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DEVELOPMENT OF A THREE-AXIS FLUIDIC AIRSPEED SENSOR

FINAL REPORT

R-08-15-72

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by

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August 1972

Prepared under Contract NAS1-11266 by

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for

NASA/LANGLEY RESEARCH CENTER
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The system is adapted to aircraft and requires only the standard aircraft 28V dc supply to function.

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FOREWORD

This report presents the work performed under Contract NAS1-11266 by the Bowles Fluidics Corporation, Silver Spring, Maryland, during the period 15 December 1971 through 15 July 1972. The work was accomplished under the direction of Mr. Milton Skolaut of the NASA Langley Research Center.

ABSTRACT

A three axis fluidic airspeed sensor system has been fabricated and wind tunnel tested. The complete system consists of the fluidic sensor, air power supply and instrumentation and readout.

The system is adapted to aircraft and requires only the standard aircraft 28V dc supply to function.

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LIST OF FIGURES

SECTION 1.0

INTRODUCTION

In a previous NASA-sponsored program, a basic study was performed to demonstrate the feasibility of applying no moving part fluidic techniques to the problem of low speed airspeed measurement (Ref. 1) for VSTOL and helicopter applications.

During the course of that work, two techniques were investigated. These having been termed the "parallel flow" and "cross flow" techniques. The parallel flow technique was found to offer advantages in the areas of velocity range and air power consumption, and it was, therefore, selected as the model to be built for a flight test model (Ref. 2). The subsequent effort was aimed at providing a single axis sensor, but it was immediately obvious that for such a sensor to be useful it must have a well-defined output signal variation with angle of incidence with the wind. Thus, a secondary objective of the program was to configure the external geometry of the sensor to provide a cosinusoidal variation of the output pressure signal with varying wind direction. At the conclusion of that program, this goal was only partially met.

Meanwhile, with an interest in meteorological applications, the Navy sponsored the development of a two-axis system with the capability of measuring both wind speed and direction. The first part of a two-part program had as its prime objective the achieving of a cosinusoidal variation in output signal with wind direction (Ref. 3). The configuration which was developed in that program has been incorporated into the three axis system reported herein.

The three axis sensor is adapted to boom mounting, contains all the manifolding necessary for pneumatic input supply and output signals and is deiced. The deicing is relatively easy since there are no moving mechanical parts. Ancillary equipment consists of an air compressor, pressure regulator, relief valve, and an instrumentation package. The instrumentation package has provision for pneumatic outputs, electrical outputs and also three panel meters for forward, vertical, and sideslip velocities. The complete system has been wind tunnel calibrated over the velocity range $-41.2 \leq V \leq 41.2$ m/sec ($-80 \leq V \leq 80$ kts), with the panel meters being calibrated in knots.

SECTION 2.0

PRINCIPLE OF OPERATION OF THE PARALLEL FLOW SENSOR

The operating principle of the parallel flow sensor may be likened to a wheatstone bridge, wherein bridge unbalance is the result of the different viscous dissipations of a jet blowing into a wind and jet blowing with the wind. The physical arrangement is shown in Figure 1.

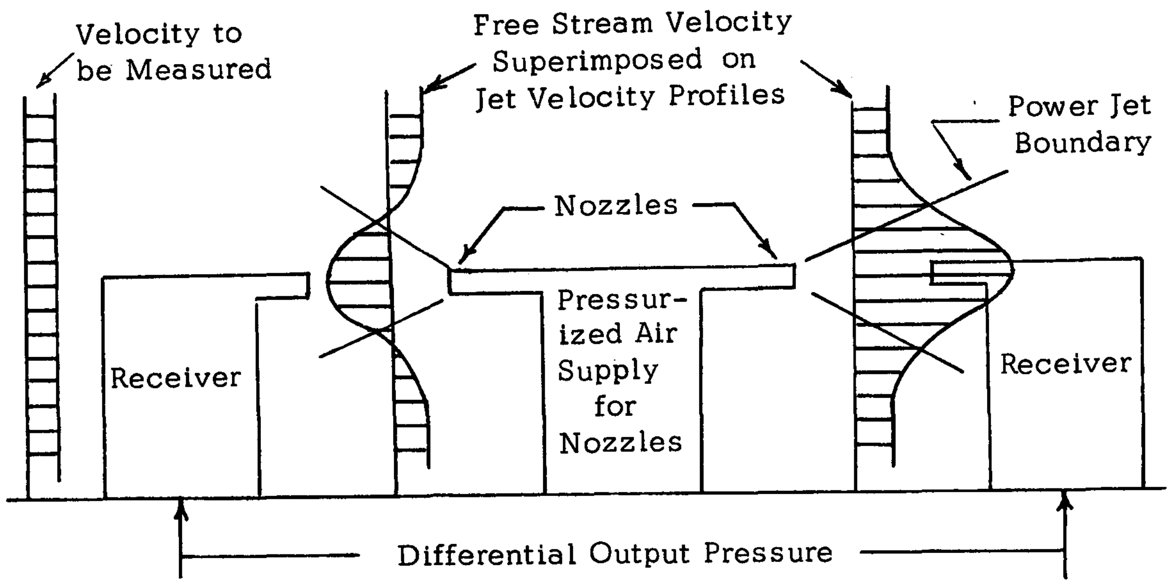


FIG. 1. PARALLEL FLOW SENSOR CONFIGURATION

Flow entering the power supply nozzle divides evenly between the two nozzles mounted on a common centerline. Separated from these nozzles at a fixed distance along the same centerline are two signal pressure receivers. By virtue of the difference in jet mixing of the power jet into and the power jet with the wind, a differential pressure is obtained.

This superposition of a high velocity (provided by the power jets) upon the low velocity flow to be measured has the effect of measuring a change in velocity at a level where a pitot tube has high sensitivity.

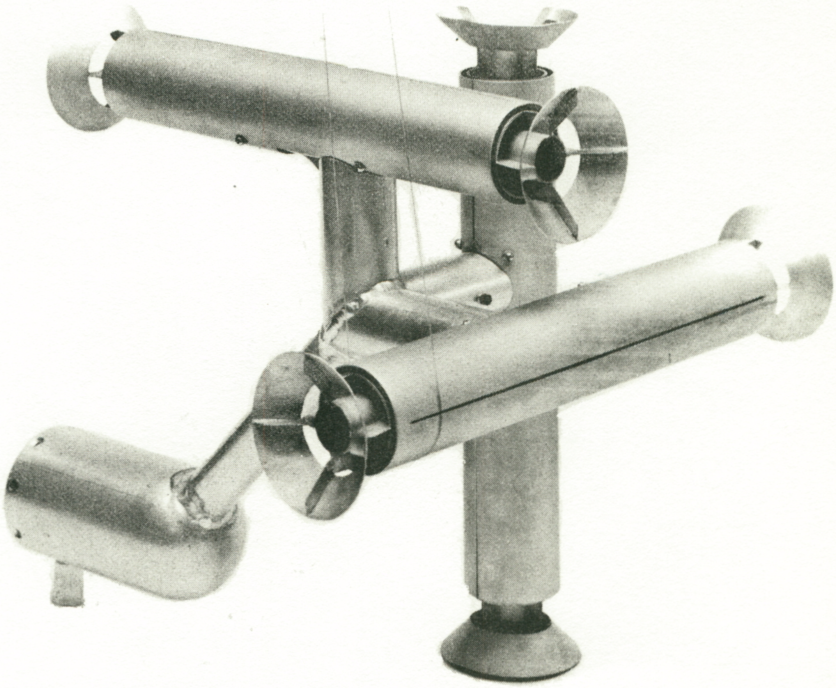
SECTION 3.0

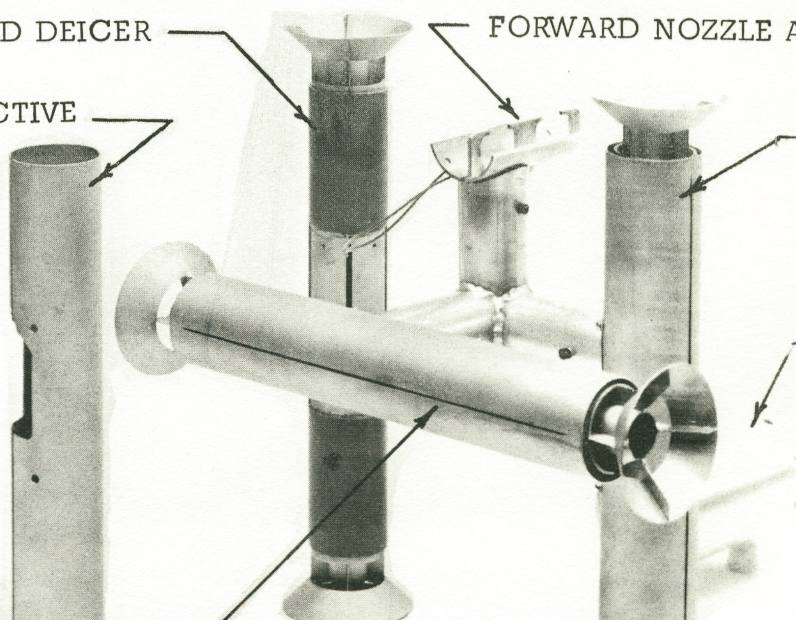
THREE AXIS SENSOR

Figure 2a shows the three axis sensor. Each of the sensors, shown in detail in Figure 2b, is the same and is fabricated by the process of panto-milling the air flow channels in an aluminum base using a 2:1 silhouette for increased accuracy. The cover plate is bonded to the channel-containing piece by the technique of dip brazing. This fabrication procedure is a significant advance over the earlier models in that the adjustment which was previously needed is eliminated. Some difficulty was experienced with the brazing filler material entering the air flow passageways, but this can be eliminated in future models with slightly more sophisticated preparation for the dip brazing. Figure 3 shows an x-ray of a nozzle assembly. This x-ray shows that the channel is free of aluminum, but that there is a considerable amount of salt flux remaining in the channel from the dip brazing process. This was removed by leaving the workpiece in a beaker of boiling water for several hours. Then, when a small passage-way was clear, the unit was flushed with hot water for several more hours. This problem can also be alleviated in future models by blowing air through the channels while the flux is still hot and soft. Final cleaning is recommended to be ultrasonic.

The cone/fin entrance configuration on either end of the flow alignment tube is responsible for generating the cosine output, and its principle operation is discussed in Reference 3. Here, too, the method of assembly is dip brazing. Preliminary tests were run which indicated that the length of the flow alignment tube could not be much less than 9 inches if a good facsimile of a cosine curve was to be obtained with a supporting structure which withstands airspeeds up to 154 m/sec (300 kt). Due to the afore-mentioned problem of minor aluminum filler build-up in the nozzles, the units exhibit a slight reduction of range in one direction of air flow. Because of the non-symmetry of ranges sought on the panel meters (to be discussed later) the nozzles were oriented to take advantage of this non-symmetry. Unfortunately, this resulted in more support interference than had been anticipated. The extent of this will be shown in the discussion of the recorded wind tunnel data.

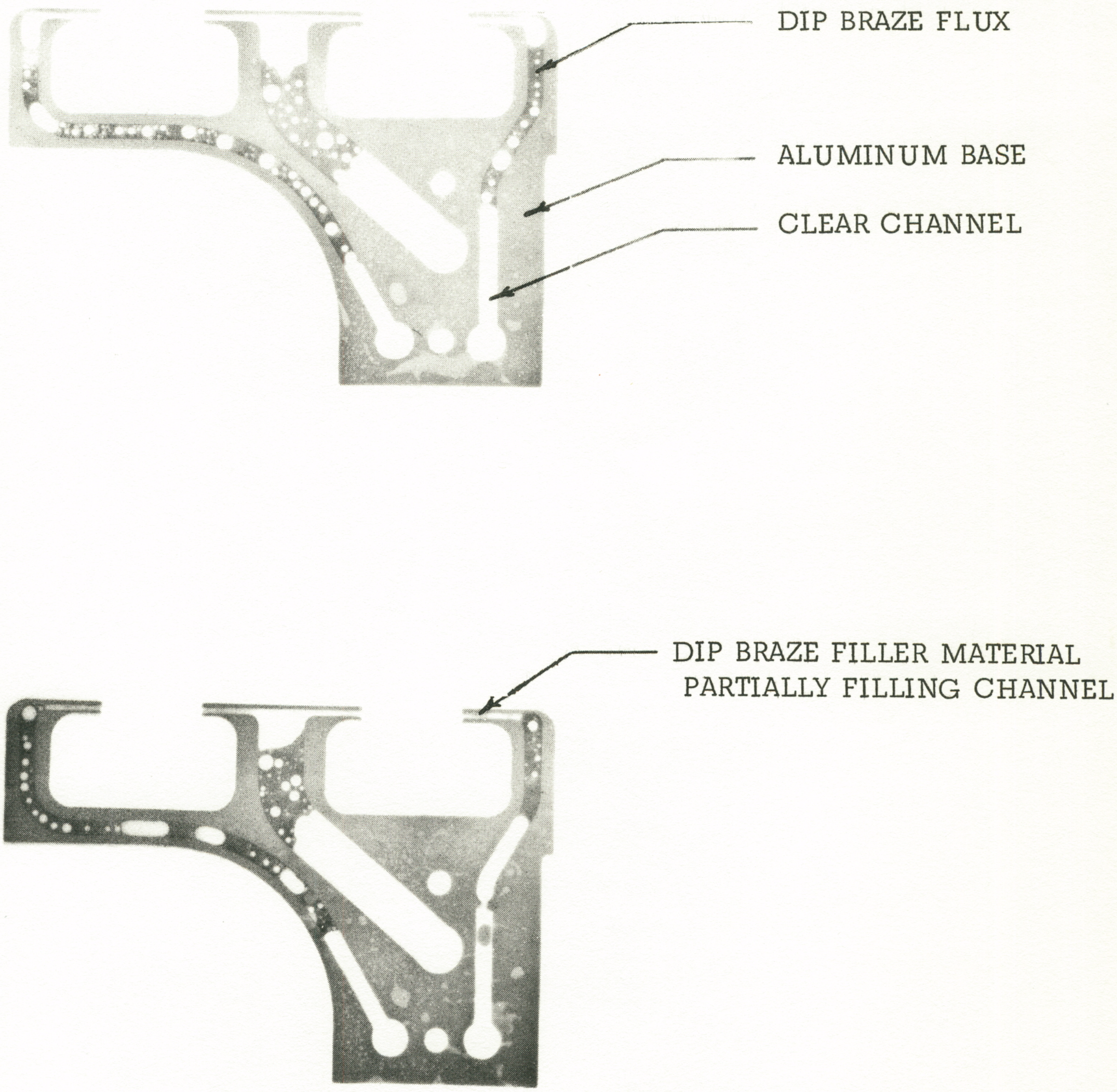
Bonded to the outer surface of each flow alignment tube is a deicer. This deicer incorporates a safety thermostat for each tube since the sensor would get excessively hot if energized under a no wind condition. The thermostats are located in the boom adaptor portion of the support structure, and as such, measure the model temperature instead of the air temperature. Since the model is exclusively aluminum, the heat transfer should permit





