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Improved Pressure Measurement System for Calibration of the NASA LeRC 10x10 Supersonic Wind Tunnel

Philip Z. Blumenthal
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

and

Stephen M. Helland
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

NASA

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Philip Z. Blumenthal
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

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Stephen M. Helland
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

This paper discusses a method used to provide a significant improvement in the accuracy of a Electronically Scanned Pressure (ESP) Measurement System by means of a fully automatic floating pressure generating system for the ESP calibration and reference pressures. This system was used to obtain test section Mach number and flow angularity measurements over the full envelope of test conditions for the 10x10 Supersonic Wind Tunnel. The uncertainty analysis and actual test data demonstrated that, for most test conditions, this method could reduce errors to about one-third to one-half that obtained with the standard system.

INTRODUCTION

The 10x10-Foot Supersonic Wind Tunnel, shown in Figure 1, is NASA's only high-speed (Mach > 2.0) wind tunnel with propulsion cycle capabilities. This facility has had an extensive history of both aeronautic and propulsion systems testing since it started operations in 1955, ranging from solid fuel ram jet testing for the Air Force in the 1950's to a recent National Aerospace Plane (NASP) propulsion research program. Air flow in the 3.05 m (10-ft) high, 3.05 m (10-ft) wide, 21.2 m (40-ft) long test section can be varied in speed from Mach 2.0 to Mach 3.5 and in altitude from 15.2 to 45.7 km (50,000 to 150,000 ft).

Although calibrations of the 10x10 test section were performed in 1956, 1958, and 1964, significant improvements to the data system have been made in the intervening years. These improvements could help to achieve a desired measured Mach number accuracy of 0.001 and a flow angularity accuracy of 0.1°. In addition, longitudinal distributions of free stream Mach number, pressure recovery and flow angularity that were not considered important during the initial calibrations are necessary for the types

of research being conducted today.

SURVEY RIG

A photograph of the flow calibration survey rake is shown in Figure 2. The survey head consists of an array of 17 wedges, sixteen of which were equally spaced in a four foot square. The seventeenth wedge was located in the center of the square which is at the intersection of the horizontal and vertical tunnel centerlines. This array is attached to the end of a remotely controlled rack and pinion arrangement mounted on two fixed struts. The rack and pinion provides eight feet of longitudinal translation for the survey head. The survey rig was installed in the tunnel so that the wedge leading edges were perpendicular to the tunnel centerline within $1.0°$ and the wedges were individually aligned parallel to the tunnel centerline by shimming until the wedge half angles were equal. The final result was, in general, that all wedges were aligned to within $0.05°$ or less.

A sketch of the $20°$ half angle wedge used is shown in Figure 3. The wedge pressure instrumentation consists of a top and bottom pitot tube (H_{1T} & H_{1B}), a left and right oblique wedge surface total (H_{2L} & H_{2R}) and a static port on the left and right surface of the wedge (P_{SL} & P_{SR}). Each wedge support also holds one high recovery, aspirated Chromel-Alumel type thermocouple to measure the local total temperature.

COMPUTING PROCEDURE

The local free stream Mach number at each wedge is a function of H_2/H_1, the average of the left and right oblique totals divided by the average of the top and bottom pitots. Using this Mach number and the measured pitot pressure, the local free stream total pressure was than calculated. In the previous 10x10 SWT calibration tests the Mach number computations were performed by solving the series of quadratic equations relating Mach number to the H_2/H_1 pressure ratio during the batch processing. During the current test it was determined that the data acquisition system (ESCORT D+) was capable of providing an on-line iteration with the governing equations for all 17 wedges while maintaining the required one-second update. Very little difference was found between the results calculated from the quadratic curve fits and those by the iteration technique. The difference in the wedge surface static pressures (P_{SL} - P_{SR}) was used to determine the local flow angle.

ESP PRESSURE MEASUREMENT SYSTEM

The Electronically Scanned Pressure system, which is enclosed in three temperature controlled cabinets, is shown with the insulated doors removed in Figure 4. For the Tunnel Calibration test, thirteen 32 port plug-in modules were arranged in three pressure range groups and two Pressure Calibration Units containing six quartz pressure reference transducers (designated DQ's) were used. During normal tunnel testing the pneumatic valve in each module is set to the in-situ calibration position every 20 minutes and three cal pressures (Lo, Mid, and Hi) are applied in succession to the measurement port of all transducers and the appropriate DQ pressure standard in a given range. For the Tunnel Calibration test,

however, a ESP calibration was performed before data acquisition at each test condition.

The ESP Data Acquisition and Control Unit (DACU) software establishes a second order curve fit for each transducer based on the three cal values measured by the quartz pressure standard and the millivolt outputs of the transducers. All transducers used in the ESP modules are differential and, except for the 500 psi unit, can be used from plus to minus full scale range. An improvement in accuracy can be obtained if they are calibrated and used in only one direction from their reference (backside) pressure. This is because the transducer output curve may be an third order through zero. This type of correction curve cannot be calculated from only three cal points. Although the transducer output capability (and thus the output resolution) is degraded by calibration in one direction, the improvement in matching the non-linearity curve results in better overall accuracy.

