A System to Vary the Stability and Control of a Deflected-Jet, Fixed-Wing VTOL Aircraft

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A research program to provide variable control power and damping for a hovering VTOL aircraft is described. This paper presents the requirements for the variable-stability system, the servosystem design with particular emphasis on the motorized nozzles and safety subsystem, simulation studies, and performance of the system. The system was installed in the Bell X-14 aircraft that uses engine bleed air at the wing tips and tail for attitude control in hovering. For variable-stability control a set of low-power electric servodriven air jet nozzles was added to generate additional control moments about the three axes. The nozzle torque and centering characteristics for several types of rotor orifice edge are discussed. Operational modes provided were rate damping, cross coupling, pilot control power, and stiffness with maneuverability cutout. Problems concerning the safety of a VTOL aircraft when hovering at low altitude and pilot safety controls are discussed. This system has been performing in flight tests and is a very satisfactory and versatile system for research purposes. Similar systems should prove useful with other VTOL designs.

Introduction

THE inherent aerodynamic damping of the VTOL aircraft tends toward zero when flight velocity approaches zero and hovering is reached. In addition, usual aerodynamic control moments are not generally available in hovering aircraft and hence must be provided by diverting power from the propulsion system or by using some auxiliary source. Control system research has shown that the ability of a pilot to control a system depends on the damping and control parameters. For VTOL aircraft the choice of these parameters is exceedingly important, first, to assure good handling qualities, and second, to keep total power requirements at a minimum.

Ames Research Center has completed a research program directed at determining the control power and damping that lead to good handling qualities of a hovering aircraft. The results of this program, reported in Ref. 1, are pertinent to all VTOL aircraft and are particularly applicable to jet VTOL aircraft. This program required that the aircraft be equipped with systems enabling ready variation of control power and artificial damping about all three axes. The development of the control system, to provide the aircraft with the desired values of control power and damping, is the subject of the present report.

The aircraft used for the study was the Bell X-14A, a deflected-jet, fixed-wing, VTOL aircraft (Fig. 1). The damping and control moments about the three axes of the aircraft are generated by reaction jets on each wing tip and on the tail. Two sets of moments are available. The original control moments for the X-14 are provided by nozzles mechanically coupled to the pilot's stick and pedals. The variable-stability moments are obtained by the use of motorized nozzles. Both sets of moments require hot air to be bled from the engines and thus are furnished at the expense of lift power. The system permits varying damping moments as a function of vehicle angular rates and also varying pilot control. The design and development techniques incorporated in this system and its components have evolved over a considerable period of flight research with variable-stability aircraft. Previous work has been with conventional aircraft and this is the first hovering aircraft to be equipped with a variable-stability system at Ames Research Center. Procedures established at Ames for variable-stability aircraft were used in analyzing the control system requirements. The motorized nozzle, which presented a major problem, required detailed study of flow control and safety considerations.

This paper presents the requirements for the variable-stability system, a description of the aircraft, the servosystem design with particular emphasis on the motorized nozzle and safety subsystem, simulation studies, and performance of the system.

Requirements for the Variable-Stability System

In aircraft handling qualities research, it has been necessary to have aircraft that permit exploring a wide range of the fundamental aircraft parameters in flight, such as the damping and control power about each axis. This type of aircraft enables the pilot to evaluate combinations of variables under realistic flight conditions involving specific tasks. Investigations of new handling qualities concepts, exploration of characteristics of aircraft in the design stage, or improvements of existing aircraft may all be accomplished. The

