Piloted Simulation of Hover and Transition of a Vertical Attitude Takeoff and Landing Aircraft

Gary C. Hill*
NASA Ames Research Center, Moffett Field, California

Piloted simulation studies of candidate control systems for vertical attitude takeoff and landing aircraft were conducted on a six-degree-of-freedom simulator. Hover and transitions from wingborne to hovering flight were performed, with and without turbulence, on a representative high-performance fighter configuration. Deflection of the rear engine nozzle provided pitch and yaw control moments in concert with reaction controls for roll. Unique motion cues in hover result from the vertical displacement of the cockpit and the thrust vectoring nozzles. The control power available from moderate engine nozzle deflection combined with rate feedback for stability augmentation provided very satisfactory control.

Introduction

IN 1946, the X-13 experimental aircraft built by Ryan Aircraft Company[1,2] performed impressive demonstrations of using vertical attitude as a vertical takeoff and landing (VTOL) mode. Although the feasibility of vertical attitude was proven by the X-13, technology was not available to provide sufficient mission performance. Today, the thrust-to-weight ratios of conventional fighter aircraft have advanced to and exceeded unity. Recent studies have shown that the capability to maintain controlled flight at lift coefficients beyond stall could have considerable payoff for air-to-air combat and may be necessary for survival in an intense antiaircraft environment. Together, the capabilities of low-airspeed controllability and more thrust than weight give a potentially VTOL capable fighter.

Vertical attitude takeoff and landing (VATOL or tailsitter) provides the least compromise to mission range and performance of all supersonic VTOL concepts. Operationally, the disadvantages of VATOL are the ground handling considerations, which reduce some of the deployment versatility and questionable STOL preformance with overload capability. Technically, the major unknowns for the tailsitter are the stability and control characteristics, the flying qualities in the hover, and transition to hover flight regimes. These studies were undertaken in order to fill that void.

Facilities and Equipment

This experiment utilized the S.01, one of the NASA Ames Research Center's six-degree-of-freedom simulators. This simulator consists of a single-place cab mounted within a gimbal structure, which in turn is supported by three translational frames. The cab can rotate ±45 deg from center in each of the three degrees of rotation—roll, pitch, and yaw. The translational structure permits the cab to travel 20 ft (±10 ft) in the vertical, longitudinal, or lateral directions. A simplified pictorial diagram of the simulator is shown in Fig. 1.

The simulator cockpit arrangement is shown in Fig. 2. A standard center stick controller provides lateral and longitudinal control. Maximum deflection of the stick is ±5 in., and it is attached to hydraulic control loaders for which deadbands and breakout forces can be varied. A beeper-type trim button is incorporated into the top of the control stick. Rudder pedals have approximately ±4 in. of travel, and their force gradients may also be set to any desired level. The left-hand throttle quadrant is also conventional, except that a detent was provided near the midpoint of the 3.5 in. of allowable travel. The purpose of the detent will be explained later. The "speed brake switch" atop the throttle was used as a controller for cockpit tilt; this function will also be elaborated upon later.

The cockpit instrument panel is also shown in Fig. 2. All of the basic instrumentation of a conventional aircraft and helicopter is included, plus indicators of angle of attack α, angle of sideslip β, and the lateral velocity. The other unique indicator is the cockpit angle indicator. Note that the forward velocity registers backwards up to −20 knots.

Two modes of operation were utilized: an open cockpit with one-to-one motion for hover conditions and a closed cockpit with washout motion for flight with forward velocity. One-to-one motion is a real-time simulation of hovering flight where the simulator cab duplicates the exact trajectory and attitudes of the aircraft. This simulates the visual hovering task. For flight in instrument conditions, a hood is placed on the cabin, and normal cockpit instruments are relied upon. Here cab motion is washed out before translational limits are reached, leaving the pilot only acceleration motion cues.

Mathematical Model

The mathematical model used to conduct this simulation exercise was developed for NASA by the Vought Corporation, Dallas, Texas. The model, described in detail in Ref. 3, is generic, all digital, and complete. Euler angles, commonly used for kinematic equations, are not acceptable for the VATOL simulation. At hover, where the cosine of the pitch angle goes to zero, a singularity is created; therefore, direction cosines are used in the computations. Aerodynamic coefficients and stability derivatives are generated in body axes and are derived from the methods of Refs. 4 and 5, or may be entered tabularly as from wind-tunnel tests.