3-AXIS AIR VELOCITY SENSOR

FIGURE 3.



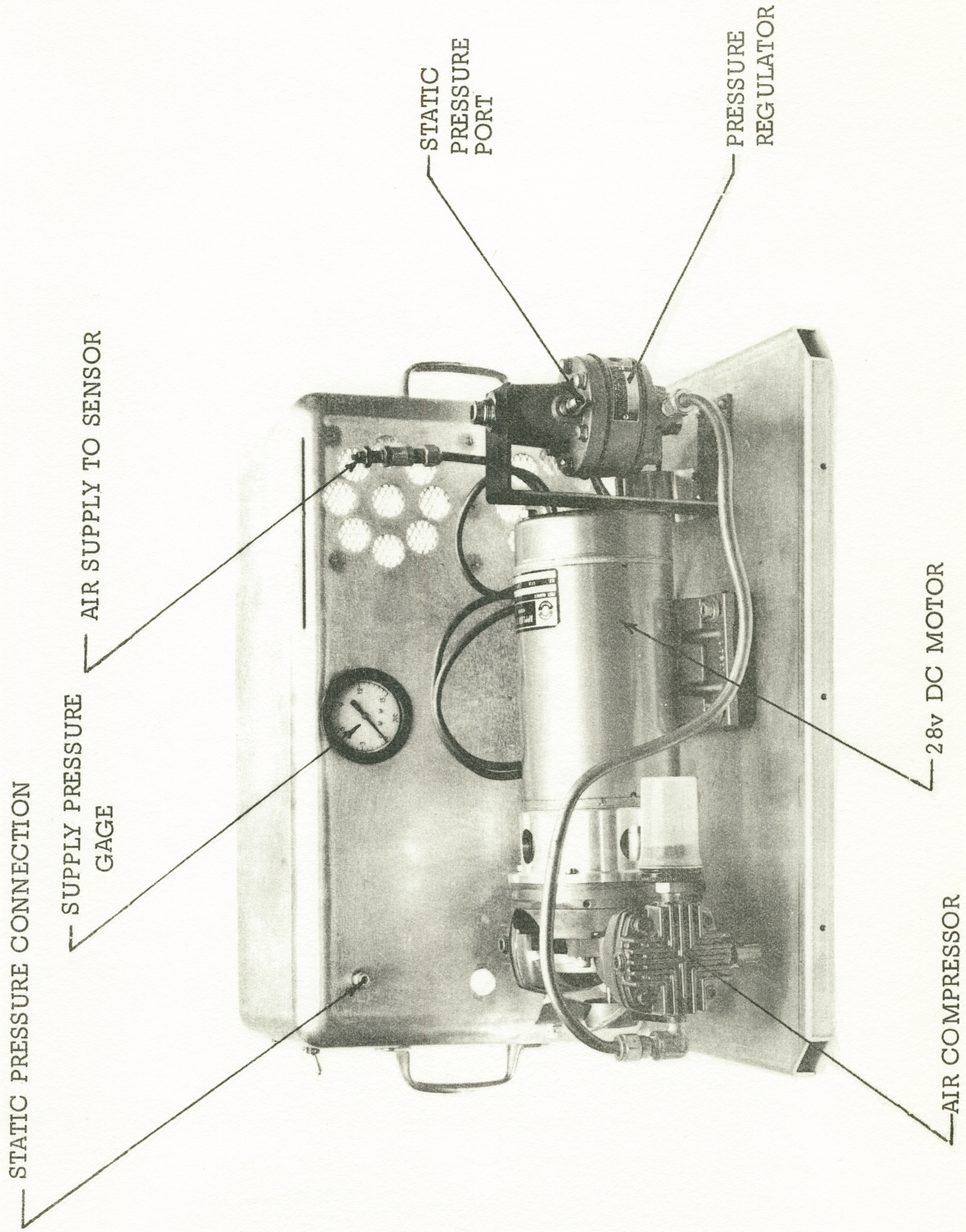
X-RAY PHOTOGRAPH OF NOZZLE ASSEMBLY

negligible error. The units consume approximately 0.465 watts/cm^2 and operate from the aircraft's 28V dc electrical supply. The thermostats are set so that they close at 280°K and open at 289°K.

SECTION 4.0
AIR SUPPLY PACKAGE

The air supply to the fluidic sensors is a self-contained unit consisting of an oil-less piston air compressor which was adapted to be driven by a 28V dc totally enclosed non-ventilated 188 watt (1/4 HP) permanent magnet motor. The choice of electrically-driven compressor over a bottled compressed air supply was predicated on a requirement that the system be operable for at least four hours. The output air from the compressor (which has a pressure relief valve) is regulated using a pressure regulator whose reference port may be connected to the local static pressure. In this way, the pressure to the sensor is regulated to the static pressure, while the air supply package may be in a pressurized area of an aircraft. The complete unit is shown in Figure 4.

FIGURE 4.



AIR SUPPLY PACKAGE

B

SECTION 5.0

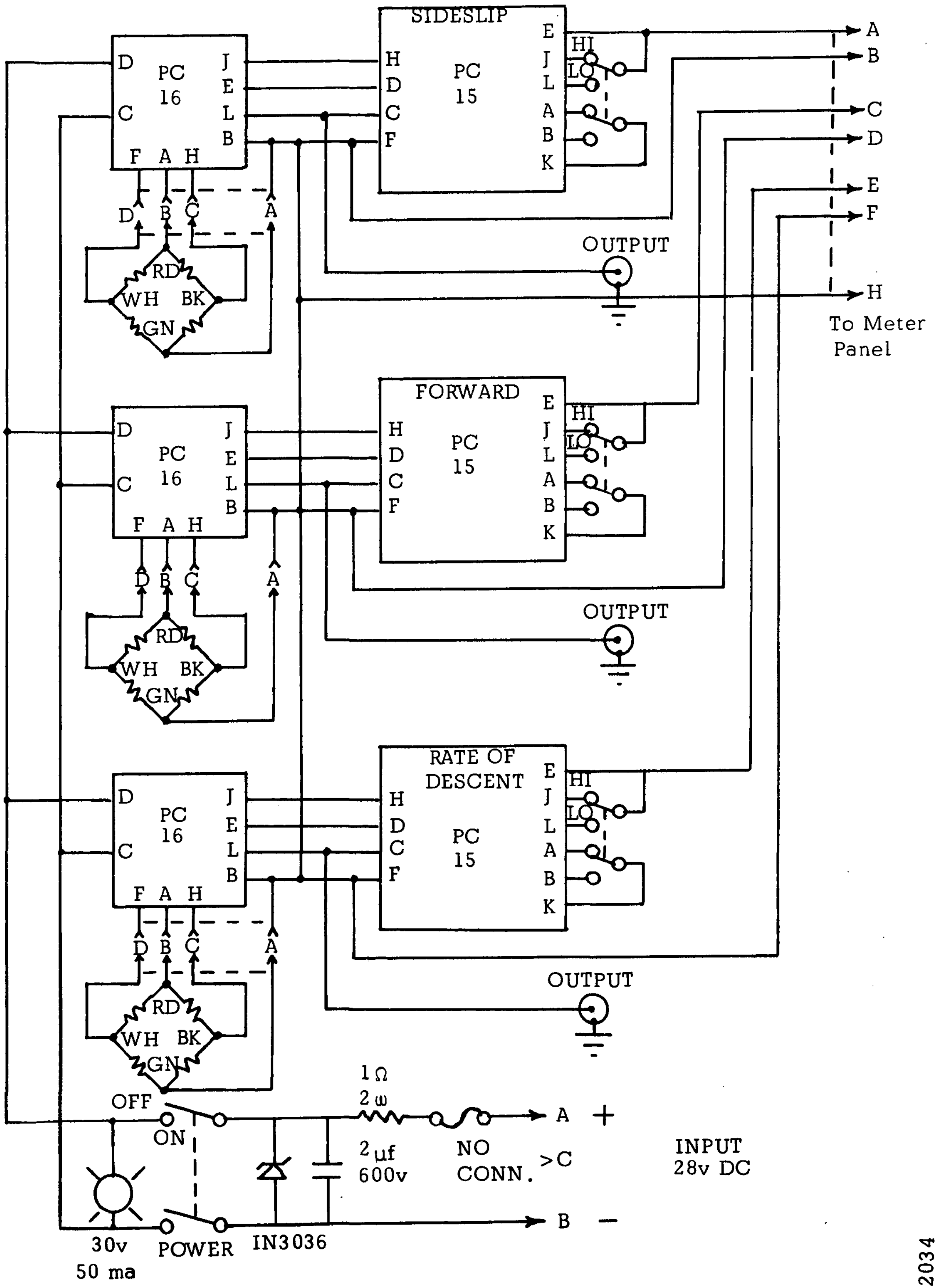
CIRCUITRY

Each sensor's differential pressure signal is transduced into an electrical signal by a strain gage pressure transducer. The electrical signal is amplified to provide a low-impedance output signal of ± 5 V full scale to ensure compatibility with recording instruments. This signal is also filtered using a Butterworth active filter to facilitate data interpretation. In addition to this electrical output, the signal is fed to three panel meters mounted on a rack which may be located remotely from the instrumentation package.

The schematic is shown in Figure 5. All three channels are powered by the same (aircraft) 28 V dc source. Each channel has its own 28 V dc to ± 15 V dc converter. From the +15 V dc, the transducer bridge excitation is also supplied. The potentiometer which governs the bridge voltage may be used as a coarse gain adjust. The instrumentation amplifier which is used to provide the ± 5 V dc output has the capability of a fine gain and coarse zero adjusts. An external potentiometer on the active filter enables fine zero control. With these adjustments, the output voltage to recording equipment may be set for the pre-determined levels. That same voltage which goes to the output connectors is also fed into the panel meters for the respective axes. Each axis has for the purpose of the panel meters another printed circuit board. This second printed circuit board permits offsetting of the panel meter needle to accommodate the different plus and minus velocity ranges prescribed. In addition, this circuit board also contains a sensitivity select switch which is used to increase the accuracy of reading over the low velocity portion of the range.

The instrumentation unit operates on 28 V dc and is protected from standard aircraft electrical power surges by filtering for high frequency spikes. In addition, the unit is fused. Power consumption is 60 watts. Figure 6 is a photograph of the instrumentation unit.

