NASA Technical Memorandum 78707

A METHOD OF CALIBRATING WIND VELOCITY SENSORS WITH A MODIFIED GAS FLOW CALIBRATOR

(NASA-TM-78707) A METHOD OF CALIBRATING WIND VELOCITY SENSORS WITH A MODIFIED GAS FLOW CALIBRATOR (NASA) 20 p HC A02/MF A01 CSCL 14B N78-21426
Unclas
G3/35 12449

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APRIL 1978

MAY 1978
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National Aeronautics and Space Administration

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SUMMARY

This paper describes a procedure for calibrating air velocity sensors in the exhaust flow of a gas flow calibrator. The average air velocity in the test section located at the calibrator exhaust is verified from the mass flow rate accurately measured by the calibrator's precision sonic flow nozzle. Air at elevated pressures (7×10^5 to 4×10^6 newtons per square meter) flows through a series of screens, diameter changes, and flow straighteners, resulting in a smooth flow through the open test section. The modified system generates air velocities of 2 to 90 meters per second with an uncertainty of about 2 percent for speeds below 15 meters per second and 4 percent for the higher speeds. Wind tunnel data correlated well with that taken in the flow calibrator.

INTRODUCTION

An important part of Langley's aeronautical research program includes studies to determine stall characteristics of high-speed aircraft models. Instrumented models, including those of the F-4, F-14, F-15, and B-1, are dropped from helicopters at altitudes of 1600 meters and, during descent, are maneuvered into stall conditions. On-board sensor and recording instrumentation is used to measure the pertinent flight parameters of which airspeed is one of the most essential. Airspeed is measured with fan-type velocity sensors developed by Langley's flight instrumentation engineers to cover the speed range 2 to 90 meters per second.

For accurate on-board measurements, however, it was necessary to verify sensor performance through calibration. Since no velocity calibration standard was available at Langley, an existing gas flow calibrator was modified for this work. The modification, which was in accordance with established flowmetering principles of the American Society of Mechanical Engineers (ASME, ref. 1) and the American Gas Association (AGA, ref. 2), consisted of attaching appropriately sized test sections to the discharge of the calibrator so that the sensors could be placed in the flow stream near the exit. Here the air velocity can be related to the mass flow rate as determined by the gas flow calibrator. The standard used to determine the mass flow rate in the calibrator was a precision sonic flow nozzle. This nozzle was installed such that it discharged into the plenum chamber through a pipe section which increased in diameter in three steps for aiding in the smooth, even distribution of air flowing into the test section. As a cross check on the accuracy of the velocity determined from the calibrator's mass flow rate, independent test section velocity measurements and velocity profiles were obtained by means of a Pitot-static probe which was traversed across the test section.

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As an additional test on the validity of this calibration technique, several velocity sensors calibrated in the manner described above were also calibrated in a 7- x 10-foot low-speed wind tunnel. The wind tunnel results showed good agreement with those obtained in the modified gas flow calibrator.

APPARATUS

Gas Flow Calibrator

The gas flow calibrator used was the Cox model 610 which includes an instrument and control console for controlling the flow rate, and a wind tunnel-like plenum chamber containing a precision subsonic flow nozzle for measuring the flow rate. This calibrator produces mass flow rates that are known to within 0.75 percent. For these tests, the plenum chamber nozzle was removed to aid the smooth even flow of air through the plenum and a sonic nozzle was installed near the entrance. This simplified the measurement technique in that only upstream nozzle pressure and temperature measurements were required to determine the mass flow rate which remained the same (law of continuity) throughout the flow system, including the plenum discharge where the velocity measurements were made. Also, the mass flow rate is more easily controlled and remains stable through a sonic nozzle once steady-state conditions of pressure and temperature are reached. For valid velocity measurement comparisons, it was necessary to hold the mass flow rate constant while the Pitot-static probe traverses were made.

Sonic Flow Nozzle

The sonic flow nozzle (fig. 1) used to determine the mass flow rate was the bellmouth converging-diverging type with a throat diameter of 10.14 millimeters. NASA Technical Note D-2565 (ref. 4) entitled "Real-Gas Effects in Critical-Flow-Through Nozzles and Tabulated Thermodynamic Properties," was used for calculating the mass flow rate through this nozzle.

Velocity Test Section

The velocity test sections (fig. 2) were designed such that they could be bolted to the discharge of the gas flow calibrator plenum chamber. They consisted of three round aluminum ducts nominally 10, 15, and 25 centimeters (cm) in diameter. To minimize turbulence, a flow straightener (refs. 1 and 2) was designed and installed at the entrance of the attached test section. Pressure and temperature taps and Pitot-static probe connections (ref. 1) were also installed in each test section. At the maximum flow rate of the gas flow calibrator (900 grams per second), the maximum velocities in the three test sections nominally 10, 15, and 25 cm) are 90, 40, and 15 meters per second, respectively.

Velocity Sensors

The velocity sensors (fig. 3) are the fan-anemometer type in which a small propeller is mounted on the shaft of a precision dc generator. The generator output voltage is proportional to the rotational speed of the propeller, which in turn is proportional to the air velocity moving through the propeller blades. In tests, these sensors are sting mounted on the nose of the various aircraft drop models for the determination of model speed.

THEORY OF OPERATION

Calibration of the Test Section

A Pitot-static probe was installed in a track-mounted vise beside the outlet of the 25-cm test section (fig. 4) such that it could be moved horizontally across the outlet in a smooth motion. A scale was installed parallel to the track to facilitate the positioning of the Pitot-static probe at repeatable settings when traversing the test section. Eleven measurement points were taken across the traverse span.

The measurement technique was to set the flow calibrator to some predetermined value and then run a Pitot-static probe traverse. At each measurement point the pressure and temperature associated with the flow calibrator were observed and recorded, making sure the flow rate had not changed. Simultaneously, the differential pressure associated with the Pitot-static probe was observed and recorded.

