AD-755 374

True Airspeed Sensor for V/STOL Aircraft

Air Force Flight Dynamics Laboratory

DECEMBER 1972

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AFFDL-TR-72-131

TRUE AIRSPEED SENSOR
FOR V/STOL AIRCRAFT

K. W. McELREATH, CAPTAIN, USAF

TECHNICAL REPORT AFFDL-TR-72-131

DECEMBER 1972

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AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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AIR FORCE/56780/25 January 1973 — 450

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Air Force Avionics Laboratory Air Force Systems Command	2a. REPORT SECURITY CLASSIFICATION 2b. GROUP

3. REPORT TITLE

TRUE AIRSPEED SENSOR FOR V/STOL AIRCRAFT

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

K. W. Elreath, Captain, USAF

6. REPORT DATE December 1972	7a. TOTAL NO. OF PAGES ~~27~~ 34	7b. NO. OF REFS

8a. CONTRACT OR GRANT NO. b. PROJECT NO. 643A c. Task 643A0 d.	9a. ORIGINATOR'S REPORT NUMBER(S) AFFDL-TR-72-131 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Flight Dynamics Laboratory Wright-Patterson Air Force Base, Ohio

13. ABSTRACT

One factor which has hindered the development of an effective low-speed flight control capability for helicopters and other V/STOL aircraft is the lack of an accurate airspeed sensor which will operate at speeds below 40 knots. One device which does meet this requirement is an advanced electronic true airspeed sensor developed by J-Tec Associates of Cedar Rapids, Iowa. Under the USAF Flight Dynamics Laboratory's Advanced Development Program 643A, "Tactical Airlift Technology," a J-Tec Associates true airspeed sensor has been evaluated for use by low-speed aircraft, using a Sikorsky CH-3E helicopter as a test bed.

The results of the wind-tunnel and flight testing conducted at Wright-Patterson AFB showed that the sensor has excellent characteristics particularly in the low-speed flight regime, where it maintained its accuracy even at high yaw and pitch angles.

This report concludes that the system has capabilities which will make it effective as an airspeed sensor at low velocities. Recommendations are presented to guide further testing and development to produce a system for operational use.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
True Airspeed Sensor						
V/STOL						
Helicopter						
Airspeed Sensor						

*U.S.Government Printing Office: 1973 — 759-490/311

AFFDL-TR-72-131

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FOREWORD

This report presents the results of a development and evaluation effort conducted by the Air Force Flight Dynamics Laboratory (AFFDL/FGF) during the period of 1 July 1970 through 31 March 1972. The work was a portion of AFFDL's Advanced Development Program 643A, Tactical Airlift Technology.

The system concepts and mechanization were developed by J-Tec Associates, Inc., Cedar Rapids, Iowa.

The author wishes to acknowledge the significant assistance rendered during the flight test phase of the program by Messrs. Ralph Thomas and James Klein of Collins Radio Company, program support contractor.

This report was submitted by the author October 1972.

This report has been reviewed and is approved.

Tracy A. Scanlan

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ABSTRACT

One factor which has hindered the development of an effective low-speed flight control capability for helicopters and other V/STOL aircraft is the lack of an accurate airspeed sensor which will operate at speeds below 40 knots. One device which does meet this requirement is an advanced electronic true airspeed sensor developed by J-Tec Associates of Cedar Rapids, Iowa. Under the USAF Flight Dynamics Laboratory's Advanced Development Program 643A, "Tactical Airlift Technology," a J- Tec Associates true airspeed sensor has been evaluated for use by low-speed aircraft, using a Sikorsky CH-3E helicopter as a test bed.

The results of the wind-tunnel and flight testing conducted at Wright-Patterson AFB showed that the sensor has excellent characteristics particularly in the low-speed flight regime, where it maintained its accuracy even at high yaw and pitch angles.

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SUMMARY

For effective velocity control of an aircraft, the pilot must know what his actual airspeed is. Accuracy becomes most important in the low-speed flight regime, where aircraft stability and lift characteristics change rapidly with airspeed.

The AFFDL/FGF test program included testing of a J-Tec Associates True Airspeed Sensor (TAS) under various flow conditions in the Vertical Wind Tunnel at Wright-Patterson AFB, and in-flight testing on a CH-3E Helicopter. The conclusions of this test effort are that the sensor's characteristics make it attractive for use in low-airspeed sensing, because of its response time, insensitivity to yaw and pitch angles, and useful range. Further testing is recommended to produce an operationally suitable sensor system.

SECTION II

INTRODUCTION

The goal of the CH-3E flight test program under ADP 643A was to develop an all-weather terminal area operations capability for V/STOL tactical aircraft, including the necessary guidance and control sensors. One deficiency which appeared early in the program was the lack of reliable airspeed data below 40 knots. The CH-3E was equipped with two airspeed references, both using pitot-static dynamic pressure (q) sensing. One is the standard airspeed system which displays to the pilot the indicated airspeed (IAS), and the other is a Kollsman computing system which corrects IAS for variations in air density (ρ) to derive true airspeed (TAS).

Pitot-static systems have the following disadvantages for use on V/STOL aircraft:

(a) Since such systems rely on q as the sensed parameter, the system accuracy degrades rapidly at low speeds ($q \triangleq 1/2\rho V^2$, where V = TAS). The CH-3E flight manual (AF T.O. 1H-3(C)C-1), for example, has an airspeed correction chart which the pilot uses to adjust his indicated airspeed (IAS) to get calibrated airspeed (CAS). This chart is reproduced in Figure 1. As may be noted, at 20 knots IAS in level flight the error is 30%.

(b) At low speeds, angles of yaw and pitch to the relative wind are often high, and pitot-static sensing is adversely affected.

