in these areas could seriously affect simulation validation and simulator findings, especially in VTOL phases of flight.

Investigations of acceptable cockpit controls have proved the value of the research simulator for such purposes. The simulator provided a reasonably quick and efficient tool in the investigations of a number of promising schemes by several experienced test pilots. The problem of demonstrating the advantages or deficiencies of various schemes was equally simplified.

The simulator of this type also proved to be an excellent tool in demonstrating the VTOL transport concept to a large number of people of varying interests and experience. It proved to be a useful device in promoting the VTOL concept to both the technical and civil authorities, when a particular aspect of civil VTOL transport operation could be quickly and often, convincingly, demonstrated. In addition, this could be achieved economically and in complete safety.

The pilots who participated in these investigations were chosen with particular care and all had sufficient simulator flying experience to give a balanced assessment. It is suggested that airline pilots should be invited to participate in future VTOL transport research simulator trials.

However, where the simulation validation is concerned, more general experimental work is still needed, and more efficient interchange of information is required between research and flight centers.

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A Fluidic Low-Speed Air-Speed Indicator

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Crossflow and parallel flow techniques were investigated. The parallel flow technique was chosen. A prototype has been wind-tunnel tested. It has a near linear response from 0.3 to 90 fps. This sensor is light in weight, simple in operation and has no moving parts. Efforts are underway to optimize the sensor performance and develop a flightworthy unit. Reynolds number scaling was used to relate the sensors behavior in water with colored dye as a tracer.

Introduction

THE advent of the V/STOL aircraft has generated the need for instrumentation unique to the operation of these aircraft. One of the parameters which would be particularly useful during takeoff and landing is relative wind speed. Because of the nature of these aircraft, very low air speeds in all three orthogonal directions occur during their operation near the ground. At present, no practical wind sensing instruments are available for this purpose. The conventional pitot tube air-speed sensor is simple and reliable and performs very well down to the takeoff and landing speeds of conventional aircraft. However it is generally unsuited for measuring air speeds below about 20 or 30 mph.

Several other concepts have been developed for sensing low air speeds. The concepts involve hot wire or film instruments, ultrasonic pulse, ion tracers, cup anemometers and two pitot tubes mounted on the ends of a spinning boom. These concepts are either cumbersome, unreliable or have a high threshold of sensitivity. What is needed is a technique for measuring very low wind velocities which is sufficiently rugged, yet markedly lower in cost and complexity than an equivalent electronic or electro-mechanical technique.

Two concepts using fluidic techniques were formulated for measuring very low wind speeds. In these concepts, the wind is impressed on an air jet which produces an amplified pressure signal directly related to wind speed. The two concepts are categorized as: 1) parallel-flow sensors in which an air power stream is directed parallel to the wind component being measured. 2) cross-flow sensors in which an air power stream is directed perpendicular to the wind component being measured.

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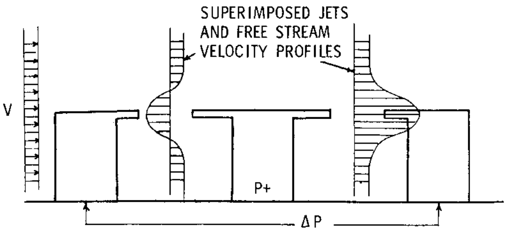

Fig. 1 Schematic of parallel-flow concept.

Parallel-Flow Sensor Concept

This concept is shown in Fig. 1. Flow entering the power supply port, $P+$, divides evenly between two nozzles mounted on a common centerline. Separated from these nozzles at a fixed distance are two signal pressure receivers. This subassembly is mounted within a flow straightening tube so that the wind velocity vector is parallel to the nozzle and receiver assembly. To further insure parallel flow, honeycomb flow

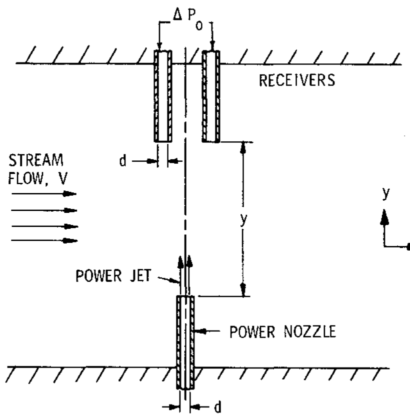

Fig. 2 Schematic of cross-flow concept.

straighteners are mounted at each end of the tube. By virtue of the different jet mixing in the power jets into and with the wind which flows along the axis of the tube, a differential pressure, ΔP, is recorded at the receivers.

