Moving-Base Simulator Study of an All-Mechanical Control System for VTOL Aircraft

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The controllability requirements necessary during VTOL hover and transition have, in the past, been met through the use of electronic stability augmenters. As a new solution of this problem, a primary control system containing only mechanical components, such as springs, bobweights, and dampers, is conceived to provide the pilot with a control mechanization that is capable of preshaping his displacement control commands into a more suitable output form. A simulation study has been conducted to determine the optimum type of shaping. Pilots were required to control motion about all axes while evaluating a single mode. Pilot ratings and the orthogonal squares technique were used to optimize the control parameters for each mode. These control parameters were then designed into physical hardware which was installed in the simulator and evaluated by the same pilots. This procedure has successfully established required criteria and demonstrated the effectiveness of the mechanization. The simulated airframe with conventional control is given a Cooper rating of from 5–7, the addition of rate stabilization reduces the rating to 2–3½ and, with the mechanisms as developed and installed, the pilot's rating is comparable to that where rate stabilization is used.

A VTOL aircraft is capable of flying at very low speeds where conventional control surfaces are almost useless. Ordinarily, control at these speeds is obtained through the use of reaction jets and/or differential thrust. However, successful employment of such controls requires a high level of pilot skill due to the small airframe aerodynamic damping and restoring moments. In addition, destabilizing effects due to the propulsion system, ground proximity, and gyroscopic coupling may increase the pilot's workload. In an ideal configuration these effects could be small enough to be neglected and the aircraft could be considered to be essentially a mass supported by the engine thrust. In the conventional approach to VTOL aircraft control at low speeds angular acceleration generally proportional to the control displacement is provided, rather than the airplane rotational rate commonly associated with pilot control commands. The pilot has to sense the airplane's displacement from the desired attitude, the aircraft's instantaneous angular velocity, and the change of velocity resulting from his command in order to maintain control. In other words, it is necessary for him continually to perform both single and double differentiation of position error. The use of artificial rate damping reduces the pilot's workload by reshaping the angular acceleration commands. This type of control provides steady-state angular velocity directly proportional to control displacement.

As a new approach to the solution of this problem, a primary control system containing only mechanical components, such as springs, bobweights, and dampers, is conceived to provide a control mechanization that is capable of modifying the form of the control output torque.

A mechanical control that revises the form of the control output command could make the VTOL aircraft as easy to control open-loop during the VTOL flight phase as it is when stability augmentation is provided, or during cruise conditions where aerodynamic damping and restoring moments are present. For example, if the control moment command is changed to a moment pulse instead of a steady moment, the pilot's control becomes an angular velocity controller rather than an angular acceleration controller. Changing the applied moment to a moment followed by a countering moment of equal magnitude causes it to become an attitude controller (stick steering).

The mechanical concept discussed here is shown schematically in Figs. 1 and 2. The mechanization shown in Fig. 1 would be affected by airplane or simulator motion. Although this could be advantageous, the mechanisms were designed so that vehicle motion did not affect them as this investigation was concerned solely with development of the open-loop handling qualities. In Fig. 2, the transfer function of the device is given together with the corresponding definitions of the parameters. The pilot's input motion displaces an output mechanism and a spring-mass-damper system simultaneously. This system, depending on the physical relationship of its elements, can modify the output commands as required. For example, if ζ_n is set equal to 1.0, and ω_n and z set equal to the desired level of apparent damping in units of 1/sec, a neutral vehicle will respond to control stick inputs in a manner identical to one in which closed-loop rate-damping is used. It has been established by previous work that preshaping of the output command is useful; therefore the problem at hand is, "What form of shaping best fits the pilot's needs?" Rather than attempting an analysis of the system with a pilot in the loop, it was decided to use a simulator in a systematic testing.[1] The development of a suitable transfer function for a VTOL pilot would be outside the scope of this research and certainly a flight test program could not be undertaken with any assurance of success without more knowledge than was then available. The criterion used to determine an optimum control is pilot's opinion based on the Cooper rating system shown in Table 1.

