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FLIGHT EVALUATION OF TIP-TURBINE-DRIVEN FANS FOR LATERAL CONTROL IN A HOVERING VTOL AIRCRAFT

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16. Abstract

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FLIGHT EVALUATION OF TIP-TURBINE-DRIVEN FANS FOR LATERAL CONTROL IN A HOVERING VTOL AIRCRAFT

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SUMMARY

A flight evaluation was made of small tip-turbine-driven fans as a means of augmenting the lateral control characteristics of a VTOL aircraft in hover. Two 12.8-inch-diameter fans were designed, constructed, and tested on the X-14A VTOL test vehicle. Although the fans used less bleed air for a given thrust output, they were unacceptable because of the high time constants of the control system. The time constant reductions which can be provided by closing the control loop with rpm feedback are eliminated when a full command is required.

INTRODUCTION

The lateral control required for a satisfactory pilot's rating of a VTOL aircraft in hover has long been a subject of research and conjecture. For those classes of VTOL aircraft that use engine bleed air for attitude control, severe performance penalties can result if large amounts of engine bleed air are needed. As a means of supplying sufficient control power without causing severe performance losses, methods of augmenting the thrust provided by bleed air have been considered. One possible method for augmenting the bleed air control power is the use of a tip-turbine-driven fan. The ability of a tip-turbine-driven fan to augment the force capabilities of a high-pressure airstream has been demonstrated for many years. However, the use of a fan for aircraft control has been questioned because of the poor time response characteristics and possible undesirable induced flow effects.

To gain insight into the possible problems associated with the use of tip-turbine-driven fans as the control moment producer, a research program was undertaken to flight test a fan control system in a jet lift VTOL research vehicle (X-14A). Two small fans (12.8-inch dia.) were mounted on the wing tips and used to produce lateral control.

This report presents the characteristics of the tip-turbine-driven fans and the results of a brief flight test of the X-14A aircraft with the fans installed.

SYMBOLS

F	fan thrust, lb
T_{BA}	temperature bleed air, °F
θ_a	temperature ratio, $\frac{°R}{519}$
ϕ	bank angle, deg
$\dot{\phi}$	rolling velocity, deg/sec
$\ddot{\phi}$	rolling acceleration, deg/sec^2
δ_a	pressure ratio, $\frac{\text{pressure}}{14.696}$
δ_s	pilot stick deflection, in.

DESCRIPTION OF EQUIPMENT AND TESTS

Fans

The tip-turbine-driven fans tested in this investigation were designed and manufactured under NASA contract by Airesearch Manufacturing Company, Phoenix, Arizona. The specifications called for a small size to permit installation in the X-14A wing tip; low inertia for low time constants; and 150-pounds thrust when supplied with minimum air bled from the compressors of the J-85-5 turbojet engines installed in the X-14A aircraft. Figure 1 is a photograph of the completed fan, and the dimensional data are presented in table 1.

The fan is a lightweight unit that provides 150-pounds thrust at 11,000 rpm. The stator section downstream of the fan was designed to reduce swirl and produce maximum thrust over the operating range. The tip turbine was designed with convergent sonic nozzles, which were chosen over a more sophisticated convergent-divergent nozzle design to produce better efficiencies over a wide range of operating points. The nozzle block is a partial-admission type with provision for up to 27 nozzle passages (about 140° of entry). The tip-turbine is primarily an impulse turbine which assists in reducing the leakage from the nozzle to the fan prior to turbine entry. The steady-state performance over the operating range of the fans is given in figures 2, 3, and 4.

Fan control.- Fan thrust is controlled by varying the pressure ratio to the tip-turbine and thus by controlling fan speed. With one fan mounted on each wing tip of the X-14A aircraft and a control valve for each fan, rolling moments are generated by operating the fans at a differential speed. Since both fans will operate at the same median rpm when roll moment is not required, lift is supplied to the aircraft from both fans. When a roll command is given, one fan is accelerated, which increases the thrust, and the opposite fan decelerated, which reduces the thrust. The summation of the thrust still provides net lift while the differential thrust provides a roll moment.

Fan dynamics.- To document the dynamic characteristics and determine the time constants for thrust changes, a series of step changes were run on the Airesearch ground stand. Figure 5 shows the variation of fan thrust, fan speed (rpm), and duct pressure for one such step change run. Data from numerous runs with various size steps and initial fan speeds were used to determine the variation of time constant with fan speed, as shown on figure 6. These data show that the open-loop time constant for this fan, when operating at the mid-thrust point (≈7,000 rpm), is 0.58 second.

The response characteristics of the fan system can be improved by supplying a closed-loop control system. Response is improved by this system because error signals generated during transient cause the control device to "overdrive" and bring the fan to speed more quickly. With this control, the pilot commands fan speed changes; fan speed is sensed, compared with the command, and the error is used to modulate the control valve. When desired fan speed is reached, the error signal is reduced and the control valve is automatically set at its required equilibrium position. The closed-loop control can be expected to improve fan response at all points except at maximum and zero speed. As the ground tests of this fan indicated that the time constants were long, it was decided to provide a closed-loop control before the flight tests. Consequently, Airesearch designed and manufactured a control of this type. Figure 7 shows a comparison of the fan response for a given control step for an open- and a closed-loop control system. The trace of valve position illustrates the function of the closed-loop system as the valve initially opens to a wider angle and then closes to the commanded position. Opening the valve wide initially reduced the effective first-order time constant from 0.58 to 0.34 second.