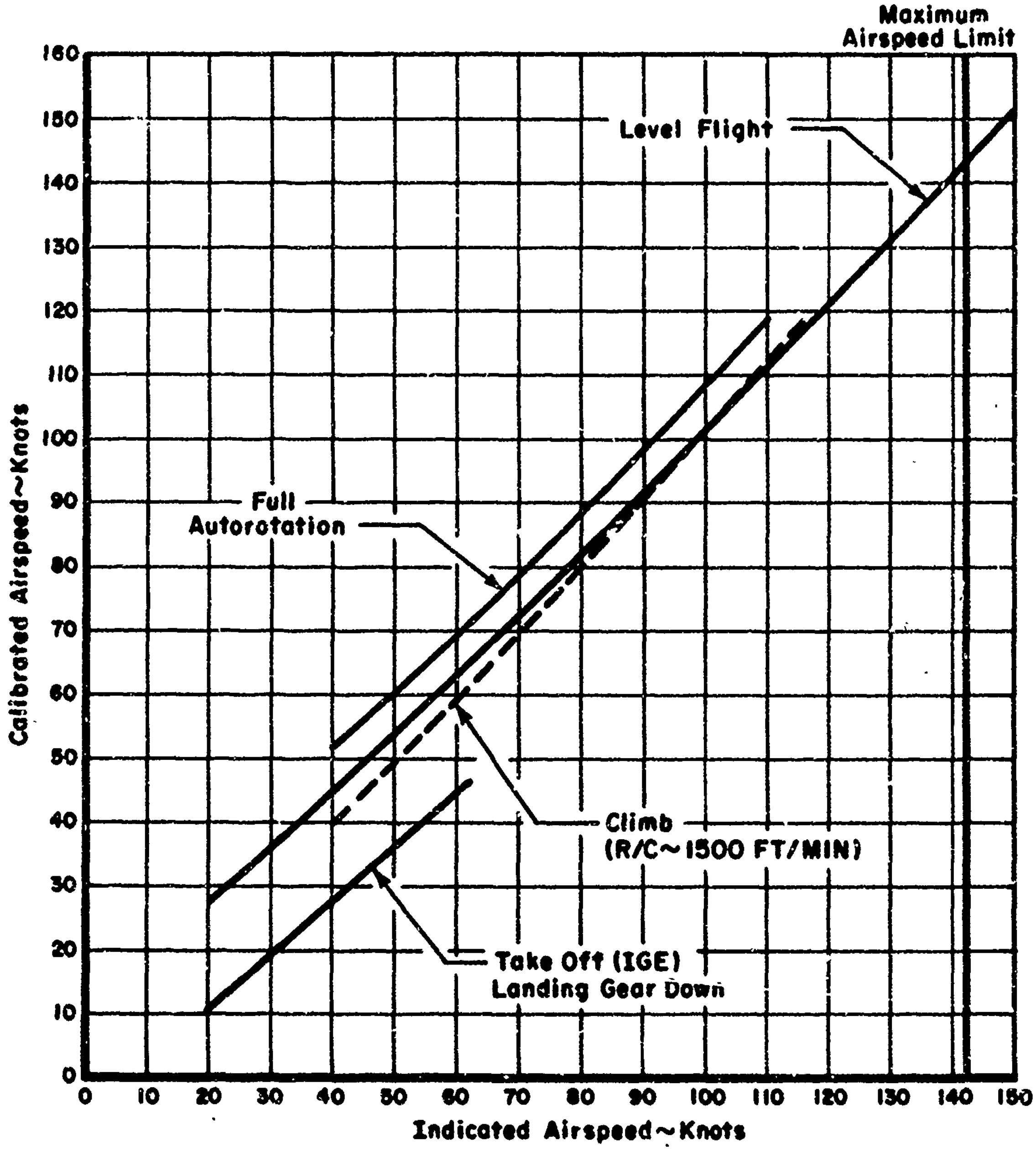

Figure 1. Pitot-Static Correction Chart

(c) Since it is a pressure device, the output of a pitot-static system is generally not suitable for automatic airspeed control. It has time lags on the order of five seconds, and the output must be converted to an electronic signal.

In order to find an alternate data source without the low-speed deficiencies of pitot-static sensing systems, one J-Tec Associates TAS sensor system was procured by AFFDL for testing in both wind-tunnel and flight environments.

The wind-tunnel testing was completed and the results documented in AFFDL-TM-70-1-FGS, December 1970. Significant portions of those results are reproduced herein to illustrate the sensor's output linearity and its insensitivity to yaw and pitch angle variations.

In July 1971 the system was installed on a CH-3E helicopter at Wright-Patterson AFB. It was configured to use aircraft power and have its output voltage displayed as TAS on an indicator on the copilot's instrument panel.

Through several modifications the system was adapted so that it met the requirements for a V/STOL aircraft TAS sensor system.

SECTION III

SENSOR THEORY OF OPERATION

The J-Tec Associates TAS sensor operates on the aerodynamic phenomenon of vortex shedding from a bluff body. In past empirical studies it has been found that the frequency of the shed vortices is proportional to the velocity of the fluid, regardless of the fluid density. The relationship between the vortex frequency and the fluid velocity referred to as the Strouhal number is defined as:

$$S = \frac{Kfd}{V} \quad \text{or} \quad V = \frac{Kfd}{S}$$

S - Strouhal number

K - empirical constant

f - vortex frequency, in cycles per second

d - diameter of the cylinder or rod used to generate the vortices, in feet

V - fluid velocity (TAS), in feet per second

The Strouhal number is independent of fluid density and is constant for Reynolds numbers ranging from 40 to approximately 10^4. For speed regimes from 10 mph to 150 mph the J-Tec sensor is therefore also independent of fluid viscosity. With the same electronics package, the useable velocity range can be shifted by changing the rod diameter.

Since the Strouhal number is independent of fluid viscosity and density, the above relationship shows that the vortex frequency varies linearly with velocity for a fixed rod diameter. Through electronic processing of the frequency change, an analog or digital signal can be supplied to an indicator for displaying TAS to the pilot.

In the J-Tec sensor, a cylindrical rod is used to generate the vortices. The shedding frequency is sensed as it modulates an acoustical carrier signal generated by a crystal contained in one of the struts and received by a crystal in the opposite strut, as shown in Figure 2. The transmitted signal is modulated two cycles per vortex pair. In a digital system, this signal could be used directly. In the present system, a frequency to analog converter provides a direct current signal with its output voltage proportional to fluid velocity, or TAS. A block diagram of the signal flow is shown in Figure 3.