An improvement in accuracy is also obtained by setting the Lo and Hi cal pressures to the minimum and maximum values expected to be measured. This provides the DACU with the data to produce the closest fit possible to the non-linearity curve for each transducer. Although this further degrades the transducer output resolution, the net effect is still a reduction in measurement uncertainty.

The ESP system was configured to operate in the averaged data mode. Each Escort data scan was composed of an average of eight ESP scans. Each ESCORT data point taken was an average of five cyclic data scans. At each test condition three data points were manually taken to provide a good statistical average of steady state conditions and to determine the repeatability of the data.

ESP SYSTEM CONFIGURATION FOR THE 10X10 CALIBRATION TEST

Three groups (racks) of ESP modules were used to meet the test objectives and measurement requirements for the 10x10 Calibration. The tunnel measurements these groups were used for is as follows:

Group 1. Flow Angularity (P_{SL} - P_{SR}).

Left and right statics on each side of the 17 wedges used ±5 psid modules with the transducer reference connected to tunnel static. For the in-situ calibration the transducer reference was switched by the pneumatic valve to atmosphere to allow use of a ±6 psid DQ pressure reference without damage from overrange.

Group 2. Tunnel Total and Static Pressures.

Over the range of test conditions full scale range requirements vary from less than 2 psia to 54 psia. This was accomplished by changing module ranges (±15 or ±30 psid) and by changing DQ reference standards (15, 30, and 65 psia) for the various run conditions.

Group 3. Survey Rake Wedge Total (H_1) and Oblique (H_2) Pressures

Precise measurement of these pressures is crucial to meet the accuracy required in determining local wedge Mach number. Because H_2 and H_1 varies from 1.75 and 1.5 psia respectively at low Mach and

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Reynolds numbers up to 20 psia and 10 psia at max conditions, different module ranges (±2.5, ±5, & ±15 psid) were used. To avoid overpressuring the low range transducers, the module reference pressure was varied for each test condition. In addition, to provide the maximum accuracy, the Lo, Mid, and Hi cal pressures needed to be varied for each test condition. To avoid setting all these pressures for each test point, a method was devised for automatic pressure adjustment by modification of several industrial pneumatic computing relays.

AUTOMATIC PRESSURE GENERATING SYSTEM

The new system, shown in Figure 5, provides a completely automatic floating pressure generating system for all calibration and reference pressures required for the low range ESP Modules. The lowest absolute pressures to be measured at each test condition are the wedge totals and the highest are the wedge obliques. However, a wedge total cannot be used directly as a reference or calibration pressure because it can not supply sufficient flow without causing a large pressure drop in the line. Therefore, the total tube from the model is used only as a dead-ended reference for a Pneumatic Power Booster. This unit reproduces pneumatic signals in a 1:1 ratio and provides isolation between the input signal and the output and supplies a large volume flow for the output. Although the manufacturer's specifications indicate that the unit can only be used for gage pressure applications, it was experimentally verified that this device operates accurately with a sub-atmospheric input signal by connecting a vacuum source to the exhaust port.

The Mid Cal and Hi Cal pressures for each test condition are each generated by a Pneumatic Biasing Relay. This device can provide an output pressure with a predetermined bias from a input signal. This bias pressure holds constant regardless of wide changes in flow or supply pressure. The bias value is set by an adjusting a knob which varies the force on the spring which pushes against the regulating diaphragm assembly. This device was also modified for sub-atmospheric operation. Four tubes were epoxied into the vent holes and into a specially built manifold which was connected to the vacuum source. A precision pressure readout is used to monitor the setting of each bias pressure.

Typical results of the bench tests of this system are shown Figures 6 for the 2.5 psi range. Data was taken for both increasing and decreasing input pressure over the entire operating range. Supply pressure was adjusted to 5.5 psig for the 2.5 psi range and 7.5 psig for the 5 psi range. The dotted and solid lines shown on the plot are the theoretical values for perfect bias from the input points and the symbols plotted are the actual measured data points.

When the ±2.5 and ±5 psid ESP modules were used on the 10x10 Calibration Test, the Module Reference and Calibration Pressures automatically floated with the Wedge Total pressure. The Reference and Lo Cal, driven by the Power Booster, was essentially equal to the Wedge Total, and the Mid Cal and Hi Cal were biased 1.25 and 2.5 psi respectively for the ±2.5 psi modules and 2.5 and 5 psi for the ±5 psi modules.