The simulator used in this program is shown in Figs. 3 and 4. Motion is produced only about the pitch and roll axes. Signals from the simulator's controls are directed to analog computers which in turn compute the aircraft's motion. Appropriate signals from the computers are then directed to the simulator's display system and the pitch and roll angle signals to the hydraulic servomechanism which provides its motive power.

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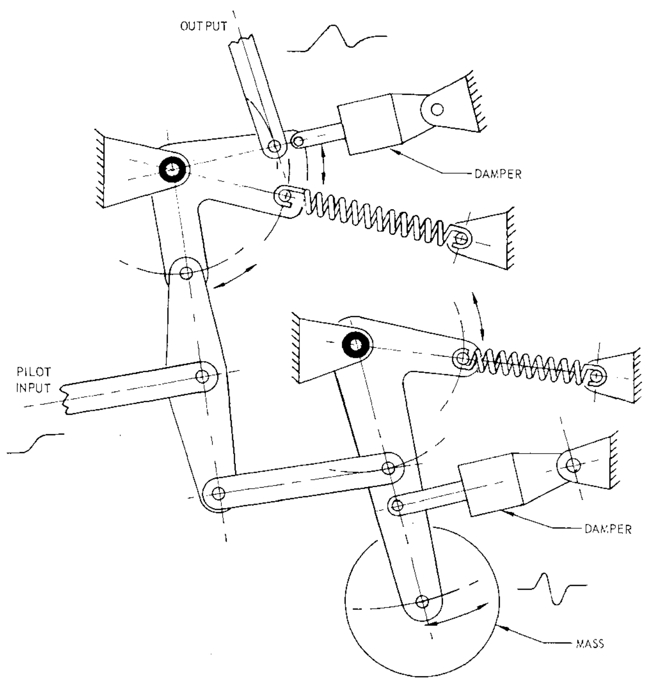
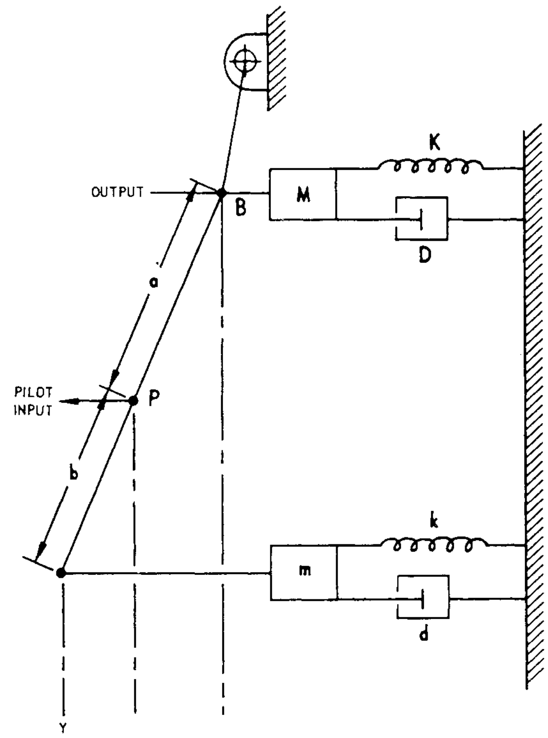


Fig. 1 Mechanical schematic.



$$G_c(s) = A \frac{s(s + z)}{s^2 + 2\zeta_n\omega_n s + \omega_n^2}$$

where, for $k = 0$,

$$z = d/m \qquad R = b/a$$

$$\zeta_n = \frac{D + R^2 d}{2[K(M + R^2 m)]^{1/2}}$$

$$\omega_n = \left[\frac{K}{M + R^2 m}\right]^{1/2}$$

Fig. 2 Schematic diagram of mechanism and definition of parameters.