The representative VATOL fighter configuration utilized for these tests is shown in Fig. 3. The delta wing with canard layout typifies future conventional fighter designs. The single-engine design shown is incidental to this study. Factors other than VTOL stability and control will determine the number of engines in the design of an operational aircraft. It is important that the aerodynamic and propulsion system performance suitably represent a class of next-generation high-performance aircraft.

Aerodynamic data used in the program are derived from Refs. 4 and 5 and validated with NASA Langley wind-tunnel tests of a similar delta-wing model.[6] Few sources of complete aerodynamic data to 90-deg angle of attack and beyond exist at this time.

Propulsion system performance and engine dynamics are based on a parametric cycle deck, CCD-0284-03.1, supplied by Pratt & Whitney and by the system described in Ref. 7. The

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*Aerospace Engineer. Member AIAA.

engine characteristics are appropriate for a 1995 initial operating capability (IOC). The only unique aspect of this powerplant is that it can use augmentation at low power to improve heave rate response in the hover mode. Propulsion system modeling includes the effects of ram drag, exhaust nozzle deflection, compressor bleed, and gyroscopic forces. Throttle response rates can be geared to simulate several engine types including variations in airflow, bypass ratios, and compression ratios.

Weights and inertias that result from this representative configuration are close to the values of CTOL fighters. The inertia-to-weight ratios that determine the center of rotation have a greater effect on the hovering control system design than do aerodynamics. This will be discussed in detail later.

Aerodynamic control is provided by elevons in pitch, rudder in yaw, and differential elevon in roll. These are blended with wing leading-edge slats and canard flaps to produce favorable trimmed lift contributions. At slow speeds where aerodynamic control surfaces become ineffective, pitch and yaw control is integrated with the propulsion system through deflection of the exhaust nozzles of the main engines. In addition, the program has provisions for up to 10 reaction controls and for thrust vectoring. Thrust losses resulting from the reaction control system (RCS) bleed are also computed. Control actuators may be commanded by stick, pedals, throttle, or as a function of angle of attack or state variables.

Turbulence was generated with the application of the computerized digital gust model routine detailed in Ref. 8. It is based on a zero-mean Gaussian (normal) random turbulence field.

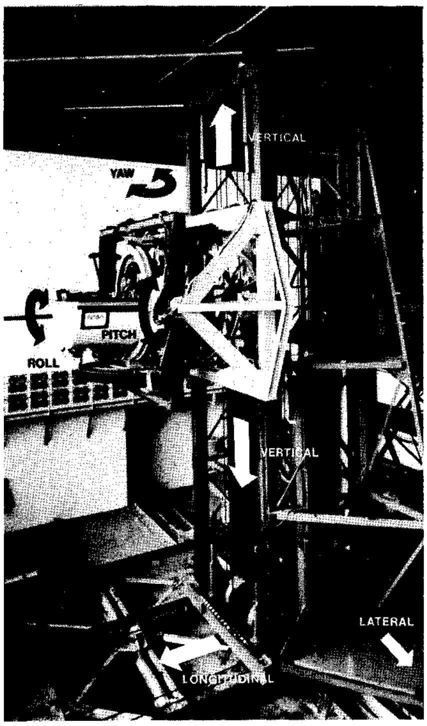


Fig. 1 S.01 six-degree-of-freedom simulator.

Scope of the Experiment

Flying qualities of the aircraft for attitude control and for translational control were explored in hover. Attitude, trajectory, and configuration management were assessed during transition from cruise to hover.

When hovering with open cockpit, pilots did station-keeping and position-changing tasks, both with and without turbulence, to evaluate and rate the flying qualities. The purposes of these tests were to learn about the basic motions of the VATOL vehicle and to investigate various control modes, rather than to develop an optimum control system tailored for this particular vehicle.

