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ROTOR SYSTEMS RESEARCH AIRCRAFT AIRPLANE CONFIGURATION FLIGHT-TEST RESULTS

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Abstract

The Rotor Systems Research Aircraft (RSRA) has been undergoing ground and flight tests by Ames Research Center since late 1979, primarily as a compound aircraft. The purpose was to train pilots and to check out and develop the design flight envelope established by the Sikorsky Aircraft Company. This paper reviews the preparation and flight test of the RSRA in the airplane, or fixed-wing, configuration and discusses the results of that test.

Nomenclature

$C_{n\beta}$ = yawing moment due to sideslip
c.g. = center of gravity, longitudinal
CPU = control phasing unit (changes sensitivity and range of rotary and fixed-wing control surfaces)
FSAA = Flight Simulator for Advanced Aircraft
G.W. = gross weight
 H_d = density altitude
 I_w = wing incidence angle
KCAS = knots calibrated airspeed
KIAS = knots indicated airspeed
KTAS = knots true airspeed
WL = waterline station

Introduction

The Rotor Systems Research Aircraft (RSRA)^{1,2} was designed as a pure research aircraft and dedicated rotor test vehicle whose function is to fill the void between design analysis, wind tunnel testing, and flight results. The RSRA program

has existed since 1970 as shown in Table 1. The concept originated in the late 1960s when an effort was made to advance the state-of-the-art in rotor systems technology. There was a concern of the inability to predict with any accuracy the characteristics of a new rotor system based on results obtained from flight data. Sikorsky Aircraft was contracted by NASA/Army to deliver two aircraft to provide this capability. One of those aircraft is being tested by Ames Research Center and the second aircraft, after completing test programs in the pure helicopter configuration is currently being modified for the development and in-flight demonstration of the "X-wing" design. This paper is limited to describing the aircraft and the government flight testing of the airplane configuration at the NASA Ames Dryden Flight Research Facility (Ames Research Center).

The ability to measure precisely the exact rotor state as a function of time and flight condition was the critical element that was missing and the one that prevented significant advances in complex rotor systems. The costly method of trial and error exposed a great risk to both the flight-crews and program budgets. A development or modification of an existing airframe was required to match each new rotor system under study; thus, a total aircraft development program was usually necessary. This concept did not allow innovative investigations to depart very far from proven, successful designs. The "flying wind-tunnel" concept of the RSRA is a dedicated rotor test vehicle whose function it is to fill this development need.

In order to be useful, research vehicles must have certain basic capabilities. These capabilities must include the expected flight envelopes of future rotor systems and a versatile flight control system to exploit this envelope. A data acquisition system must provide an accurate measurement and recording of all the desired flight parameters that are needed to perform a comprehensive analysis.

To provide this unique performance capability, there are three configurations of the RSRA: helicopter, compound helicopter, and fixed-wing airplane.^{1,2} The fixed-wing configuration is the same as the compound helicopter but with the rotor removed. The primary purpose of the fixed wing is to provide a fly-back capability should it become necessary to sever an unstable rotor system in flight; this configuration was tested at the Ames Dryden Flight Research Facility.

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Description of the Test Aircraft

The test aircraft has a basic helicopter fuselage with the wings and the lower horizontal all-flying stabilator installed. Two auxiliary power plants are mounted on either side of the fuselage. These GE TF-34, high bypass turbojet engines are used to offset drag effects when rotor systems are being tested with the aircraft in the compound configuration and to provide thrust for the airplane configuration. Each engine can input 8250 lb of thrust. In the airplane configuration, the RSRA weighs about 28,000 lb maximum. The conventional helicopter tail rotor was retained for the airplane configuration flight tests. Two GE 58 engines provide power to the tail rotor and aircraft systems. The 45-ft wing, whose angle of incidence can be varied between 15° leading edge up and 9° leading edge down, was restricted to 15° leading edge up and 0° leading edge down. The wing contains conventional ailerons and flaps, both of which can be operated by an on-board digital computer when it is installed. The computer was not installed for the fixed-wing tests.

The tail section contains a conventional helicopter tail rotor, a lower horizontal all-flying stabilator, an upper fixed horizontal tail plan, a conventional rudder, and an aft-mounted split-panel drag brake, all can be operated from the cockpit controls or by the electronic flight control system.

Test Objectives

There were five test objectives:

- 1) Demonstrate the RSRA as a fixed-wing aircraft
- 2) Obtain fixed-wing control power and stability data in support of the NASA/DARPA X-wing program
- 3) Develop the flight envelope to 250 knots
- 4) Obtain baseline main-rotor-off acoustics data
- 5) Obtain rotor-hub drag data

It was planned to attain the above objectives with and without the main hub rotor installed. The design envelope, with tail rotor installed, is shown in Fig. 2.

Test Preparation

When the requirement to demonstrate the RSRA fixed-wing configuration was confirmed, it was first necessary to define the tasks that would prepare the aircraft and personnel for a safe flight program. This preparation started with an "Action Item List" on which action items were assigned to specific individuals for performance by a specified date. This action list was modified as necessary at regularly scheduled program meetings. Eventually, the list comprised of more than 60 action items. The most important items were as follows:

- 1) Reanalysis of aerodynamic predictions
- 2) Aeroelastic analysis

- 3) Tail-rotor pitch adjustment
- 4) Piloted moving base simulation
- 5) In-flight fixed-wing simulation
- 6) TF-34 engine thrust control redesign
- 7) Emergency escape system redesign
- 8) Landing gear up-rating
- 9) Landing gear door analysis and modification
- 10) Low-speed, stall, and spin analysis
- 11) Test site
- 12) Administrative planning

Each of these 12 items is discussed in the following paragraphs.