The simulator cockpit display, shown in Fig. 5, consists of two oscilloscopes and several instruments clustered about them. The upper oscilloscope displays a line to represent the horizon, thus showing the change in roll and pitch. A lower oscilloscope displays two lines, one horizontal and one vertical. These lines move to depict aircraft fore-and-aft translation and side translation. Both of these displays are "inside-out" displays. The instruments displayed around the oscilloscope are: thrust deflection angle, compass, coarse airspeed, angle of attack, fine airspeed, fine rate-of-climb, fine altimeter, coarse altimeter, *g*'s, thrust-to-weight ratio, coarse rate-of-climb, clock, and rpm. Yaw angle is displayed by a moving calibrated ring on the perimeter of the lower oscilloscope and by the compass. This display, somewhat representative of the Bell "RAILS" system is not regarded as an optimization, but rather the minimum necessary to provide the pilot with situation information. The display turned out to be less than optimum for the task, and several suggestions received from the pilots for improvement indicated that when an optimized display is provided for pilots of VTOL aircraft, the control mechanization can be less refined. An additional brief investigation showed that pilots tended to assign a poorer Cooper rating to a control when the simulator was held fixed, suggesting that the motion cues were important. It is felt that the absence of linear acceleration simulation did not detract from the validity of the results because the missions performed did not require appreciable values of these accelerations.

The simulator is able to move through pitch and roll angle ranges of ± 35°. The lateral stick force gradient is 3 lb/in. with a 0.7-lb breakout. In pitch, the gradient is 3.6 lb/in. with a 1.0-lb breakout force.

The airplane simulated is a 40,000-lb-deflected jet supersonic VTOL fighter using jet reaction attitude controls. The equations of motion employed in the simulation are the Euler equations referred to a frame of reference fixed to the airplane. The airplane principal axes are selected as the reference axes and, for the deflected jet-type airplane being simu-

Table 1 Cooper pilot opinion rating system

Operating conditions	Adjective rating	Numerical rating	Description
Normal operation	Satisfactory	1	Excellent, includes optimum
		2	Good, pleasant to fly
		3	Satisfactory, but with some mildly unpleasant characteristics
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics
		5	Unacceptable for normal operation
		6	Acceptable for emergency condition only[a]
No operation	Unacceptable	7	Unacceptable even for emergency condition[a]
		8	Unacceptable—dangerous
		9	Unacceptable—uncontrollable
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape

[a] Failure of a stability augmenter.

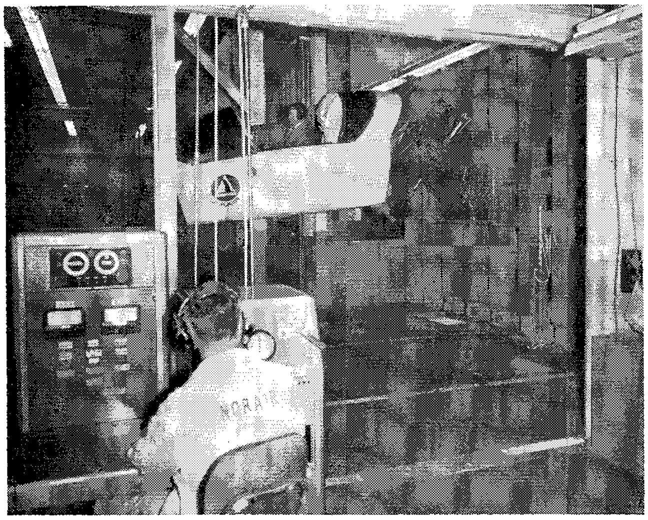


Fig. 3 Simulator with operator at control console.

lated, it is assumed that the engines are mounted approximately parallel to the X principal axis. The assumption of small angles is made and all second-order angular displacement terms are neglected. All attitude and displacement information displayed to the pilot is referenced to the ground. The external forces and moments acting on the aircraft are due to gravity, propulsion, aerodynamic effects, and reaction control inputs. A number of simplifying assumptions are made to facilitate representation of the external forces and moments:

1) The thrust vector is always through the center of gravity.
2) The thrust variation with engine RPM is linear.
3) Engine airflow is constant and equal to airflow in hovering.
4) Ground effects are negligible.
5) Time lags, other than those in the throttle system, are negligible.
6) Aircraft weight is constant.
7) The body axes are coincident with the principal axes.
8) The reaction controls produce pure couples and therefore produce no net force change.
9) The environment is sea level atmosphere, standard day.
10) The rate of change of engine RPM is relatively small.