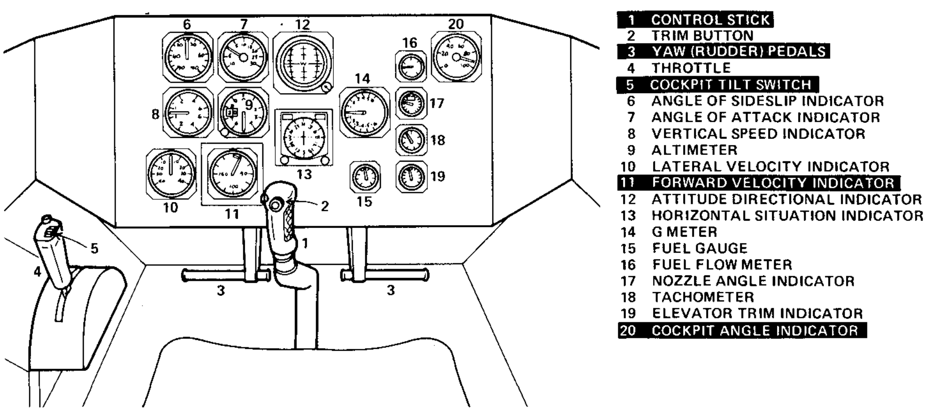
Limitations of the simulator range of motion would not allow the cab to pitch more than 45 deg nose high. Tests were therefore limited to simulation of a VATOL vehicle with a rotating cockpit (Fig. 4) that keeps the pilot in a relatively upright position when the aircraft is in its vertical attitude. An alternative approach, used by the X-13, was to rotate the pilot's seat within the cockpit. Thus, in hover, with the cockpit rotated, aircraft roll and yaw become reversed. Experiments in the transition phase were mainly concerned with the phasing of these control senses. Subsequent references to roll and yaw are relative to cockpit (pilot) fixed axes. Four modes of hover control systems were tested: unaugmented control (UC), rate command (RC), rate command attitude hold (RCAH), and attitude command (AC). They formed a hierarchy from simple to complex system mechanization and were implemented by selection of appropriate feedback loops and parameters. Gain and lead/lag functions were varied to provide the most desirable flying qualities. These four control modes are shown schematically in Fig. 5.

Unaugmented control: UC is a pure manual control mode with no feedback loops. Nozzle deflection is proportional to stick deflection, with only control sensitivity as a variable. UC provides acceleration commands.

Rate command: This mode is closest to conventional aircraft. Pitch, roll, and yaw rates are made proportional to stick and pedal deflection. The feedback system is comparable to many stability augmentation systems in common usage today.

Rate command attitude hold: RCAH exhibits the control characteristics of RC with the addition of attitude disturbance suppression. During translational maneuvers it is identical to RC. When control inputs are removed, forward loop in-

Fig. 2 Simulator cockpit.



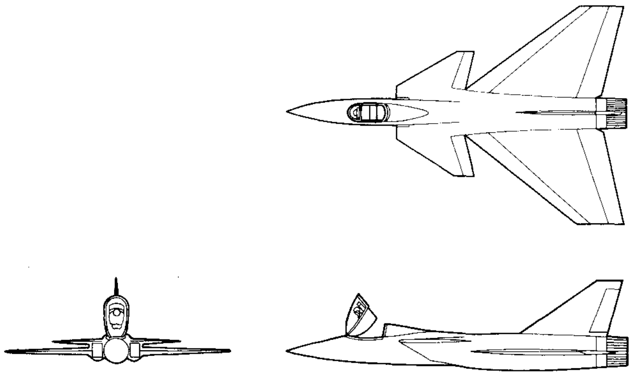


Fig. 3 VATOL fighter configuration.

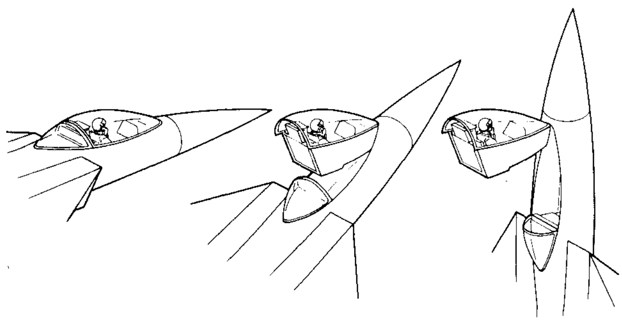


Fig. 4 Articulating cockpit.