Cross-Flow Sensor Concept

The basic cross-flow wind sensor concept is depicted in Fig. 2. A supply pressure, $P+$, jet is directed toward two receiver tubes. The wind acts upon this jet and changes the relative pick-up pressures of the two receiver tubes. The resulting differential pressure is a direct reading of wind speed.

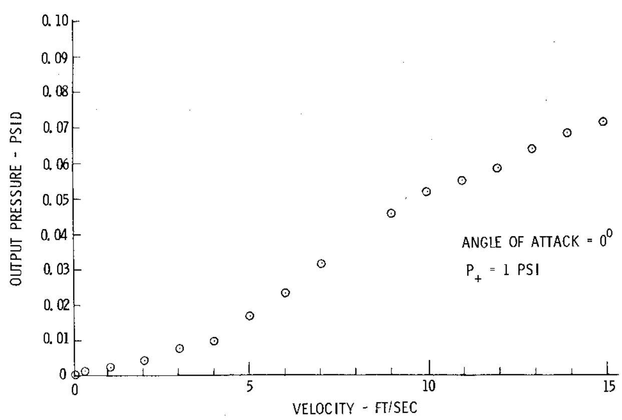

Fig. 3 Parallel-flow wind sensor output pressure vs wind velocity.

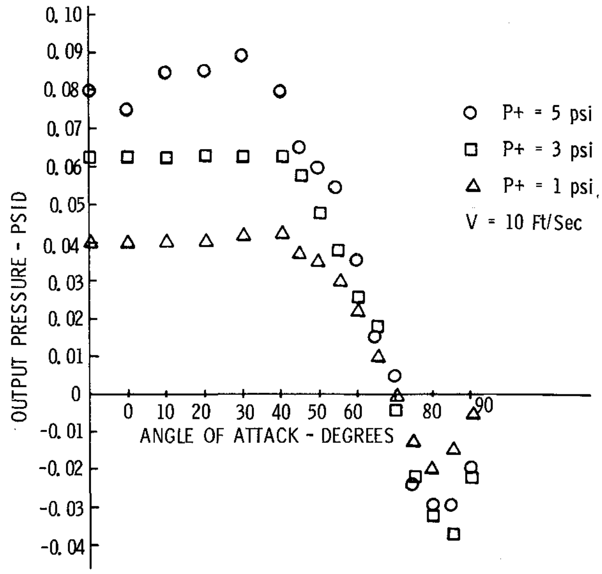

Fig. 4 Parallel-flow wind sensor output pressure vs angle of attack.

Wind-Tunnel Tests

An elaborate mechanical apparatus was constructed in order that various parameters of the parallel and cross-flow concepts could be investigated. Various nozzle diameters were tried and the distance to the pick-up were varied. These experiments were conducted in a specially constructed wind tunnel capable of wind speeds as low as 0.3 fps and a high-speed capability of 90 fps. Jet cross section profiles were recorded on a x-y plot. These experiments provided valuable insight to the fluidic behavior of the two concepts from which several operating models were designed. Table 1 is a summary of the results of the wind-tunnel tests.

Results

The parallel-flow concept showed the best results since it takes less supply pressure, has a near linear response with no saturation and has about the same sensitivity as the cross-flow model. Figure 3 shows the output pressure vs velocity at zero angle of attack. Figure 3 shows the results of wind-tunnel tests at various angles of attack. Note the negative reading at angles from 70°–90°.

The results of the wind-tunnel testing of the first models were encouraging but there were two problems which were

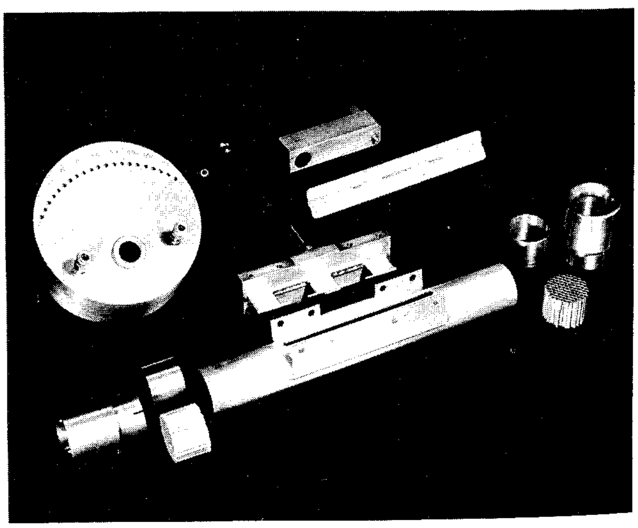

Fig. 5 Fluidic parallel-flow wind sensor.