In addition to the foregoing assumptions, certain others are required to allow a practical representation of the aerodynamics which would be adequate for the speed range from hover to stall speed. Essentially, the aerodynamic forces and moments in hovering are considered to be dominated by momentum changes of the engine airflow. These forces act approximately at the inlets. In forward flight, however, the aerodynamic forces on the airframe dominate the equations. The aerodynamic representation is flexible enough to describe the hovering regime (where angle of attack and sideslip vary over wide ranges) as well as transition to conventional flight.

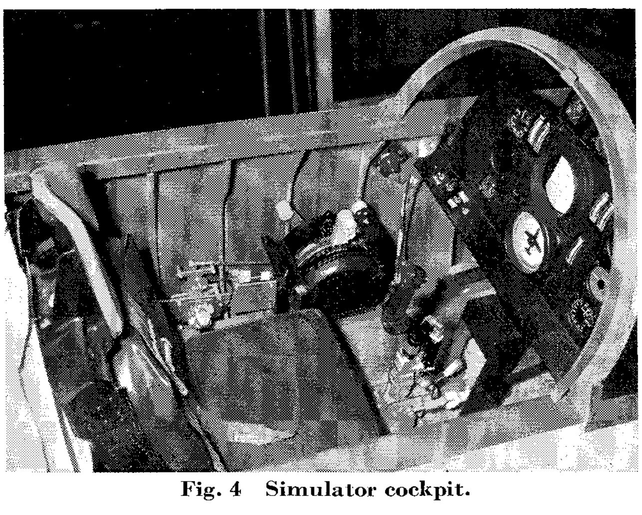


Fig. 4 Simulator cockpit.

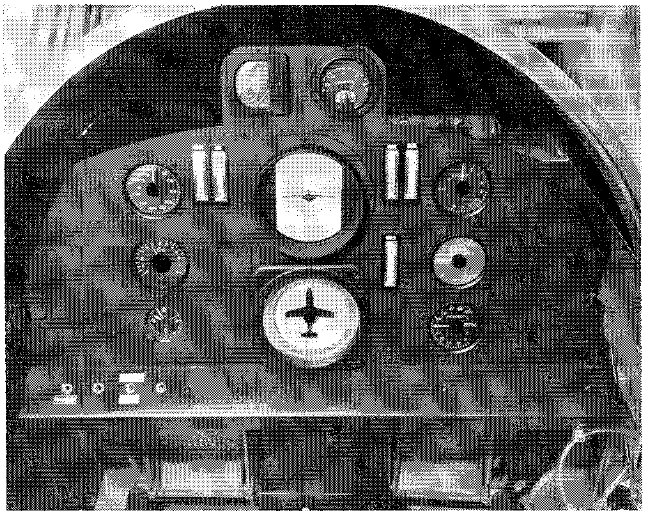


Fig. 5 Simulator instrument panel.

The test program provides for the determination of the optimum values of the control parameters on the three primary axes plus the throttle (or height) control. The testing procedure for each of these four control systems is based upon a pilot flying the simulator on instruments under a hood with the control simulated on the analog computer. The parameters for the control under test are set at particular values by means of the computer potentiometers. A pilot opinion based on the Cooper rating system is then given and a new set of parameters set up. At the conclusion of the tests of all the simulated controls, a series of tests with the actual mechanisms installed on the simulator is performed.