Test Airplane

The flight tests of the tip-turbine-driven fans were conducted on the X-14A VTOL VSS research vehicle. The X-14A is a vectored thrust VTOL aircraft which has been used extensively by the NASA to investigate the handling-quality requirements of VTOL aircraft in hover. Figure 8 is a photograph of the X-14A aircraft which is described extensively in references 1 and 2. To enclose the tip-turbine-driven fans, a wing-tip extension of constant chord and thickness to match the X-14A wing tip was constructed and mounted on the aircraft. Figure 9 shows the wing tip in its original configuration and modified. A cutout in the leading edge of the extension, at its junction with the wing, permits the exhaust from the variable stability nozzle to escape.

System operation.- Both the electronic and pneumatic subsystems were found to be simple to operate and reliable. Bleed air to the fan turbines was supplied from the reaction nozzle manifold system and turned on during the conversion procedure prior to deceleration to the VTOL speed range. A fan control panel, located on the right-hand side of the cockpit, was used to select fan control parameters such as zero rolling moment fan-trim speed, lateral control sensitivity (gain), and open- or closed-loop operation.

Flight Tests

The majority of the tests were conducted at near-hover conditions at approximately 2,500 feet to allow the pilot sufficient height to recover safely from any unusual attitudes or uncontrollable maneuvers. Two brief attempts were also made to establish a hover from the ramp. The evaluation maneuvers at altitude were: (1) wings-level transition to hover; (2) steady hover; (3) lateral step response (with a chain stop) and recovery; (4) mild lateral reversals (±10° bank angle); and (5) wings-level transition to conventional flight (conversion).

RESULTS AND DISCUSSION

The effectiveness of a control device to furnish attitude control of a hovering aircraft is reflected by the Cooper rating number (ref. 3) assigned by a pilot. The pilot's ratings of the X-14A aircraft equipped with tip-driven fans or reaction nozzles for lateral control are compared in the following table. For comparison purposes only the basic X-14A roll performance was used (i.e., no rolling moment supplied by the variable stability nozzles).

	Control fans	Reaction nozzles
Maximum control power	0.65 rad/sec^2	0.70 rad/sec^2
Time constant, sec	0.34 closed loop 0.58 open loop	0.08
Pilot rating	6-1/2 to 7-1/2	4-1/2 to 5-1/2

To calibrate the control power of the X-14A with the fan controls a series of abrupt 1-inch control deflections and recoveries were performed. Figure 10 presents a time history of several aircraft parameters obtained during one of these maneuvers and shows a pilot's heavy workload in righting and stabilizing the aircraft. The results in the above table show that the pilot rated the lateral control of the aircraft with the fans as unacceptable even for emergency conditions because of his constant tendency to overcontrol roll attitude and thus induce oscillation during any maneuver. The additional problem associated with the control system lag is shown in the fan speed records. The fan speed never stabilized so the commanded fan thrust was never attained. The control system lag and the increases in the aircraft's moment of inertia caused by the control fans on the wing tips eliminated the desired increases in roll performance resulting from the fans having greater thrusts than the nozzles.

The lateral step data of figure 10 are further analyzed in figure 11 where the variation of computed aircraft bank angle with time for the initial portion of this maneuver is presented. The stick deflection and rolling velocity curves are repeated on this figure for reference. The effect of high control-system time constant on aircraft response is quite evident in the lags observed between the initiation of control movement and changes in aircraft attitude. The pilot consistently tended to get the control motion out of phase with aircraft motion thus inducing oscillations and a large increase in bank angle following control reversal. This attitude reversal problem is shown in figure 11 where the control was reversed at a bank angle of about 5° but the angle kept increasing until about 15° before attitude began to decrease.

The maximum time constant that a pilot will accept in a control system for a hovering VTOL aircraft is not clear at this time. Figure 12 contains the results of a brief study (ref. 4) on the Ames six-degrees-of-freedom motion simulator in which a lateral control maneuver was used to investigate the effect of first- and second-order time constants in a control system. According to these data, the pilot rating of a rate damped system, the type utilized in the X-14A, will be downgraded by approximately two rating numbers when the first-order time constant is increased from 0 to 0.34 second. These simulator data show the same downgrading in pilot's rating as was observed during flight tests with the control fans.

The current specifications for hovering vehicles recommended by the military (ref. 5) and AGARD (ref. 6) stipulate that the aircraft shall move in the direction of the control input within 0.2 second after initiation of the control motion. The data on figure 11 show that the X-14A with the fan controls fails to meet this requirement since about 1.0 second was required for the aircraft to stop moving and begin to move in the direction of the control.

Even though it became evident early in the flight tests that the response characteristics of the fans would result in an unacceptable aircraft, it was not possible in the time available to investigate any modifications to the fans or the control system that might improve the time constants. Although these tests indicated the fans were unacceptable for control, they indicated other benefits which warrant additional consideration of the fans as control devices. For equal values of thrust, the fans required less than half the bleed air required by the reaction nozzles. Hence, the total bleed air requirement would be reduced by about 20 percent. This less stringent requirement would mean the jet engine would produce 4 percent more thrust, and the need to operate the jet engines above their temperature limit during vertical lift-off would be reduced with the fan controls.

One feature of the tip-driven fans which these tests clearly demonstrated, and which must be kept in mind when considering fans for controls, is that even though the time characteristics of a fan system are capable of improvement (by such means as closing the loop with rpm feedback), full operation of the control eliminates the fan speed-up capabilities provided by the closed loop, and the fans revert to their open-loop time constants.