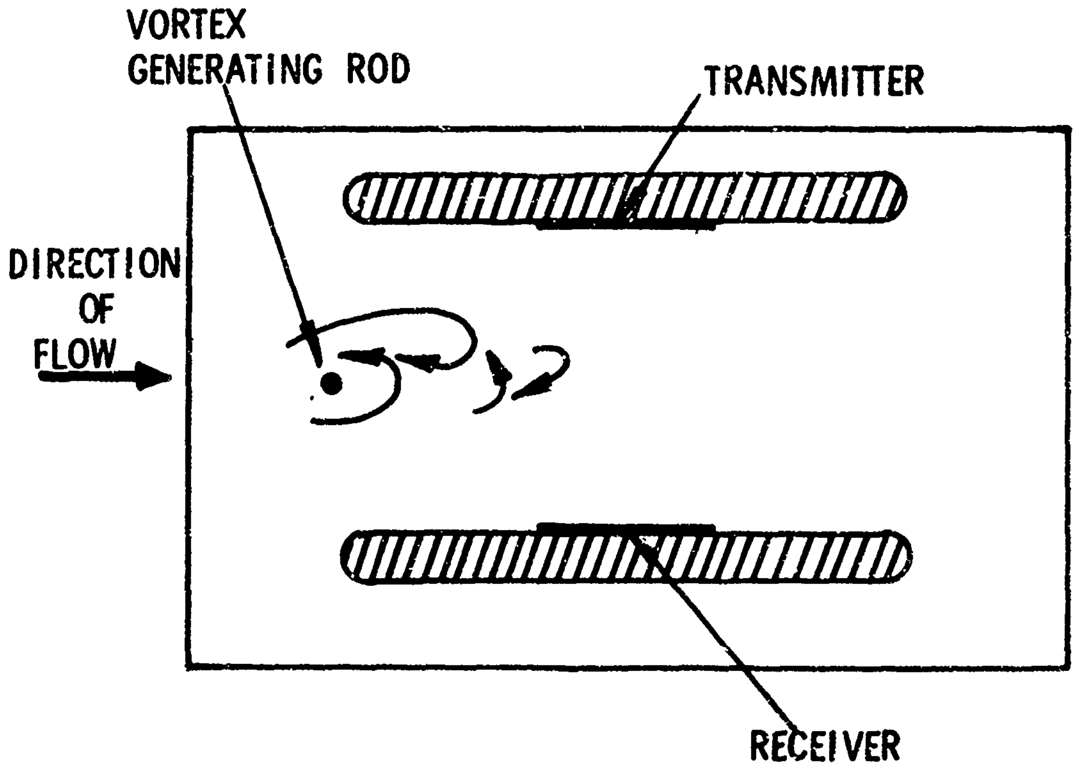

Figure 2. J-Tec Sensor Operation

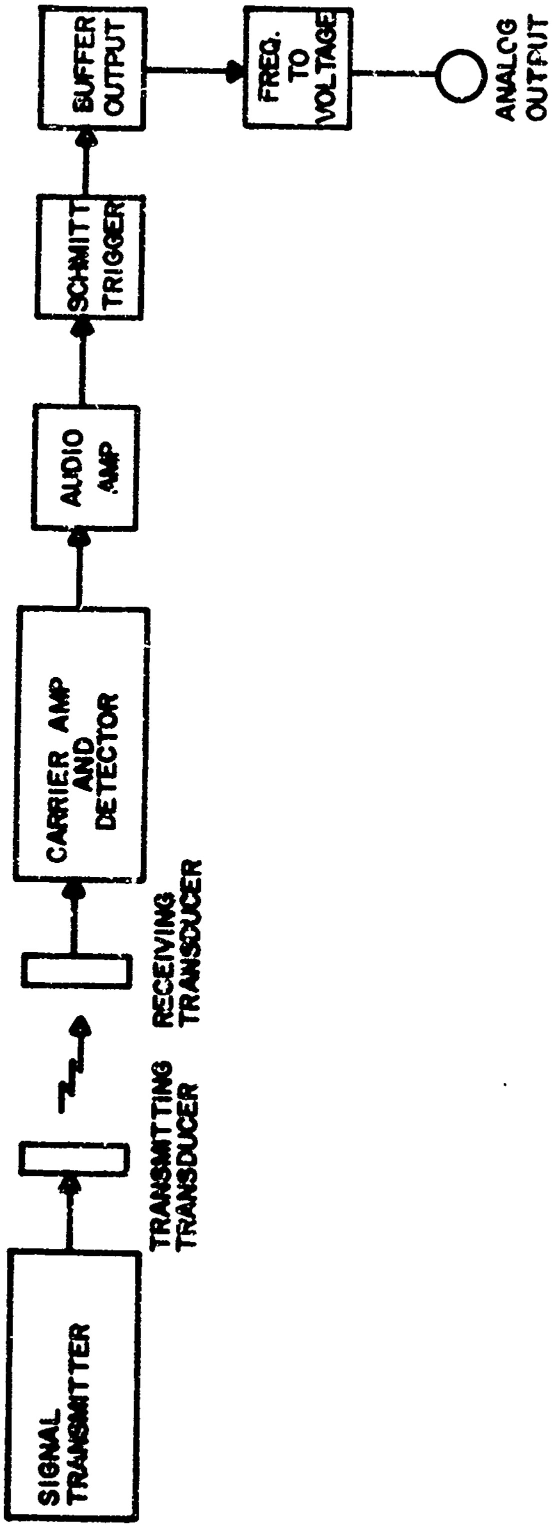

Figure 3. Block Diagram of J-Tec Sensor

SECTION IV

WIND-TUNNEL TESTING

1. APPARATUS

For actual flow calibration, the Vertical Wind Tunnel (VWT) at Wright Patterson AFB was used. It is a low-speed tunnel, used primarily for the testing of new parachute concepts. The tunnel was calibrated for a velocity range of 14 to 86 mph. Certain points within this velocity range were selected for J-Tec sensor data points. Sensor output voltages were recorded with a digital voltmeter and printer. The wind-tunnel velocity was measured with a sensitive pitot-static probe, calibrated for atmospheric conditions at the time of the test.

2. MEASUREMENTS

Data was recorded at velocities from 14 to 86 mph (12 to 75 knots), the useful range of the tunnel. Since the sensor output at zero velocity was known, a linear relationship from zero to 14 mph was assumed, indicated by dashed lines on the graph in Figure 4. The sensor output was recorded at points throughout the velocity range at many combinations of pitch and yaw angles, from zero to 80 degrees in pitch and from -40 to +40 degrees in yaw. In addition, the yaw and pitch angles were varied while the tunnel velocity was maintained at a constant value. The last element to be varied was the input voltage, to check the system's tolerance of voltage variations.

3. WIND-TUNNEL RESULTS

The complete results of the wind-tunnel testing are reported in AFFDL-TM-70-1-FGS, December 1970. The data from the three most significant test runs are shown in Figures 4, 5, and 6. Figure 4 presents the sensor output at 0° pitch and yaw over the tested velocity range. Figure 5 shows the variations in sensor output at constant velocity and different pitch angles, and Figure 6 shows the output at constant velocity but varying angles of yaw.

A chart of output vs. power supply voltages at constant velocity is not presented, but it was found to be essentially constant from 13.5 to 17 volts DC. Beyond these extremes the output varied.

From the results of the wind tunnel tests, it was determined that the sensor showed sufficient performance to warrant testing in flight. The results indicated that the output was linear over the range tested, was insensitive to pitch angles up to ± 40° and yaw angles up to ± 25°, and was not affected by minor input voltage fluctuations. It was decided to install the device on a CH-3E helicopter for flight testing and evaluation.