The test section velocity was then calculated two ways. The velocity determined from the calibrator's measured mass flow rate was

$$V_s = \frac{\dot{M}}{A\rho_s} \tag{1}$$

The velocity determined by the Pitot-static probe measurements was

$$V_s = \sqrt{\frac{2\Delta p}{\rho_s}} \tag{2}$$

In both equations the airspeed was corrected to one atmosphere and 288 K.

The symbol definitions are:

V_s velocity at 1 atmosphere and 288 K, meters/second

$\dot{M}$ mass flow rate, grams/second

A area of test section, meter^2

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ρ_s air density 1225 grams/meter^3 at 1 atmosphere and 288 K (ref. 5)

Δp differential pressure, newtons/meter^2

Sample Calculation

The first calibration point taken was at a mass flow rate of 144.401 g/sec and an average differential pressure of 3.67 n/m^2. The test section diameter was 0.2475 meters. Inserting these values in equations (1) and (2), the velocities based on the measured mass flow and the average Pitot-static Δp were, respectively,

$$V_s = \frac{\dot{M}}{A_s} = \frac{144.401}{\frac{\pi(0.2475)^2}{4} 1225} = 2.450 \text{ m/sec}$$

and

$$V_s = \sqrt{\frac{2\Delta p}{\rho_s}} = \sqrt{\frac{(2)\ (3.67)}{1.225}}$$

$$= \sqrt{5.99} = 2.44 \text{ m/sec}$$

Interference Effects Caused by the Velocity Sensor

It was necessary to determine if adverse effects such as a change in profile or airspeed would occur when the velocity sensor was placed in the test section outlet. For this purpose, an additional Pitot-static-probe traverse was made with the velocity sensor in place. The mounting attachment used for holding the sensor during calibration was designed such that the sensor could be moved horizontally along a 90-cm track parallel to the test section. Mechanical stops were installed at each end of the track and the sensor sting was alined such that in the test position, the sensor would be located at the center of the test section, with its leading edge 6 mm from the back edge of the Pitot-static probe. With steady-state flow conditions a Pitot-static probe traverse was made with and without the velocity sensor located in the airstream. Twenty-two traverses, each including 11 data points, were made covering the velocity range of 2 to 13 meters per second (242 data points). However, in comparing the Pitot-static probe velocity with the flow calibrator velocity, the Pitot-static probe velocities were averaged according to Spink (ref. 6) as follows:

$$\text{Average velocity} = \frac{V_1 + V_2 + V_3 \cdots}{n}$$

Tabulated results are given in table 1.

Pressure Measurements

The upstream nozzle pressure was measured with a Heise bourdon tube pressure gage having an uncertainty of 0.1 percent of reading. The static pressure in the test section was measured with a Meriam 15-cm inclined water manometer.

The differential pressure (ΔP) across the Pitot-static probe was measured with an MKS Baratron pressure system employing a capacitance-type sensor and having a full scale range of 400 n/m^2, a resolution of 0.13 n/m^2, and an uncertainty of 0.2 percent of reading.

Temperature Measurements

Temperature was measured with a bare probe iron-constantan thermocouple having an uncertainty of $\pm$ 0.5 percent of reading and recorded on a strip chart recorder.

RESULTS AND DISCUSSION

Data Analysis

The 25-cm test section was the first to be attached to the flow calibrator. All the tests for the evaluation of this calibration technique were performed with this test section and the results (table 1) include the following:

1. The velocity determined from the flow calibrator mass flow measurements (sonic nozzle)

2. The average velocity as determined by Pitot-static probe measurements without the sensor in the airstream

3. The average velocity as determined by Pitot-static probe measurements with the sensor in the airstream

The difference between the flow calibrator value and the unobstructed average Pitot-static probe value was 0.81 percent.

The difference caused by placing the sensor in the airstream was approximately 2 percent (worst case) in the center of the test section. The average velocity with the sensor in the airstream, and with it out, differed by 0.70 percent. However, since the velocity was high in the center of the test section, where the sensors were tested, they were subjected to slightly higher velocities than that calculated from the mass flow rate. As a result of these tests, it was concluded that velocities generated in the 25-cm test section could be determined from the mass flow rate measurement with an uncertainty of no greater than 2 percent.

Tunnel Calibrations

As a cross check on the gas flow calibrator technique, two low-speed velocity sensors were calibrated in a 7- x 10-foot low-speed wind tunnel. Figures 6 and 7 are plots showing the results of these calibrations and also the calibrations performed on the gas flow calibrator. As can be seen, there is close agreement between the two independent calibrations. The test values are given in table 2.

The 10-cm and 15-cm test sections were calibrated by using six velocity sensors as transfer standards between the gas flow calibrator and the 7- x 10-foot, low-speed wind tunnel. While the accuracy of this tunnel is not precisely known, tunnel engineers feel it is approximately 2 to 3 percent. Data was taken at two points, 13 and 40 m/sec. The same calibration technique as previously described for the gas flow calibrator was used, except that no Pitot-static probe measurements were made.

The sensors were first tested on the gas flow calibrator (fig. 8) at the two predetermined airspeeds and subsequently tested in the 7- x 10-foot tunnel. These airspeeds were selected to suit the tunnel speed capabilities. Forty m/sec was the top speed of the 7- x 10-foot low-speed wind tunnel. However, these sensors have a full scale range of 90 m/sec and were tested to this speed on the gas flow calibrator. Table 3 shows the results of these tests. It is felt that the larger errors at the high airspeeds were due to the effects of different velocity profiles on the sensor output and on the pressure measurements. The sensor output was averaged over 10-second intervals because of the more unstable airflows at the higher velocities.

CONCLUDING REMARKS

The discharge portion of a gas flow calibrator was modified to accommodate 25-, 15-, and 10-cm diameter test sections to permit calibration of fan-type velocity sensors over the range 2 to 90 m/sec. The Pitot-static velocity measurements in the test sections were verified by (1) those determined from precise mass flow rate measurements made with the flow calibration standard sonic nozzle upstream of the test section and (2) those obtained from calibrations performed in a 7- x 10-foot wind tunnel with several sensors used as transfer standards. Results showed that, by observing the ASME and AGA standards for maintaining smooth flow characteristics, velocity sensors could be calibrated in the modified gas flow calibrator with an uncertainty of 2.0 percent at air speeds to 15 m/sec and 4 percent at airspeeds to 90 m/sec.