CONCLUDING REMARKS

Flight tests of two small (12.8-in. diameter) tip-driven control fans on the wing tips of the X-14A VTOL test vehicle indicated these fans were unacceptable for providing lateral control. Poor pilot ratings were based primarily on the undesirable high time constants of the control system which resulted in pilot induced oscillations and long lags between control initiation and aircraft's following motion. The tip-driven control fans required about half the bleed air, for the same thrust, needed by the reaction controls, which permitted the jet engines to produce 4 percent more thrust. Although it is possible to improve the time characteristics of a tip-driven fan by means of a closed loop with rpm feedback, the fan reverts to its unacceptable open-loop time constant when full command is used.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, May 16, 1969

REFERENCES

1. Rolls, L. Stewart; and Drinkwater, Fred J., III: A Flight Determination of the Attitude Control Power and Damping Requirements for a Visual Hovering Task in the Variable Stability and Control X-14A Research Vehicle. NASA TN D-1328, 1962.

2. Rolls, L. Stewart; Drinkwater, Fred J., III; and Innis, Robert C.: Effects of Lateral Control Characteristics on Hovering a Jet Lift VTOL Aircraft. NASA TN D-2701, 1965.

3. Cooper, George E.: Understanding and Interpreting Pilot Opinion. Aero. Eng. Rev., vol. 16, no. 3, March 1957, pp. 47-51, 56.

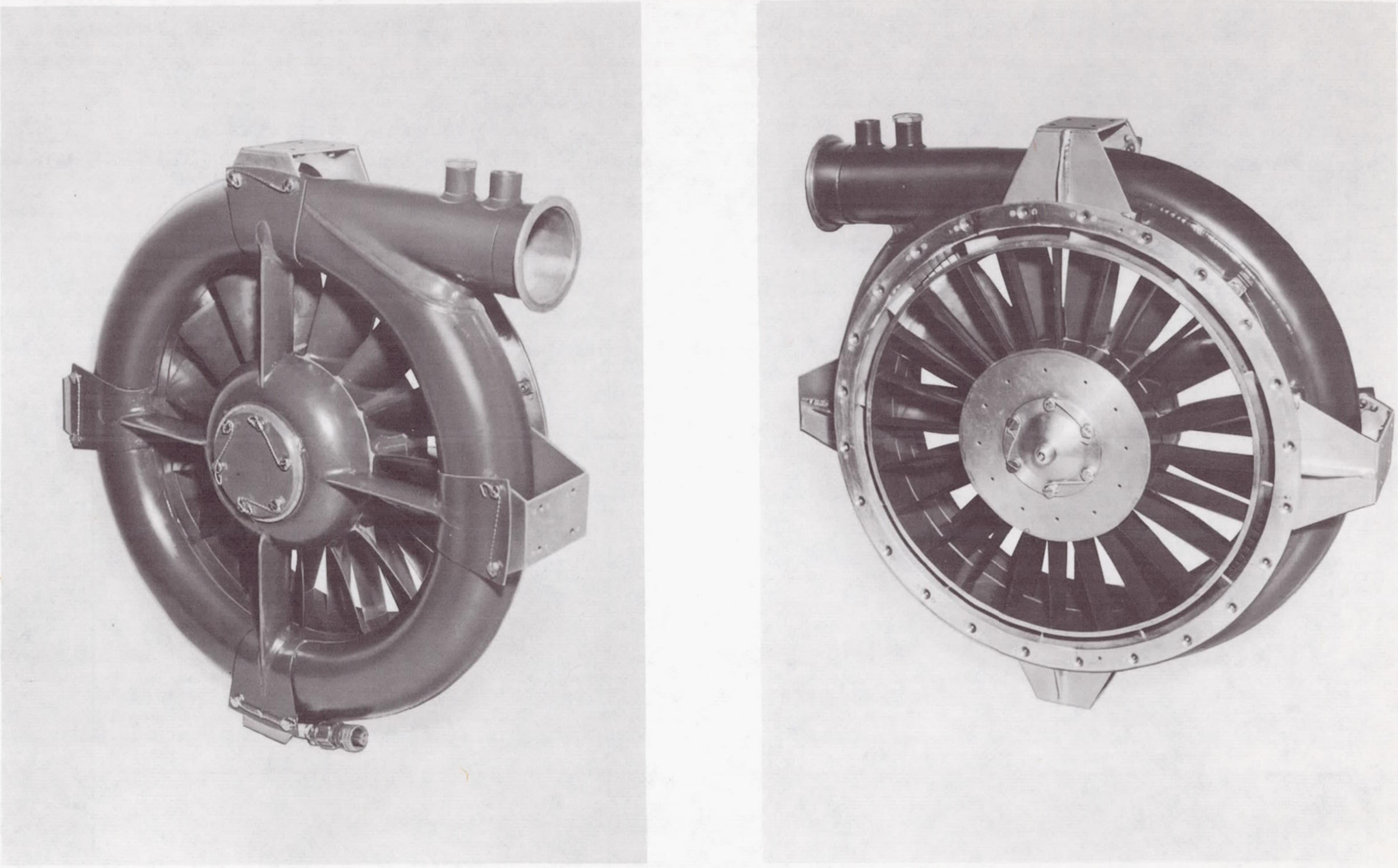
4. Anderson, Seth B.: A Discussion of the Use of Thrust for Control of VTOL Aircraft. Presented at Flight Mechanics Panel of AGARD (Gottingen, West Germany), Sept. 11-13, 1967.

5. Anon.: Helicopter Flying and Ground Handling Qualities; General Requirements for Military Specification Mil-H-8501A. September 7, 1961, Amendment 1, April 3, 1962.

6. Anon.: Recommendations for V/STOL Handling Qualities. AGARD Rep. 408, Oct. 1962.

TABLE I.- FAN DIMENSIONAL CHARACTERISTICS.

Fan diameter	12.8 inches
Turbine diameter	13.9 inches
Nominal fan assembly thickness	4.5 inches
Fan assembly weight	21 lb
Rotating assembly inertia	0.020 ft-lb-sec^2
Number of stator blades	24
Number of fan blades	15
Number of turbine nozzles	23
Number of turbine blades	135
Design point:	
Fan speed	11,000 rpm
Fan thrust	150 lb
Available turbine inlet pressure	80 psia
Available turbine inlet temperature	385° F



A-40441.1

(a) Inlet side.