Aerodynamic Predictions

It was presumed that original analytical predictions by Sikorsky, made in the mid-1970s, were dated and that they probably did not incorporate the results of the last wind-tunnel tests. The new predictions made for this program supported the previous ones, however, and further enhanced our confidence in anticipated stall speeds and aircraft control and stability characteristics. These predictions were performed using the Sikorsky General Helicopter Simulation Program for the RSRA modified to remove the rotors.³

Aeroelastic Analysis

The original fixed-wing aeroelastic analysis was reviewed and found adequate. The tail rotor was reanalyzed because of structural and aeroelastic considerations. This opened the analyzed envelope for the tail rotor to 250 KTAS from 200 knots, sea level standard. Three conditions were made requisite: that the tail-rotor pitch remain at 0° at speeds above 200 knots, that the tip Mach number not exceed unity, and that sideslip be less than 7°.

Tail Rotor Pitch Adjustment

To comply with the condition of the tail-rotor structural and aeroelastic analysis and to achieve full authority tail-rotor thrust in each direction, the tail-rotor pitch was adjusted to provide equal control in each direction and the yaw-control phasing unit (CPU) was modified to provide zero pitch when the yaw CPU lever was placed in the zero rotary control gradient position. Figure 3 shows the function of the CPU yaw control with respect to tail-rotor pitch.

Piloted Moving Base Simulation

A simulation of the RSRA was performed on the six-degree-of-freedom Flight Simulator for Advanced Aircraft (FSAA) at Ames Research Center. A static validation of the simulation was accomplished by comparing data for the compound configuration of the RSRA with FSAA output for the same configuration. The rotor module was then removed from the FSAA program, and the pilots were trained on the simulator for nearly a month. This simulation was quite useful in establishing technique and wing incidence and

flap configurations for takeoff and landings, as well as the other flight regimes. Previous recommendations had specified a 10° wing incidence (I_w) as optimum, but the piloted simulation showed that an I_w of 5° was preferred. Later flight experience substantiated the fidelity of this simulation from a quantitative and a qualitative standpoint. This simulation is documented in Ref. 4.

In-Flight Fixed-Wing Simulation

Several flights were made with the compound RSRA to investigate flying characteristics of the RSRA at minimal rotor lift. This was accomplished by lowering the collective to full low position. In some high-speed cases, rotor lift was reduced to 2000 lb, but at lower speeds it was in the 4000- to 8000-lb range. The purpose of this test was to load the wing with the full weight of the aircraft and investigate stall speeds and characteristics.

Stall speed was determined (approximately) in the 100- to 110-knot range with full flaps. Stall approach roughness, if any, tended to be masked by vibration of the main rotor. Stall did occur without sudden yaw departure as in the moving-base simulation. The primary characteristic of the stall was the sudden and rapid increase of main rotor speed as the main rotor tried to pick up the load. During level flight to 150 knots the fuselage provided about 2000 lb of lift. This lift decreased as wing incidence was increased to 10° . Figure 4 shows the effect of flap position on wing lift and drag.

TF-34 Engine Thrust Control Redesign

The original RSRA auxiliary engine thrust control system (throttle control) had poor fidelity relative to pilot inputs and was unacceptable for fixed-wing flight. This was redesigned using F-15 throttle control components including a boost device using engine bleed air pressure. The redesigned system characteristics were very satisfactory.

Emergency Escape System Redesign

The RSRA was equipped originally with an emergency escape system that featured a blade-severance subsystem and a crew-extraction subsystem. A Stanley Yankee Extraction seat was used. As installed, the operation of this extraction seat was validated to 200 knots only. To obtain improved speed capability for the fixed-wing program, a Martin-Baker MK US 10 LT ejection seat was used. This modification provides an emergency escape envelope from zero altitude-zero speed through the entire design speed range of the RSRA (360 knots).

Landing Gear Up-Rating

The landing gear of the RSRA, as delivered, was rated to 120 knots only. Analysis was performed to extend this rating to 192 knots at a sink rate of 8 ft/sec for a 28,500 lb vehicle. This extension was required to accommodate the fixed-wing configuration for which normal touchdown speeds of 130 knots were planned. Consideration of flaps-up emergency landings and high-density altitudes raised the possible touchdown speeds to the 160-knot range.

Landing Gear Door Analysis and Modification

On the last flight of the RSRA in the compound configuration, the left main-landing-gear door was blown from the aircraft. Analysis, redesign, and fabrication of a strengthened door were accomplished. The new door, although analytically validated to 200 knots, was limited to 170 knots maximum in the extended position to reduce the possibility of another failure.

Low-Speed Stall and Spin Analysis

Stall speeds were recalculated using the latest version of the RSRA GENHEL model,³ to determine stall speeds. A stall speed of 110 knots with $I_w = 5^\circ$ and full flaps at 28,500 lb gross weight was confirmed. This result also was supported by the compound low speed, low collective tests of the compound configuration.

Spin-departure tendencies were analyzed by calculating $C_{n\beta}$ dynamic from simulation and previous wind-tunnel data. This calculation obtained $C_{n\beta}$ dynamic for a range 0.001 to 0.0037 which, per Ref. 5, should provide acceptable stall behavior with no yaw-departure tendency if stall is not prolonged. This result was also supported by the FSAA moving base simulator. Figure 5 presents the descriptive phraseology for specific $C_{n\beta}$ dynamic values.

The stall and spin characteristics were predicted to be acceptable. However, since no specific aerodynamic model testing was performed, it was decided to avoid stall in the test program and limit wing angle of attack to a maximum of 15° .