REFERENCES

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2. American Gas Association - Orifice Metering of Natural Gas; Gas Committee Report No. 3, 1955.

3. Johnson, R. C.: Real-Gas Effects in Critical-Flow-Through Nozzles and Tabulated Thermodynamic Properties. NASA Technical Note D-2565.

4. U.S. Standard Atmospheres, 1962 Edition.

5. Spink, L. K.: Principles and Practice of Flow Meter Engineering. Ninth Edition, 1967.

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TABLE 1 Tabulated values of velocity in a 25-centimeter-diameter test section at the following conditions.

(A) The velocity based on the mass flow rate determined by a sonic nozzle located upstream of the test section.

(B) The velocity based on averaged Pitot-static probe measurements with no test sensor in the air-stream.

(C) The velocity based on averaged Pitot-static probe measurements with a test sensor located in the air-stream.

VELOCITY (m/s)			DIFFERENCE IN PERCENT	
(A)	(B)	(C)	A & B	B & C
2.451	2.440	2.411	0.40	0.46
3.355	3.313	3.293	1.25	0.60
4.388	4.417	4.385	0.66	0.72
5.217	5.254	5.212	0.70	0.80
6.228	6.244	6.204	0.26	0.64
7.094	7.101	7.044	0.10	0.80
7.821	7.800	7.702	0.27	1.26
9.045	8.978	8.940	0.74	0.42
10.062	9.920	9.860	1.41	0.60
10.990	10.851	10.792	1.26	0.54
13.323	13.082	12.967	1.81	0.88
		AVG % DIFF	0.81	0.70

TABLE 2 - Tabulated values of sensor output versus air-speed for 2 anemometer type velocity sensors.

SERIAL NO.	7 X 10 TUNNEL		GAS CALIBRATOR	
	VELOCITY (m/s)	OUTPUT (mv)	VELOCITY (m/s)	OUTPUT (mv)
FDV-2-2	3.130	82.11	2.394	56.698
	4.608	128.15	3.315	92.941
	6.261	174.17	4.251	120.432
	7.774	214.64	5.121	146.344
	9.391	262.57	6.027	172.510
	10.919	307.77	6.957	198.920
			7.900	223.347
			8.775	248.985
			9.692	274.088
			10.591	301.030
FDV-3-2	3.130	72.03	2.411	44.971
	4.608	112.33	3.321	75.358
	6.261	158.11	4.227	101.797
	7.774	198.92	5.145	127.062
	9.391	242.09	5.998	152.658
	10.919	282.83	6.946	178.054
			7.896	202.342
			8.779	226.915
			9.692	250.303
			10.591	274.600

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TABLE 3 - Calibration results of 6 fan-type velocity sensors tested in a 7X10-foot low-speed wind tunnel and on a modified gas flow calibrator.

SENSOR (S/N)	SENSOR OUTPUT (mv)			
	13 m/s		40 m/s	
	GAS CAL.	7X10	GAS CAL.	7X10
1-4	156	156	707	712
2-4	170	173	693	717
4-4	164	169	666	686
5-4	159	154	667	705
6-4	130	135	669	676
9-4	168	172	696	706