A-40442.1

(b) Exhaust side.

Figure 1.- Photograph of tip-driven control fan.

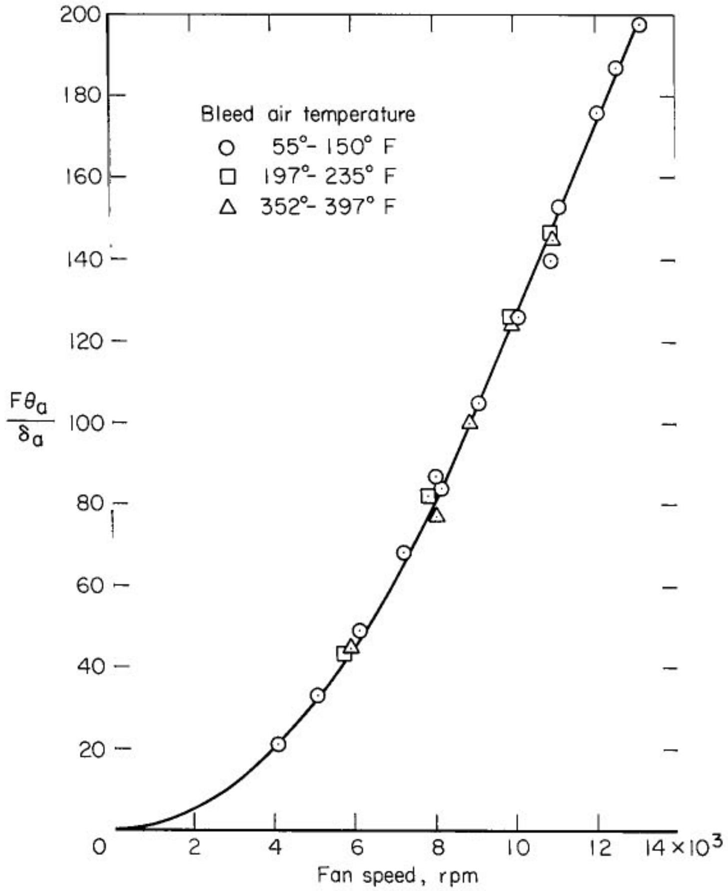


Figure 2.- Variation of thrust with fan speed; test stand data.

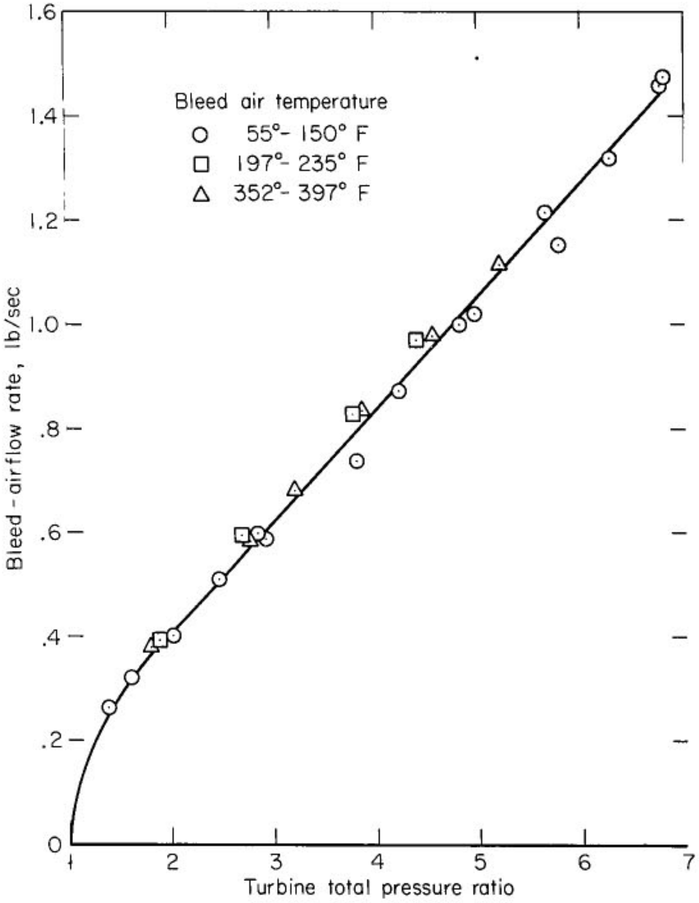


Figure 3.- Bleed-airflow requirements; test stand data.

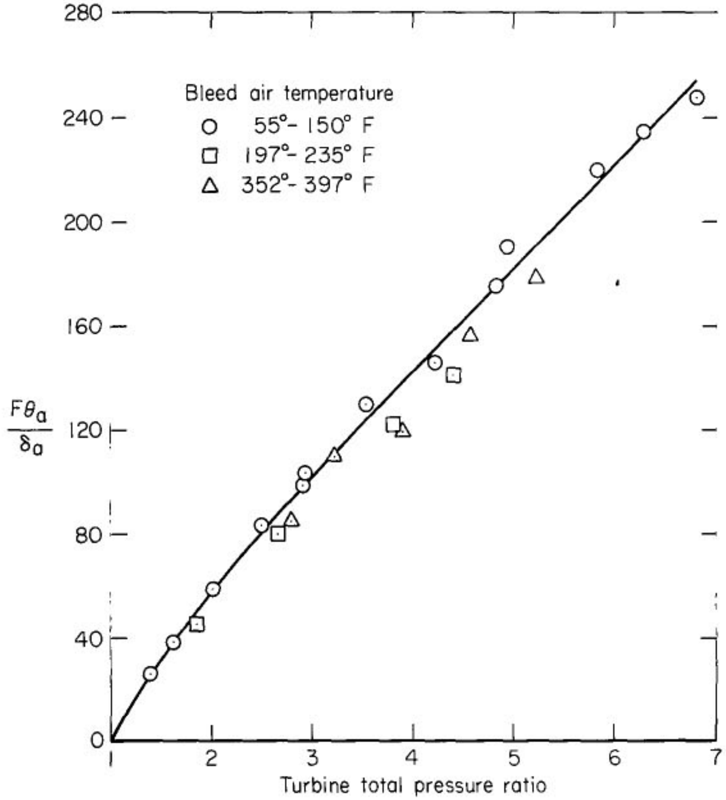


Figure 4.- Variation thrust with turbine total pressure ratio; test stand data.