UNCERTAINTY ANALYSIS

An analysis was performed to determine the uncertainty in the local Mach number and flow angularity results. For the scope of this paper only the results computed for data at test section Tunnel Reynolds Numbers of 0.5, 1.5, and 2.5 x 10^6 are shown. The technique that was used for this analysis is in accordance with the procedure given in Reference 3. The first step in this process requires a complete audit of all elemental error sources starting with the base calibration of the reference transducers by the calibration laboratory with traceability to National Institute of Standards and Technology (NIST). Additional elements of the measurement system were then evaluated to account for errors due to the characteristics of the transducer and data conditioning equipment, installation and environmental effects, and data acquisition and data processing systems. Each error is considered to have two components: a random or precision value (S) and a fixed or bias value (B). After all precision errors are combined and the bias errors are combined (by computing the root-sum square of each), the measurement uncertainty (U) is calculated as follows:

$$\pm U = \pm(B_t + t_{95} S_t)$$

Where:

B_t = Root-sum-square of all bias (fixed) errors
S_t = Root-sum-square of all precision (random) errors
t_{95} = 95th percentile point for the statistical
        parameter used in calculating the precision errors

Since the number of data scans and independent data points taken at each test condition provided more than 30 data samples, t_{95} is assumed to be a value of 2.

Table I shows an evaluation of the error sources that affect the pressures measured on the wedges. An evaluation of the quantitative value of each error source (in Percent of Full Scale Range) was determined from Calibration Certificates, manufacturer's specification sheets, and engineering analysis, tests, and estimates. The values obtained for the pressure measurement system are listed in the second column of Table I. Finally, the magnitude (in psi) of each significant elemental error was calculated for each range used in the pressure system.

FLOW ANGULARITY UNCERTAINTY

As described previously, the calculation for the local flow angle at each wedge is a function of the difference in the wedge surface static pressures, P_{SL} and P_{SR}. The sensitivity of the resultant flow angle to this pressure difference is also a function of the tunnel total pressure, H_0. The ESP configuration for measurement of P_{SL} and P_{SR} used ±5 psid modules with the transducer reference in each module connected to tunnel static. For the in-situ calibration, the transducer and quartz references were switched to atmosphere to allow use of a ±6 psid range reference without risk of damage from overrange. Using the elemental error values given in Table I, the pressure measurement uncertainty for P_{SL} and P_{SR} is calculated as follows:

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$$B_p = \pm \sqrt{\sum_i (b_{ip})^2} = \pm \sqrt{B_1^2 + B_2^2 + B_3^2 + B_5^2 + B_6^2}$$

$$= \pm 0.00163 psi = \pm 0.235 psf = \pm 2.36 \times 10^{-7} \, Pa$$

$$S_p = \pm \sqrt{\sum_i (s_{ip})^2} = \pm \sqrt{S_1^2 + S_2^2 + S_3^2 + S_5^2 + S_6^2 + S_7^2 + S_9^2}$$

$$= \pm 0.00197 psi = \pm 0.283 psf = \pm 2.6 \times 10^{-7} \, Pa$$

$$U_P = \pm (B_P + 2 S_P) = \pm 0.803 \text{psf} = \pm 8.09 \times 10^{-7} \, Pa$$

Similarly, the uncertainty for bellmouth total, H_o, was also calculated for each module range used.

Tabulations of the computed data output for a selected number of test conditions were examined to determine the effect of a small change in P_L, P_R, and H_o on the flow angularity (α). The resultant matrix of influence coefficients for these parameters is displayed in Table II, where angularity error (in minutes) is shown per pressure measurement error (in psi). Since the error due to H_o is proportional to the flow angle α, a value of 30' was arbitrarily chosen for the uncertainty evaluation. It was found that the error in the measurement of H_o had a very slight effect at a Reynolds number of 0.5×10^6 and was negligible at higher values of R_c.

The final step was to calculate the uncertainty values for each test condition in the matrix. The equations used are given below:

$$B_\alpha = \pm \sqrt{\left(\frac{\Delta \alpha}{\Delta P_{SL}} * B_p\right)^2 + \left(\frac{\Delta \alpha}{\Delta P_{SR}} * B_p\right)^2 + \left(\frac{\Delta \alpha}{\Delta H_o} * B_h\right)^2}$$

$$S_\alpha = \pm \sqrt{\left(\frac{\Delta \alpha}{\Delta P_{SL}} * S_p\right)^2 + \left(\frac{\Delta \alpha}{\Delta P_{SR}} * S_p\right)^2 + \left(\frac{\Delta \alpha}{\Delta H_o} * S_h\right)^2}$$

$$U_\alpha = \pm (B_\alpha + 2 S_\alpha)$$

The tabulated results are shown in Table III. This table shows that the desired flow angle measurement accuracy goal of ± 0.1 degree ($\pm$ 6') could be achieved with the ESP system configuration used at all but the lowest Reynolds numbers.

MACH NUMBER UNCERTAINTY

The local free stream Mach number at each wedge, as described under COMPUTING PROCEDURE, is a function of H_2/H_1, the average of the left and right oblique total pressures divided by the average of the top and bottom pitot pressures. These pressures were measured using four of the ESP modules in Group #3. To obtain the greatest accuracy for each tunnel test condition four different configurations for Rack #2 were to be used which were designated as "A", "B", "C-1", and "C-2". These

configurations used different module ranges ($\pm2\frac{1}{2}$, ±5, & ±15 psid) and different DQ transducer ranges (15 & 23 psia).