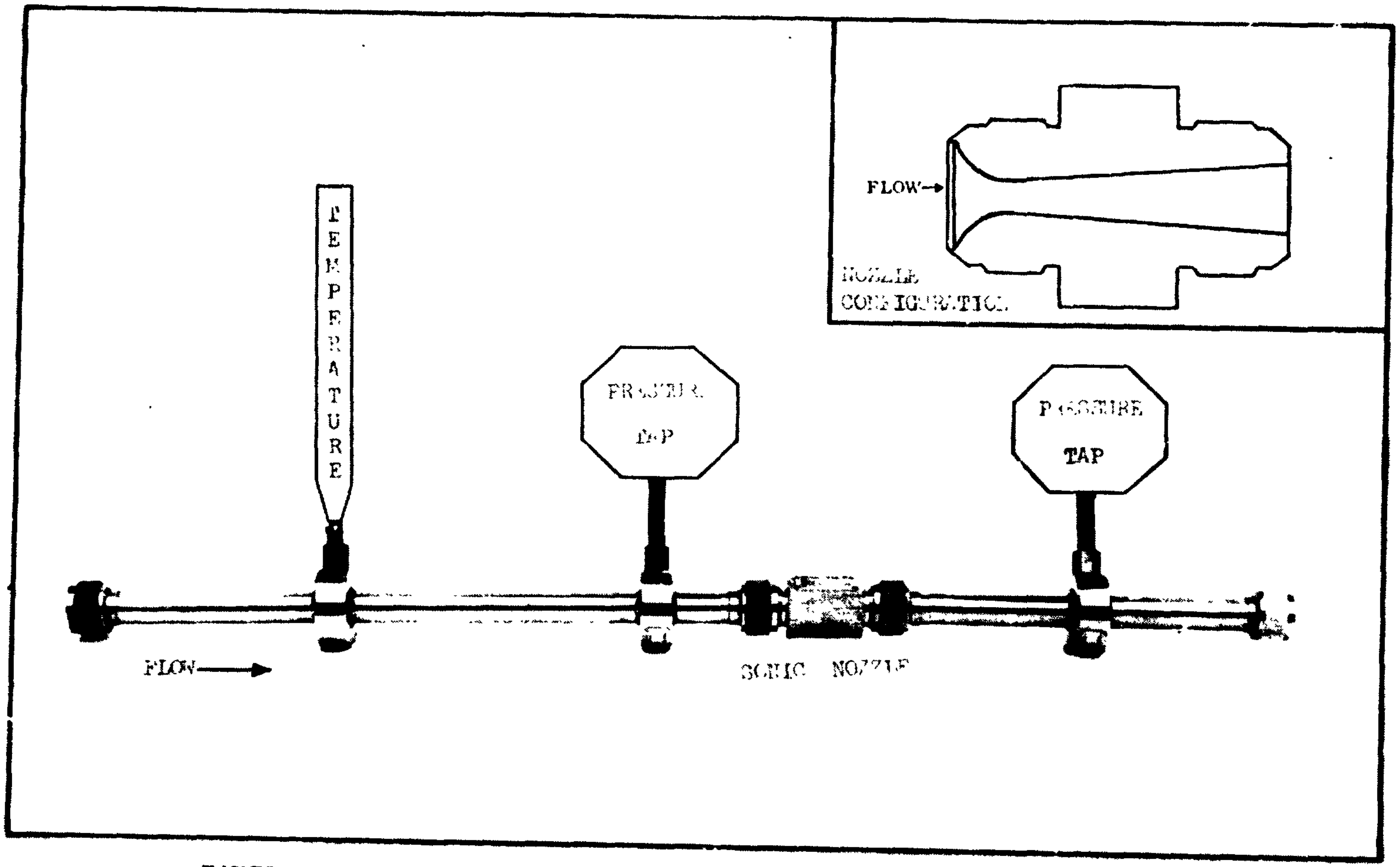

FIGURE 1 - Sonic flow nozzle used for determining test section velocities on a modified gas flow calibrator.

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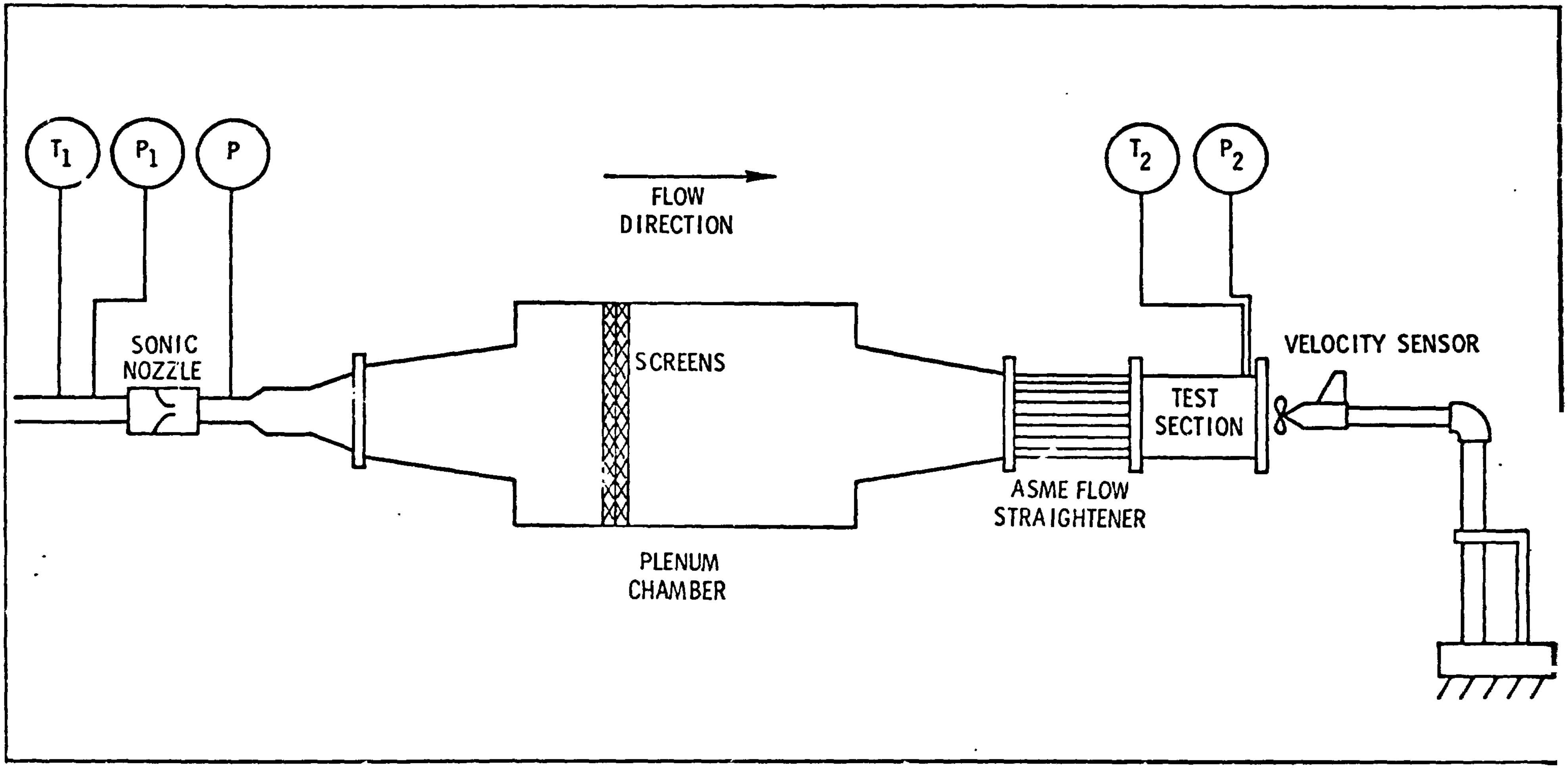

FIGURE 2 Diagram of the test set-up used for calibrating velocity sensors. Under actual test conditions, velocity sensor propeller projected approximately 10mm into the test section exit.