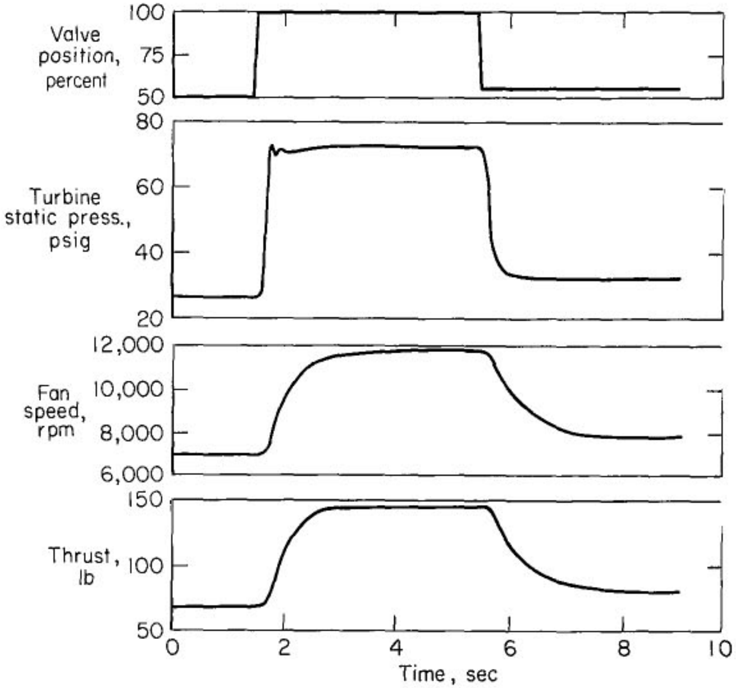


Figure 5.- Response to a step change in valve position; open loop.

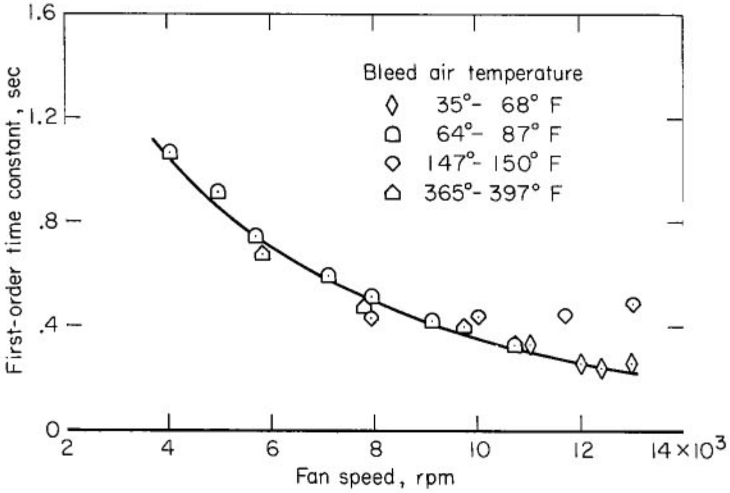


Figure 6.- Open-loop fan response characteristics; test stand data.

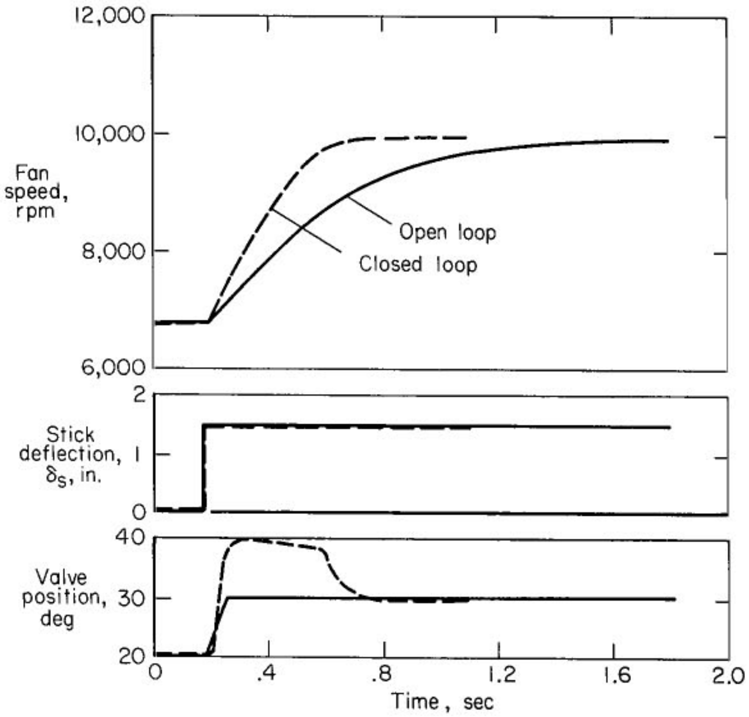


Figure 7.- Comparison of fan response for open- and closed-loop controllers.