In the case of the Mach number computations, the influence of the bias and precision errors due to the DQ reference standard on the results was different than the influence due to the ESP transducers and electronics. Therefore the DQ error values (B_D, S_D, and U_D) and the transducer error values (B_T, S_T, and U_T) were calculated for each configuration using the elemental pressure system error values given in Table I. A summary of these results are given in Table V.

The measured pressures in the ratio H_2/H_1 are both calibrated against the same readings of the DQ reference standard during each calibration cycle, and thus the same errors in these readings will either be added or subtracted essentially in equal measure to both H_2 and H_1. The individual ESP transducer errors, however, might cause an increase in the value of H_2 and a decrease in H_1 or vice versa, which results in a much greater error in the ratio H_2/H_1. The Mach number influence coefficients were calculated using the worst case effects.

A two-step procedure was used to determine the influence coefficients matrices shown in Table IV. First, the change in Mach number for a number of incremental changes in the ratio H_2/H_1 (abbreviated to R) was calculated for each test condition evaluated, and the average value of these were used in the $\Delta M_o/\Delta R$ columns in Table IV. Second, the change in the nominal H_2/H_1 ratio (ΔR) was computed for the Digiquartz errors (B_D,S_D) by adding each of these errors to both the numerator and the denominator and (ΔR) was computed for the transducer errors (B_T,S_T) by adding these errors to the numerator and subtracting them from the denominator.

The Mach number uncertainty matrix could then be calculated from the following equations:

$$B_{M_o} = \pm\sqrt{(\Delta\frac{M_o}{\Delta(R)} * \Delta(R)_{B_D})^2 + (\frac{\Delta M_o}{\Delta(R)} * \Delta(R)_{B_T})^2}$$

$$S_{M_o} = \pm\sqrt{(\Delta\frac{M_o}{\Delta(R)} * \Delta(R)_{S_D})^2 + (\frac{\Delta M_o}{\Delta(R)} * \Delta(R)_{S_T})^2}$$

$$U_{M_o} = \pm(B_{M_o} + 2\ S_{M_o})$$

The results of these computations is shown in Table V for both the new floating reference system and the standard ESP system. Although the accuracy goal of ±0.001 Mach number was not achieved for the low Reynolds number conditions, the results were much better than could be obtained if the low range modules with the floating reference/calibration pressures had not been used. The actual data results from a previous calibration test using the standard range modules (±15 psid) for these conditions displayed from 2 to 3 times greater uncertainty, which agrees closely with the analysis in Table V.

CONCLUSIONS

In most types of wind tunnel tests the normal incremental type of test data obtained with the standard

facility data systems is adequate because the tunnel free stream conditions are common to all of the data, and therefore the bias in the these conditions cancel. However, during the course of propulsion system and flight vehicle development programs, a large number of tests are conducted to provide test data such as inlet and nozzle performance, lift and drag, and net thrust. This data is then merged and extrapolated to flight Reynolds numbers to obtain the total aircraft performance. If the incremental errors added from different test facilities is excessive, the vehicle may not meet the critical mission requirements. Therefore, it is extremely important that the absolute values of the wind tunnel baseline free stream conditions be known and documented with a very high degree of accuracy, and that this accuracy is traceable to the national standards.

For the recent 10x10 Test Section Calibration test, a number of improvements in the specially designed ESP system demonstrated that the higher accuracy provided by this system could be achieved without an unacceptable amount of monitoring or support required. The floating pressure generating system provided the proper calibration and reference pressures for each set of test conditions automatically without any operator attention. This system has provided a significant increase in accuracy of Mach number measurement.

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Table I. Error Source Evaluation
(Pressure Measurement System)

ERROR SOURCE	ERROR $\pm\%F.S.$	DESCRIPTION
B_1	0.020%	DQ calib certif (6,23,30 & 65 psi range)
	0.025%	" " (15 psi range)
B_2	0.003%	DQ temperature error (70° F ± 3° F)
B_3	0.005%	DQ electronics time base accuracy
B_4	0.020%	Ref barometer calib certif (20 psia Sonix)
B_5	0.005%	DQ calib curve fit error
S_1	0.005%	DQ Repeatability
S_2	0.005%	DQ Hystersis
S_3	0.0005%	DQ electronics counter resolution
S_4	0	ESP sys data reduction resolution $2^{-64} \approx 0$
S_5	0.010%	Repeatability (transducer, mux, amp)
S_6	0.005%	Hysteresis
S_7	0.012%	A/D converter resolution
B_6	0.010%	ESP curve fit error
S_8	0	ESCORT D+ Computational resolution $2^{-64} \approx 0$
S_9	0.0067%	ESP system output resolution

Table II. Influence Coefficient Matrix for Flow Angularity Measurements.

| M_o | REYNOLDS NUMBER ($\times 10^6$) | | | | | |
| | 0.5 | | 1.5 | | 2.5 | |
	$\Delta\alpha/\Delta P$	$\Delta\alpha/\Delta H$ at 30'	$\Delta\alpha/\Delta P$	$\Delta\alpha/\Delta H$ at 30'	$\Delta\alpha/\Delta P$	$\Delta\alpha/\Delta H$ at 30'
2.0	3.30	0.039	1.60	0	0.98	0
2.5	5.48	0.057	2.80	0	1.65	0
3.0	6.70	0.059	2.80	0	1.65	0
3.5	7.00	0.062	2.80	0	1.85	0

Table III. Flow Angle Uncertainty (Minutes).

| M_o | REYNOLDS NUMBER ($\times 10^6$) | | |
	0.5	1.5	2.5
2.0	±3.76	±1.82	±1.11
2.5	±6.23	±3.18	±1.87
3.0	±7.61	±3.18	±1.87
3.5	±7.95	±3.18	±2.10

Table IV. Influence Coefficient Matrix for Mach Number Measurements.