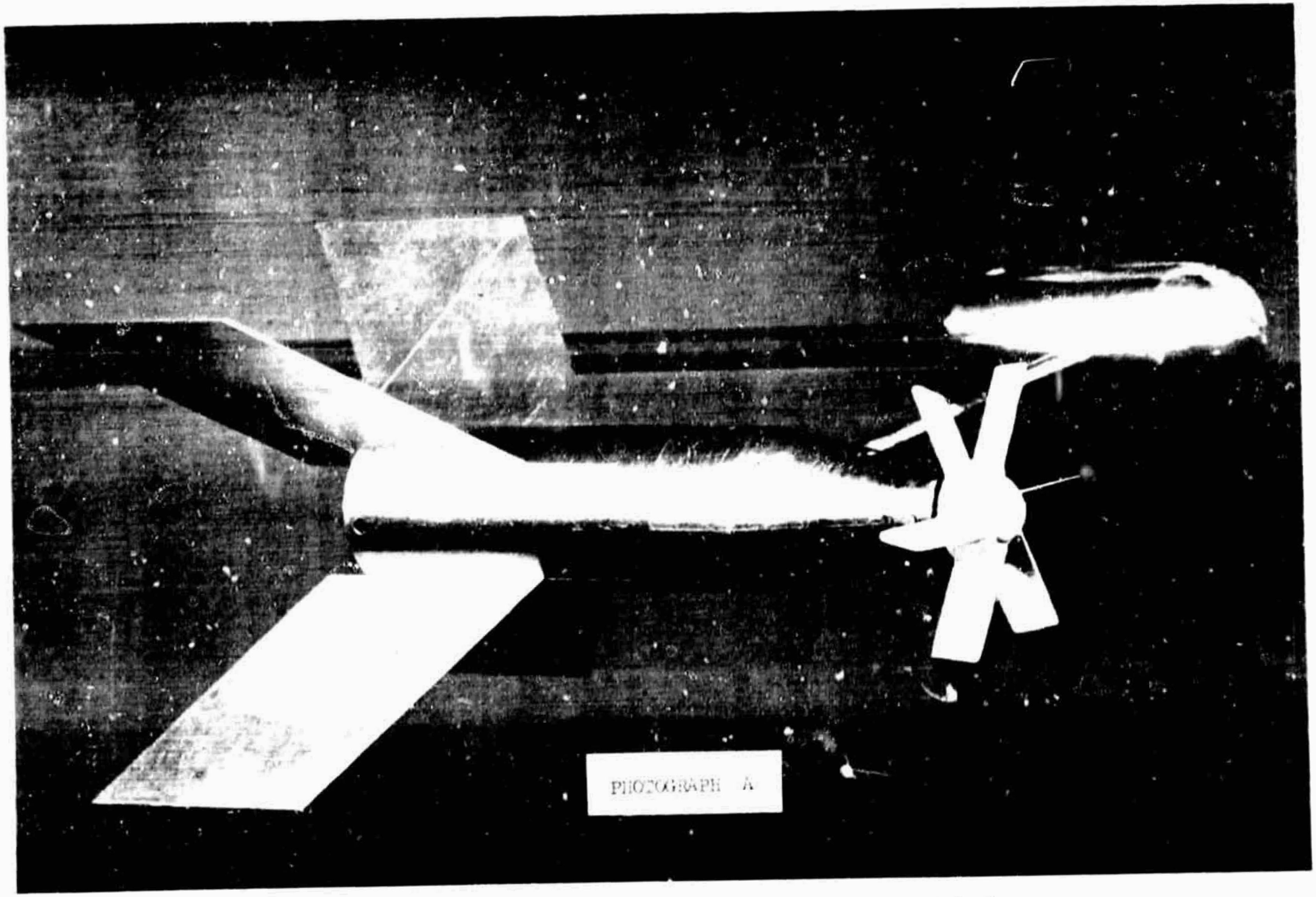

FIGURE 3   Fan type anemometers used as velocity sensors in aircraft model drop tests.

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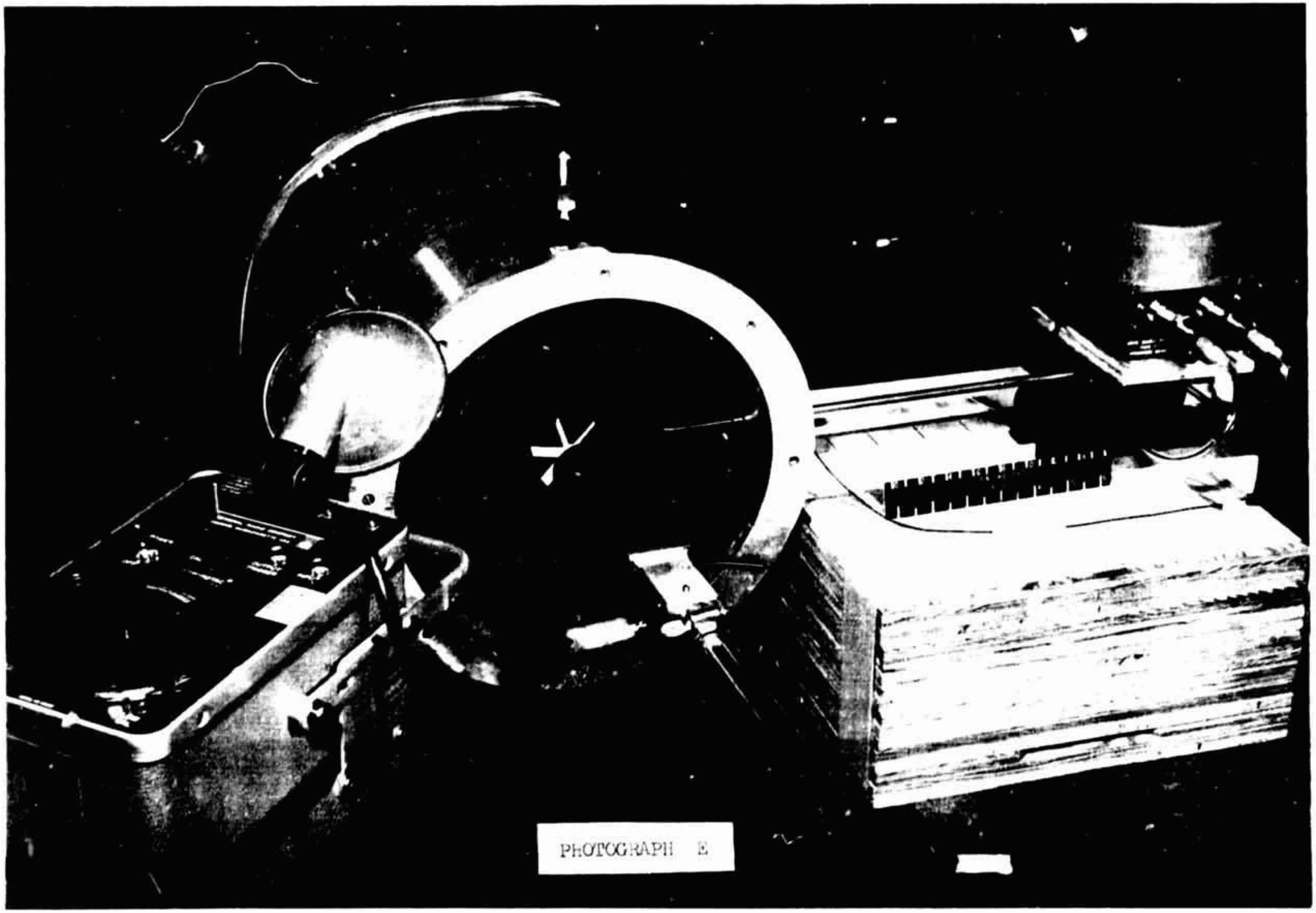