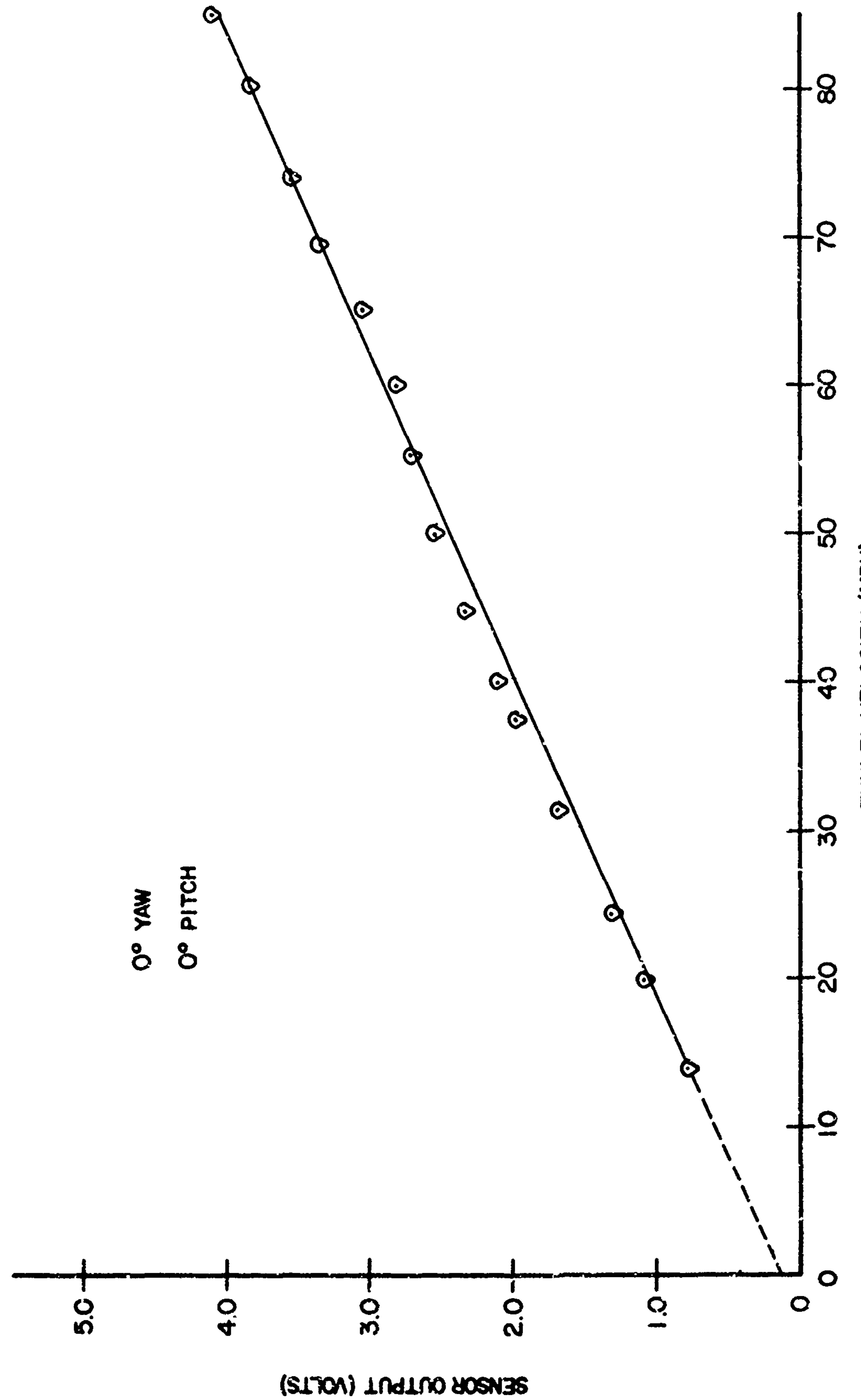

Figure 4. Sensor Output vs. Tunnel Velocity

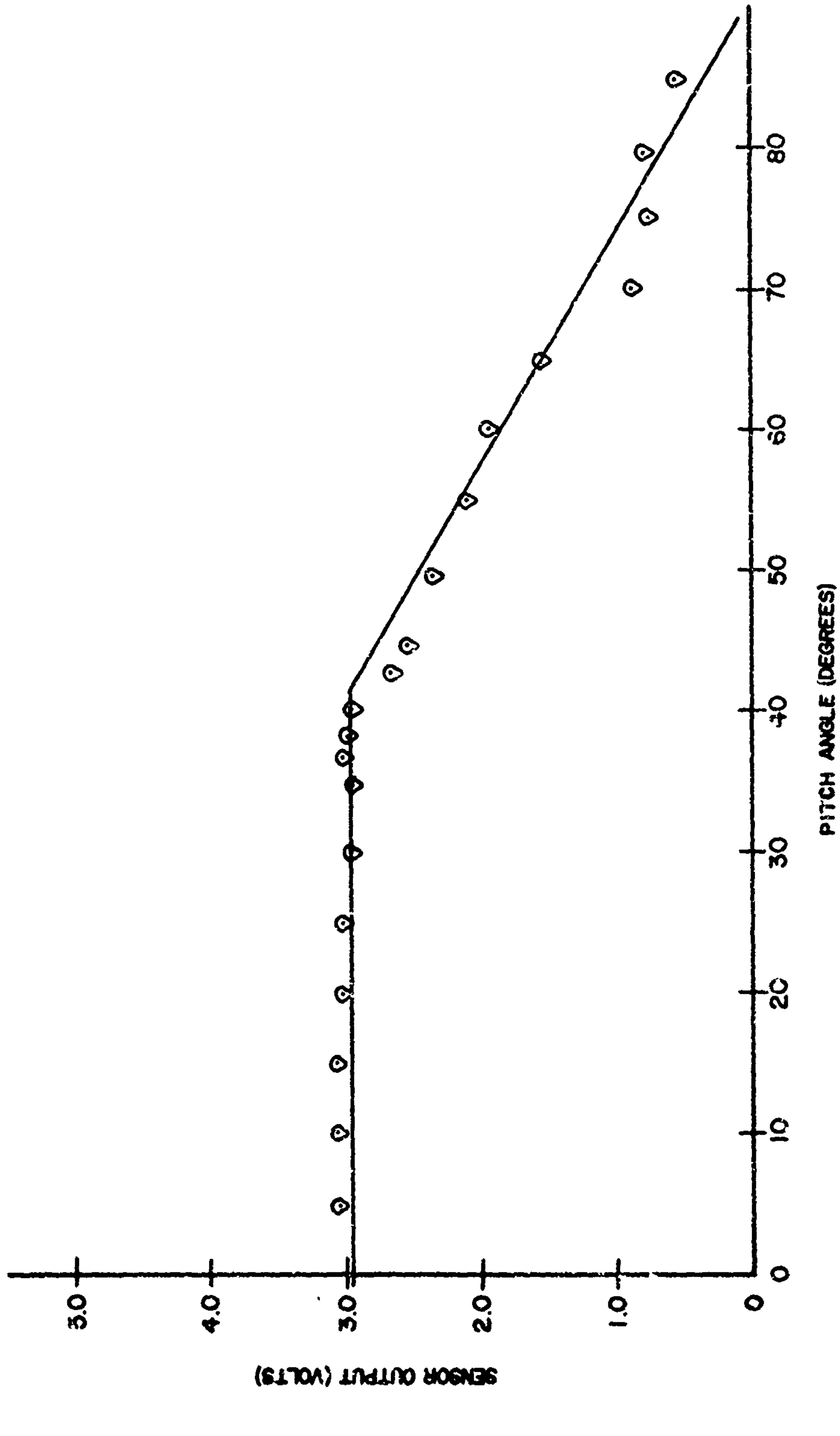

Figure 5. Sensor Output vs. Pitch Angle at Constant Velocity (≈60 KTAS)