Altitude Control (Throttle)

The altitude (or height) control comprised the first series of tests. It would seem that control of vertical velocity is at least as difficult as attitude control, and less familiar—that is, less familiar to airplane pilots assuming VTOL aircraft would be flown by these pilots rather than helicopter pilots. The simulator is equipped with two throttle control levers located in a position such that they may be operated by a pilot with his left hand in the conventional manner for aircraft with single or tandem seating arrangements. The throttle levers, shown in Fig. 6, are adjacent to each other and both may be conveniently grasped by the left hand, or they may be operated individually. The third handle in the throt-

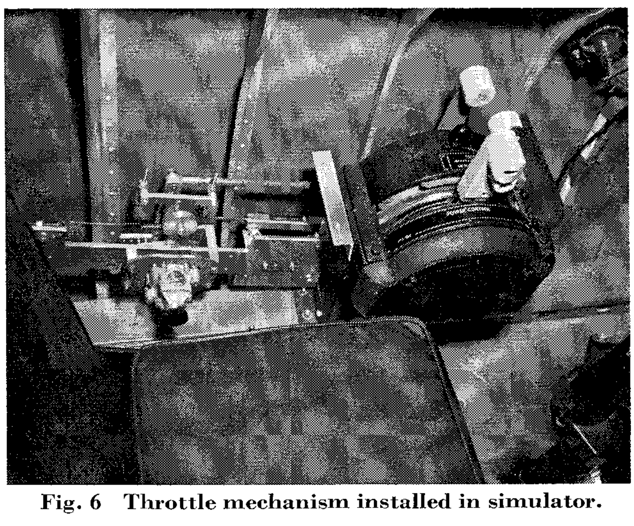


Fig. 6 Throttle mechanism installed in simulator.

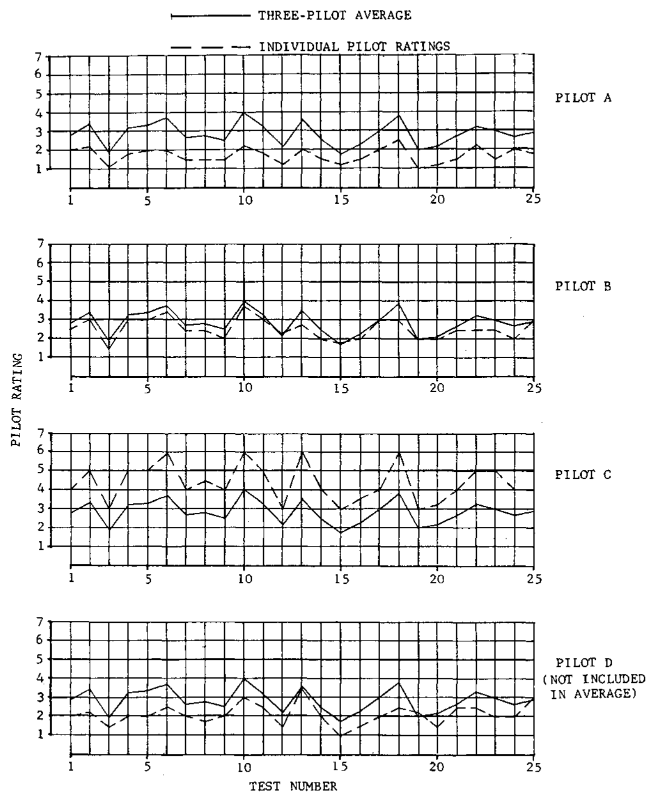


Fig. 7 Throttle evaluation pilot ratings.