FIGURE 4 Velocity test section (25cm in diameter) used for calibrating velocity sensors.

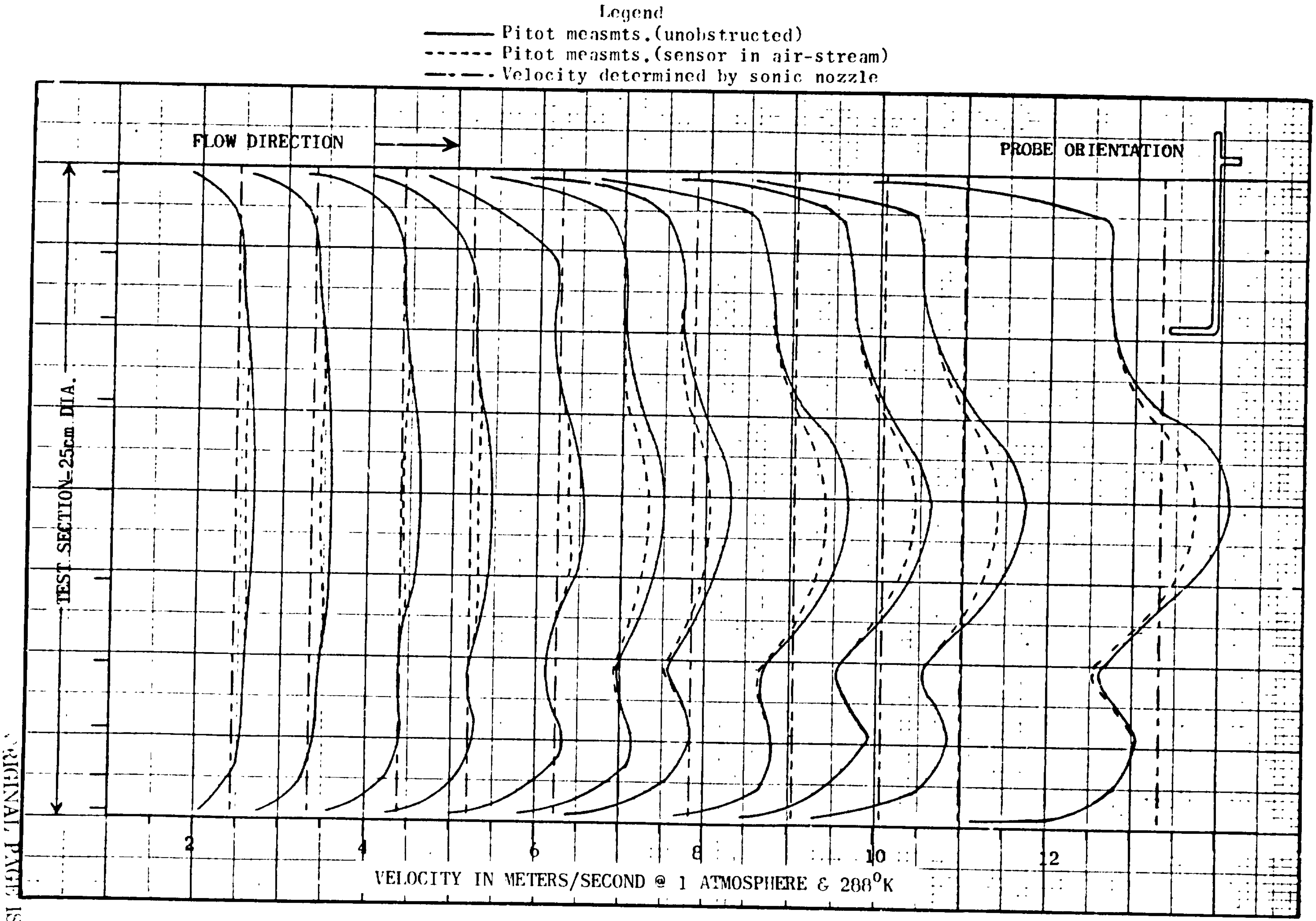

FIGURE 5 VELOCITY PROFILES IN A 25 CENTIMETER DIAMETER TEST SECTION.