Test Site

The RSRA is normally based at Ames Research Center (Moffett Field, Calif.). Since the fixed-wing testing would require high-speed taxi tests before first flight and since braking distances were estimated to be long, the RSRA was moved to the Ames Dryden Flight Research Facility (ADFRF), Edwards AFB, Calif. where a 15,000-ft runway and a 12,000-ft overrun was available. This was accomplished by a compound configuration ferry flight in two legs (a refueling stop at Vandenberg AFB). The ferry flight took place in December 1983. Upon arrival at ADFRF, the main rotor and hub were removed.

Test Administrative Planning

Preparations for the test required the development of an RSRA fixed wing operations plan which was written and established the cooperative procedure for Ames Moffett to operate with Ames Dryden. A detailed flight test plan was also developed. In addition, a data processing requirements document was written which detailed the telemetry and data processing responsibilities at both Ames Moffett and Ames Dryden. This document also specified the RSRA data-measurement system requirements and layout.

Test Results

Taxi Tests

Familiarization with the ground-handling characteristics and insight into the takeoff flight characteristics of the RSRA were accomplished by three taxi "flights." These taxi flights were conducted without the main-rotor hub which lowered the gross weight to 26,000 lb and lowered the vertical c.g. to WL 219. This represents a vertical c.g. decrease of 6 in. from the full compound configuration. Full instrumentation, telemetry, and radar tracking were used in all taxi tests. The radar tracking used a C-band transponder to give aircraft position to within inches relative accuracy.

The taxi tests confirmed the selection of $I_w = 5^\circ$ and half flaps for takeoff. Higher wing incidence caused uncomfortable nose-down attitude while holding the aircraft on the ground at speeds well above the stall speed of 110 knots. Since the "at rest" ground attitude for the RSRA is only 2° nose-up, the probability existed that the tail wheel might be on the ground for takeoff at low wing incidence. On the second taxi flight ($I_w = 5^\circ$), the aircraft lifted from the ground at 135 knots without touching the tailwheel.

Directional control of the aircraft was adequate at all times. This aircraft has a tail rotor and for that reason yaw-control power is such that no minimum yaw-control speed exists. Heading was maintained using $\pm 15\%$ of the control available. Acceleration to 135 knots required slightly less than 3000 ft. This gave the pilot time to observe the near-takeoff characteristics of the aircraft and then to decelerate to a stop with minimal use for the brakes. Concern about overheating the brakes was dispelled when the pilot found he could aerodynamically decelerate to less than 90 knots, then use the brakes sparingly and could easily be stopped before using all of the 15,000-ft paved portion of the runway. Brake temperatures rose to only a little more than half of the permissible even on the repeated runs. Brake stack temperatures were recorded by telemetry and also were displayed to the pilots. Rim temperatures were monitored by surface probes at the end of each run; fans were used to cool the brakes after each run. Stack and rim temperatures were required to show a decline and to be low enough to absorb the temperature rise of a full stop from 120 knots. For brief periods during the second and third taxi tests the aircraft flew and was then immediately landed. In one instance, the radar recorded a 50-ft altitude. All taxi tests were conducted with flight as an option to escape from a hazardous situation. Figure 6 shows the Dryden Aerodynamic Test Range radar data for a taxi run with a lift-off of a few feet. Note that the runway has a slight descent. Figure 7 is a time history of control motions during the taxi run. A confirmation of the airspeed calibration was obtained from radar ground speed in low wind conditions and also from static pressure changes at the boom. The previous calibration was confirmed:

$$\text{KIAS} + 10 = \text{KCAS}$$

First Flight

The first flight was made on May 8, 1984 at 0630. Figures 8 and 9 show takeoff data. The aircraft quickly attained 10,000 ft density test altitude. During climb-out a vibration was noted from the tail area both by the pilot and telemetry. A brief investigation showed that even the smallest amount of flaps eliminated the vibration. Subsequent flights were conducted with 5° flap settings. Since the flaps were effective, it is believed that turbulence from the inboard wing root streams aft to the lower horizontal stabilator. This turbulence excites the 10 Hz antisymmetric mode of the stabilator. To avoid any aeroelastic envelope expansion, flight speeds attained were limited to that previously explored by the compound configuration. The remainder of the flight was directed to low-speed landing simulation at altitudes to establish the landing technique and flap and wing configuration. The procedure, considered before flight, was accepted, that is, to use $I_w = 5^\circ$, full flaps, an approach speed of 140 KCAS, and slowing to 125 KCAS for landing. Main-wheels-first landings were anticipated. Several low-pass practice approaches were made before the final landing, which was slightly tail-wheel first at near 125 KCAS, but otherwise uneventful. The flight lasted 1 hr. Figure 10 shows approach and landing data. Pilots' qualitative impression of the RSRA handling was that it was comparable to that of a C-130 Hercules.

Envelope Expansion

The speed envelope was expanded to 250 KTAS (215 KCAS at 10,000 ft H_d) in two flights. This was to allow review of data at an intermediate speed before final expansion. Fixed surface damping was a minimum of 3% for the wing edgewise mode; tail-rotor damping was a minimum of 0.5% in the edgewise mode (0.5% edgewise damping is typical for the S-61 tail rotor). None of the damping ratio trends was decreasing at 250 KTAS. Tail-rotor speed was decreased to 94% (648 ft/sec rotating tip speed) and was in flat pitch above 200 KTAS. This gave a tip Mach number well below 1.0. As a convenience, the tail rotor was so configured at all flight speeds once at test altitude.