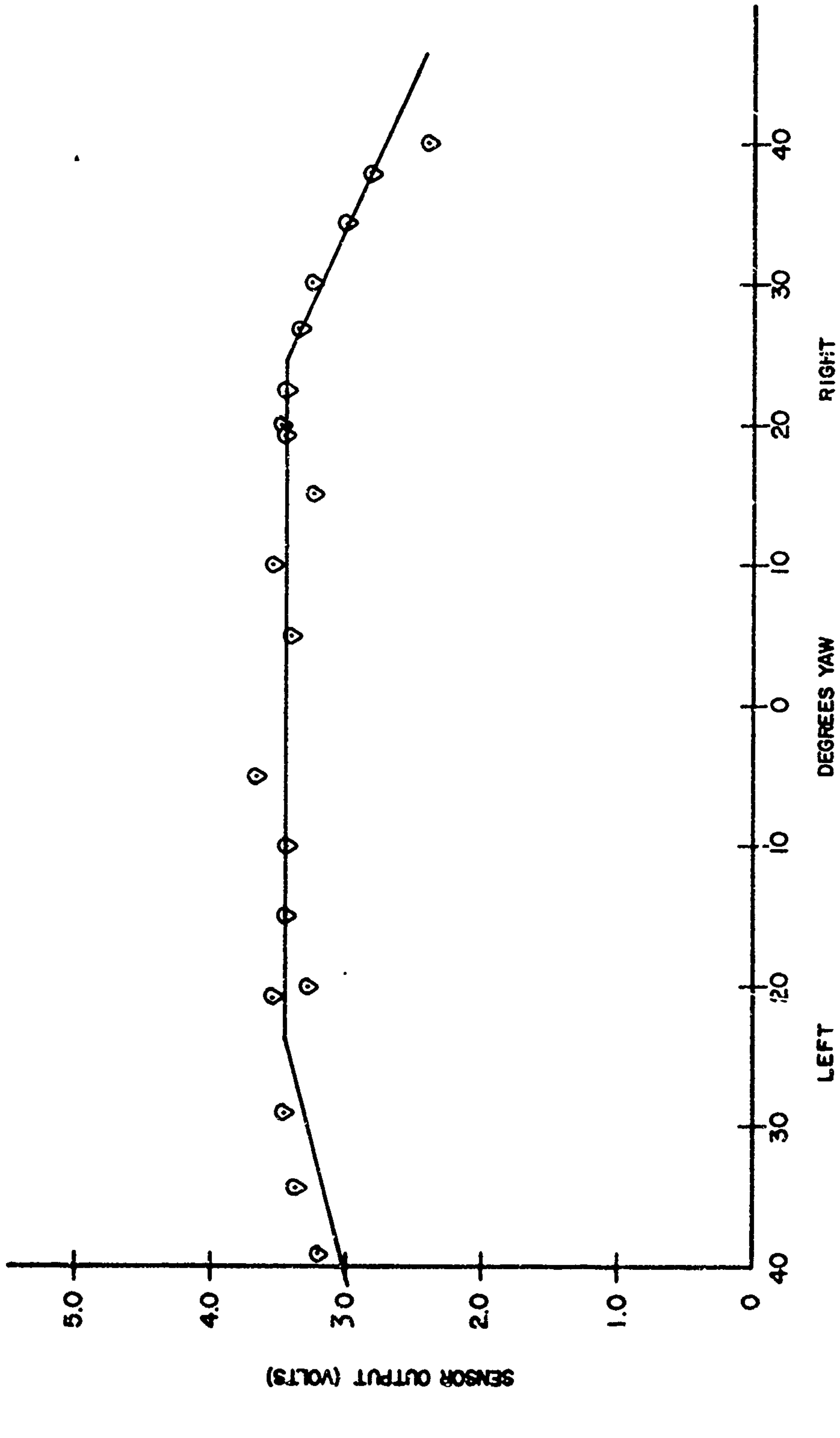

Figure 6. Sensor Output vs. Yaw Angle at Constant Velocity (≈60 KTAS)

SECTION V

CH-3E FLIGHT TESTING

1. SYSTEM CONFIGURATION DEVELOPMENT

In July 1971 the J-Tec Associates TAS system was installed for in-flight evaluation on a CH-3E helicopter, #62-12581. This helicopter was a test bed for advanced concepts in V/STOL aircraft control display systems.

Before the TAS system reached the point of being useable as a V/STOL flight parameter indicator, it was modified and reconfigured to overcome technical difficulties encountered. The following is a brief history of the stages of development during the flight test and evaluation.

a. Configuration I

In the initial installation, the TAS sensor and electronics package were used as delivered by the manufacturer. As such, several deficiencies were noted in advance of the testing: (1) the basic sensor was bidirectional and would not distinguish between forward and rearward airflows, which could lead to ambiguities at or near zero velocity; (2) the electronics box, being prototype hardware, was not up to the environmental stress standards normally required of flight hardware; and (3) the electronics package was limited by frequency response to velocities less than approximately 75 knots, although actual wind-tunnel testing had not been performed above that speed to verify that fact.

For use on the aircraft, an adaptor box was built to change 400 cycle, 110 volt AC power into the 15 volts DC required by the TAS system. For recording purposes, the aircraft was already equipped with a Honeywell Model 1108 Visicorder, which was used to trace the sensor output voltage. In addition, a Honeywell radar altitude indicator was modified to serve as a TAS indicator on the copilot's instrument panel, as shown in Figure 7. Note that an expanded scale is used on the indicator from 0 to 50 knots to improve readability at these airspeeds. Flight at these low speeds in a V/STOL aircraft is critical from a safety and controllability standpoint; thus, the need is greater that the pilot be able to easily discern small changes in airspeed. The position for the external sensor was chosen to be under the starboard side of the nose access door, as shown in Figure 8. This location had no protrusions ahead of it to disturb the airflow and cause vortices which would give false TAS readings.

Since the CH-3E already was equipped with a standard Kollsman TAS system, which corrected pitot-static IAS for density effects, a switching circuit was built to use that system as a high-speed TAS information source to complement the J-Tec's low-speed output. When the output of the Kollsman sensor was below 40 knots, the logic would select the J-Tec sensor for indication. In addition, since the dynamic response of the J-Tec sensor is extremely fast, the indicator needle was time-lagged so the high frequency flow changes would not be observed by the pilot.