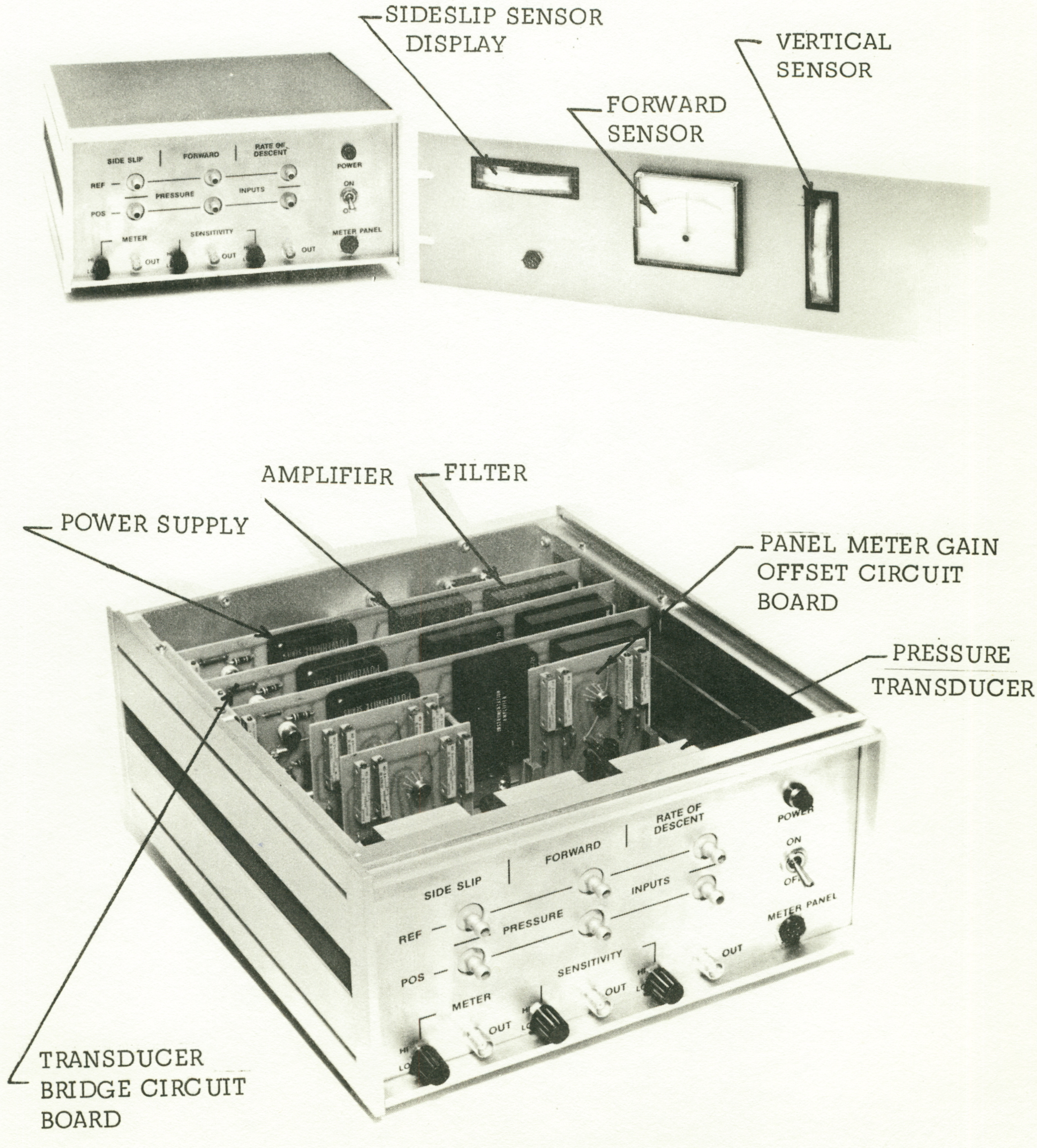
FIGURE 5.



THREE-AXIS WIND SENSOR-INSTRUMENTATION UNIT WIRING DIAGRAM

32034

FIGURE 6.



INSTRUMENTATION UNIT

SECTION 6.0
SYSTEM CALIBRATION

System calibration began with a calibration of the three fluidic sensors themselves. The University of Maryland 0.45 m x 1.2 m wind tunnel was used. While it was originally planned to test over the velocity range -51.4 m/sec $<V<$ 51.4 m/sec ($-100 \leq V \leq$ 100 kt), it was discovered at the time of the test that the tunnel had been modified to operate with a lower turbulence level. This was gained at the expense of maximum velocity, and tests were restricted to the range -41.2 m/sec $<V<$ 41.2 m/sec ($-80 \leq V \leq$ 80 kt).

Output pressures were measured using a U-tube water manometer. The data recorded ins shown in Figurea 7a,b,c; unit conversion being made according to Reference 4. Tests were repeated at 3 supply pressures for each sensor. Supply pressures were measured by a gage mounted on the air supply package. From these tests, it was decided to calibrate the meters at the lowest supply pressure since this gave adequate gain. It had been specified that the output electrical signal be approximately ± 5 V for the following velocity ranges.

Forward-Reverse, -15.4 to 51.4 m/sec
(-30 to +100 knots)

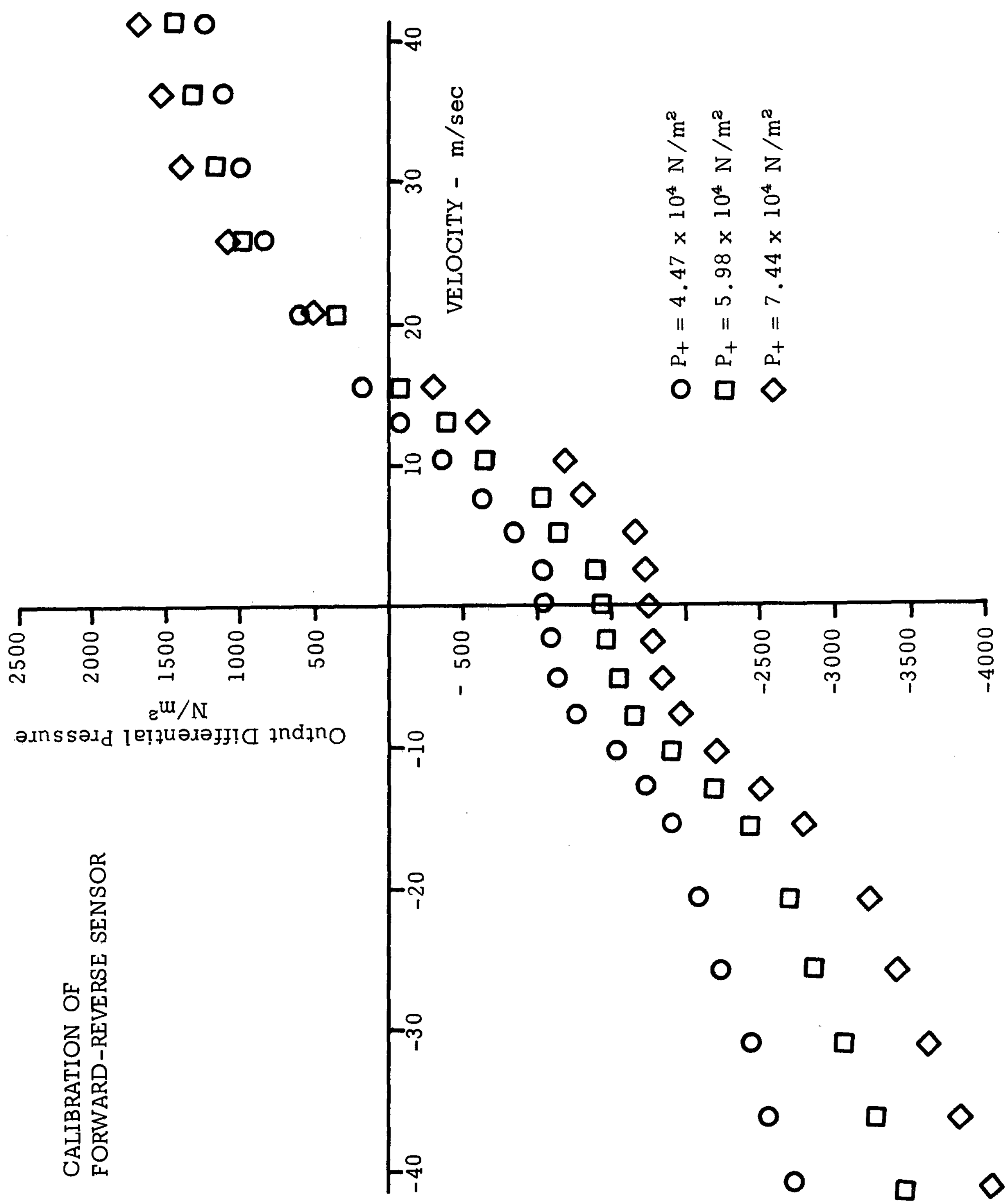
Left-Right, -30.8 to +30.8 m/sec
(-60 to +60 knots)

Vertical, -15.4 to 46.3 m/sec
(-30 to +90 knots)

The coordinate system is shown in Figure 8. With air to the sensor at 4.47×10^4 N/m^2, the strain gage transducer was balanced, giving zero voltage out. Next, the wind tunnel was set at the extreme points of the range where possible or at its maximum 41.2 m/sec (80 kt) where the prescribed velocity exceeded the maximum of the test facility. At this velocity, the gain of the amplifier was adjusted to provide approximately 5 V. This output level will be compatible with most recording equipment.

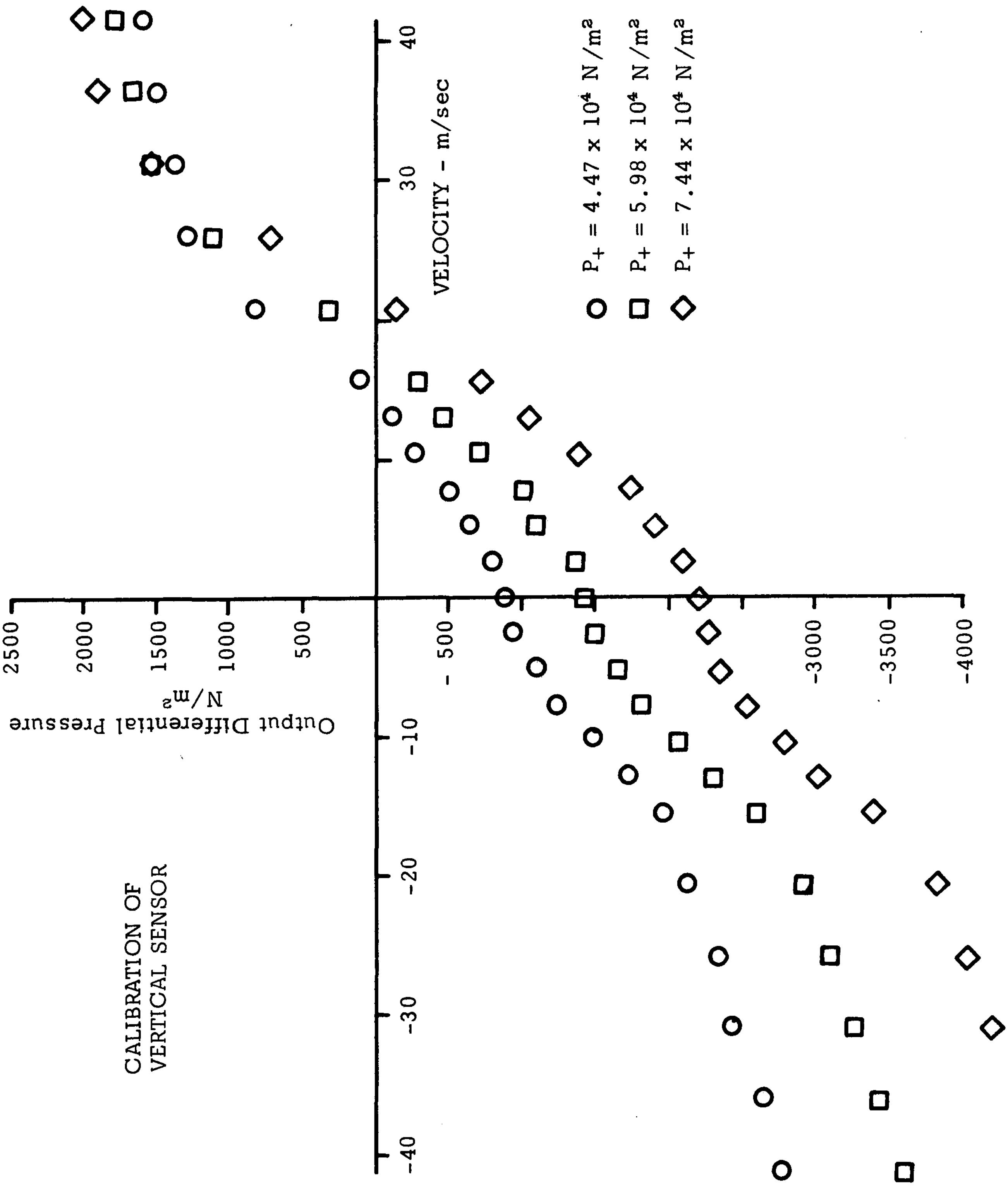
The final phase of calibration was that of the panel meters. Through an iteration process, the zero was set (differently from the meter scale in vertical and forward-reverse axes) and the maximum output voltage in each direction was adjusted to provide ± 5 V for the maximum velocities. The complete data is shown in Figure 9. The faces of these panel meters

FIGURE 7a.