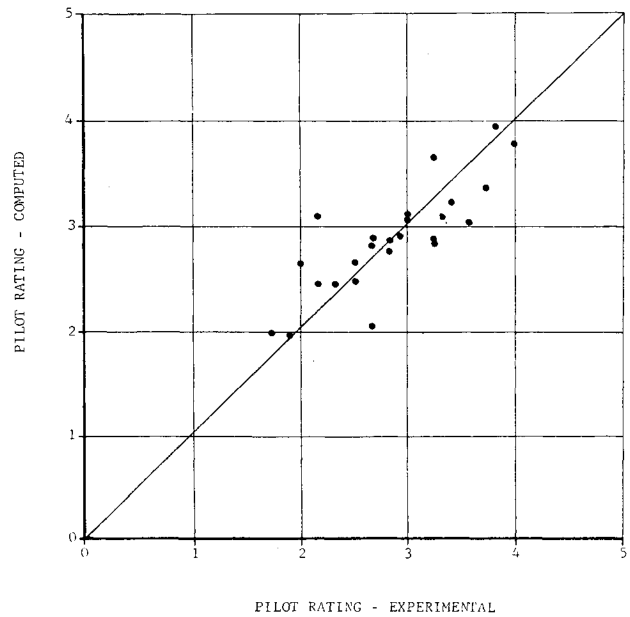


Fig. 8 Agreement of computed and experimental pilot ratings.

tle quadrant is the thrust vector control. This controls the deflection angle of the jet exhaust from 90° (downward) to 0° (aft). It is used in executing a transition to forward flight.

For "conventional" throttle operation, one throttle provides coarse or gross control, the other fine or vernier control. Hence, the throttles are acceleration controls for the control of altitude.

For the altitude control tests, the coarse or gross throttle remains a direct acceleration control. The other throttle controls thrust through the spring-mass-damper system previously described. For the first set of throttle tests, this system is simulated on the computer. Five values for each of four variables are chosen and 25 tests set up in accordance with the orthogonal squares.[2] The four variables are: control system natural frequency ω_n, control system damping ratio ζ_n, control system transfer function zero z, and control system gain A.

The vernier throttle lever of the conventional system provides the throttle control for the spring-mass-damper system. This throttle lever is spring-loaded in its center position. The scaling of the acceleration throttle (the gross throttle control of the conventional arrangement) is such that a thrust-to-weight ratio of 1.0 is produced with this throttle lever in its center position, and 1.2 and 0.8 with the lever in the forward and aft positions respectively. Hence, a flight in the simulator is normally begun with both throttle levers in their center positions. Because of practical considerations, a limit on the available thrust-to-weight ratio of 1.2 is applied. Thus, a control output pulse which would otherwise exceed this value is clipped at the 1.2 limit.

Following a period of familiarization with the simulator and the control under test, the 25 test points are flown by each pilot. The pilot is not told in what manner the parameters are varied and each pilot flies the tests in a different order. The control sensitivity, rate damping and control power limit of the conventional pitch, roll, and yaw controls are set at values somewhat less than optimum so that some attention to all of these controls is required by the pilot. The task given the pilot is to climb vertically to 400-ft alt at a maximum rate of 1000 ft/min. After hovering at this altitude briefly, a descent to 40 ft is made at 500 ft/min. Then a slow descent is made to a landing. The entire flight is to be performed with a minimum of fore-and-aft or side translation. The pilot rating for all 25 test points for 4 pilots is shown in Fig. 7.

The 3-pilot average data is processed by a digital computer programmed for the orthogonal squares technique. The orthogonal squares technique is basically one that produces a curve fitting equation for experimentally collected data. It is a statistical method for handling multiple variable problems, and when reduced to two variables, is the method of least squares. The method is used to solve for values of the pilot rating for 625 combinations of the variables (including the 25 actually tested). The agreement of the computed pilot ratings with the test results is presented in Fig. 8. It is to be expected that the other 600 points would show a similar agreement if they were actually tested.

The combination of throttle parameters yielding the lowest computed pilot rating is set into the analog computer simula-

Table 2 Summary of average VTOL pilot opinion

	Conventional controls (Refs. 3, 4, 5)		All-mechanical controls		
	Optimum sensitivity, zero damping	Optimum sensitivity, optimum damping	Calculated by orthogonal squares method	Computer-simulated	Spring-mass-damper mechanism
Throttle	$5\frac{1}{2}$	$2\frac{1}{2}$–$3\frac{1}{2}$	1.04	2.3	2.3
Roll	7	2–$3\frac{1}{2}$	0.43	2.3	2.5
Pitch	$5\frac{1}{2}$	2–$3\frac{1}{2}$	1.11	2.3	2.7
Yaw	7	2–$3\frac{1}{2}$	...	3.5	3.5

tion of the throttle control and verified by pilot opinion to be satisfactory with an average rating of 2.3. Ratings below 2 are rarely given and this is considered to be verification of a near-optimum control.