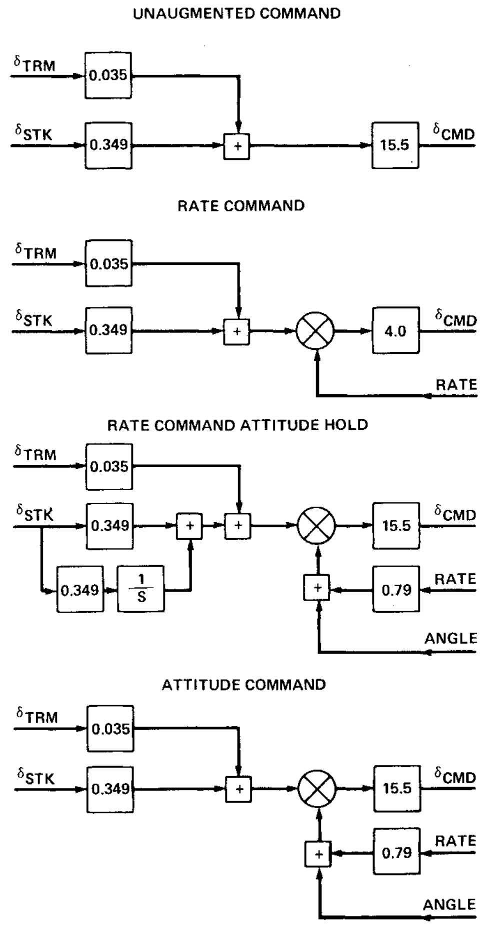


Fig. 5 Schematic of control systems.

tegrator and attitude feedback provide an attitude hold function, eliminating the necessity for retrimming.

Attitude hold: AH uses rate and angle feedback to make roll and pitch attitudes proportional to stick deflection.

Control Power

Transition

Control power sufficient to trim the aircraft with an additional margin for maneuvering is provided through the full flight range from hover to wingborne flight. Longitudinal control is accomplished with a combination of aerodynamic controls and deflection of the rear thruster nozzles to a maximum of 15 deg. The percent at maximum nozzle deflection is expressed by δ_{pitch} and is used in Figs. 6 and 7. Figure 6 shows the pitch control and thrust required to maintain trimmed flight for speeds from 0 to 500 knots. It can be seen in Fig. 6 that the most critical region occurs just below stall speed, where aerodynamic controls have lost their effectiveness and the thrust required is low, limiting the moment-generating power of the vectoring nozzles.

Figure 6 also shows the influence of accelerating and decelerating. High deceleration rates are low thrust situations, limiting control power from thrust deflection. The X-13 flew successfully, although it did not have sufficient trim power at these intermediate speeds and simply pitched from one flight mode to the other.[2] The 4-knots/s (0.2g) deceleration shown in Fig. 6 is a very rapid transition, probably more than is operationally practical. Notice that achieving -4 knots/s in the flying range of 150 to -200 knots would require thrust reversing.

Hover

Using a maximum nozzle deflection of ± 15 deg produces accelerations of 0.8 and 0.89 rad/s^2 in pitch and yaw, respectively, which are 14% and 120% greater than AGARD 577 specifications for adequate hover controllability. RCS jets at the wing tips provide roll accelerations. Roll accelerations at maximum AGARD 577 specifications of 0.4 rad/s^2 require approximately a 12% bleed.

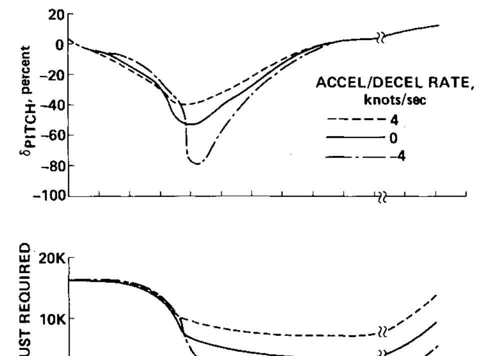


Fig. 6 Pitch control and thrust required vs forward velocity for trimmed flight.

The amount of control power required for trimming at transition speeds is more than sufficient for translational flight at hover. Figure 7 shows the control power needed to trim for hovered flight in a 35-knot wind for 180 deg of wind direction. The maximum value needed is less than 20% of the available control power. Maximum-crosswind limitations are more likely to result from the tilt angle required to hold steady against the wind, making docking risky. The required thrust increases only 2.5% in the worst-case angle at 35 knots of wind.

