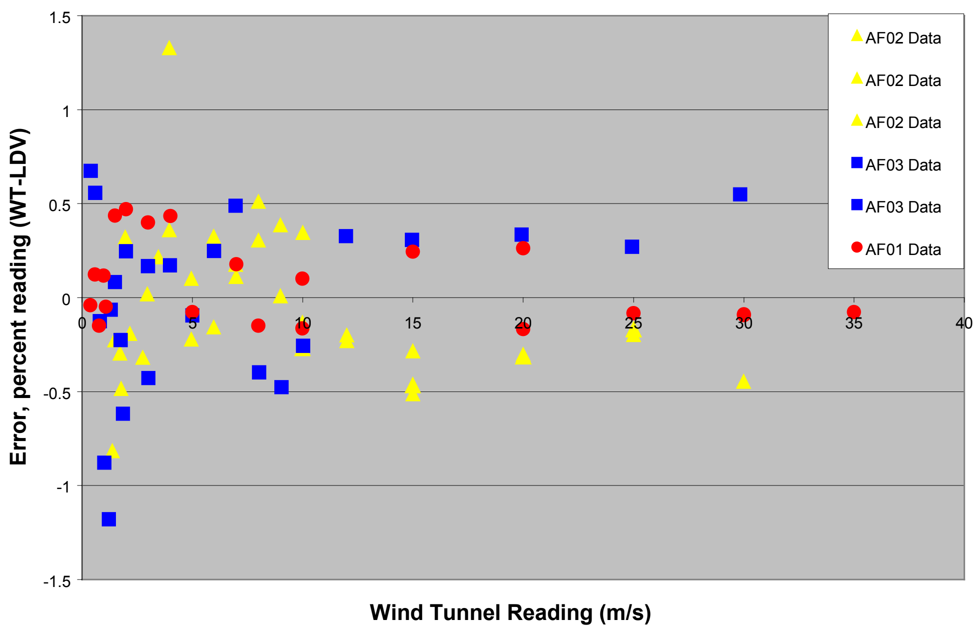

FIG. 7 LDV CALIBRATION DATA FOR THREE WIND TUNNELS (AF01, AF02, AF03)

FIELD EXPERIENCE

TRAINING

Initial setup of the upgraded WTAP system in the first three calibration laboratories has shown that minimal training is required to learn how to operate the upgraded WTAP system. An extensive operating manual coupled with intuitive software functions allows a technician to begin calibrating almost immediately after initial checkout of the system. In addition, the software features user-friendly help functions, which serve as an aid for new users.

FIELD EXPERIENCE/USER COMMENTS

Initial feedback from users at 3 sites indicates the Automated WT enhances productivity and efficiency of air velocity calibrations. Productivity improvements are a primary result of the automated data acquisition. Field technicians realized the increase in efficiency due to the ease of setting air velocity setpoints and the capability to store testpoint templates. The templates allow the user to save specific testpoints in a file for later recall when calibrating a specific part number.

SYSTEM IMPROVEMENTS

The individual field technicians are currently generating a list of possible system improvements for another version of the software. Future system improvements will be considered to enhance the automated WTAP. The integration of automatic data acquisition directly from a RS232 air velocity channel may be accomplished. Due to unique communication protocols, software modification will only be warranted if the AF workload is of a sufficient size to induce investment in additional calibration software routines for specific TMDE. Another future possibility includes utilizing the existing WTIP and WT software package with a larger WT system for performing calibrations on vane and cup-style anemometers.

SUMMARY

The ORNL/AFMETCAL team approach has brought together the strengths of two metrology-minded organizations to fulfill a critical USAF requirement. With ORNL's expertise in developing integrated sensing technologies and AFMETCAL's extensive worldwide network of PMEL calibration laboratories, the upgraded WT was developed, tested, calibrated, and fielded with the utmost attention to detail and quality. The WT system upgrades, sensor calibrations, and LDV characterizations have resulted in a significantly improved bench top wind tunnel calibration system. The initial field experience has shown that the upgraded WT has resulted in reduced man-hours per test item calibration and improvement in reproducibility of calibrations. USAF can now perform air velocity calibrations more efficiently and with better Test Uncertainty Ratios.

ACKNOWLEDGEMENTS

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