The rotor hub was removed for envelope expansion. Figure 11 shows flight trim data. To obtain comparative vertical c.g. and hub drag data, the hub and weights used to simulate the complete rotor were reinstalled. Except to monitor effects of turbulence on the tail rotor no aeroelastic envelope expansion was necessary for the hub-weight configuration.

Experimental Data Acquisition

Control power and dynamic stability data were acquired by step and reversal inputs at 180 and 230 KTAS. Representative plots of each type are shown in Figs. 12-14.

Stability data for analysis by systems identification methods were obtained by testing sine-shape control inputs, continuously increasing frequency in each axis. Figure 15 is a time history of a pitch sine input.

Trim data were acquired throughout the test speed range (145 to 215 KCAS) for purposes of determining control trim trends (Fig. 11) and performance and rotor-hub drag measurements. Hub drag measurement capability is described in Ref. 6. System acoustics signature data with the main rotor removed were to be acquired for the 160 to 215 KCAS speed range during flybys at 492 ft above ground level (AGL) and in 3° glide slope at 394 ft AGL.

Separate reports will be forthcoming to document 1) control power and stability at two vertical c.g.'s and performance with and without rotor hub; 2) rotor hub drag comparison with hub removed and hub installed; 3) systems identification analysis of aircraft stability; and 4) the acoustics of RSRA with tail rotor only.

Conclusions

The following are the principal results of these flight tests:

- 1) The emergency, fixed-wing flying characteristics of the RSRA are satisfactory.
- 2) The flaps should be extended to 5° to prevent unnecessary lower stabilator vibrations.
- 3) The landing gear can be extended and retracted up to 170 KCAS.
- 4) The RSRA operating envelope is expanded to 250 KTAS (215 KCAS).

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Table 1 RSRA development history

3 Dec. 1970	NASA/Army Working Group established
1 Nov. 1971	Joint NASA/Army development agreement
1 Mar. 1973	Request for proposal (Bell/Sikorsky)
6 Nov. 1973	Sikorsky awarded contract
12 Oct. 1976	First flight, helicopter
10 Apr. 1978	First flight, compound
12 Feb. 1979	Helicopter arrives at Ames Research Center
29 Sept. 1979	Compound arrives at Ames Research Center
23 Feb. 1980	First helicopter flight at Ames Research Center
25 Nov. 1981	First compound flight at Ames Research Center
8 May 1984	First flight, airplane

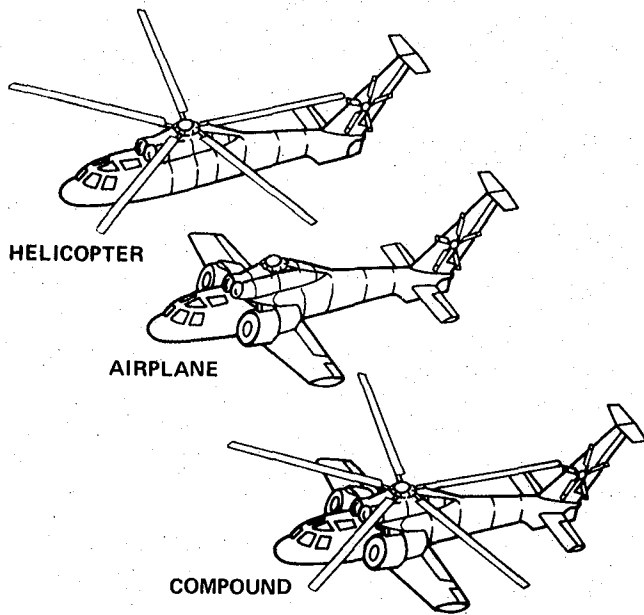


Fig. 1 RSRA flight configurations.

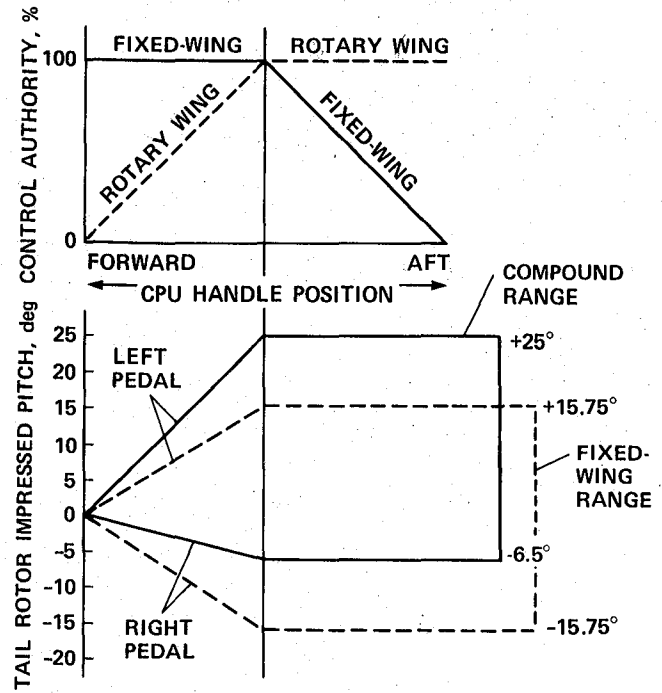


Fig. 3 Tail rotor control phasing unit.