M_O	REYNOLDS NUMBER ($\times 10^6$)														
	0.5					1.5					2.5				
	$\Delta(R)B_D$ $\times 10^{-4}$	$\Delta(R)B_T$ $\times 10^{-4}$	$\Delta(R)S_D$ $\times 10^{-4}$	$\Delta(R)S_T$ $\times 10^{-4}$	$\Delta M_o/\Delta(R)$	$\Delta(R)B_D$ $\times 10^{-4}$	$\Delta(R)B_T$ $\times 10^{-4}$	$\Delta(R)S_D$ $\times 10^{-4}$	$\Delta(R)S_T$ $\times 10^{-4}$	$\Delta M_o/\Delta(R)$	$\Delta(R)B_D$ $\times 10^{-4}$	$\Delta(R)B_T$ $\times 10^{-4}$	$\Delta(R)S_D$ $\times 10^{-4}$	$\Delta(R)S_T$ $\times 10^{-4}$	$\Delta M_o/\Delta(R)$
2.0	8.18	3.70	1.55	16.16	1.528	2.74	1.24	0.52	5.38	1.528	1.49	0.73	0.28	3.20	1.528
2.5	22.24	5.01	2.26	11.60	1.888	7.42	1.59	1.40	7.15	1.888	4.31	1.92	0.82	5.00	1.888
3.0	28.27	4.60	5.36	20.01	2.016	9.97	3.24	1.89	8.43	2.016	6.00	5.85	1.14	10.04	2.016
3.5	38.49	5.19	7.45	22.55	2.120	12.83	3.43	2.43	8.92	2.120	8.63	6.56	2.04	11.37	2.120

Table V. Local Mach Number Uncertainty.