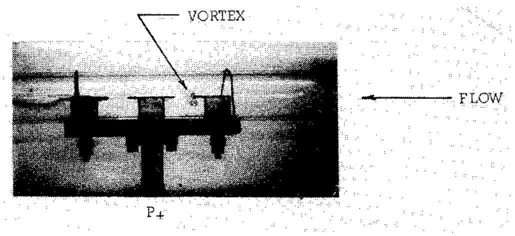

Fig. 6 Air-speed sensor in water with dye.

attacked during a second phase of development. A readout noise situation existed which probably was the result of a vortex flow in the system. Furthermore, the negative reading in the angle of attack measurements was to be corrected so that a near cosine response curve was obtained.

Figure 5 is a view of a dismantled parallel flow sensor.

Flow Simulation Analysis

Because of the complexity of the flow pattern in a configuration such as the wind sensor one must rely primarily on experimental rather than analytical techniques. Flow visualization, that is, actually observing the moving fluid, has been historically a most useful approach. This is conveniently done using water as the working fluid by injecting dye into the water at strategic locations and observing its subsequent path. Because the wind sensor is intended for use at relatively low velocities, compressibility effects on the air may be ignored and similar flow patterns in air and water may be obtained by matching Reynolds Number.

In Fig. 6 is the wind sensor submerged in water flowing from right to left. Colored water is the supply flow. That jet moving with the passing water remains a coherent stream as it impinges on the receiver (at the left). The jet issuing against the passing stream generates a localized concentration of fluid, the predicted vortex. This vortex does not remain constant with time, but grows and moves. Motion of this ring causes an oscillation of the output pressure signal. A first attempt to decrease the low-frequency noise is to break up the vortex. This can be done by locating a short honeycomb section in the vicinity of the ring. A lateral oscillation of the power jet observed in Fig. 6 causes a change in the pressure recovered by the fixed receiver and therefore in noise. Prior to attempting to stabilize this jet oscillation, a sleeve

Table 1 Summary of wind sensors

	Cross flow	Parallel flow
Air speed range, fps	0–90	0–90
Supply pressure, psig	10–15	1–3
Threshold tested, fps	0.26	0. 8
Pressure vs velocity characteristics	Modified square law with saturation	Approximate linear finite slope at $V = 0$

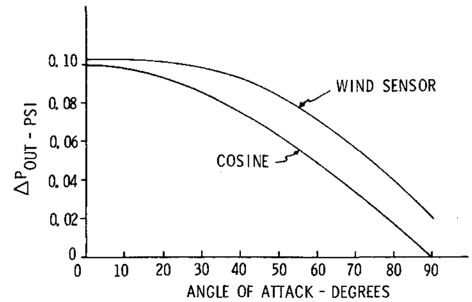

Fig. 7 Wind sensor angle-of-attack performance with modified orifice.

was fitted over the existing receiver, thereby increasing the receiver capture area from 0.030- to 0.065-in. diam. In this way an oscillating jet may still be detected by the receiver. Because the enlarged receiver averages the same recovered jet pressure over a large area than previously, one can expect less gain than was recorded with the smaller receiver. Also the effect of the honeycomb in the flow straightening tube results in less gain due to its resistance to wind. As a final test therefore, the wind sensor was tested with varying wind speeds. Comparison of these results with that of the first model shows that the gain is only slightly less (0.0037 $(psi)^{1/2}$ fps compared to 0.005 $(psi)^{1/2}$ fps). The results of the improvements incorporated through use of dye analysis showed a noise improvement of almost an order of magnitude. Since the important parameter is signal-to-noise rather than either signal or noise alone it can be stated that the performance has been increased by nearly an order of magnitude.

Water and dye tests were also performed to determine the nature of the effect of the negative flow in the sensor due to high angle of attack (as indicated in Fig. 4). The dye test at 70°–90° angle of attack confirmed the reversal of flow. A wide radius lip of the flow straightener orifice was tested with dye and found to have a desirable effect. The wide lip was then adapted to the air-speed sensor. The results were good and a near cosine curve was obtained (see Fig. 7).

Continued Progress

The parallel-flow sensor at this writing is being refined in order to be used in flight tests within the next year. As a result of this work by NASA spin-off technology relating to measurement of coal mine ventilation and some medical applications are being considered.

Conclusions

Fluidic techniques can be used for directly sensing wind speeds down to $\frac{1}{3}$ fps. Two fluidic concepts were verified as suitable for a wind sensor instrument. They are the cross-flow concept and the parallel-flow concept. The parallel-flow concept has advantages over the cross-flow concept in that it has better linearity, more dynamic range and requires a lower supply pressure for a given maximum wind speed. The sensor can be made small, rugged and sensitive.