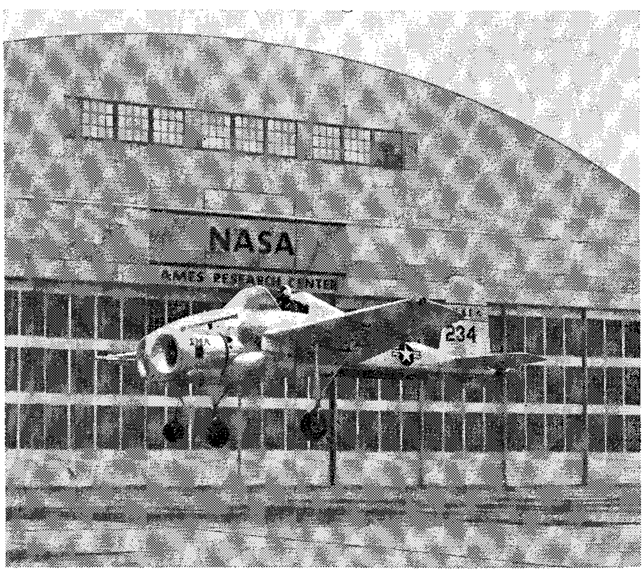

Fig. 1 X-14A in hovering flight.

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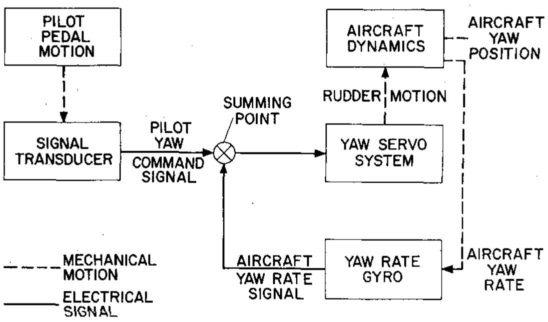

Fig. 2 Variable-stability augmentation about the yaw axis.

stability of an aircraft can be varied by servomechanisms that position the control surfaces or actuate auxiliary control devices. These servos accept stability augmentation signals and control inputs, such as pilot command, to modify the normal response of the aircraft.

As an example of changing the apparent stability derivatives of an aircraft, the yaw damping can be changed by adding algebraically to the pilot's yaw command signal, a signal proportional to the aircraft yaw rate (Fig. 2). The summed signal will cause a different aircraft response than that corresponding to the pilot's yaw command. Thus the effective yaw damping will be changed. Moreover, the magnitude and direction of the yaw damping stability derivative can be adjusted in flight. Other stability derivatives are controlled in a similar manner.

The installation of a variable-stability system, in a conventional aircraft, usually requires that the pilot's connection to the control surfaces be disconnected and a servo substituted to activate the surface in response to pilot and augmentation commands. The servos are usually electric or electrohydraulic, and use electrical input signals from various sources, such as control input from a stick position transducer, or stability augmentation inputs from a rate gyro or an accelerometer, to activate the control surfaces. Because of its adjustable characteristics, a variable-stability system is basically more complex than a normal aircraft control system. This inherently leads to greater chance of failure. In event of failure of an augmentation system, return to the original aircraft configuration is considered the safest possible action. If it is not possible to revert to the original configuration, "fail safe" features must be built into the system. Fail safe, as used here, means that if a failure occurs the system will produce the most favorable result possible, within its limitations.

Another factor that demands special safety consideration is that the pilot examines near-uncontrollable conditions to establish boundaries of controllability. In the event that these boundaries are exceeded, it is necessary that the pilot be able to return the aircraft to a safe flight condition quickly and without disturbance.

It is also important that the transition from the normal aircraft to the variable-stability operation be smooth and that inputs from the variable-stability system not be sensed through force or motion at the pilot's controls.

The concept of a VTOL variable-stability research aircraft is particularly challenging since there is such a variety of VTOL aircraft, each with its own limitations and special control problems. For example, 1) normal control surfaces and sensing devices depending on airspeed are ineffective; 2) control power is a function of engine power and not airspeed; 3) desired handling characteristics, pilot feel, and aircraft response are completely different; 4) special attitude control must be provided for hovering; 5) a compromise must be made between desired control power and aircraft payload; and 6) special consideration must be given to safety at low altitude. The problems differ from those of conventional aircraft in that normal aircraft control surfaces and sensing devices that depend on airspeed are ineffective while the aircraft is hovering and the control power does not depend upon airspeed but upon engine power. In addition, desired handling characteristics, pilot feel, and aircraft response might be expected to be completely different from conventional aircraft. For VTOL aircraft, a separate attitude control for hovering generally must be provided, whether or not a variable-stability system is used. Thus it is relatively easy for the variable-stability and pilot's basic hovering control devices to be made independent, and even utilize different power sources, if desired, which is not true of conventional variable-stability aircraft. The power for the basic hovering and variable-stability control systems must come either from the aircraft engine or from some added source. The additional power necessary for a variable-stability system in a VTOL aircraft requires very careful design studies to obtain the desired control power and damping ranges without complete sacrifice of the aircraft payload.