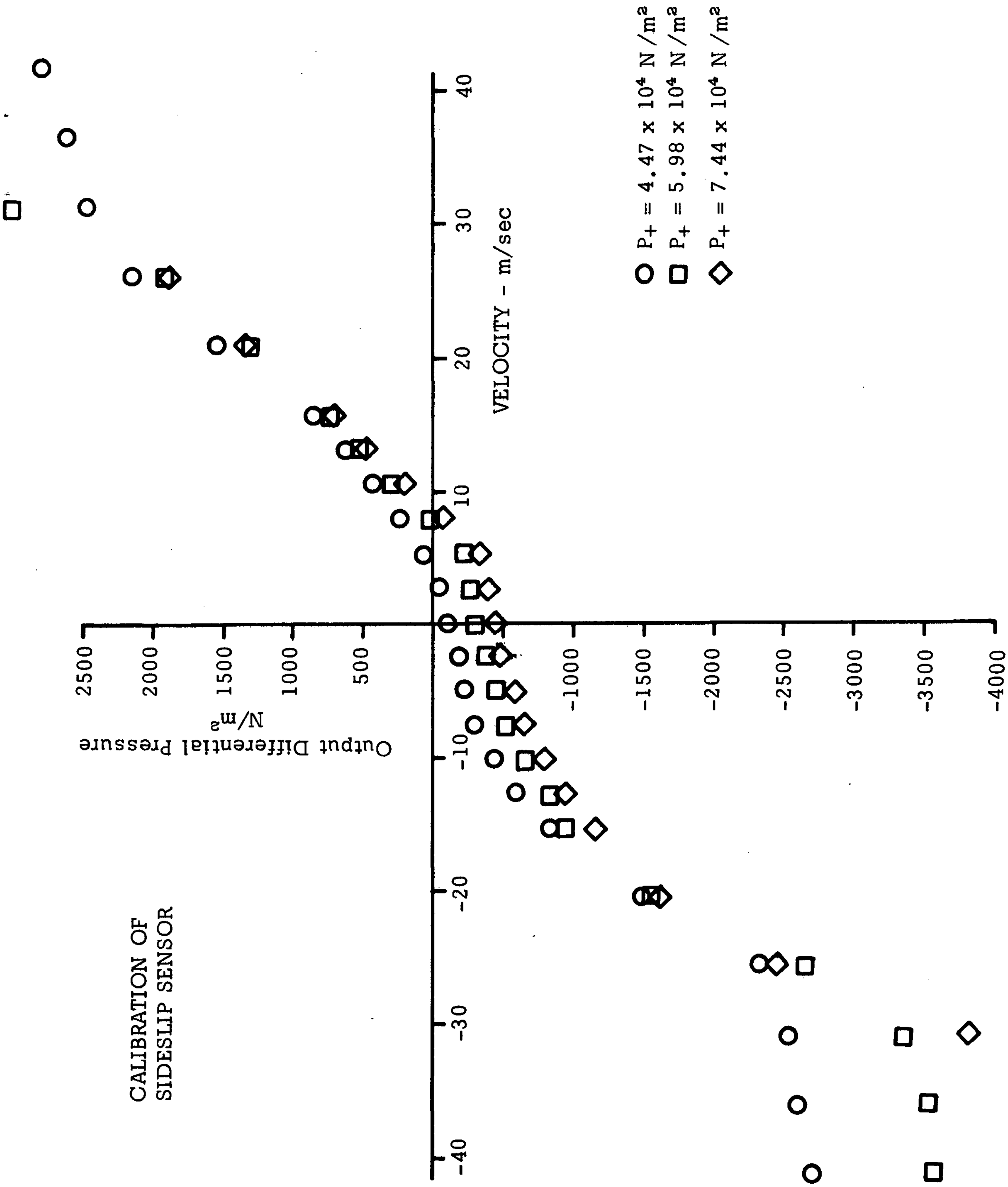
CALIBRATION OF
FORWARD-REVERSE SENSOR

FIGURE 7b.

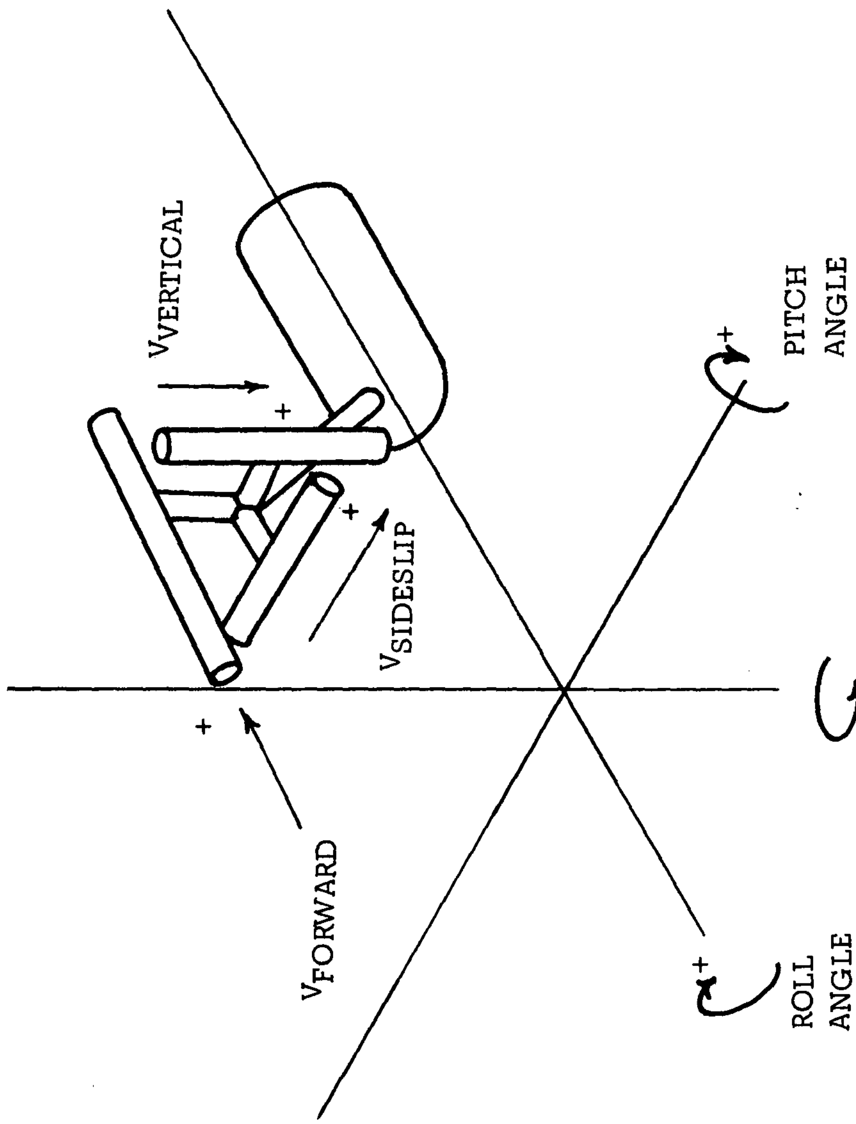


CALIBRATION OF
VERTICAL SENSOR

FIGURE 7c.

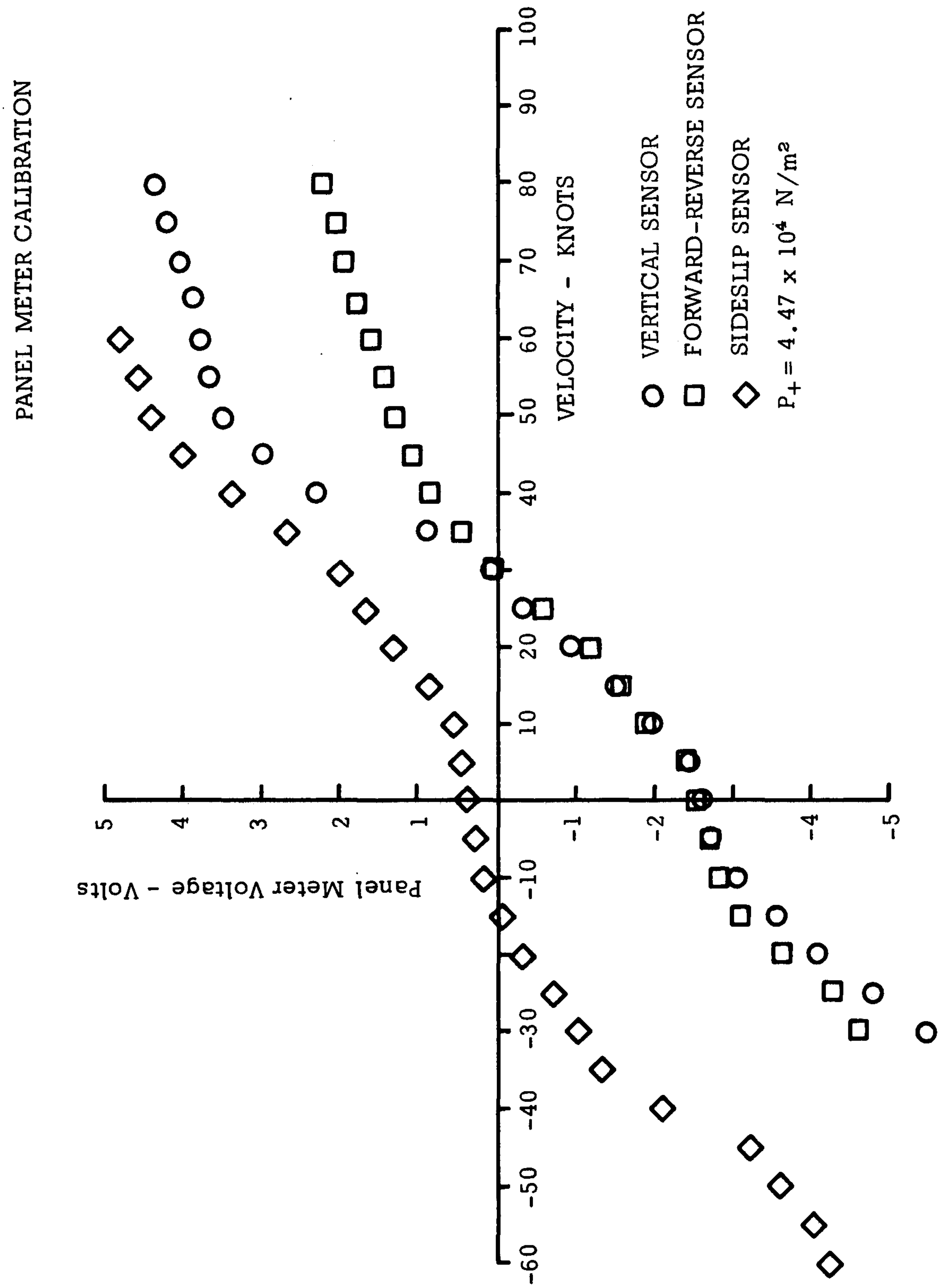


CALIBRATION OF SIDESLIP SENSOR



COORDINATE SYSTEM USED IN TESTS

FIGURE 9.


PANEL METER CALIBRATION
VELOCITY - KNOTS
Panel Meter Voltage - Volts
VERTICAL SENSOR
FORWARD-REVERSE SENSOR
SIDESLIP SENSOR
$P_+ = 4.47 \times 10^4$ N/m²
100
90
80
70
60
50
40
20
10
-10
-30
-40
-50
-60
5
4
3
2
1
-1
-2
-4
-5

were then modified to read in knots for aircraft compatibility. Note the smaller output voltage for the forward sensor. This is to provide sufficient range to accommodate extended velocity tests at a later time.

SECTION 7.0

ANGULAR RESPONSE

With the basic calibration complete, data of output signal variation with angle of incidence to the wind was recorded for each axis at appropriate velocities. The output voltage from the instrumentation package was fed into an X-Y recorder. The second input to the X-Y recorder was a potentiometer to record angular rotation of the three axis sensor assembly.

The results of this test appear in Figures 10a thru f. The most striking feature of these curves is that for the lower velocities, the approximation to a cosine curve is quite good. At higher velocities, the curve is somewhat of a square wave, a characteristic which may have been anticipated in consideration of the decrease of slope in the zero angle of incidence calibration curve (Figure 7 or 9). The velocities indicated on the graphs have been rounded off after unit conversion from the measured values in knots.

Figure 11 shows forward-reverse and vertical sensors with the three axis assembly in pitch. The agreement with a sinusoid is quite good with the exception of the forward sensor in the region $\frac{5\pi}{8} < \alpha < \frac{3\pi}{4}$ radians, where one of the entrance cones is in the wake of the boom adaptor. This anomaly disappears when the same sensor is rotated about the yaw axis, when the boom adaptor creates less disturbance (see Figure 12). Figures 13 and 14 similarly compare the same sensor when rotated about two axes. The effect of the support is slight, but nonetheless observable.

In each test, one sensor is so oriented that it should read zero throughout the complete revolution. In all the tests, this sensor spanned the short dimension of the wind tunnel rectangular test section, being fairly close to the walls (within 10 cm). This, plus the disturbance of the support itself has adversely influenced the data. Undoubtedly there will be some disturbance resulting from wake flows of the other two sensors, but it appears that much of the non-zero behavior is the result of tunnel walls and support interference. Figure 15 shows the sideslip sensor in pitch. For $0 < \alpha < \frac{3\pi}{2}$, it is reasonably near zero. For $\frac{3\pi}{2} < \alpha < 2\pi$, it lies in the wake of the other sensors, but more important in the wake of the boom support structure which was used throughout the test. The data thus suggested a worse case, and bears future testing in a larger tunnel. This could concievably be carried out in the range-extending tests which are expected to be conducted by NASA.