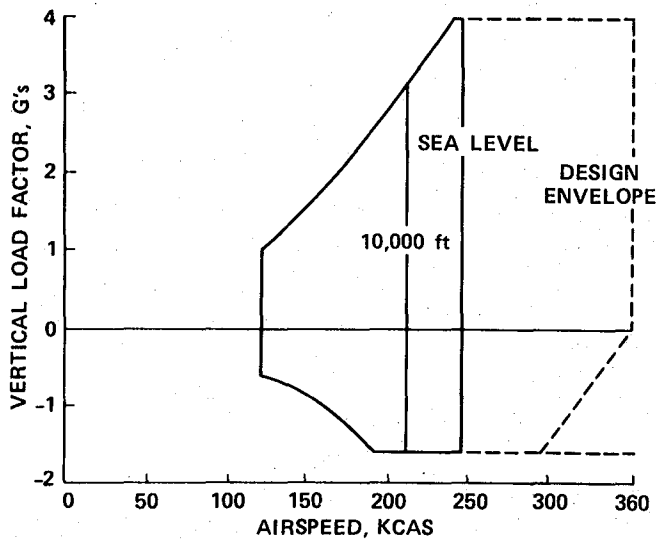


Fig. 2 RSRA planned fixed wing envelope development.

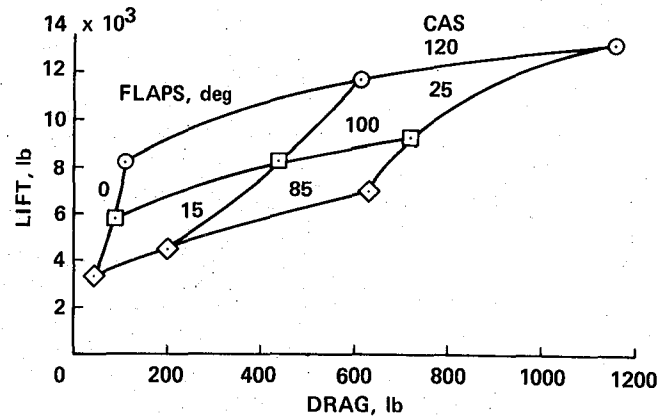


Fig. 4 Wing lift vs. wing drag: 10° wing incidence, 40% collective pitch.

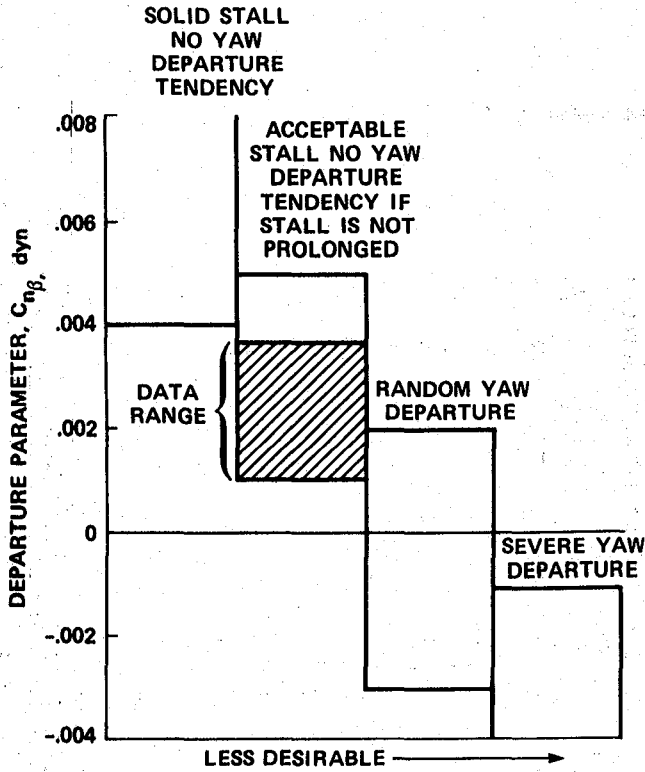


Fig. 5 Expected stall behavior as a function of C_{np} , dyn.

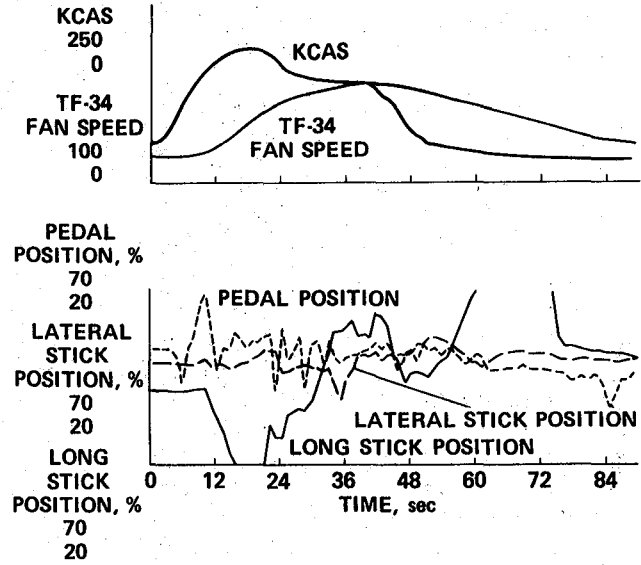


Fig. 7 RSRA fixed wing taxi.