Hovering flights of VTOL aircraft are often at altitudes of only 10–25 ft, and unlike high-altitude flights, the pilot does not have time to make corrective action in the event of a system failure that would tend to put the aircraft into a dangerous attitude. The added dangers of a system failure at low altitudes require consideration of the use of circuits that automatically detect unsafe operating conditions of the variable-stability servosystem and quickly revert the aircraft to the normal configuration.

System Description

Basic Research Aircraft

The Bell X-14 VTOL, a fixed-wing, jet-propelled, deflected-jet airplane was the test bed for the research problem. The exhaust from the jet engines passes through cascade diverters that enable the pilot to select any condition between horizontal or vertical thrust, or to make a transition from one to the other in the air. During hovering flight, basic attitude control of the aircraft is maintained by the use of air jet nozzles at the tail and wing tips. A separate system of nozzles was added for variable stability. The air for all nozzles is bled from the compressors of the turbojet engines. The basic nozzles are mechanically connected to the pilot controls (the stick and the pedals) (Fig. 3). The pitch nozzle is on the tail and has exit areas on top and bottom. Changing this differential area produces a moment; the total nozzle exit area is a constant. The nozzles on the wing tips are used for roll and yaw control. Changing the difference between the left nozzle exit area and the right nozzle exit area generates a rolling moment. Rotating, about the lateral axis of the aircraft, the thrust vector of the left nozzle in an opposite direction to the right nozzle creates a yawing moment. The total nozzle exit area of the roll-yaw system is also constant.

The combination roll-yaw nozzles have the advantages of simplifying the pilot's basic control system and of using less bleed air than two separate nozzles. However, the combination of the two functions in one nozzle causes a slight interaction between the yaw and roll commands of the basic system. For example, a yaw command, when there is a roll command present, will cause a decrease in the rolling moment. The maximum reduction in the rolling moment is 30%. The small amount of lift produced by these nozzles at the wing tips is also reduced slightly by the presence of a yawing command.

Gyroscopic cross coupling, which is the result of the angular momentum of the engine rotors, exists between the pitch and yaw axes of the aircraft. For example, a pitch-up motion causes a left yawing moment proportional to the pitching rate of the aircraft. From a handling-qualities standpoint this coupling is unacceptable, and, in fact, limits the pitch rate at which yawing can be controlled. Equally objectionable is the pitching generated by yawing rates.

Variable-Stability Control System

The first research program using the X-14 aircraft was directed at examining the control power and damping relationship in the hovering mode to define the boundaries of good, acceptable, and unacceptable pilot control.[2] The variable-stability system was designed to meet this requirement. Experience with the aircraft before the variable-stability system was installed showed that the existing proportions of maximum acceleration about the three axes seemed satisfactory to the pilots, although the magnitude of each was much lower than desired. However, other research on VTOL aircraft indicated that the proportion of pitch acceleration to roll and yaw acceleration should be increased for this investigation.

In order to carry out the desired research program the following system requirements were established:

1) To change the existing acceleration proportions from 10:3.2:2.8 for roll, pitch, and yaw, respectively, to 10:5:2.8.

2) To provide maximum amounts of control and damping capability consistent with the constraints of weight and safety.

3) To keep added weight low to conserve the already short flight time (time of hovering flight is now approximately 15 min).

4) To be independent of the pilot's basic hovering control system, which was to be left intact. This means that the variable-stability system will operate in parallel with the pilot's basic hovering control system.

5) To provide the ability to vary the control and damping parameters in the various modes of operation. This will be described later in detail.