| M_O	REYNOLDS NUMBER ($\times 10^6$)					
	0.5		1.5		2.5	
	FLOAT REF	STD SYS	FLOAT REF	STD SYS	FLOAT REF	STD SYS
2.0	± 0.0063	± 0.0163	± 0.0021	± 0.0054	± 0.0012	± 0.0032
2.5	± 0.0088	± 0.0287	± 0.0042	± 0.0104	± 0.0028	± 0.0055
3.0	± 0.0142	± 0.0295	± 0.0056	± 0.0104	± 0.0059	± 0.0062
3.5	± 0.0183	± 0.0363	± 0.0067	± 0.0121	± 0.0072	± 0.0072
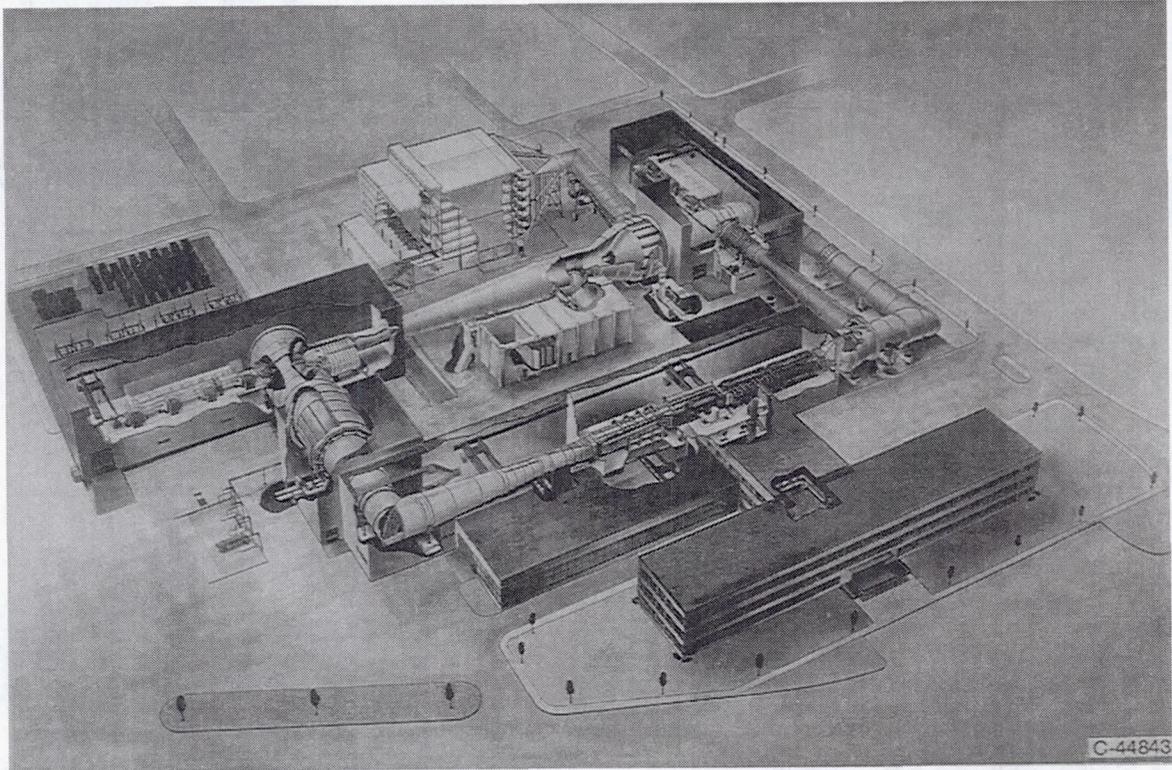
Figure 1.—10x10-ft Supersonic Wind Tunnel.
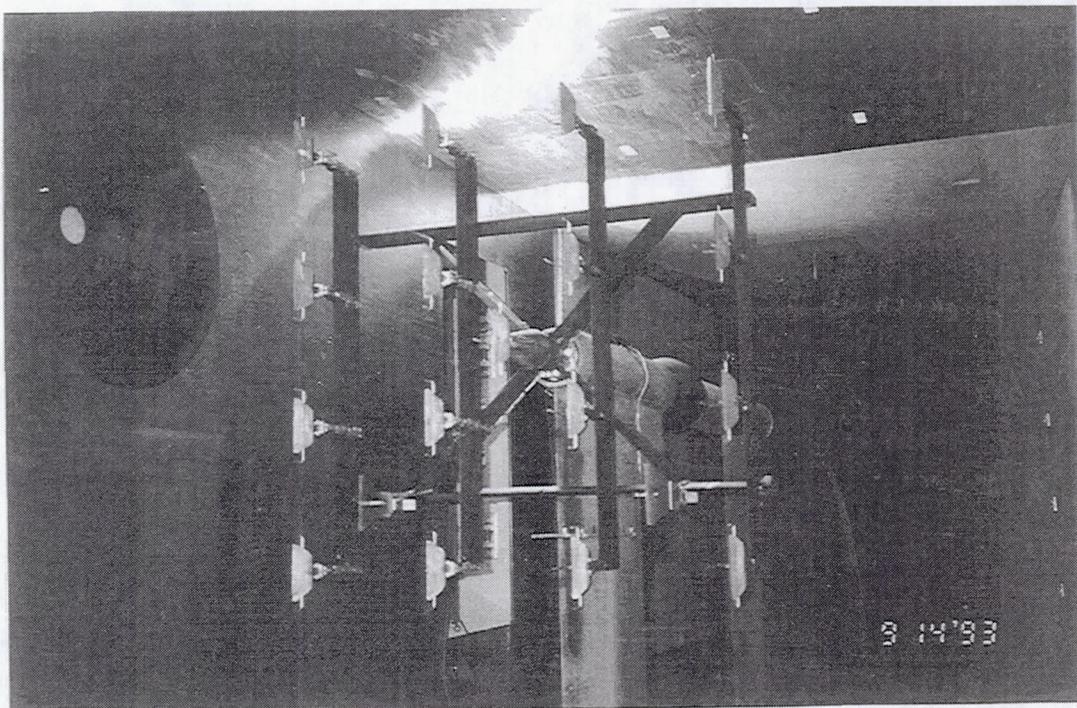
Figure 2.—Flow calibration survey rake.

Top total
(H_{1T})

Left static
(P_{2L})

Right static
(P_{SR})

Left oblique
(H_{2L})

Right oblique
(H_{2R})

See detail "A"

Oblique tubes

Detail "A"

Bottom total
(H_{1B})