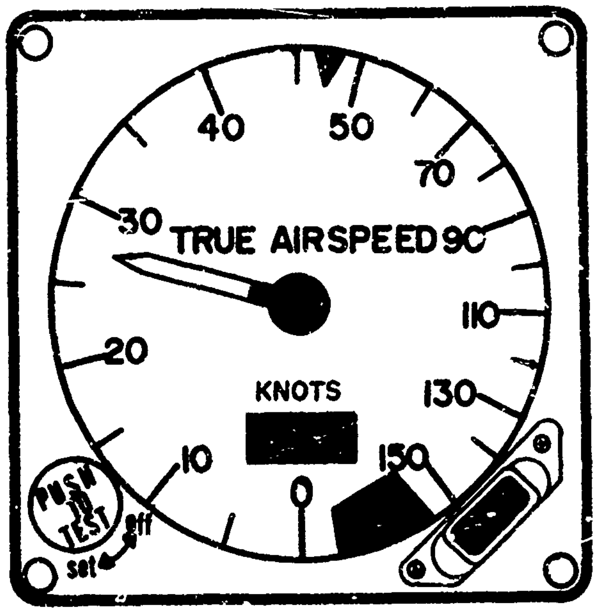

Figure 7. TAS Indicator Modified from Radar Altimeter

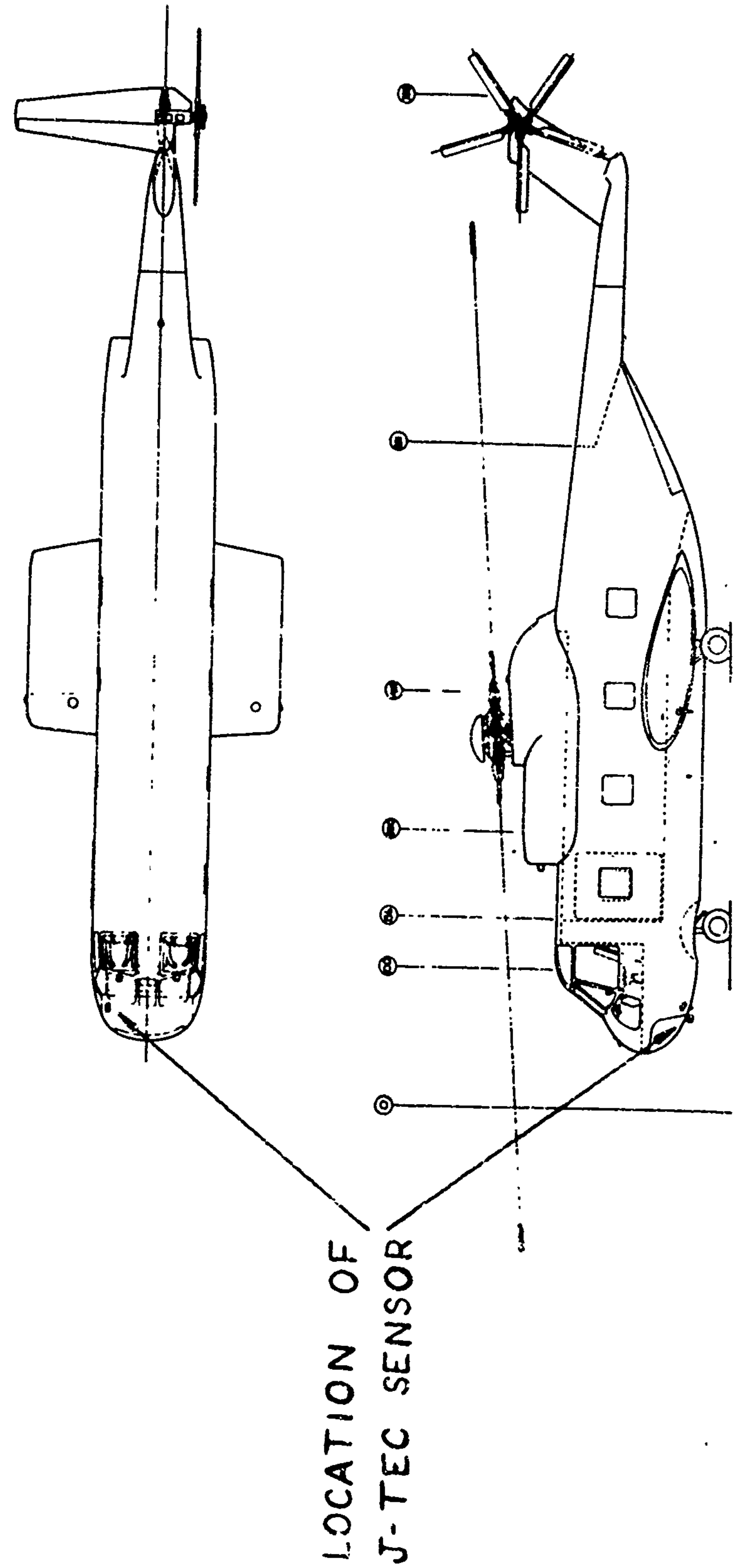

Figure 8. J-Tec Sensor Location on the CH-3E Helicopter

Initial flights with Configuration I showed that the system was indeed useable as a flight parameter indicator. However, at speeds below 10 knots TAS, the Kollsman output became erratic in ground effect, causing the logic to trip. After a cursory system accuracy check a system modification was made to extend the velocity range of the J-Tec Sensor and eliminate the Kollsman and logic circuitry.

b. Configuration II

J-Tec Association, Inc. was asked to develop an electronics package which would be accurate and responsive from 0 to 250 knots, to eliminate the need for the Kollsman switching. In addition, the circuitry was to be incorporated in a flightworthy package, using a one-quarter, short, low ATR box supplied by Collins Radio Co. A new external sensor was also built to give an output in one direction only, to eliminate the ambiguity at very low speeds. A new TAS indicator, developed by Canadian-Marconi Co., was used with this system, so that a commanded speed could also be displayed. The hardware for Configuration II is shown in Figure 9. This is the final system configuration tested on the CH-3E.

2. ACCURACY CHECK

Although absolute accuracy of the sensor was not a goal of the test program as such, in March 1972 a system accuracy check of Configuration I was made, using the Digital Optical Tracking System (DOTS) at Wright-Patterson AFB.

Runs were made at 10, 20, 30, 40, 50, 60, 80, 100, and 110 knots indicated TAS. The actual aircraft velocity, computed by DOTS and

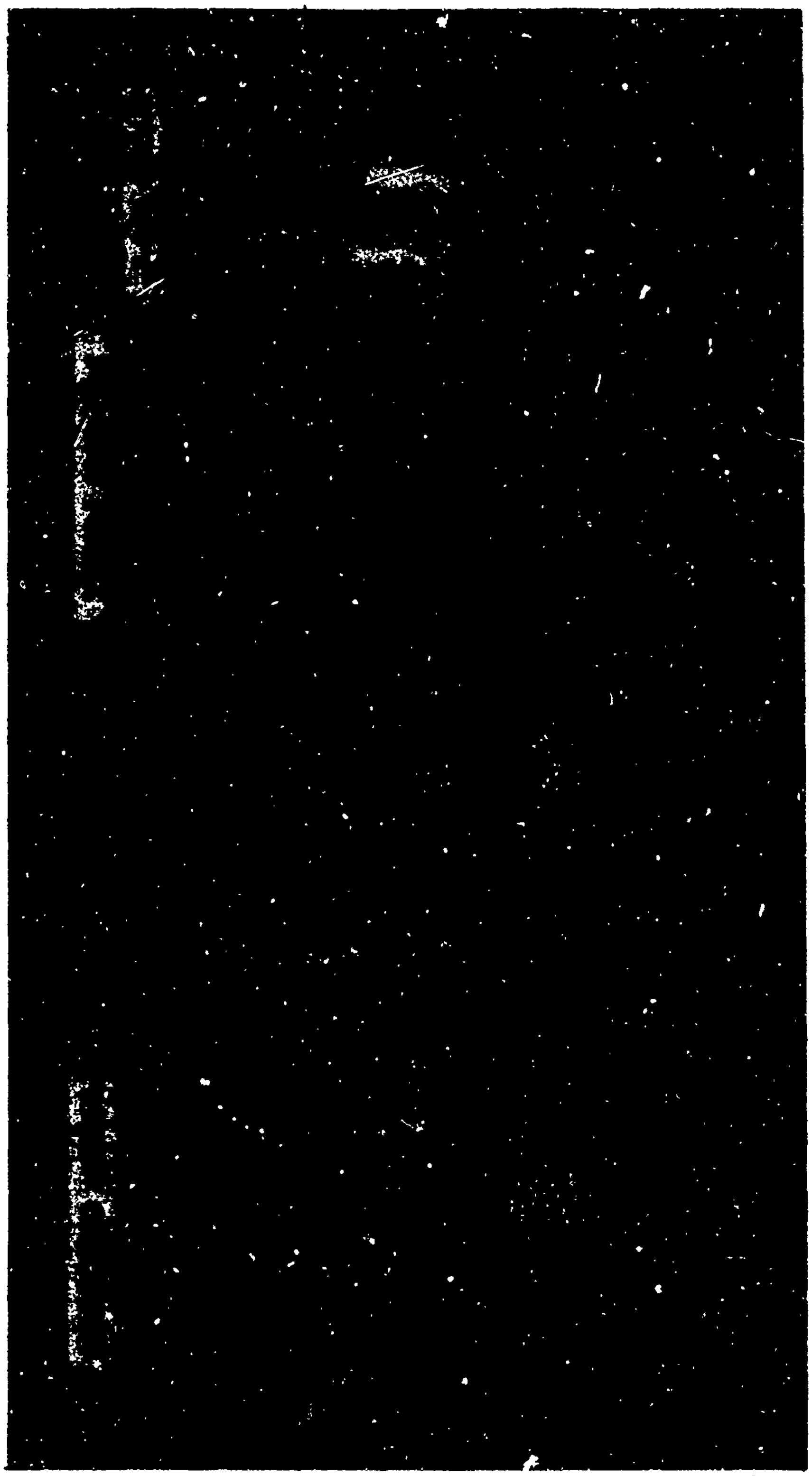

Figure 9. TAS System Final Configuration

corrected for reported steady-state wind conditions, was compared with on-board traces of the TAS system output. Data was taken over runs of 30 seconds each and average for comparison. The DOTS recorded a position data point three times per second. Speeds below ten knots or above 100 could not be recorded on board due to analog scaling and the malfunction of the Kollsman logic trip scheme below ten knots.