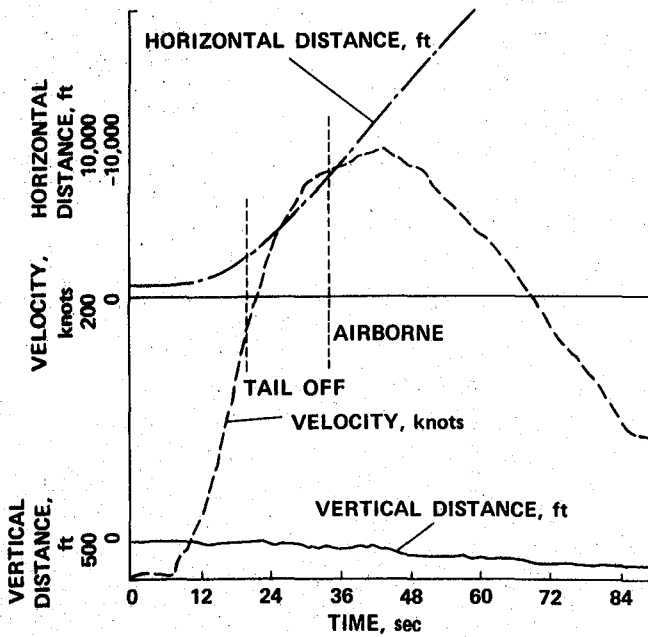


Fig. 6 RSRA fixed wing taxi—radar data, flight 5, run 24.

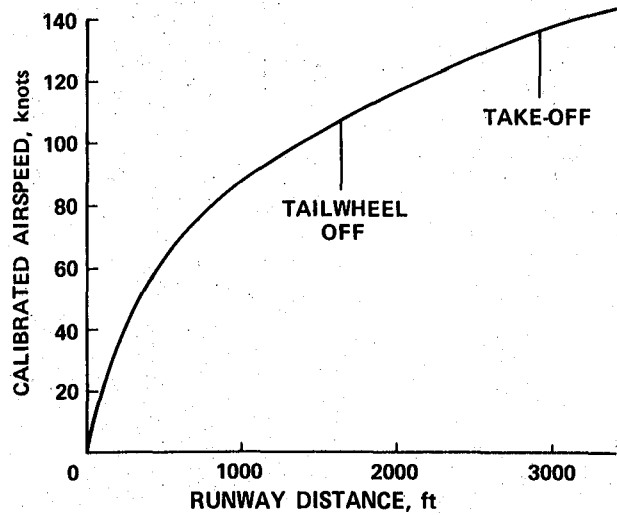


Fig. 8 RSRA fixed wing take-off, calibrated airspeed vs runway distance, radar, flight 6.

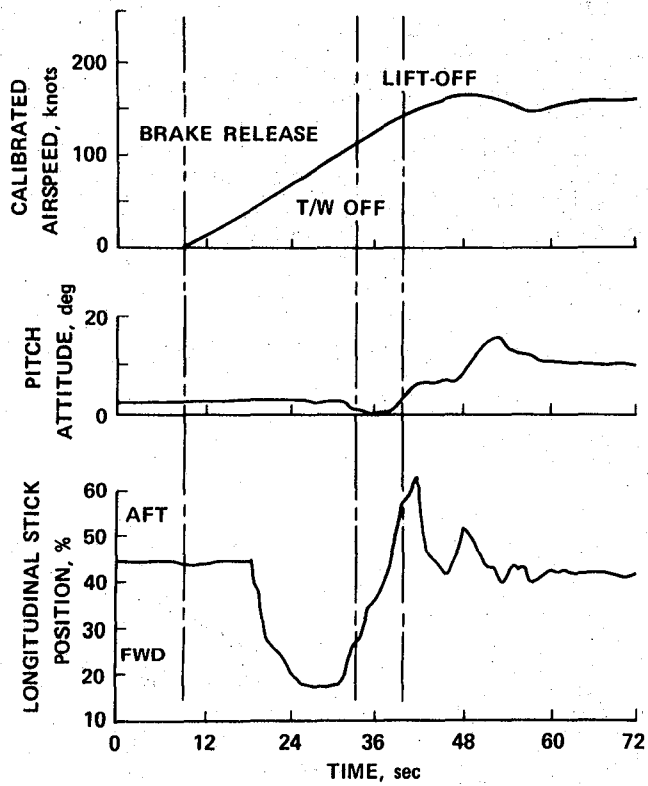


Fig. 9 RSRA fixed wing take-off, flight 6.

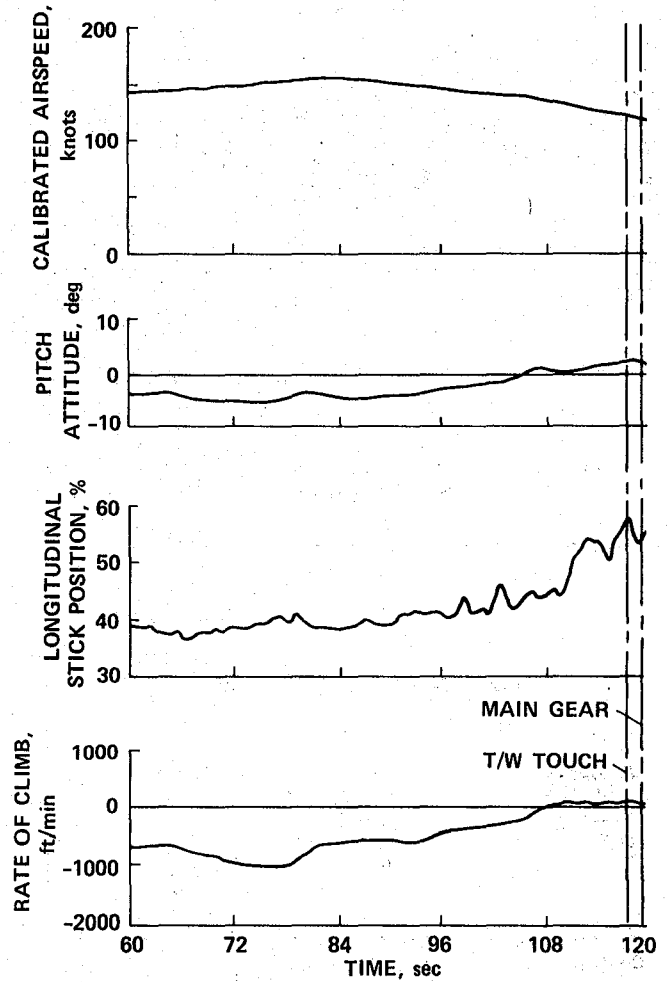


Fig. 10 RSRA fixed wing final approach and touchdown, flight 6.