FIGURE 10a.

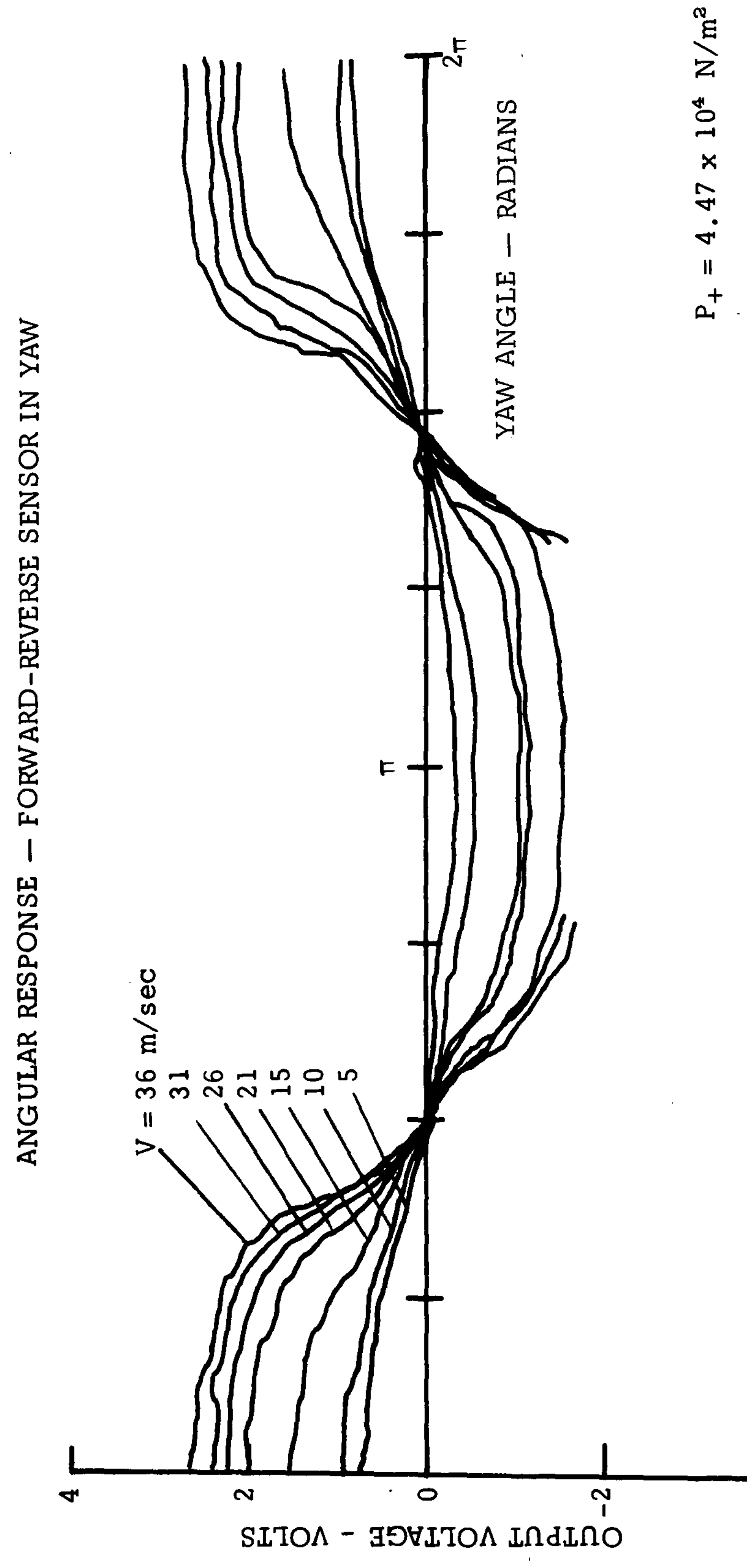

ANGULAR RESPONSE — FORWARD-REVERSE SENSOR IN YAW
V = 36 m/sec
31
26
21
15
10
5
OUTPUT VOLTAGE - VOLTS
4
2
0
-2
-4
π
2π
YAW ANGLE — RADIANS
$P_+ = 4.47 \times 10^4$ N/m²

FIGURE 10b.

ANGULAR RESPONSE — FORWARD SENSOR IN PITCH

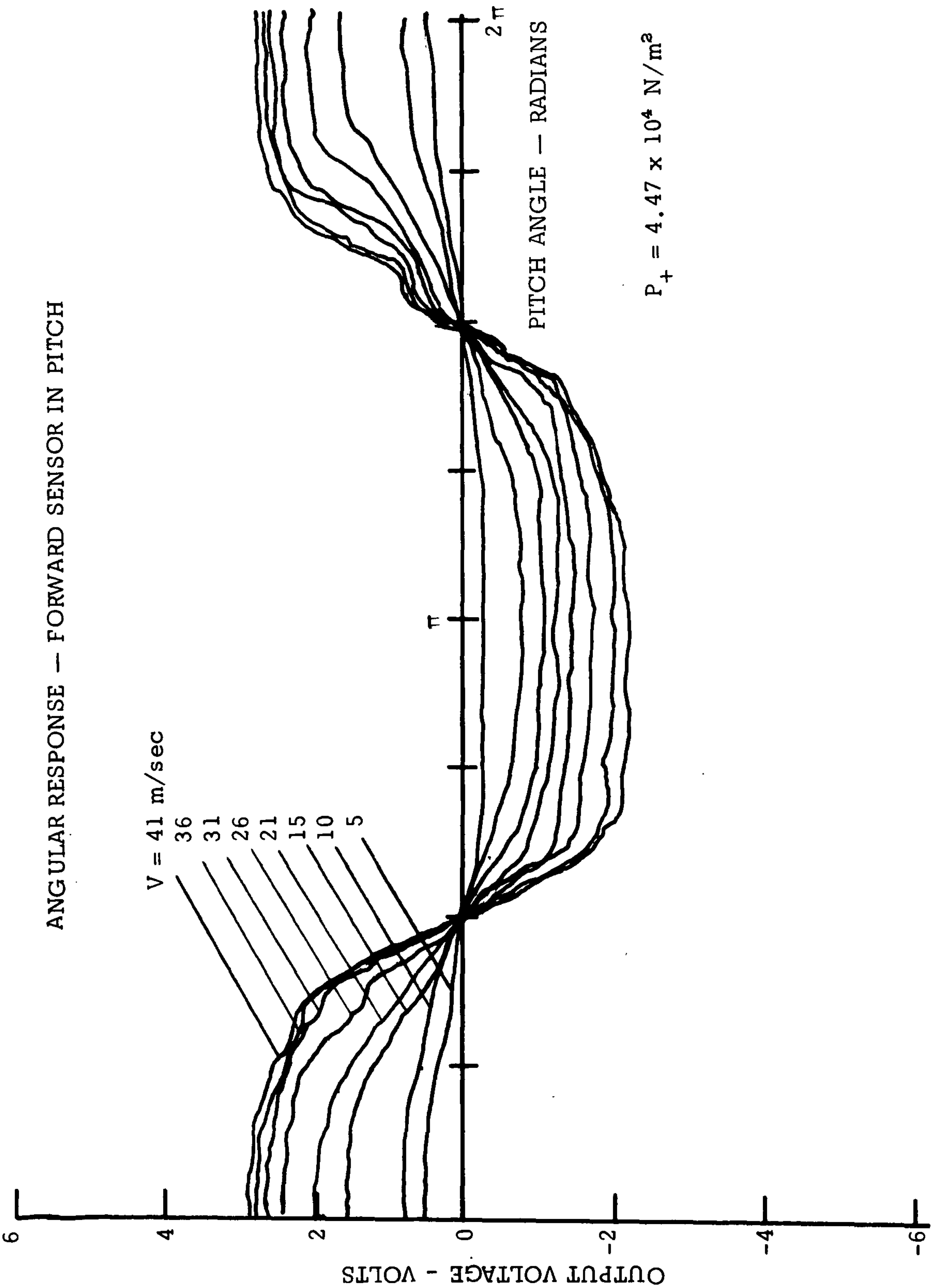


FIGURE 10c.