To enable these requirements to be met, the original engines were replaced with General Electric J-85-5A engines to provide a greater amount of bleed air for reaction control and to give 25% more thrust with about 400 lb less engine weight. Using the J-85-5A engine also resulted in less angular momentum and associated cross coupling. Variations in aircraft damping and control power were provided by the addition of a separate parallel bleed air system with a set of electrically powered servocontrolled nozzles. As shown in Fig. 3, separate pitch and yaw nozzles were placed at the tail and roll nozzles at each wing tip to eliminate control cross coupling. The existing set of mechanically operated nozzles was retained to serve as the pilot's basic hovering control system.

The system added to the basic aircraft was designed to afford the pilot the maximum possible control power and damping and to allow these to be varied to the point of unacceptability. The system was designed so that control power and damping could be varied independently around all three axes and to provide control coupling as desired. The pilot was given control of all modes and the option of reverting to the basic aircraft at any time. The control and damping parameters could be varied in the following modes of operation.

1. *Rate damping*

The system provides the capability of varying damping, either positively or negatively, about each axis independently. The damping moments are linear functions of the angular rates. The sign and slope of the damping moments are adjustable by the pilot in flight.

2. *Cross coupling*

Angular rates about any axis are capable of producing either plus or minus moments about either of the other two axes. The sign and magnitude of these moments are controllable by the pilot in flight. The moments are linear functions of the angular rates. A major function of this mode is the cancellation of the gyroscopic cross coupling caused by the angular momentum of the jet engines.

3. *Pilot control power*

The aircraft basic control system during hovering, described previously, provides the pilot with constant control moments, about any axis, for any particular control position and power setting. The augmented system provides control moments that are proportional to the position of the pilot's controls (stick and pedals) but which are variable in magnitude and sign for any particular control position. These control moments are added, algebraically, to the pilot's basic control moments. The pilot is able to select the sign and level of these control moments independently for each axis.

4. *Stiffness with maneuverability cutout*

If the weather is gusty during hovering, this servosystem provides a means of reducing the pilot effort to maintain a given attitude. The system acts like a stiff spring to reduce undesired attitude changes caused by wind gusts. The effect of a position servo is obtained by integrating the rate gyro signals, going through a washout circuit, and driving the servo with this modified position signal. The stiffness control has a maneuverability cutout that automatically disables the stiffness control circuit whenever the pilot moves the controls more than a certain preset percentage of the maximum control motion. This allows the aircraft to be maneuvered easily during the hovering task.

Before engaging the system during flight in any of the forementioned operational modes, the pilot is directed to test the system operation. This prevents the pilot and the aircraft being subject to transient forces if the system should be engaged when a failure is in existence.

Safety Aspects

Since the bleed air of the jet engines is used as the source of power for the pilot's basic control system, it is advantageous to use it as a source of power for the variable-stability system also. Strict safety provisions were required to permit this use. For safety, the pilot must always have the ability to command an acceleration about any axis. If the variable-stability system fails in a manner that produces a moment about any axis, the pilot must cancel that moment with his basic control nozzles. If the maximum moment exerted by the variable-stability system is the same or greater than the maximum moment exerted by the pilot's basic control nozzles, the pilot would have no control until the variable-stability air was shut off. This time, although short, could be fatal under certain circumstances. It was therefore decided that the basic control nozzles should create at least 10% more moment in each axis than the variable-stability control system. Furthermore, it was established that a 10% override would not be sufficient for complete safety in extreme cases,

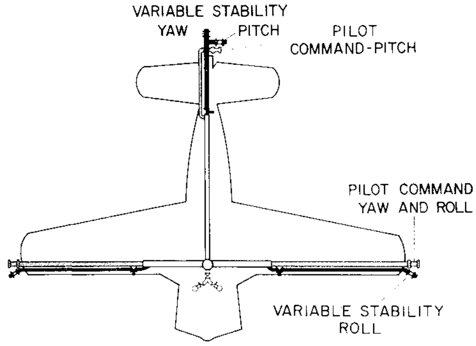

Fig. 3 Nozzle location on X-14A aircraft.