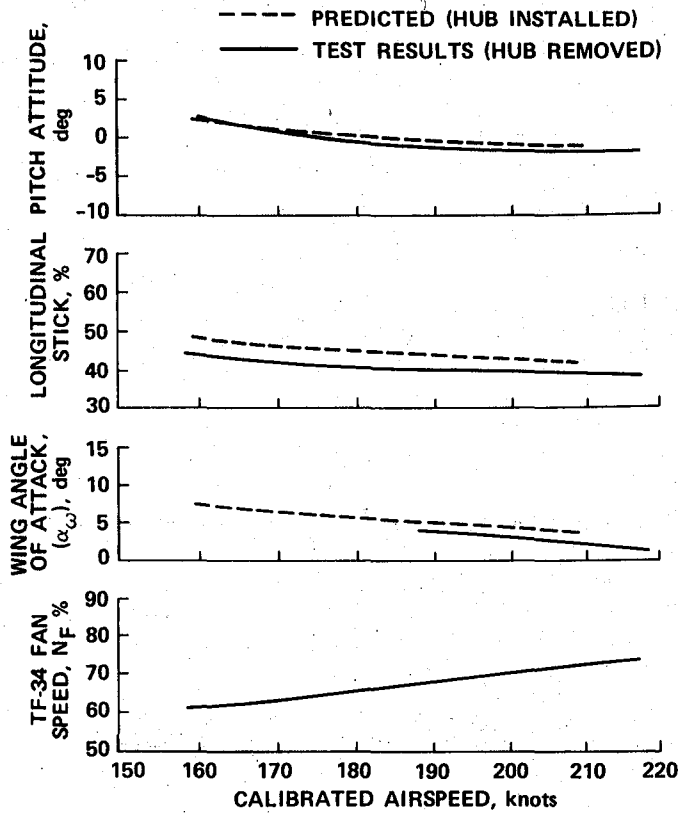


Fig. 11 RSRA fixed wing longitudinal trim:
 $I_w = 5^\circ$, $\delta_{FLAP} = 5^\circ$, $H_d = 10,000$ ft.

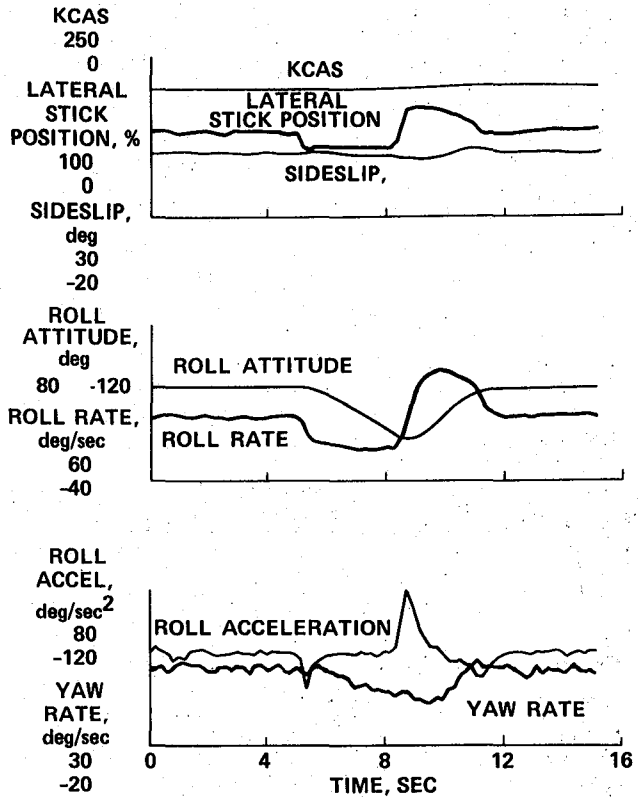


Fig. 13 RSRA fixed wing lateral step, 200 KCAS.

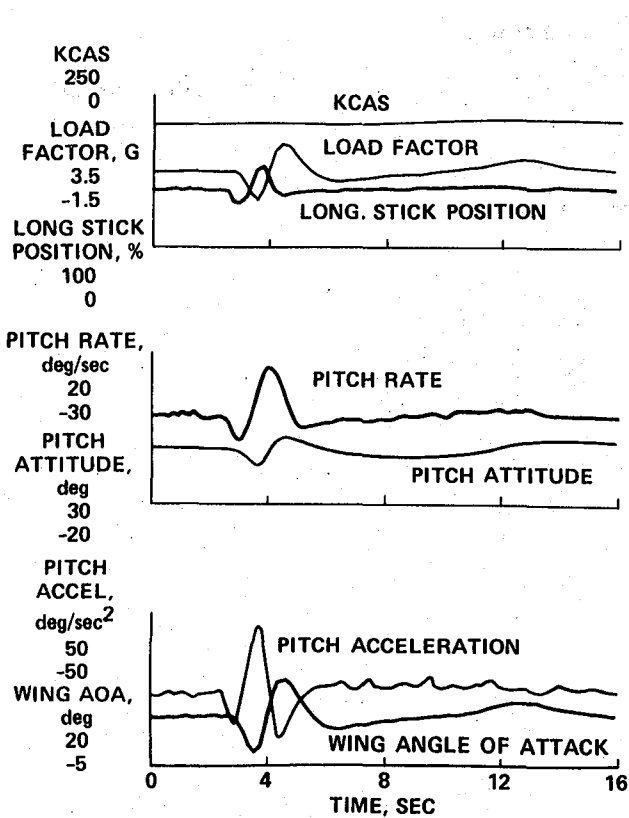


Fig. 12 RSRA fixed wing longitudinal doublet,
 200 KCAS.