SECTION VI

FLIGHT TEST RESULTS

Table I presents results for the runs made, showing the nominal TAS, the average DOTS TAS for the run, and the average recorded TAS on the aircraft. Pilot techniques in flying a nominal airspeed improved during the test so that oscillations and variations were less in the later runs. The effect of this improvement resulted in closer correlation between data, as may be noted in Table I. Since the output of the J-Tec sensor is of primary interest, several representative on-board recordings are reproduced in Figures 10 and 11. Figure 10 represents data for run number 15, taken at 20 knots TAS, with small variations about the nominal TAS. Figure 11, which is data from run number 16 at 30 knots, shows the amount of variance of TAS during that run. Table I shows that the average TAS is more in error for this run, also.

Figure 12 presents data from 6K TAS to 140 KTAS using Configuration II. This data shows a significant improvement in airspeed indication, particularly in the low speed range (6-40K).

TABLE I

TRUE AIRSPEED CALIBRATION RUN RESULTS

RUN NR.	NOMINAL TAS KNOTS	AVG DOTS TAS KNOTS	AVG RECORDED TAS KNOTS*
1	40	40.90	32
2	40	46.50	34
3	40	41.99	38
4	50	57.67	50
5	50	53.03	58
6	60	63.87	55
7	60	62.23	54
8	80	79.94	73
9	80	78.85	73
10	110	107.07	--
11	110	104.46	--
12	100	95.14	95
13	100	97.37	--
14	10	5.16	11
15	20	21.15	20
16	30	35.95	26
17	10	1.54	--
18	20	12.71	15
19	30	30.48	30
20	40	44.70	40
21	50	54.13	48
22	40	41.32	38
23	50	51.80	48
24	60	62.43	57
25	60	60.16	57
26	80	78.65	74
27	80	76.52	73
28	100	98.84	98
29	100	96.51	97
30	20	23.11	21
31	30	33.38	32
32	15	9.48	15
33	20	26.84	26
34	30	31.36	32