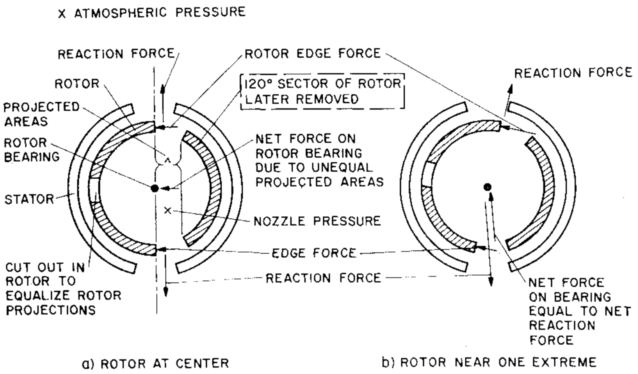

Fig. 4 Forces acting on prototype nozzle.

and so an automatic failure detection circuit also was included in the system.

Generating Variable-Stability Control Moments

To generate the variable-stability control moments proportional to inputs and to meet the system requirements, an independent motor-driven air reaction nozzle was needed. A prototype nozzle was constructed to have constant air flow with self-centering characteristics and to be mechanically suited to a servomotor and gear drive. Variable-stability response requirements dictate a low driving torque. There are two components of torque to be overcome; one is the bearing frictional torque caused by unbalanced forces on the rotor, and the other is the torque caused by the difference in the tangential forces on the rotor edge areas acting at the radius of the rotor. These torques can be illustrated by referring to the cross-sectional representation of the nozzle (Fig. 4).

With the rotor at center, the nozzle pressure inside the rotor acts on the unequal projected areas and so produces a side force on the rotor bearings. This can be minimized if an opening is cut in the rotor, as shown in Fig. 4, to equalize opposing projected areas. When the rotor is near its extreme position, the internal pressure distribution balances the reaction force output of the nozzle and so again produces a side force on the rotor bearings. The effects of these forces can be minimized by the use of antifriction bearings.

The tangential component of torque is due to pressure distribution changes, as the orifices are opened or closed, causing force on the rotor edges, which can produce large torques on the rotor. These, fortunately, tend to center the rotor in most cases.

The rotor edge of the orifice proved to be the most important parameter in meeting the design criteria. The ability of the nozzle to center in a zero net thrust position, if driving power was lost, was critical to the choice of edge for the orifice. The torque required to open was also dependent on the orifice edge area. For full thrust in one direction, one rotor edge should nominally be covered by the outer shell. However, since excessive torque was required to recover from complete opening, a stop pin was built into the rotor to maintain an opening of at least a few thousandths of an inch on the nominally closed side. Several rotor concepts were tried (Fig. 5).

1) The first had a $\frac{1}{8}$-in. wall thickness and a square edge orifice. It exhibited poor centering characteristics and high torque requirements.

2) A modified version of the first concept relieved the square edged orifice with a chamfer. This reduces the area facing the sonic stream and puts more of the edge area at nozzle pressure that exists on the opposite edge of the same orifice. Torque requirements were noticeably lower and the rotor did not lock in the closed position.

3) Further relief of the edge was not feasible since it would lead to a thin, low-strength, orifice edge; therefore, a ribbed-type edge was machined with ribs extending to and reinforcing a thin leading edge. The results of testing gave promise of centering and low torque.

4) The ribs themselves were next chamfered to reduce further the rotor edge area facing the sonic pressure. Still further improvement was noted.

For the final configuration the rotor was made thin and square edged to keep the driving torques low and to enhance the centering characteristics of the rotor edge area. Furthermore, the 120° segment of rotor between the orifices was removed to eliminate the rotor aperture edges not in the region of sonic flow at the nozzle exit (Fig. 4). Under air pressure, there initially was binding between rotor and stator of the nozzle, but this was eliminated by boring the stator to increase the clearance between the rotor and stator by 0.005 in. This increased clearance also put nearly the same pressure on the inside and outside of the rotor, and so effectively eliminated the effect of unequal opposing projected areas of the rotor. Static balance was accomplished as much as possible by the removal of metal, as shown in Fig. 6, to minimize weight actually added. Subsequent tests showed that driving torques were proportional to rotor displacement from center position and had acceptable maximum magnitudes, that centering control was available by rotor edge filing, and that measured reaction forces from the nozzle agreed with those calculated from theory. A picture of the final nozzle is shown in Fig. 7.