Looking downstream
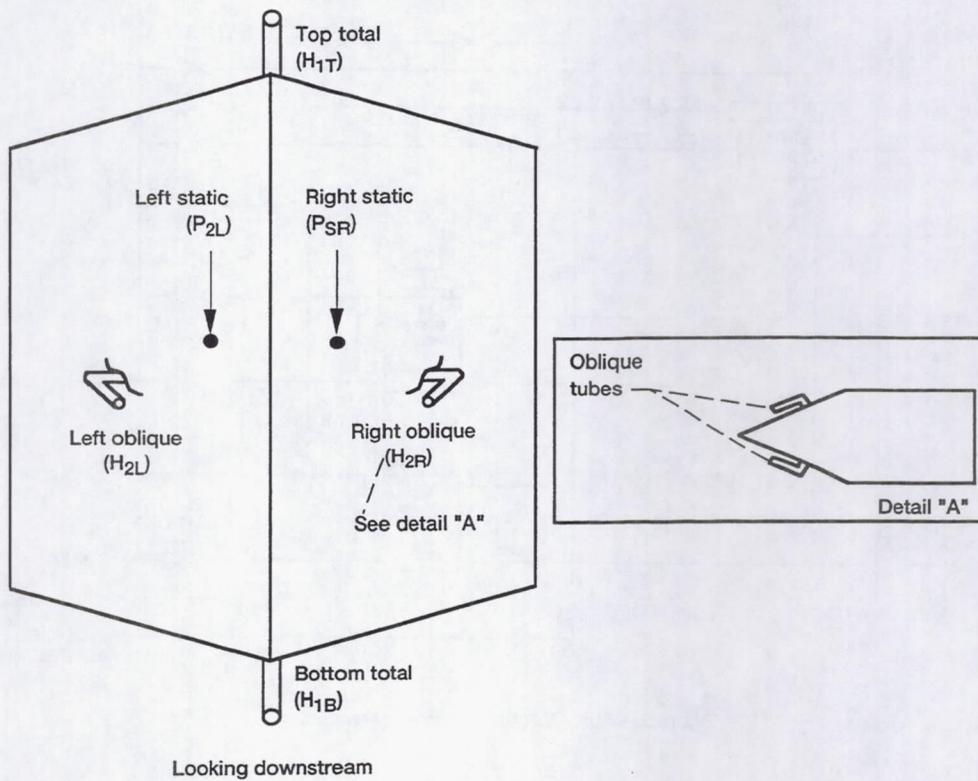
Figure 3.—Wedge instrumentation.
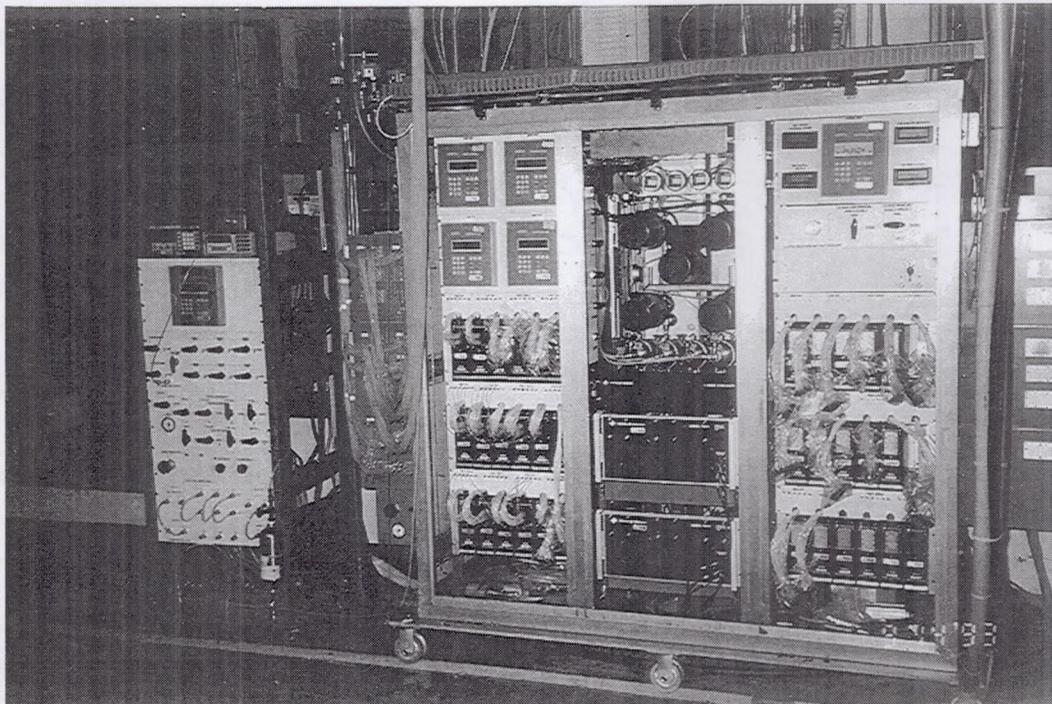
Figure 4.—Electronically scanned pressure system.