ANGULAR RESPONSE — SIDESLIP SENSOR IN ROLL

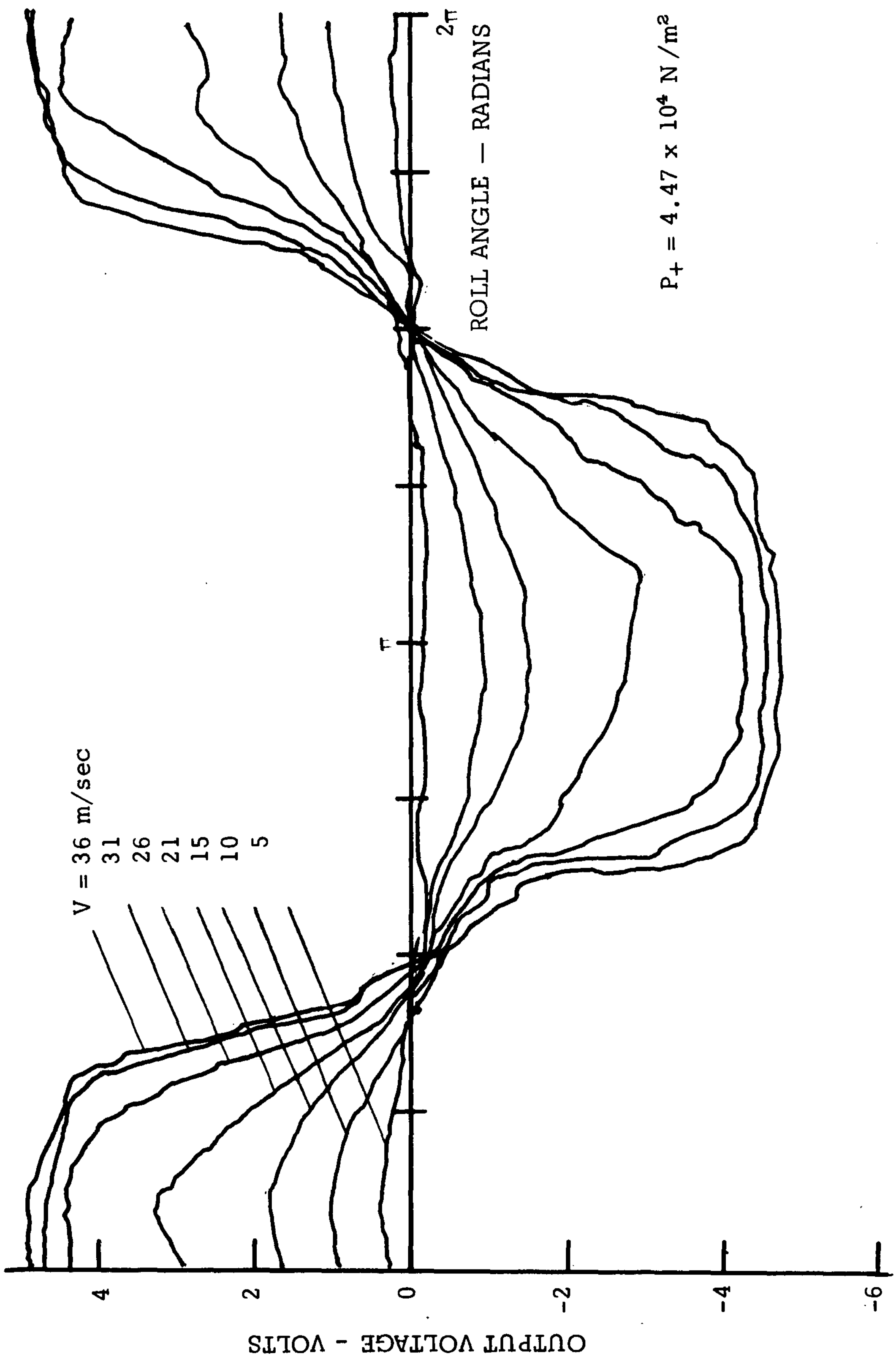
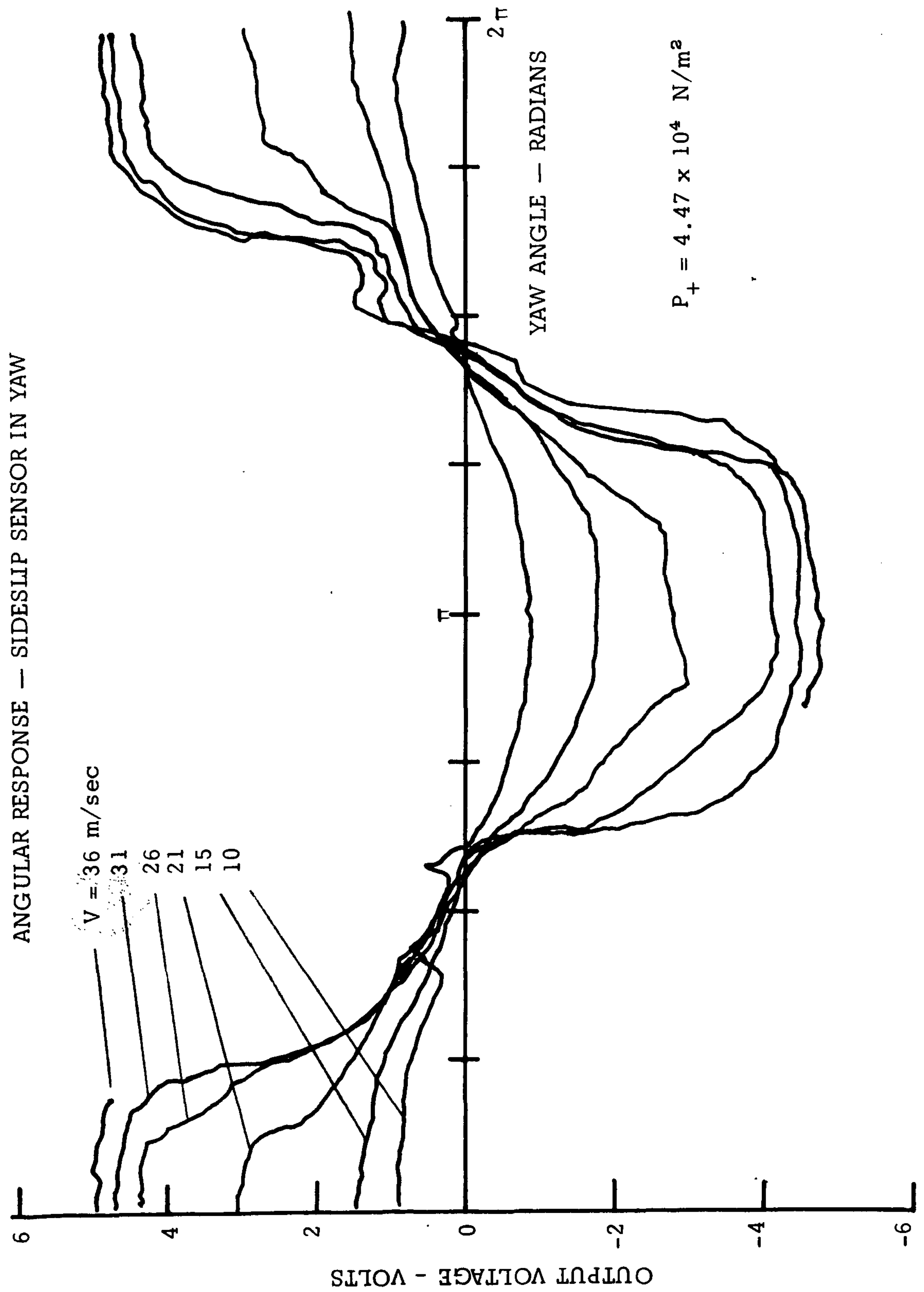
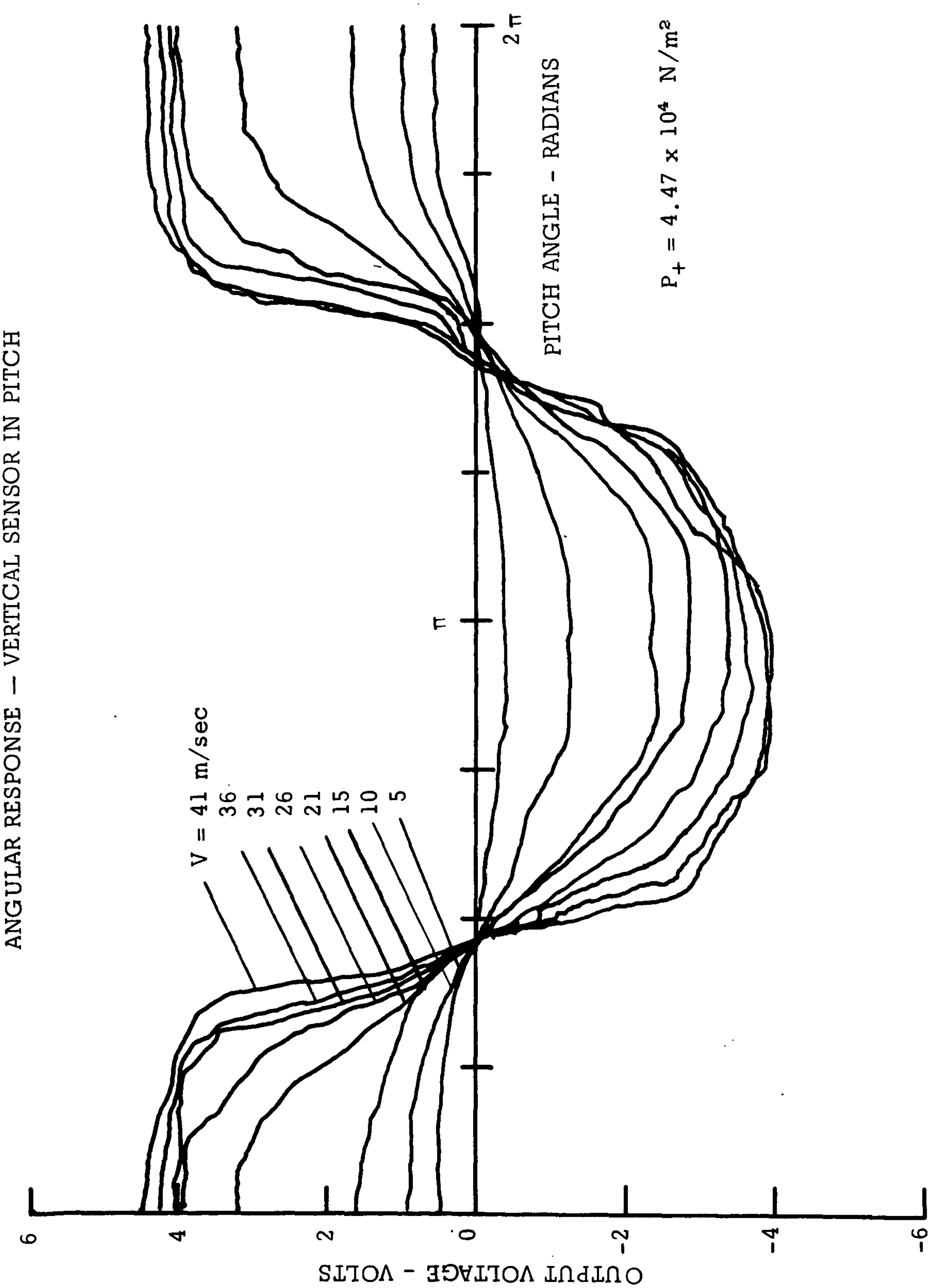


FIGURE 10d.



ANGULAR RESPONSE — SIDESLIP SENSOR IN YAW
V = 36 m/sec
31
26
21
15
10
YAW ANGLE — RADIANS
π
2π
$P_+ = 4.47 \times 10^4$ N/m²
OUTPUT VOLTAGE - VOLTS
6
4
2
0
-2
-4
-6

FIGURE 10e.



ANGULAR RESPONSE — VERTICAL SENSOR IN PITCH
V = 41 m/sec
36
31
26
21
15
10
5
π
2π
PITCH ANGLE - RADIANS
$P_+ = 4.47 \times 10^4$ N/m²
OUTPUT VOLTAGE - VOLTS
6
4
2
0
-2
-4
-6

FIGURE 10f.

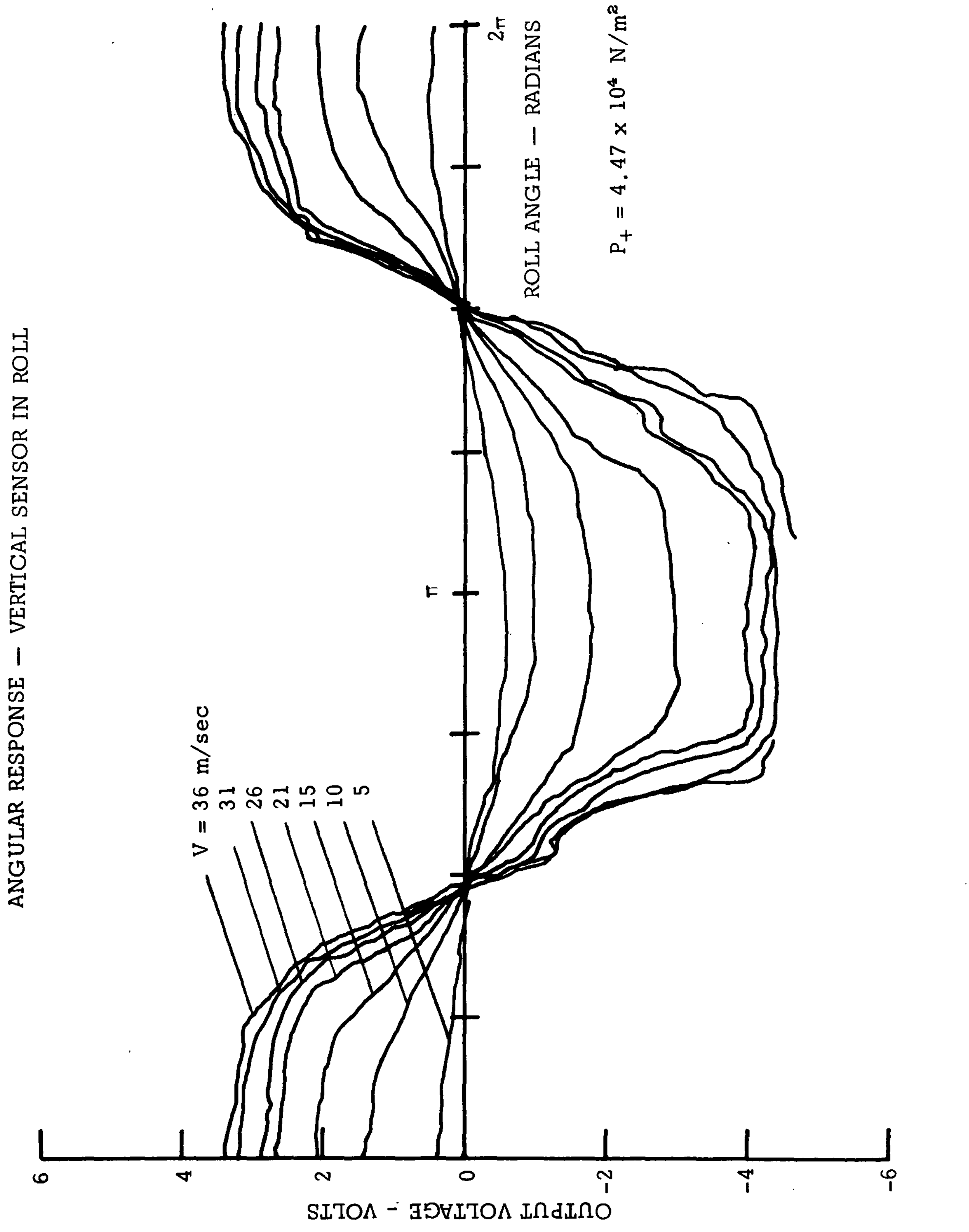
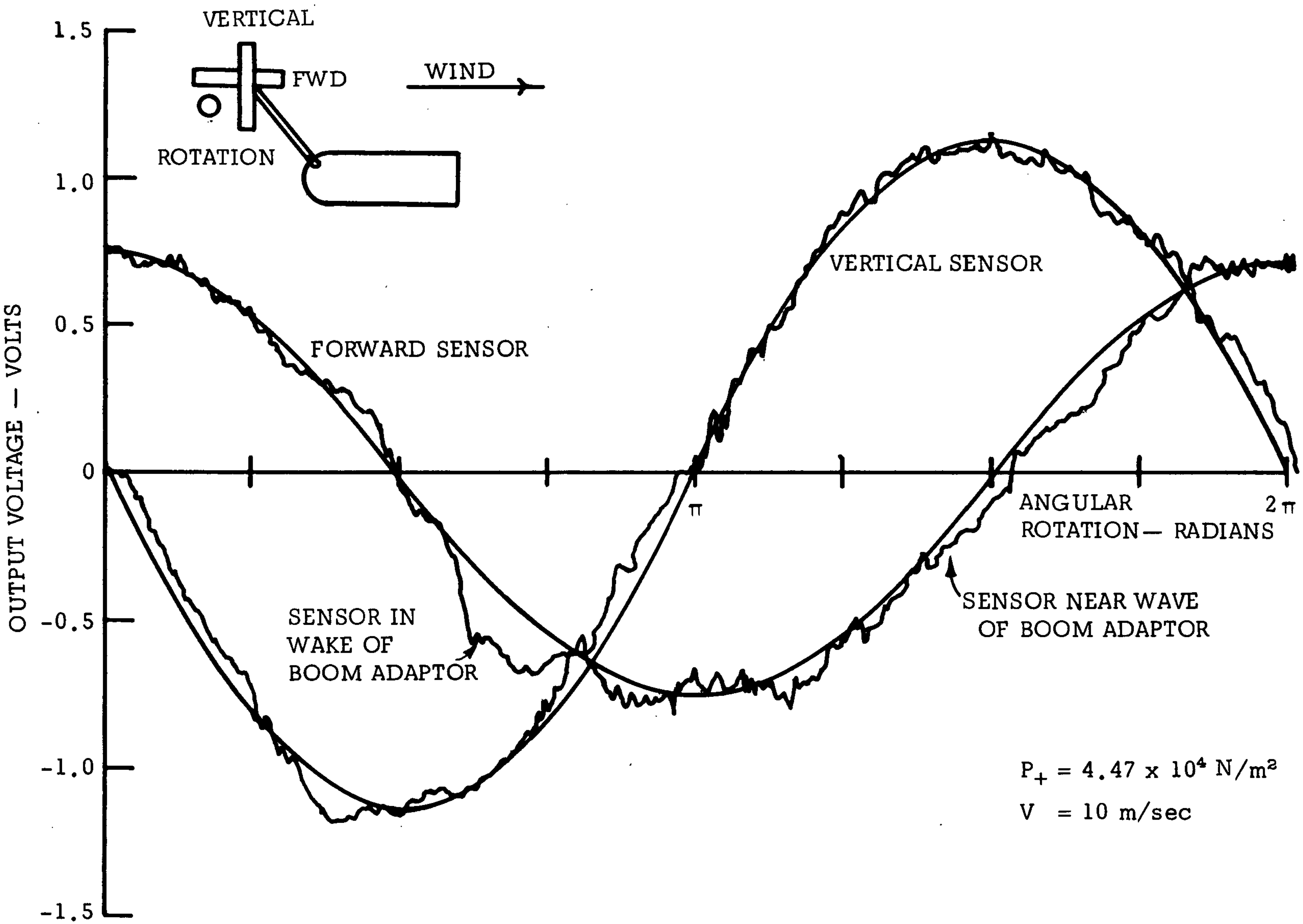