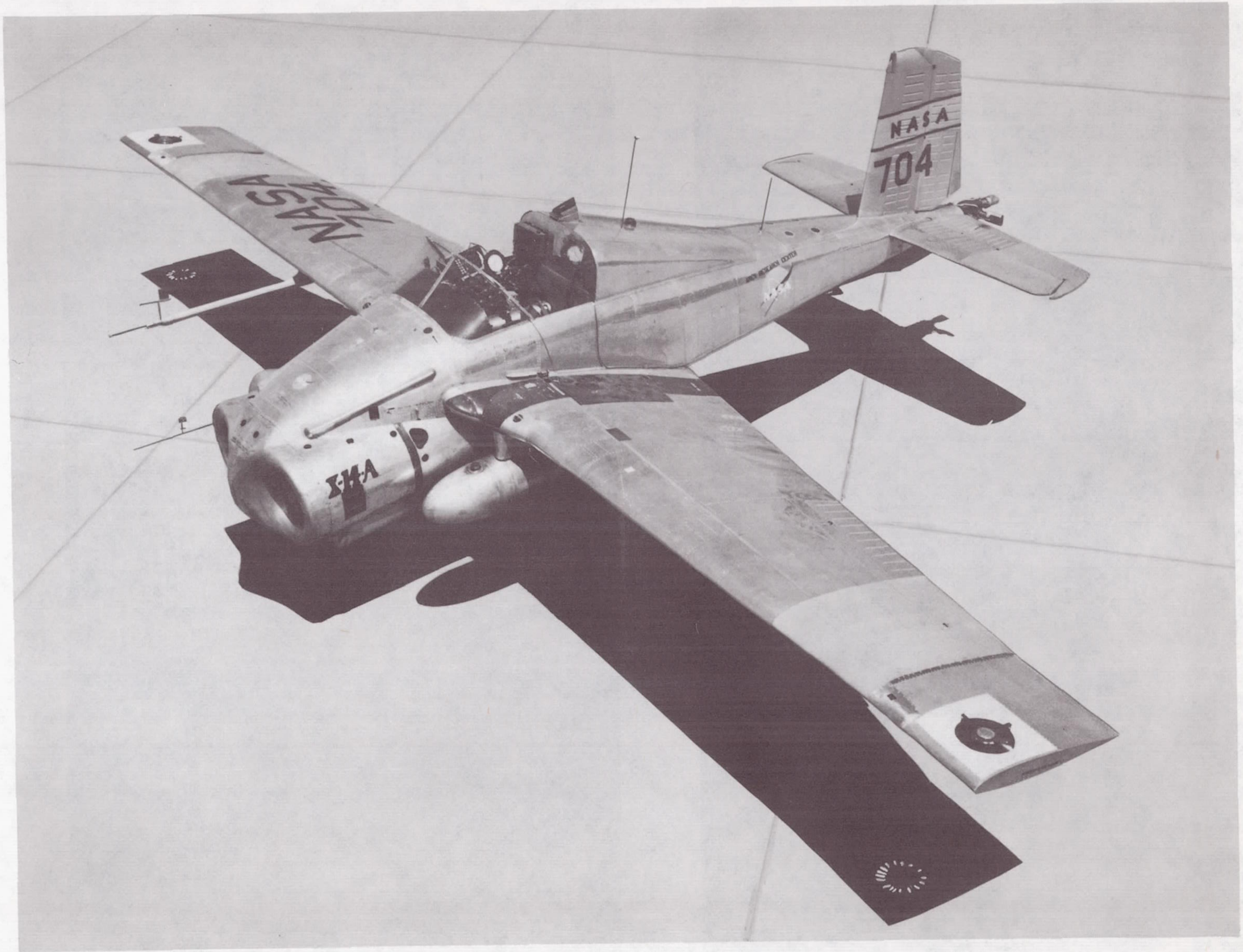


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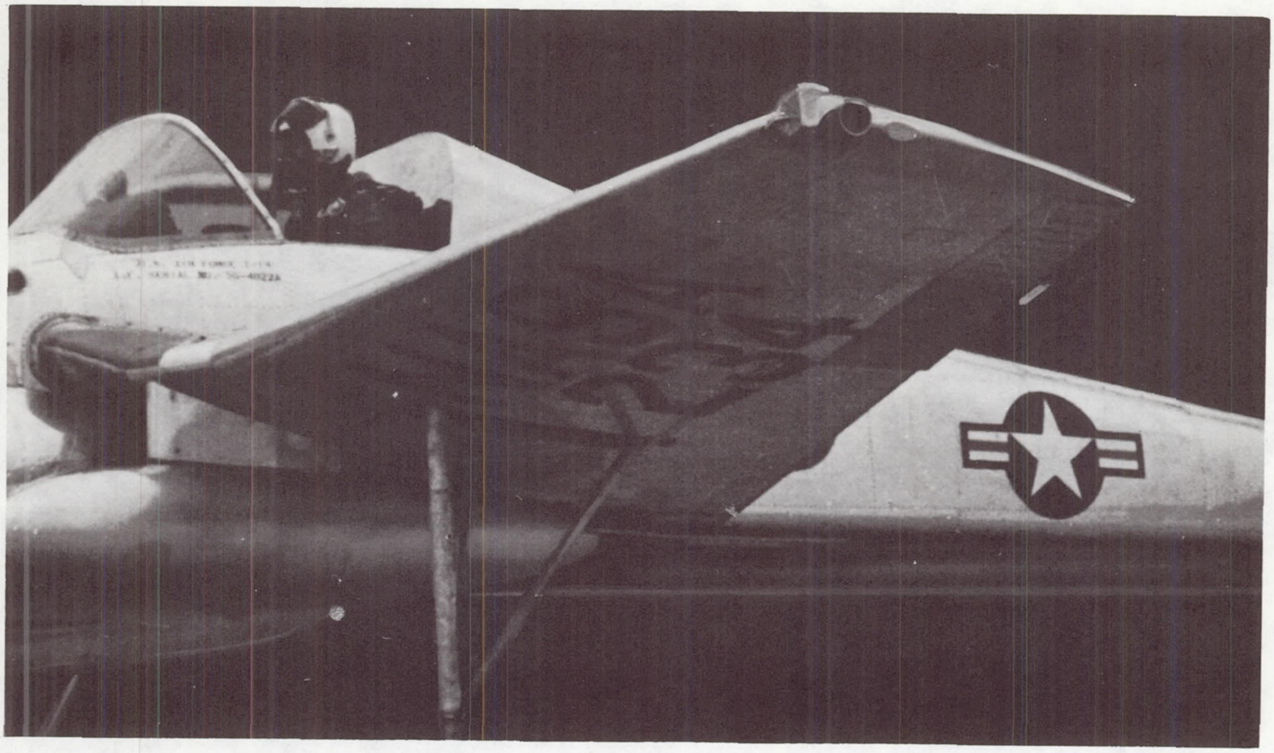
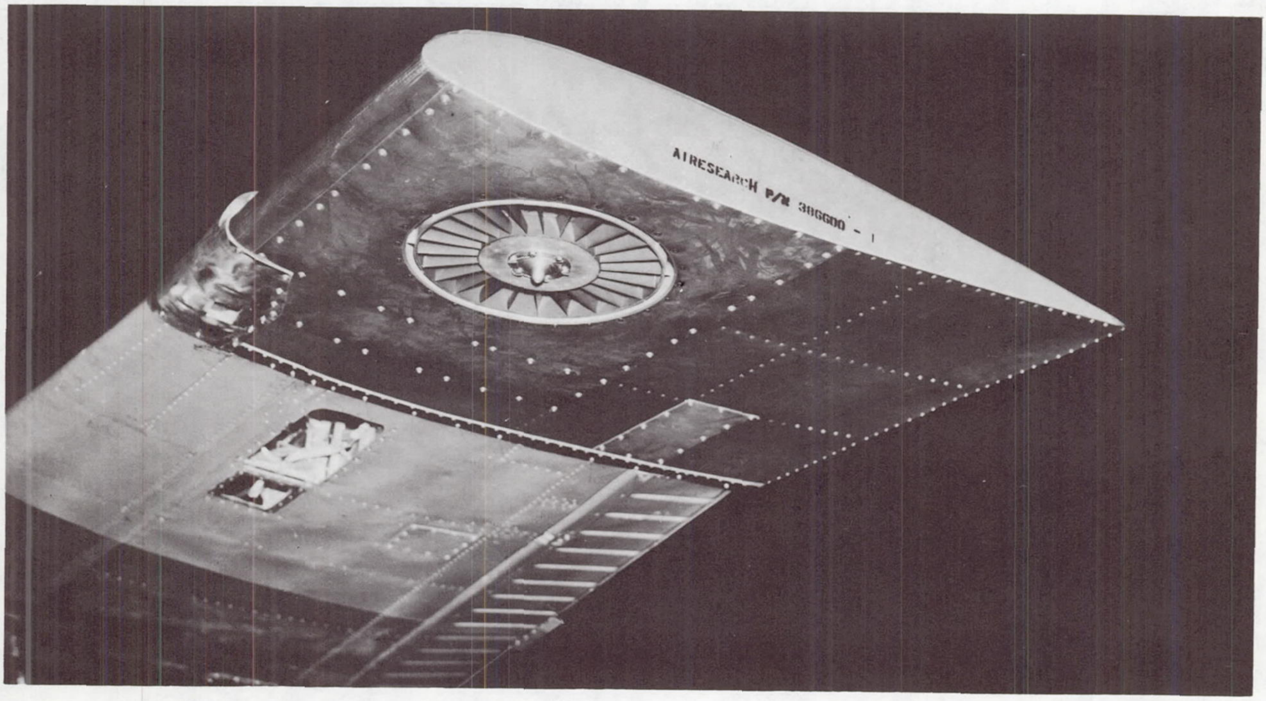
Figure 8.- X-14A aircraft with tip-driven roll-control fans installed on wing tips.



(a) Original wing tip. A-28473-5.1



(b) Modified wing tip. A-40125.1

Figure 9.- Close-up view of original wing tip and wing tip with tip turbine-driven fan.