Simulation Studies

In the study of a control system that involves new concepts, such as the one presented here, it is necessary to study the system through simulation, using as much actual flight hardware in the system as possible. Therefore, a low-friction, air-bearing supported, horizontally rotating beam was set

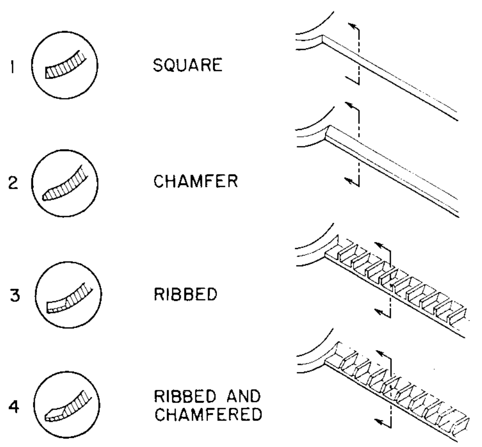

Fig. 5 Nozzle rotor-edge concepts.

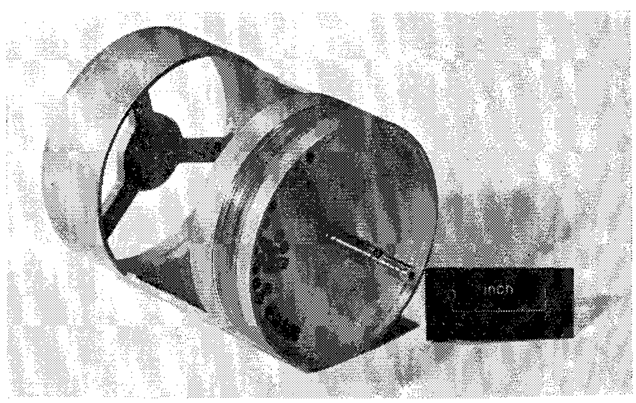

Fig. 6 Final nozzle rotor.

up to simulate the aircraft characteristics for one axis at a time (Fig. 8). This provided a capability to demonstrate how effective the control and damping would be for the aircraft and also to check the operation of the entire system before flight. Inertia weights and the lever arm for the nozzle were chosen so the acceleration would be identical to a desired axis of the aircraft. Air was piped in through a rotating joint to the test stand and provided both air-bearing pressure and nozzle reaction forces. A flow valve permitted adjustment of nozzle air pressure to obtain flow rates similar to those expected in the aircraft. The servodrive components were mounted on the rotating unit and connected to control switches and signal sources by an overhead cable. This cable was brought to the center of rotation so minimum extraneous torque would be produced on the simulator. Without added servo damping the rotational speed of the beam decreased from an initial 40°/sec to 10°/sec in $3\frac{1}{2}$ min. This natural damping was considered satisfactory for tests on the simulator.

When the nozzle servosystem was used without damping, the angular position of the beam was relatively hard to control. As servodamping was added by a signal from a rate gyro, the control characteristics became better and better so that position changes could be easily controlled. When damping was reversed in sign, the system soon became uncontrollable, depending on the experience of the operator.

Accurate centering of the individual nozzles was accomplished on the simulator. First, air centering to get zero net reaction moment was done by trial and error process of filing the rotor edge. Just a slight amount of metal removed had a large effect. Second, the follow-up was set to electrical null with the nozzle in this centered position. After these adjustments, the maximum force was measured for full open in both directions for each nozzle, and the reaction force was found to be linear with percent opening.