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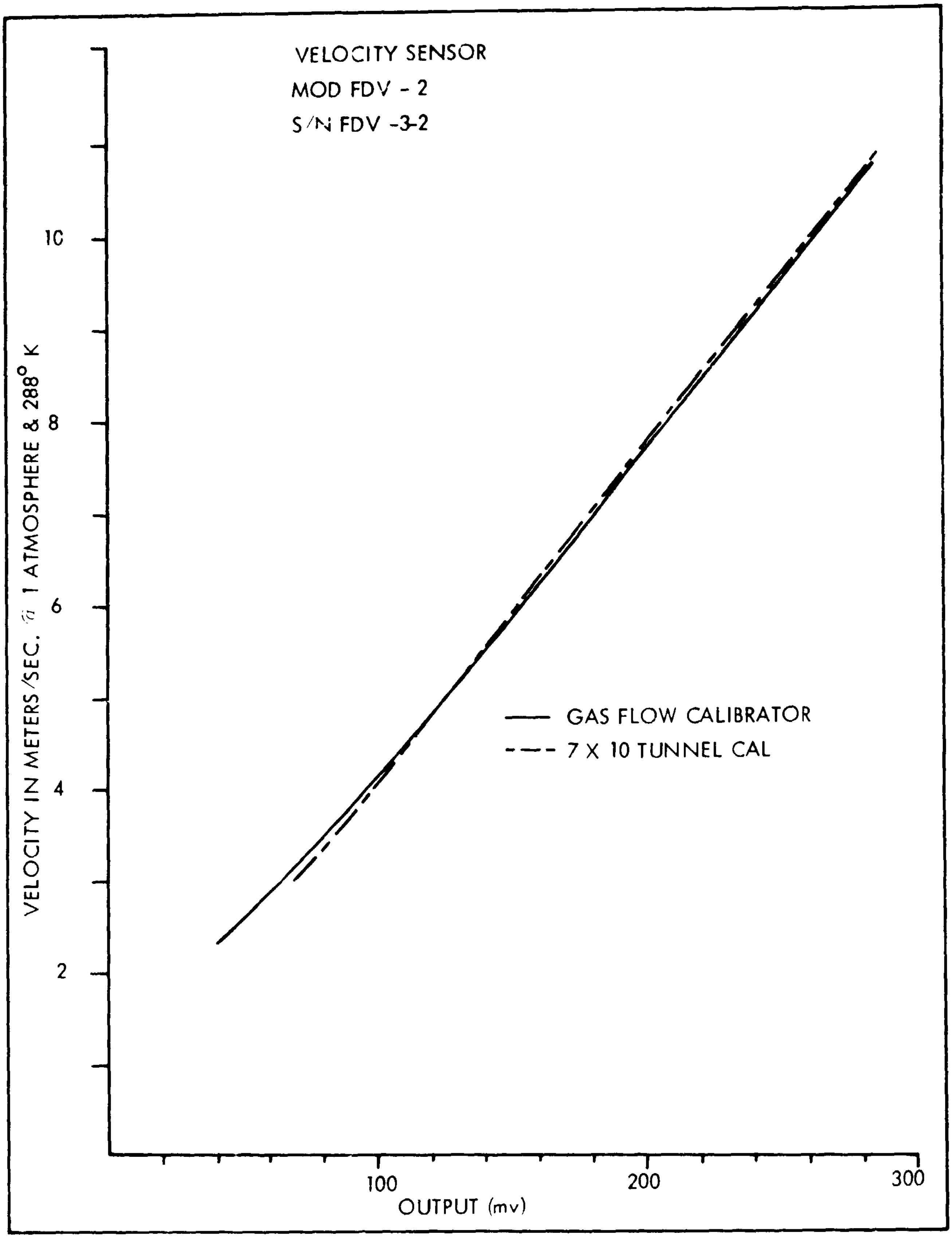

FIGURE 6 Comparision of tunnel data with that taken on a modified gas flow calibrator.

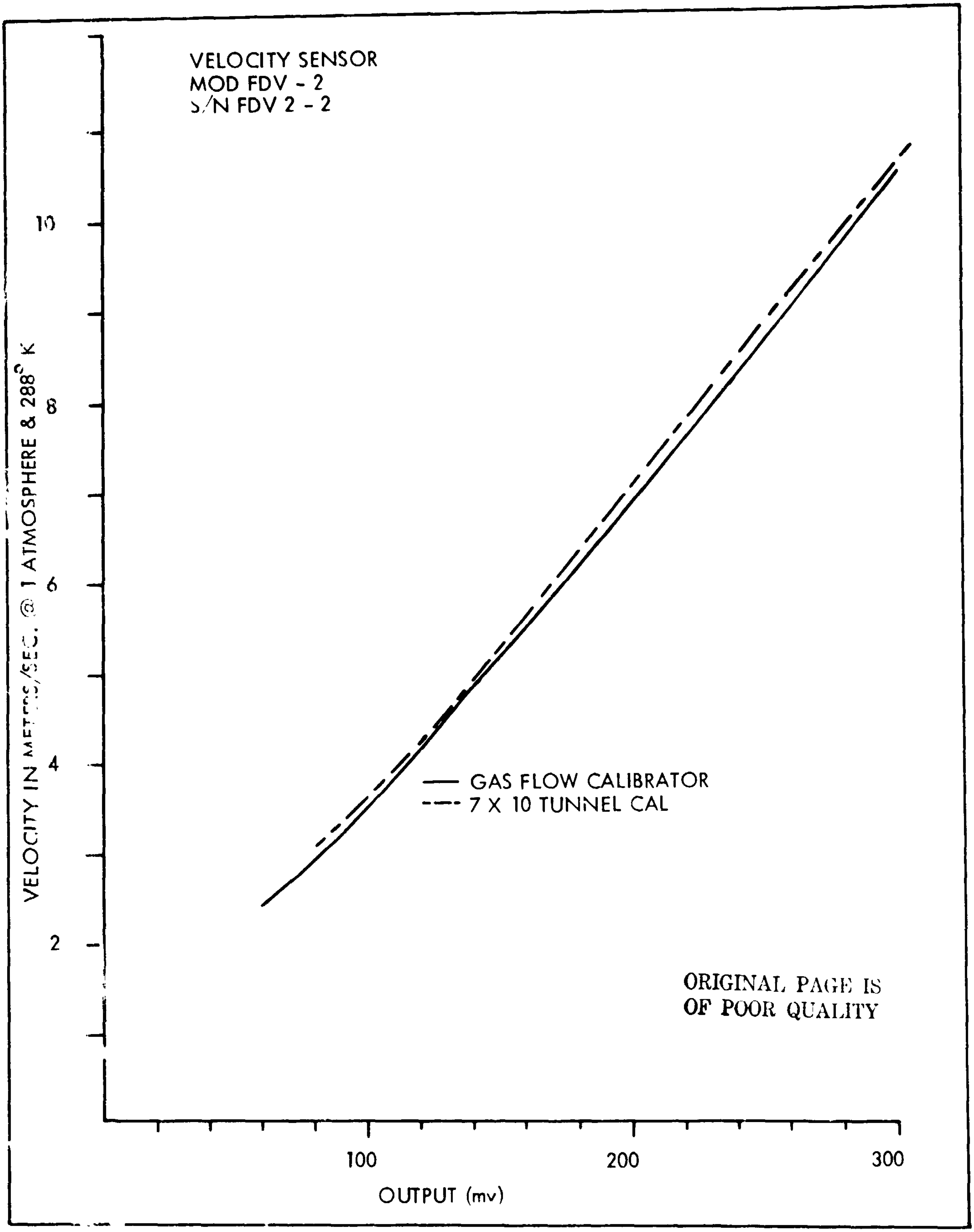

FIGURE 7 Comparison of tunnel data with that taken on a modified gas flow calibrator.