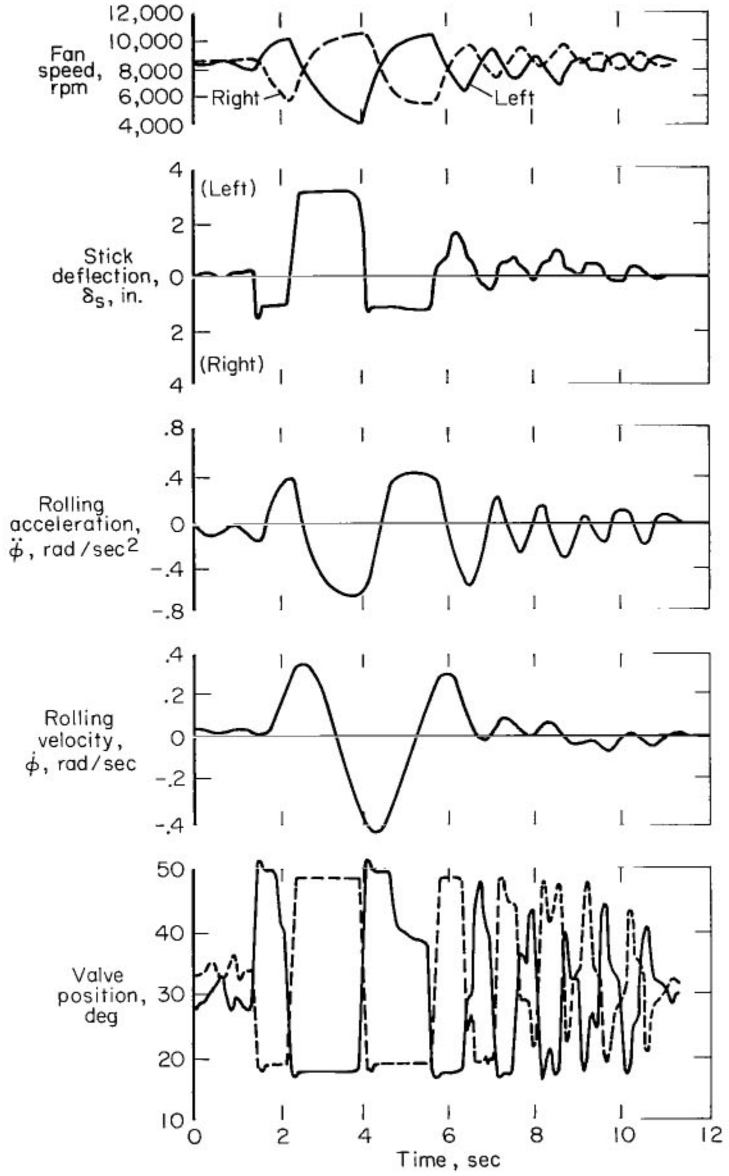


Figure 10.- Time history of a step aileron input during hover.

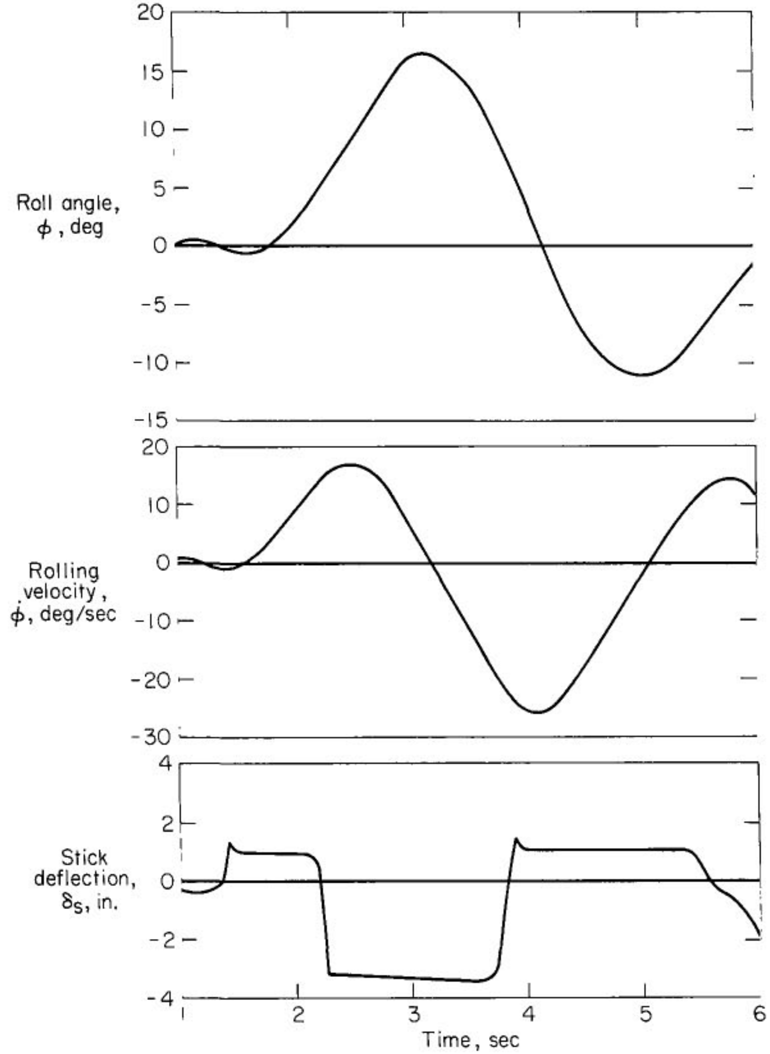


Figure 11.- Airplane response to step aileron input shown in figure 10.

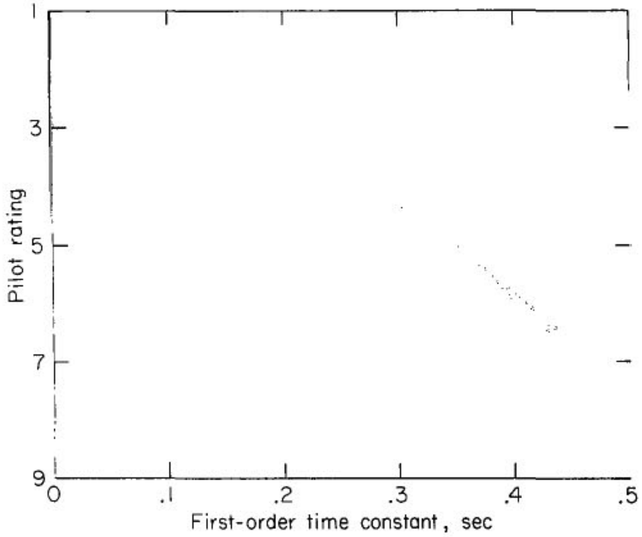


Figure 12.- Effect of first-order time constant on roll control for a rate stabilized system, six-degrees-of-freedom motion simulator (ref. 4).

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