System Reliability and Performance in the Aircraft

Electronic parts of the system have given practically no trouble. One failure did occur in the power supply during a flight and the automatic safety system operated to turn the system off. After some flight experience, the automatic safety system was found to be too sensitive, and since the pilots did not like to lose the variable-stability control unless it was absolutely necessary, the sensitivity was reduced by 50%. This has worked very well and is still much faster than the pilot's reaction. The motorized nozzles have performed well for over 150 hr of flight time. This is a very good record considering they were designed for a short research program and not for an operational vehicle. The nozzles are disassembled periodically for inspection and preventive maintenance. Several bearings have been replaced as they become noticeably rough. High-temperature grease and silicone oil have both been tried on the bearings, but neither seems to have much advantage on the basis of flight data so far. The nozzle's air centered position stayed constant. There has been practically no deformation, pitting, or deposits from the bleed air on the critical rotor edge. Some of the roll pins holding gears on shafts have loosened, have caused backlash, and have been replaced.

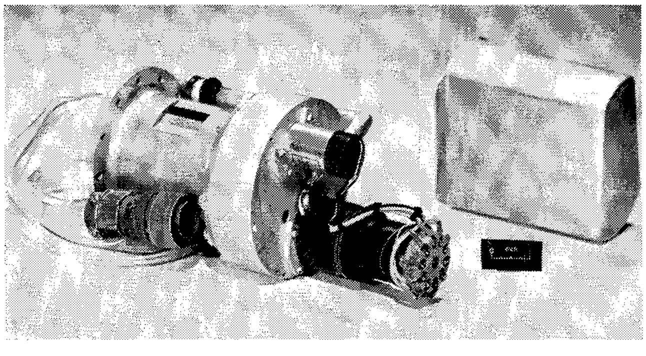

Fig. 7 Final nozzle assembly.

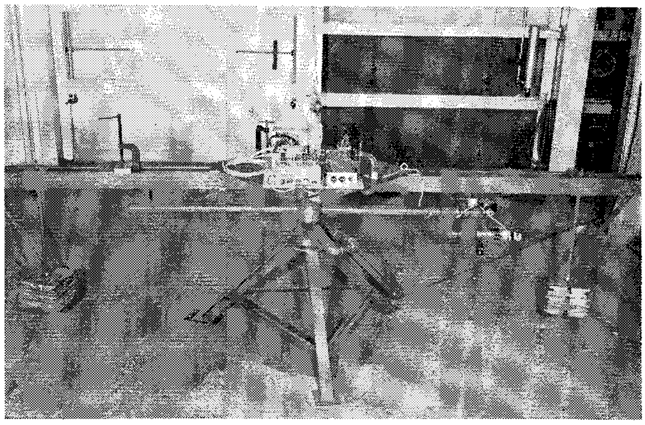

Fig. 8 Single-axis aircraft simulator.

The pilots prefer the variable-stability system to be in operation because it makes the aircraft more stable and easier to fly in the hovering mode. First, it cancels out the unwanted cross coupling due to engine gyroscopic effects, and second, it provides damping and thus makes the aircraft respond in hovering much as it does in normal flight. The pilot augmented control system permits a yaw rate of about 75°/sec and a pitch rate of about 60°/sec with no noticeable gyroscopic cross coupling between the pitch and the yaw axes. The stiffness control augmentation makes it easier for the pilot to keep the aircraft steady under gusty conditions. The safety features have proved to be valuable and have provided intangible benefits in terms of pilot confidence.

The system has operated as designed and provided a means of examining the control power and damping relationship in the hovering mode for the boundaries of good, acceptable, and unacceptable pilot control.

Conclusions

A variable-stability control system for VTOL has been developed. The system allows the damping and control power to be varied over a range of flight characteristics. The system has been used to explore the boundaries of acceptable control power and damping for a VTOL aircraft. Established procedures for variable-stability systems in conventional aircraft have been extended to the special problems of hovering VTOL aircraft. A large flow of reaction air has been controlled by a small servomotor, with satisfactory response for aircraft control.

Agreement was good between theoretical and measured reaction force from the nozzles. A rectangular orifice with a square edge gave a nozzle with a linear reaction force output and low driving-torque characteristics. This type orifice also permitted easy mechanical centering.

Safety was assured by the air-centering characteristics of the nozzles and an electronic failure detector. This system has given a versatile, reliable, and controllable vehicle for basic research on VTOL aircraft.

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