Dynamic Motion Characteristics

The VATOL, like other jet-powered VTOL aircraft, has very little natural damping or resistance to motion at low speeds. Rotational and translational damping is sufficient at normal flight speeds to give conventional fixed- and rotary-winged aircraft a natural rate or velocity command which provides a very satisfactory attitude and flight-path control. Helicopters in hover operate in the accelerated flow of their rotor wash, which provides some damping even when inertial velocities are low.

Jet-powered vehicles, operating at hover speeds, are not similarly blessed and require a control system that compensates for the lack of natural damping. This applies to rotational and translational motions.

Acceleration command systems require the pilot to compensate for the lack of damping, increasing his workload. This greater complexity is illustrated in Fig. 8, a graph of the motion of VATOL aircraft with zero damping, performing a side-step translational maneuver in hover. A helicopter would need only to roll to an angle of bank to establish a translational velocity and then be righted again to stop the motion. The top line of Fig. 8 shows a similar rolling (aircraft yawing) to an angle of bank, but, when the desired velocity is reached, the bank must be taken out to prevent acceleration to higher velocities. With low drag, bank angles are proportional to acceleration increase of velocities. Terminating the side velocity in Fig. 8 requires a similar double maneuver: rolling in the opposite direction, and then correcting back to an upright position.

The bottom trace of Fig. 8 shows the angular nozzle deflections required to perform the translation maneuver. Notice that starting and stopping each roll requires two pulses: one to start and one to bring the rolling acceleration back to zero. In the absence of roll damping, a doublet replaces the pulse. Along this bottom line we see eight individual pulses, representing an eightfold increase in the number of control inputs.

Stability augmentation systems (SAS) are the means of compensating for inadequate damping. On conventional aircraft SAS is usually employed for only one or two weakly damped degrees of freedom which are not as void of damping as the jet-powered VTOL. In order for an SAS to be effective, there must be adequate control power and response rate. The VATOL, fortunately, has an excess of both and, with an application of the emerging fly-by-wire and control-configured vehicle technologies, should be able to have very favorable stability and control characteristics.

These consequences of low damping apply to all jet-powered VTOL vehicles, including the Harrier, VAK-191, and X-14. An element of control and motion unique to the VATOL results from the vertical displacement of the pilot above the center of gravity (c.g.), and from the nozzles far below. Deflecting the thrust nozzles creates a rolling moment about the c.g.; however, the vehicle rotates about an instantaneous center of rotation that is a function of the moment of inertia and distance to the nozzle, and is defined by the expression

$$\text{center of rotation} = \frac{(\text{radius of gyration})^2}{\text{thrust moment arm}} = \frac{(I_{yy} \text{ or } zz)/m}{X_{\text{nozzle}}}$$

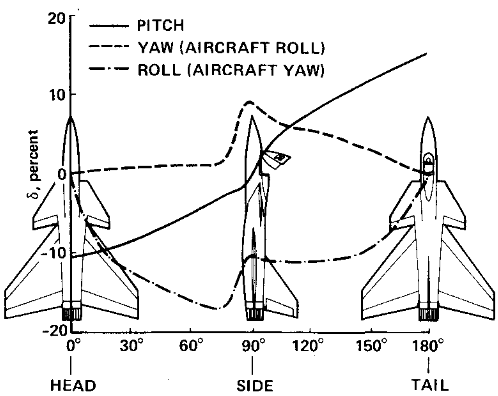


Fig. 7 Control required to trim in hover in a 35-knot wind.