ANGULAR RESPONSE — VERTICAL SENSOR IN ROLL
V = 36 m/sec
31
26
21
15
10
5
π
2π
ROLL ANGLE — RADIANS
P+ = 4.47 x 10^4 N/m^2
6
4
2
0
-2
-4
-6
OUTPUT VOLTAGE - VOLTS

FIGURE 11.



FORWARD-REVERSE AND VERTICAL SENSORS WITH THE 3-AXIS ASSEMBLY IN PITCH

FIGURE 12.

VERTICAL SENSOR OUTPUT AS A FUNCTION OF PITCH AND ROLL ANGLES

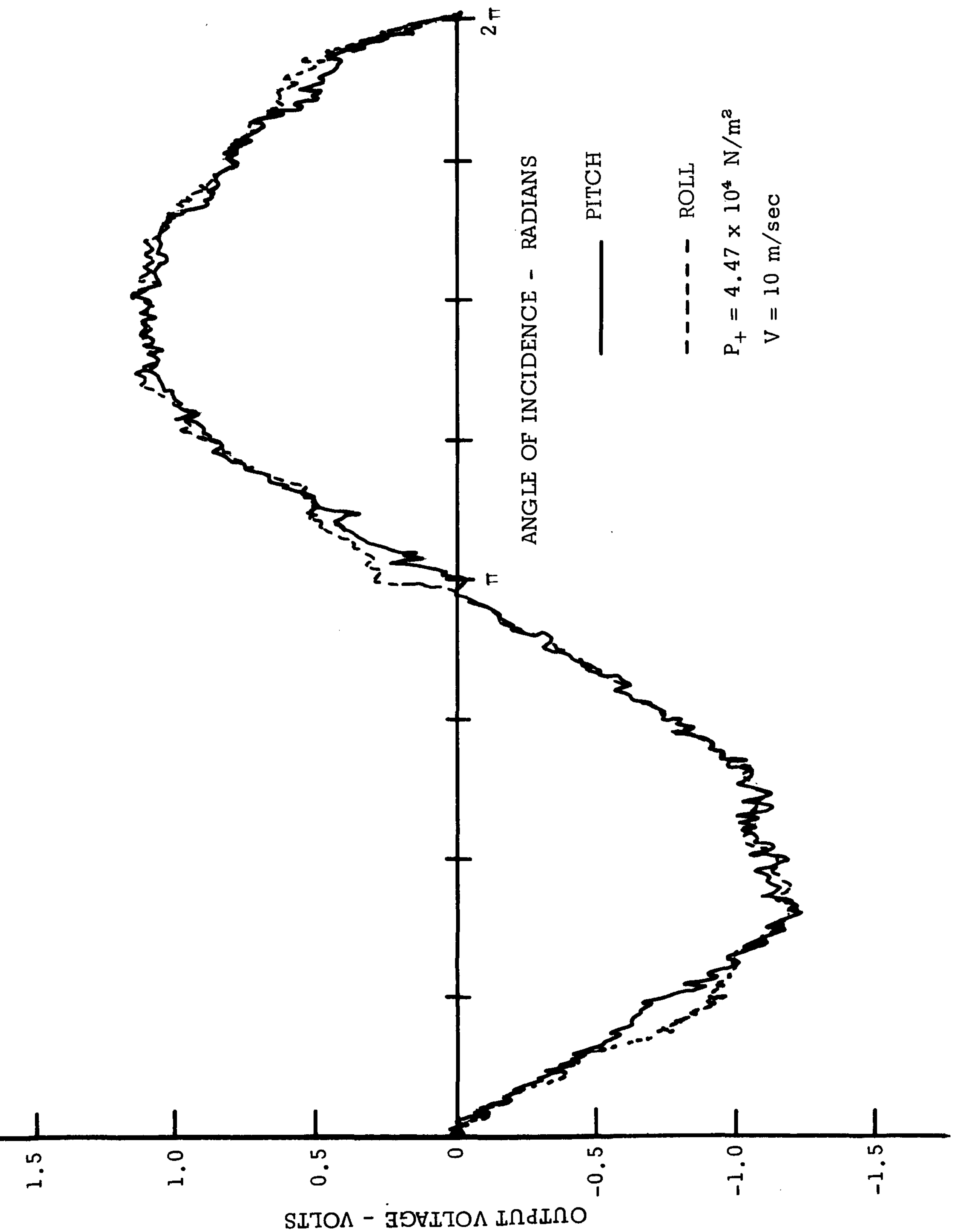


FIGURE 13.

SIDESLIP SENSOR OUTPUT AS A FUNCTION OF YAW AND ROLL ANGLES

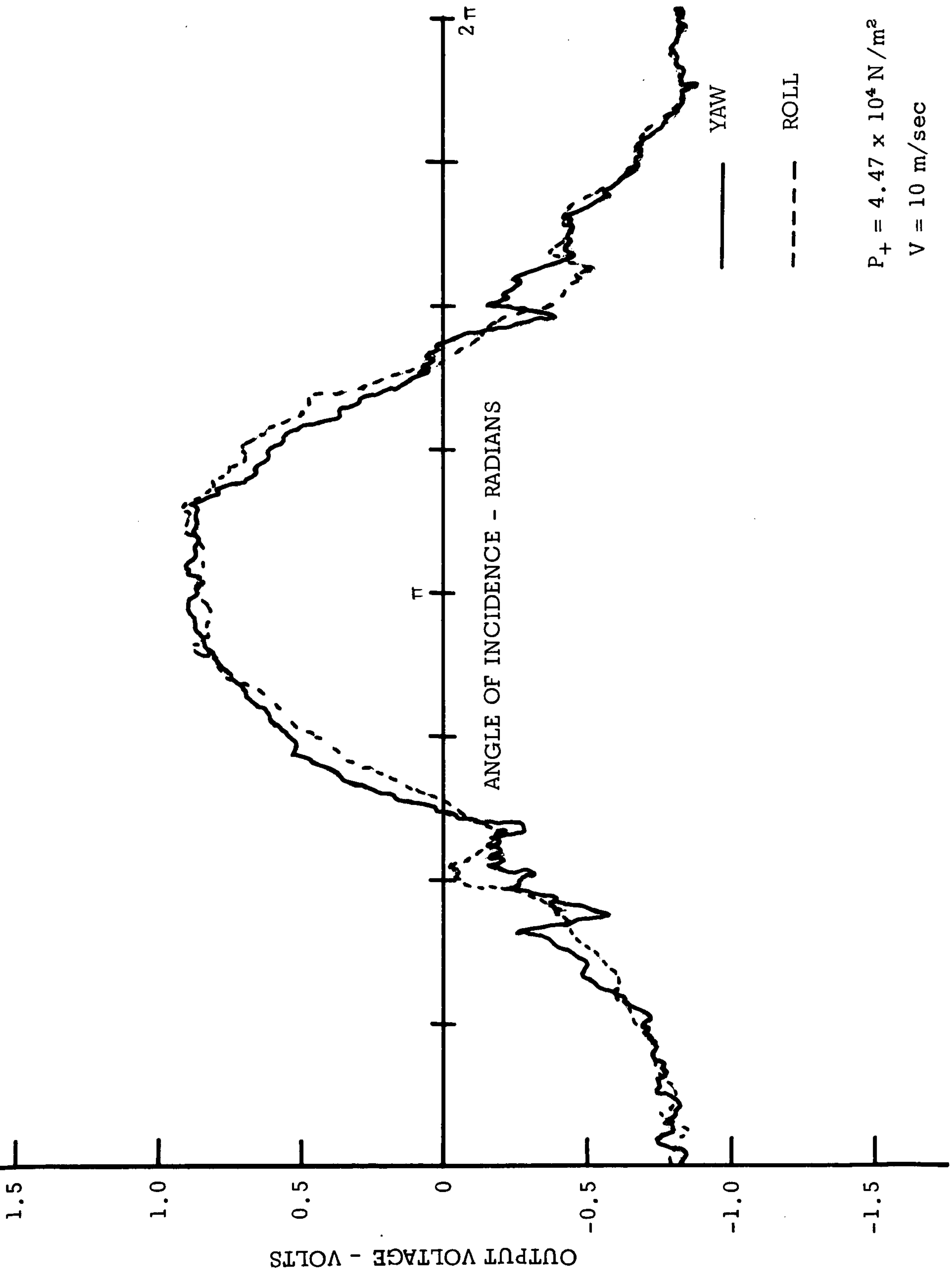


FIGURE 14.