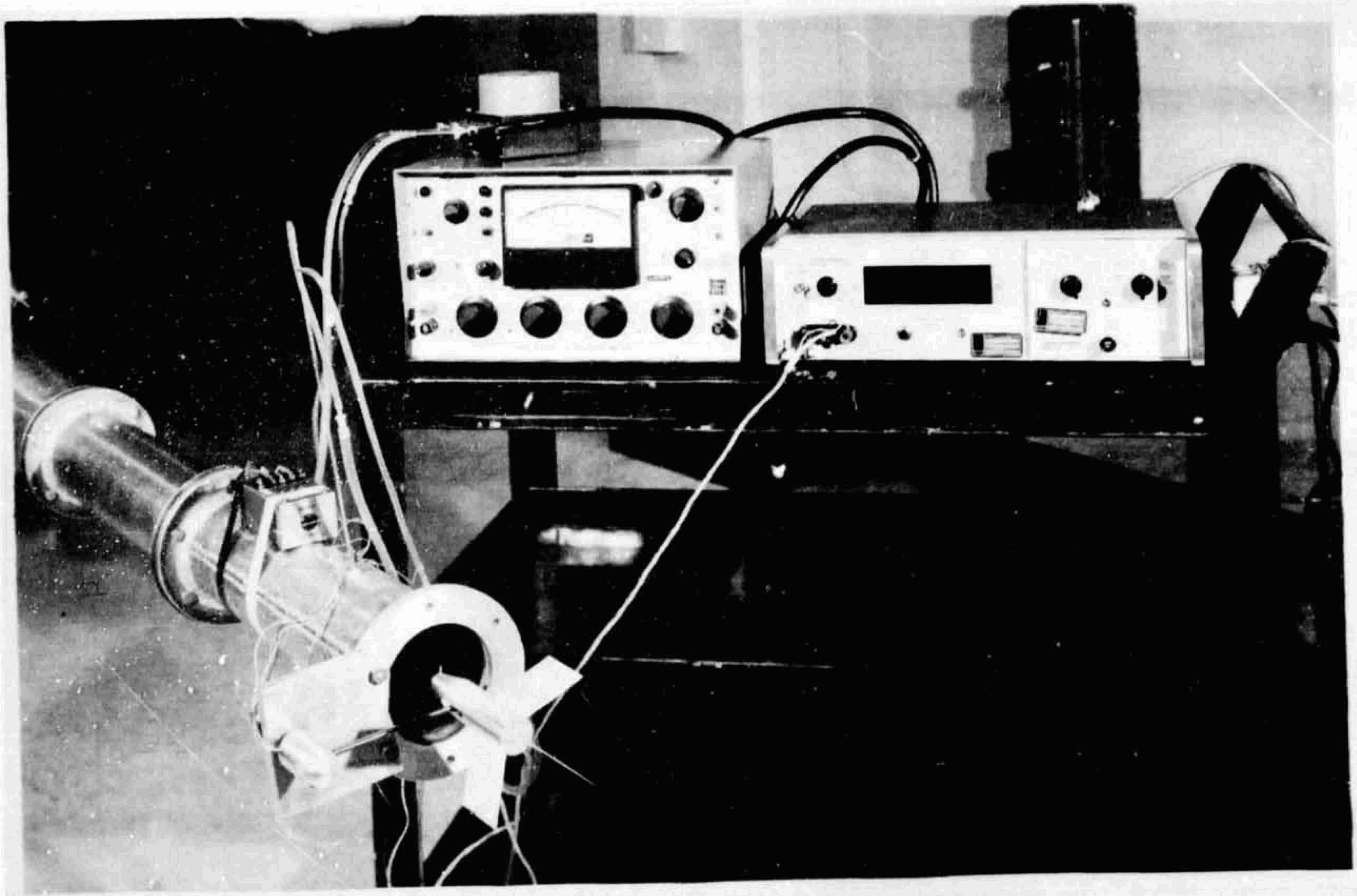

FIGURE 8 Velocity sensor being tested up to 90 meters/second in a 10 centimeter diameter test section.

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1. Report No. NASA TM 78707	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A METHOD OF CALIBRATING WIND VELOCITY SENSORS WITH A MODIFIED GAS FLOW CALIBRATOR		5. Report Date April 1978
		6. Performing Organization Code 1275
7. Author(s) Hampton P. Stump		8. Performing Organization Report No.
		10. Work Unit No. 992-19-00-18
9. Performing Organization Name and Address Langley Research Center Hampton, VA 23665		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A procedure is described for calibrating air velocity sensors in the exhaust flow of a gas flow calibrator. The average air velocity in the test section located at the calibrator exhaust is verified from the mass flow rate accurately measured by the calibrator's precision sonic nozzles. Air at elevated pressures (7×10^5 to 4×10^6 newtons per square meter) flows through a series of screens, diameter changes, and flow straighteners, resulting in a smooth flow through the open test section. The modified system generates air velocities of 2 to 90 meters per second with an uncertainty of about 2 percent for speeds below 15 meters per second and 4 percent for the higher speeds. Wind tunnel data correlated well with that taken in the flow calibrator.

17. Key Words (Suggested by Author(s)) Flow, Calibration, Wind Sensor, Flow Nozzle, Velocity Measurement	18. Distribution Statement Unclassified Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	17	$4.00

* For sale by the National Technical Information Service, Springfield, Virginia 22161