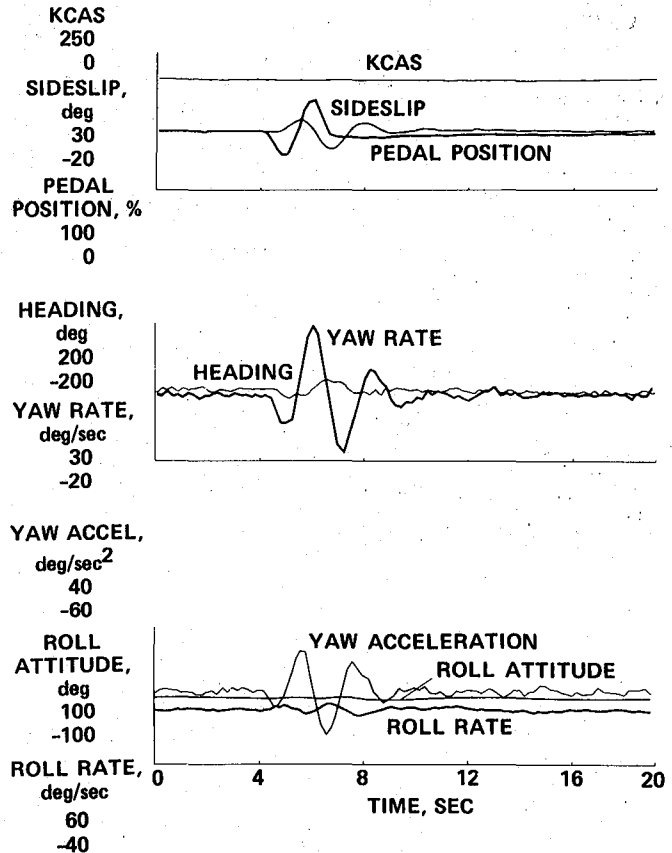


Fig. 14 RSRA fixed wing yaw doublet, 200 KCAS.

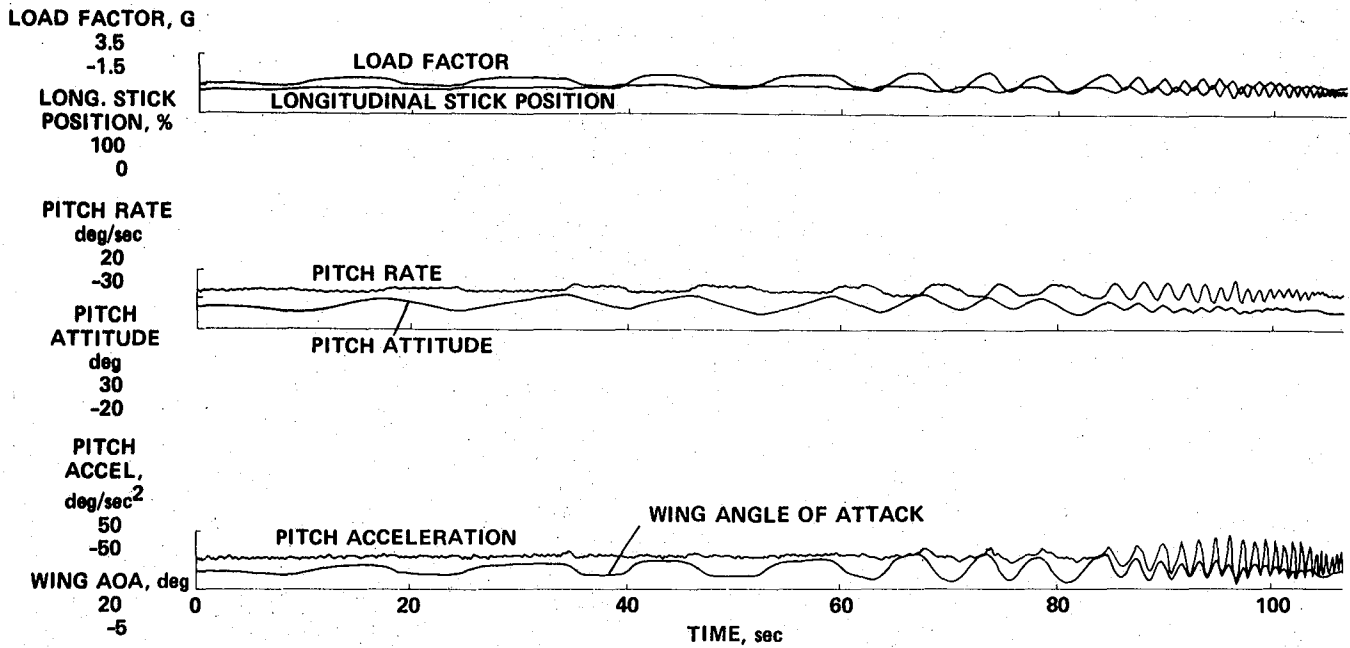


Fig. 15 RSRA fixed wing pitch sine input, 200 KCAS.

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