*NOTE: J-Tec below 40 KTAS, Kollsman above 40 KTAS

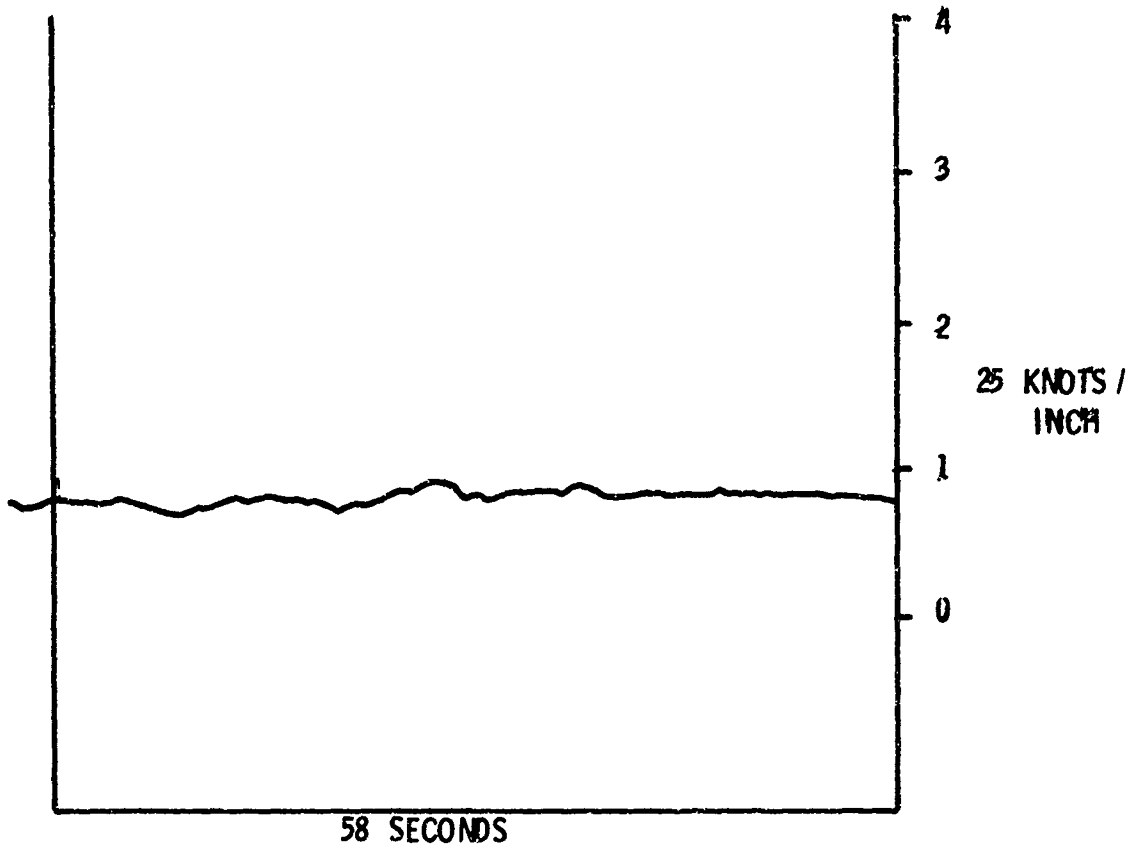

Figure 10. Data for Run 15 - 20 KTAS

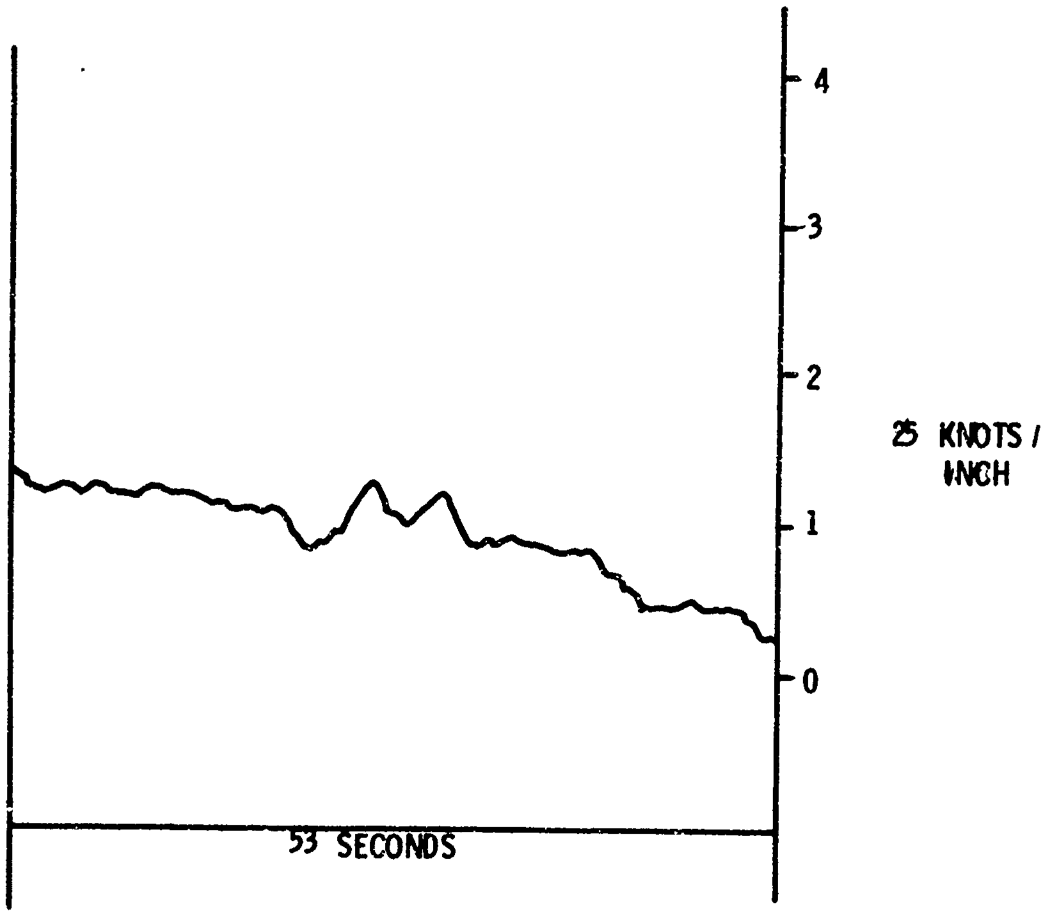

Figure 11. Data for Run 16 - 30 KTAS

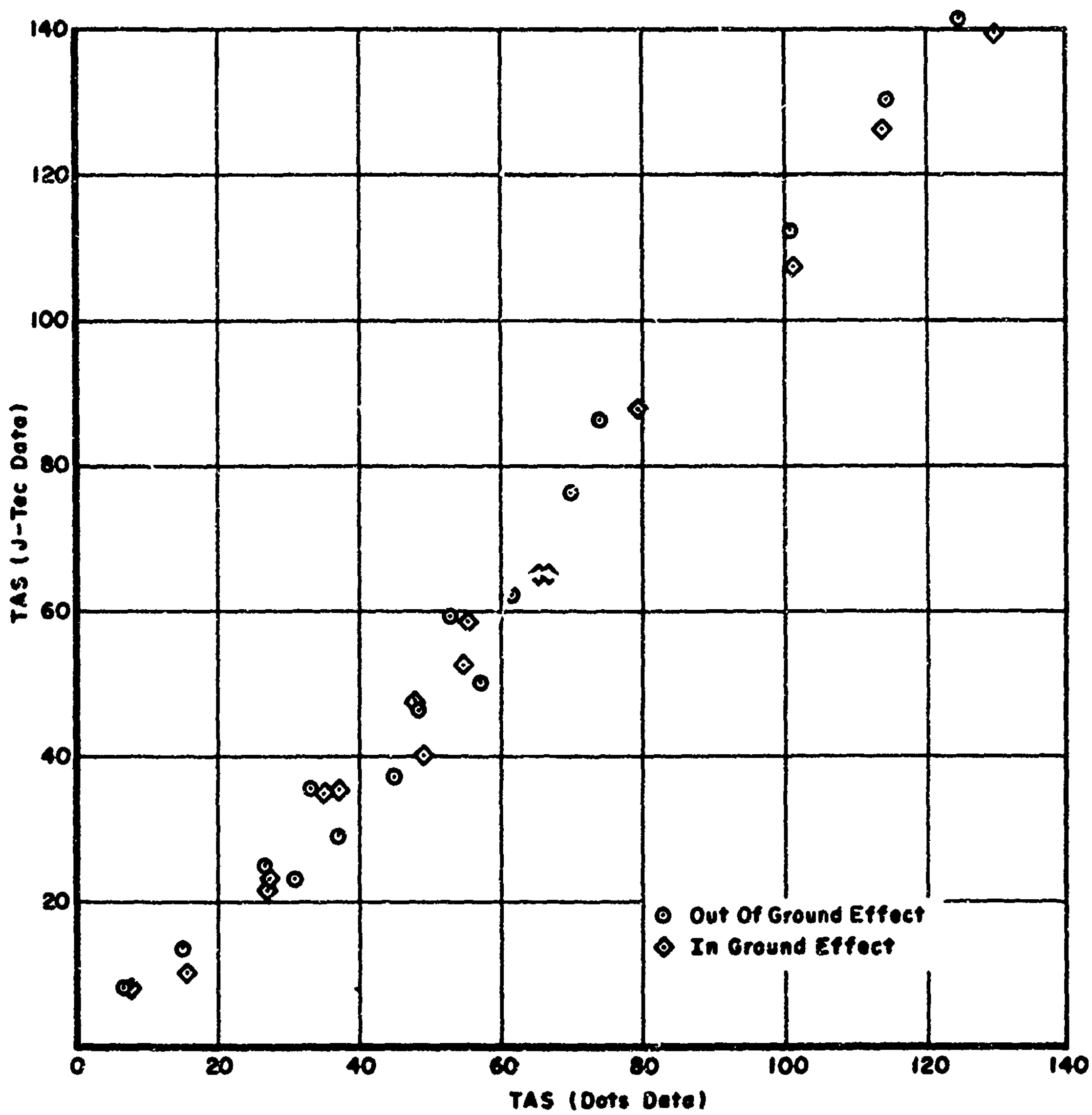

FIGURE 12. J-TEC TAS ERROR DATA

SECTION VII

CONCLUSIONS

For use as an aircraft TAS sensor, particularly in the low-speed region of V/STOL flight, the qualities of the J-Tec, have been shown to be superior to those of other types of sensors. These qualities are as follows:

(1) Velocity range 0 to 250 knots.

(2) The scale of the sensor output is directly proportional to the velocity over the entire range, not the square of the velocity, as in pitot-static systems.

(3) It is insensitive to yaw angles within $\pm$ 25° and to pitch angles within $\pm$ 40°.

(4) It should measure true airspeed, regardless of variation in the normal flight regime of temperature, pressure, density, or viscosity.

(5) It gives an electronic output, either digital or analog, which can be displayed or employed in schemes for manual or automatic flight control.

(6) The external sensor is small and light and causes a minimum of disturbance to the flow about the aircraft. It can be easily configured for anti-icing by heating the sensor elements.

(7) It is compatible with aircraft power systems. It is insensitive to voltage variations up to 25% from nominal, and it uses very little power.

SECTION VIII

RECOMMENDATIONS

Since the primary area of concern in the AFFDL CH-3E V/STOL IFR Control/Display Technology Development Program is aircraft controls, displays, and guidance, the time and effort devoted to testing and evaluation of the J-Tec Assocaited TAS sensor was insufficient to allow any statistical evaluation of its performance. However, using the system in flight will provide experience adequate to evaluate it for its operational potential. From the limited CH-3E flying acccmplished prior to publishing this report, the following recommendations are made for further work:

(1) Test to determine the optimum location for the external sensor to minimize velocity perturbations due to rotor-induced flow.

(2) Test to determine the effects, if any, of ground effect upon the sensor output. This phenomenon appears to affect pitot-static sensors more than the J-Tec TAS sensor.

(3) Further develop the system to include anti-icing provisions.

The advantages of the J-Tec Associates TAS system for low-speed flight make it attractive for use on present and future V/STOL aircraft, where airspeed information to the pilot is a critical, but heretofore unavailable, flight parameter.