Following the tests of the simulated control, tests of the actual mechanism installed in the simulator are made. The springs and damping of the mechanism are adjusted, and the bobweight mass is selected so that an output identical to that of the optimum simulated control is produced. The gain of the signal from the mechanism's potentiometer is adjusted in the analog computer to agree with the optimum gain. The mechanism, installed in the cockpit, is shown in Fig. 6 mounted just aft of the throttle quadrant. Average pilot rating for the throttle control with the mechanism in the system is 2.3, again verifying a near-optimum control. These last tests are not conducted until the roll and pitch control mechanisms are installed and optimized. Thus the evaluation of the throttle mechanism is made with the roll and pitch mechanisms functioning and the yaw control in a conventional configuration.

Roll and Pitch Control

The roll and pitch control tests are conducted in a manner similar to the altitude tests. For both of these sets of tests, a small amount of direct acceleration control is provided varying linearly with stick grip travel. In the case of the roll tests, this acceleration parameter is varied and the control-system transfer function zero is not varied. The pilot's task for the roll control tests is the same as for the altitude control. For the pitch tests, the pilot's task is to climb to 200-ft alt and accelerate to 50 knots simultaneously. This is followed by a reduction in airspeed to zero and a descent to a low altitude. Because of computer limiting on the amount of forward translation possible, holding a slight rearward airspeed for a short time returns the fore-and-aft reference line to the field of the scope and a landing with the two reference lines centered can be made. The test data are again processed in accordance with the orthogonal squares method. In each case, the selected parameters, when set into the analog computer simulation of the controls, are verified by pilot opinion to be satisfactory with an average rating of 2.3. Average pilot rating for the roll control with the mechanism in the system is 2.5 and for the pitch control mechanism 2.7, verifying satisfactory controls in each case.

Yaw Control

The orthogonal squares method is not used to optimize the yaw control. Instead, a shorter, less systematic testing program based on the experience gained with the other controls is used. The parameters tested are the same as in the altitude and pitch tests. A small amount of direct acceleration control is provided.

Two pilot's tasks are used to evaluate the yaw control. The first requires the pilot to hold a constant heading while translating sideways at side velocities of up to approximately 15 knots without side wind; and the second to execute a transition to forward flight of 50 knots and back to hover at a constant heading in a 15 knot side wind. An average pilot rating of 3.5 is obtained for the yaw tests, both with the control simulated on the computer and with the actual mechanism installed.

The yaw control evaluation suffers from lack of simulator motion and lag in the cockpit display. Because the yaw rate is appreciable during these tests, especially with non-optimum controls, increased pitching acceleration is experienced through gyroscopic coupling. Consequently, the work load of the pilot is increased tending to deteriorate the rating of both pitch and yaw. To gain an insight as to the measure of this effect, flights made without coupling show the average pilot rating to be approximately one unit better on the Cooper scale in both pitch and yaw. The effects of gyroscopic coupling are considered to be beyond the scope of this study and therefore are not treated in great detail.

Conclusions

A two-axes moving-base simulation of a representative neutrally stable jet reaction controlled VTOL aircraft has been accomplished. During thrust supported flight in gusty air under IFR conditions, combinations of the best acceptable control parameters have been developed, mechanized, and demonstrated.

1) The pilot ratings show that optimized preshaping of the pilot's control displacement commands improves the pilot's control capability to a level comparable to that where rate damping is used. A summary of the pilot ratings obtainable with rate-damped and all-mechanical control systems is presented in Table 2.

2) The preshaping of the pilot's control displacement commands has been accomplished with conventional mechanical control elements and test flown on a two-axes simulator.

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