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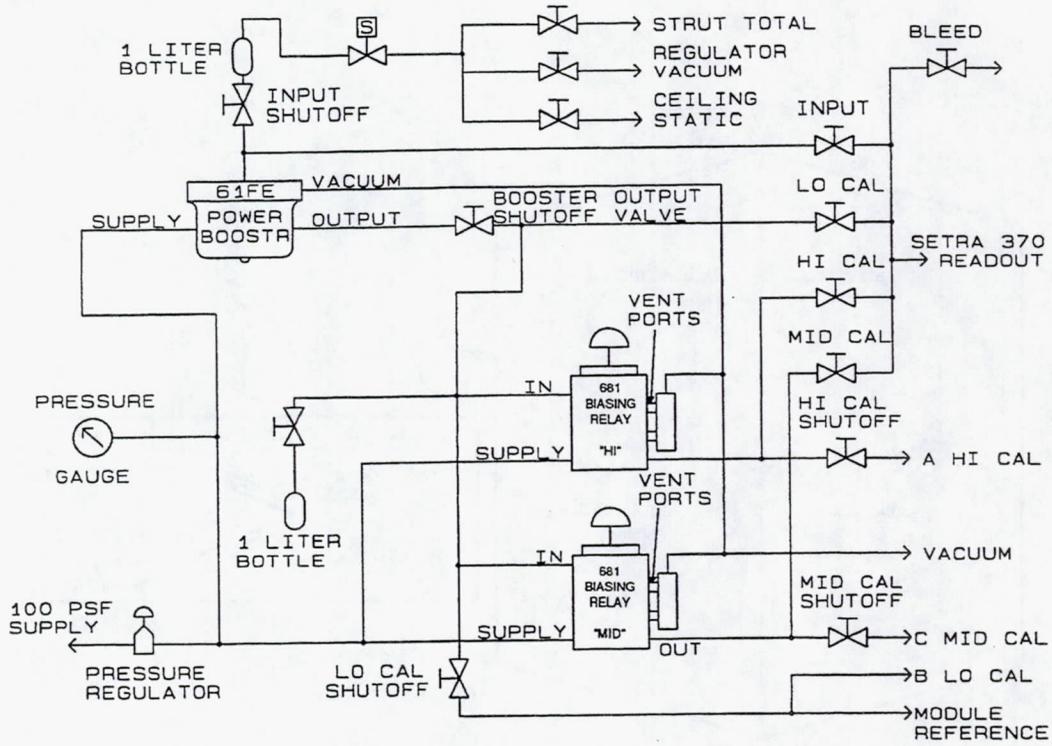
Figure 5.—Auto Cal supply panel schematic.
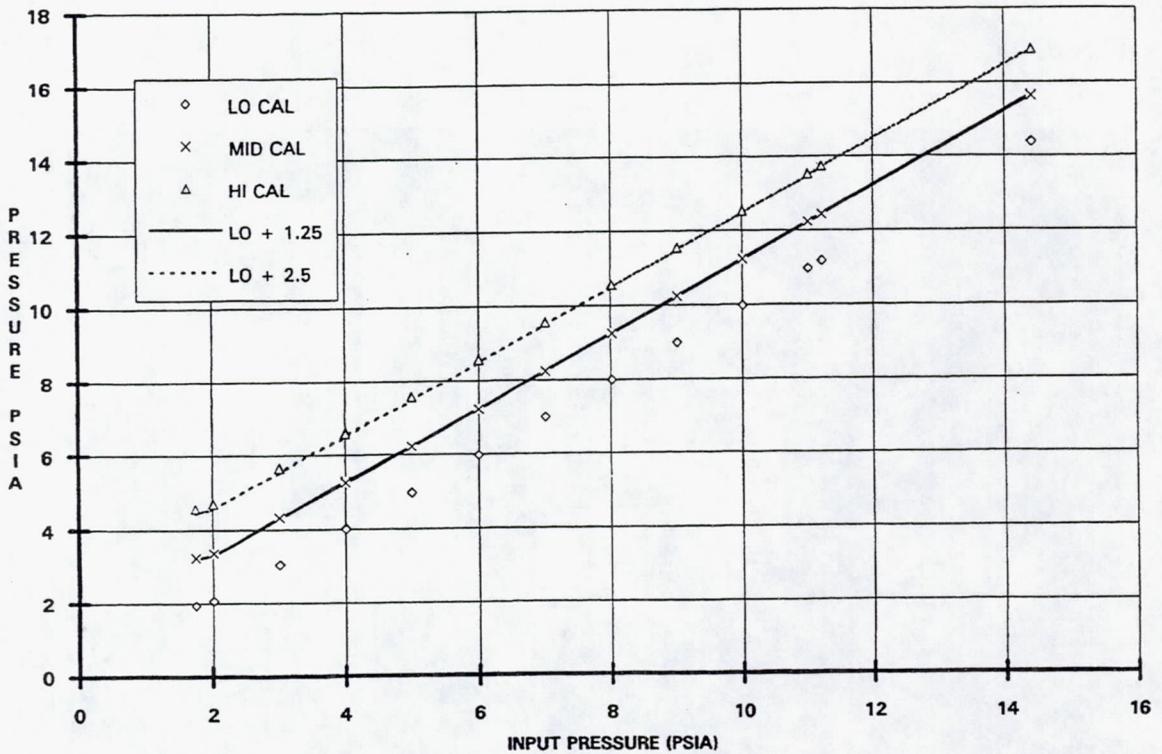
Figure 6.—Calibration of pressure generating system.

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Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

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Philip Z. Blumenthal and Stephen M. Helland

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Lewis Research Center
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13. ABSTRACT (Maximum 200 words)

This paper discusses a method used to provide a significant improvement in the accuracy of a Electronically Scanned Pressure (ESP) Measurement System by means of a fully automatic floating pressure generating system for the ESP calibration and reference pressures. This system was used to obtain test section Mach number and flow angularity measurements over the full envelope of test conditions for the 10x10 Supersonic Wind Tunnel. The uncertainty analysis and actual test data demonstrated that, for most test conditions, this method could reduce errors to about one-third to one-half that obtained with the standard system.

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