FORWARD-REVERSE SENSOR OUTPUT AS A FUNCTION OF PITCH AND YAW ANGLES

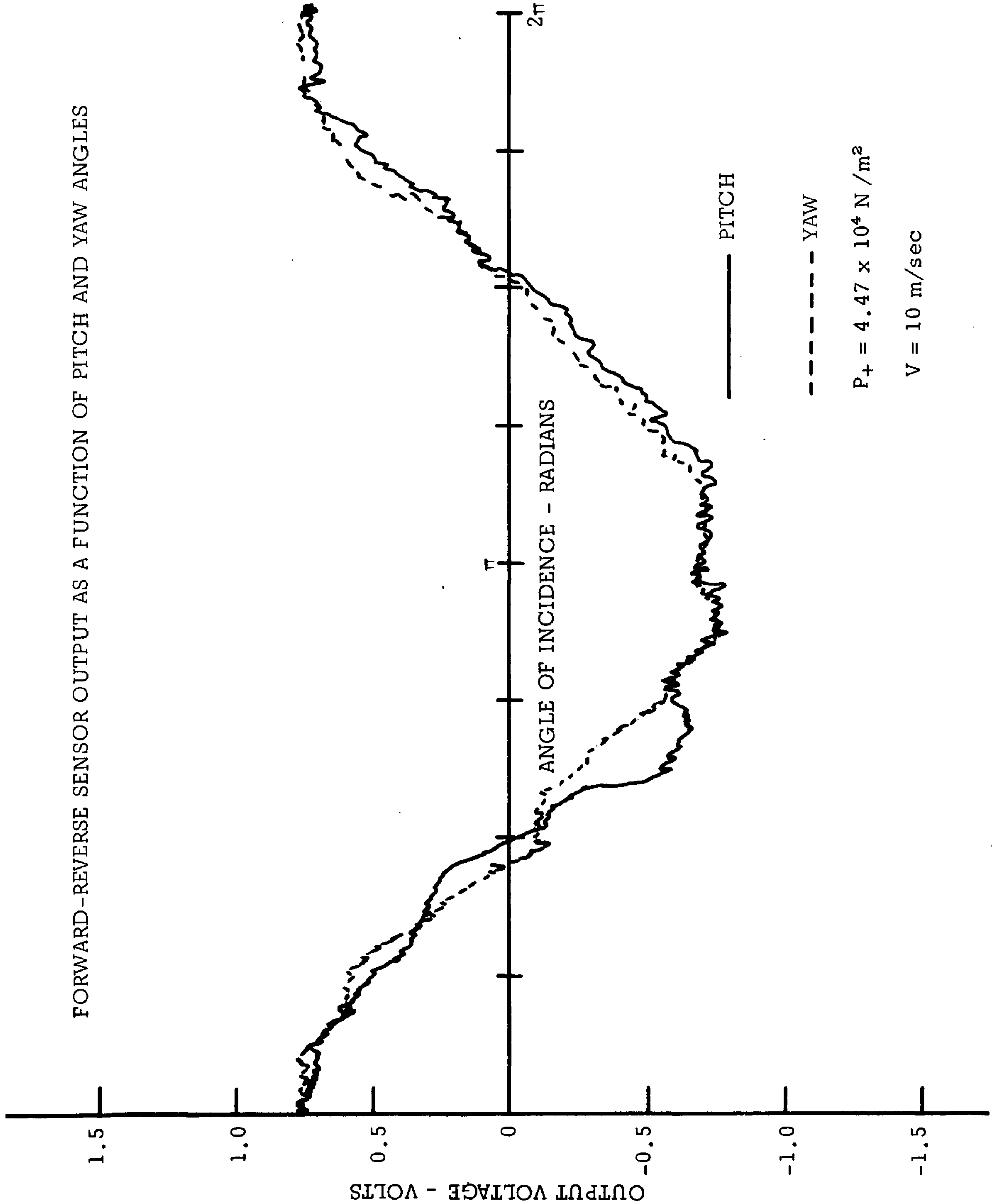
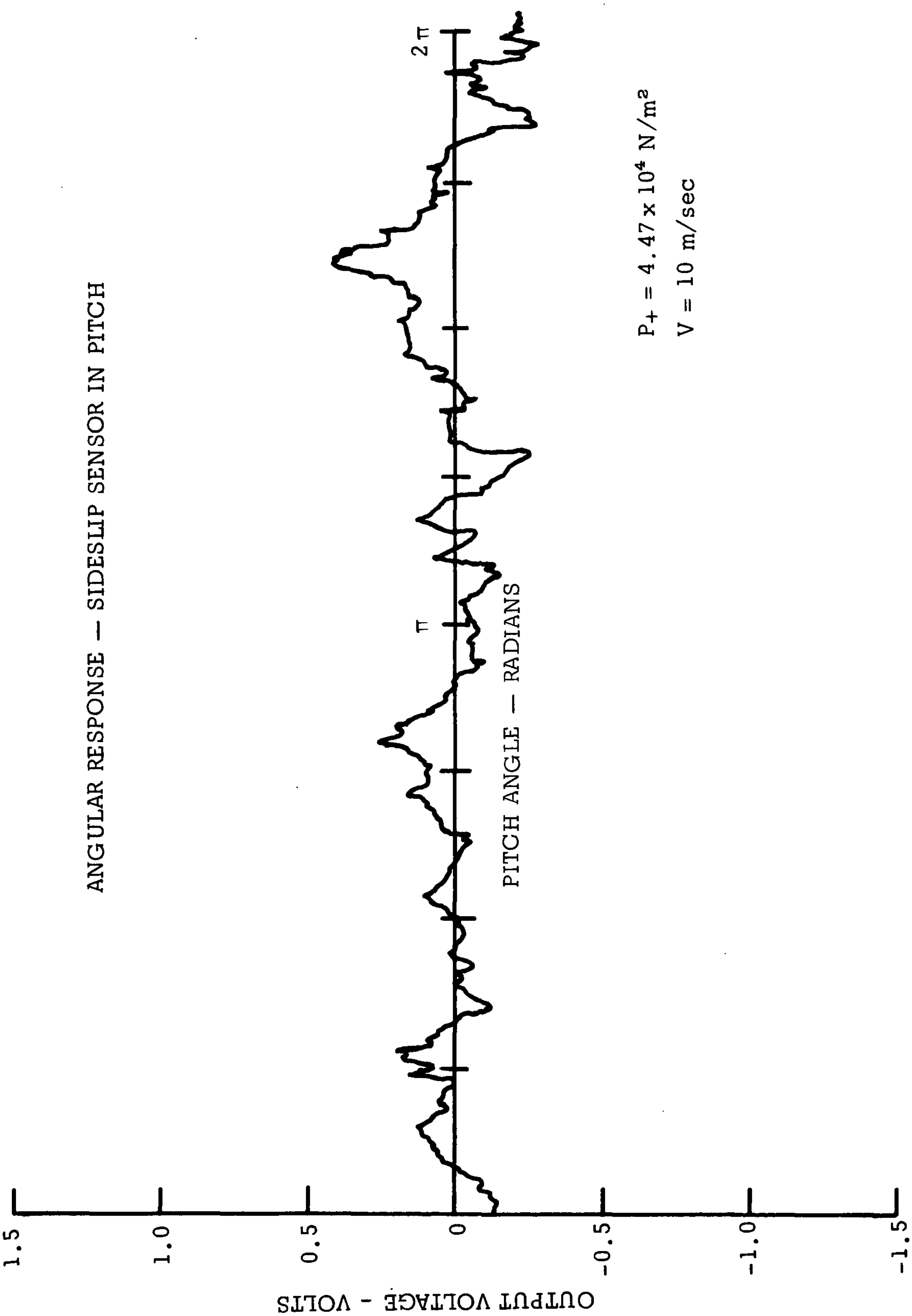


FIGURE 15.


ANGULAR RESPONSE — SIDESLIP SENSOR IN PITCH
PITCH ANGLE — RADIANS
π
2π
$P_+ = 4.47 \times 10^4$ N/m²
V = 10 m/sec
OUTPUT VOLTAGE - VOLTS
1.5
1.0
0.5
0
-0.5
-1.0
-1.5

SECTION 8.0

SUMMARY

A complete prototype of a fluidic system for measuring aircraft velocities in three directions simultaneously has been fabricated and wind tunnel tested. The system is suitable for flight testing, and nothing is required from the aircraft except the standard 28V dc electrical power. The system is made up of three distinct components to provide maximum flexibility in testing. Namely,

- o Three axis fluidic sensor
- o Air supply package
- o Instrumentation and readout.

While pneumatic readout of the sensors' signals is easily done, the signal is transduced to an electrical one in order to permit ease in recording of the data. This electrical signal is also displayed on panel meters which are calibrated in knots for aircraft compatibility.

As had been specified, the sensors' calibrations are approximately linear. A portion of what non-linearity does exist is by design. This is the break in the curve at 50 knots, where the slope is considerably less than at lower velocities. In this way, the complete range (which is to be extended by NASA) may be contained on a single scale. That non-linearity near zero velocity is believed to be the result of the dip braze filler material in the channels and it's effect on the resultant air flow. As has been discussed, this problem is thought to be resolvable in future nozzle assemblies.

SECTION 9.0

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APPENDIX

TABULATION OF DATA

SENSOR CALIBRATION

SENSOR: FORWARD-REVERSE

VELOCITY (kt)	OUTPUT DIFFERENTIAL PRESSURE (INCHES OF H_2O)		
	P_+ = 6.5 PSI	P_+ = 8.7 PSI	P_+ = 10.8 PSI
-80	-11.0	-13.8	-16.1
-70	-10.2	-13.0	-15.3
-60	- 9.7	-12.2	-14.4
-50	- 8.9	-11.4	-13.6
-40	- 8.3	-10.7	-12.8
-30	- 7.6	- 9.7	-11.1
-25	- 6.9	- 8.7	-10.0
-20	- 6.05	- 7.6	- 8.8
-15	- 5.0	- 6.6	- 7.9
-10	- 4.5	- 6.2	- 7.4
- 5	- 4.3	- 5.8	- 7.05
0	- 4.2	- 5.7	- 7.0
0	- 4.2	- 5.7	- 6.8
5	- 4.1	- 5.6	- 6.8
10	- 3.3	- 4.5	- 6.6
15	- 2.5	- 4.1	- 5.1
20	- 1.4	- 2.6	- 4.75
25	- 0.25	- 1.5	- 2.4
30	+ 0.70	- 0.4	- 1.2
40	+ 2.4	+ 1.40	+ 2.0
50	+ 3.3	+ 3.90	+ 4.30
60	+ 3.90	+ 4.6	+ 5.55
70	+ 4.45	+ 5.2	+ 6.1
80	+ 4.95	+ 5.75	+ 6.7

SENSOR CALIBRATION

SENSOR: VERTICAL

VELOCITY (kt)	OUTPUT DIFFERENTIAL PRESSURE (INCHES OF H_2O)		
	P_+ = 6.5 PSI	P_+ = 8.7 PSI	P_+ = 10.8 PSI
-80	-11.05	-14.4	-18.1
-70	-10.6	-13.7	-17.5
-60	- 9.7	-13.0	-16.75
-50	- 9.3	-12.4	-16.1
-40	- 8.5	-11.7	-15.3
-30	- 7.9	-10.35	-13.6
-25	- 6.9	- 9.2	-12.1
-20	- 6.0	- 8.2	-11.1
-15	- 4.9	- 7.2	-10.1
-10	- 4.35	- 6.6	- 9.3
- 5	- 3.7	- 5.9	- 9.0
0	- 3.55	- 5.7	- 8.8
0	- 3.55	- 5.7	- 8.8
5	- 3.2	- 5.4	- 8.4
10	- 2.6	- 4.3	- 7.6
15	- 2.0	- 4.0	- 7.0
20	- 1.0	- 2.8	- 5.5
25	- 0.45	- 1.85	- 4.2
30	+ 0.40	- 1.05	- 2.8
40	+ 3.3	+ 1.3	- 0.6
50	+ 5.25	+ 4.5	+ 2.9
60	+ 5.5	+ 6.2	+ 6.2
70	+ 6.0	+ 6.6	+ 7.65
80	+ 6.35	+ 7.2	+ 8.1

SENSOR CALIBRATION

SENSOR: SIDESLIP

VELOCITY (kt)	OUTPUT DIFFERENTIAL PRESSURE (INCHES IN H_2O)		
	P_+ = 6.5 PSI	P_+ = 8.7 PSI	P_+ = 10.8 PSI
-80	-10.8	-14.2	-18.35
-70	-10.35	-14.15	-17.8
-60	-10.1	-13.45	-15.3
-50	- 9.35	-10.6	- 9.7
-40	- 5.9	- 6.1	- 6.45
-30	- 3.3	- 3.8	- 4.55
-25	- 2.4	- 3.15	- 3.75
-20	- 1.8	- 2.6	- 3.15
-15	- 1.2	- 2.0	- 2.55
-10	- 0.85	- 1.75	- 2.4
- 5	- 0.7	- 1.5	- 1.85
0	- 0.45	- 1.25	- 1.65
0	- 0.45	- 1.4	- 1.75
5	- 0.2	- 1.05	- 1.6
10	+ 0.3	- 0.9	- 1.35
15	+ 0.1	+ 0.1	- 0.3
20	+ 1.7	+ 1.1	+ 0.8
25	+ 2.45	+ 2.05	+ 2.0
30	+ 3.4	+ 2.85	+ 2.95
40	+ 6.1	+ 5.1	+ 5.25
50	+ 8.6	+ 7.8	+ 7.4
60	+ 9.9	+12.0	+13.9
70	+10.4	+12.85	+15.8
80	+11.2	+13.5	+16.4

PANEL METER SCALING
AT 6.5 PSI

SENSOR: FORWARD-REVERSE

VELOCITY (kts)	OUTPUT VOLTAGE	
	LOW SENSITIVITY	HIGH SENSITIVITY
-30	-4.55	
-25	-4.25	
-20	-3.6	
-15	-3.05	
-10	-2.8	-4.5
- 5	-2.65	-3.4
0	-2.5	-2.5
5	-2.5	-2.4
10	-2.0	+1.3
15	-1.55	+4.5
20	-1.2	
25	-0.6	
30	+0.05	
35	+0.45	
40	+0.85	
45	+1.1	
50	+1.3	
55	+1.45	
60	+1.6	
65	+1.8	
70	+1.95	
75	+2.05	
80	+2.2	

PANEL METER SCALING
AT 6.5 PSI

SENSOR: SIDESLIP

VELOCITY (kts)	OUTPUT VOLTAGE	
	LOW SENSITIVITY	HIGH SENSITIVITY
-60	-4.2	
-55	-4.0	
-50	-3.6	
-45	-3.2	
-40	-2.1	
-35	-1.3	
-30	-1.0	
-25	-0.7	
-20	-0.3	-4.0
-15	0.0	-2.2
-10	+0.2	-0.8
- 5	+0.3	0.0
0	+0.4	+0.4
5	+0.45	+1.1
10	+0.55	+2.2
15	+0.9	
20	+1.3	
25	+1.7	
30	+2.0	
35	+2.7	
40	+3.4	
45	+4.0	
50	+4.4	
55	+4.6	
60	+4.8	

PANEL METER SCALING
AT 6.5 PSI

SENSOR: VERTICAL

VELOCITY (kts)	OUTPUT VOLTAGE	
	LOW SENSITIVITY	HIGH SENSITIVITY
-30	-5.5	
-25	-4.8	
-20	-4.1	
-15	-3.55	
-10	-3.05	-4.8
- 5	-2.7	-3.1
0	-2.7	-2.7
5	-2.45	-1.4
10	-1.9	+1.3
15	-1.5	+3.5
20	-0.9	
25	-0.3	
30	+0.1	
35	+0.9	
40	+2.3	
45	+3.0	
50	+3.5	
55	+3.7	
60	+3.8	
65	+3.9	
70	+4.05	
75	+4.25	
80	+4.4	

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