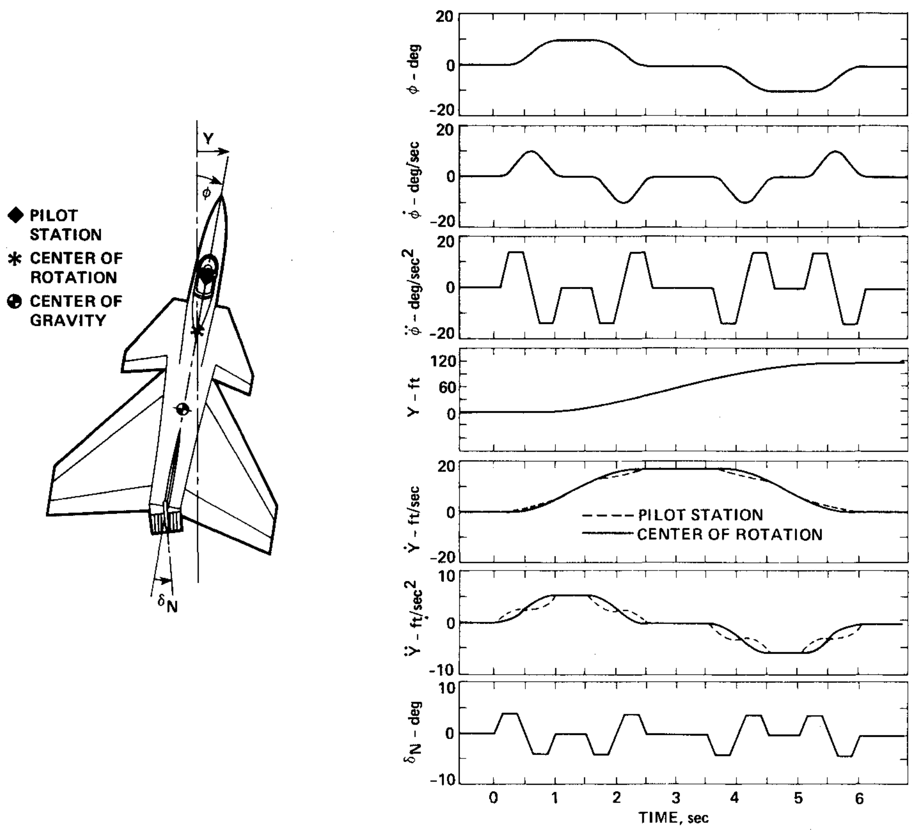


Fig. 8 Strip charts on a 6-s side-step maneuver.

The center of rotation, seen in Fig. 8 to be located between the pilot station and the center of gravity, causes the pilot to feel lateral translations from pure rolling motions. This has both favorable and adverse effects on the control of translations. Its undesirable features are the addition of extraneous movements that are not representative of the vehicle's position and that it makes the motions at the pilot station more jerky. There is an important positive aspect: not only are the translational motions resulting from rotation in the same direction as the translation that will result from the rotation, but they precede them, thus giving the pilot lead information and enhanced cues of sensitivity to motion. This phenomenon can be seen in Fig. 8 by following the trace of translational acceleration, where the cockpit translational acceleration can be seen as differing from the translational acceleration of the center of rotation by as much as 1 ft/s^2.

Results

The dynamic motion characteristics associated with the vertical displacement of the pilot above the center of rotation did not produce significant adverse consequences to the flying qualities of the simulated VATOL. These characteristics were readily apparent and unique and gave an accurate feeling of the displacement from the center of rotation. Jerkiness appeared when response gains were high, but this is only partly attributable to displacement of the cockpit and can be compensated with control input filtering.

The four modes of hover systems were tested. Gains and lead/lag functions were varied to provide the most desirable flying qualities, but they were always a compromise between being either too jerky or too sluggish. Slow-response parameters were described as wallowing. Rapid systems, which were more precise, tended to cause the pilot's head to lurch about. Matrices of gains were investigated to provide the maximum crispness without the adverse effects.

UC: The complexity of acceleration command was borne out in attempts to fly the simulator in manual mode, with stick deflection directing controlling-nozzle deflection. Oscillations quickly built up with changes in direction greater than the simulator could generate, tripping out the motor drives. Even if the frequency response of the S.01 were adequate to represent the motion accurately, this mode, which received ratings of 9 and 10, would not be suitable for an aircraft application.

RC: The pilot ratings for rate command were 3 to 4: very satisfactory, lacking only a degree of precision to be judged even higher. Deviations from targeted stopping points were 2-3 ft or less; it was felt that reducing these values would be desirable. Maintaining attitude and position was easy; however, attention was needed to ensure that the simulator cab did not wander. Overall, the system was very stable, requiring almost no adaptation or training.

RCAH: The self-trimming feature was not considered especially valuable by the pilots, who felt that it was a nice gadget but not a significant improvement to the controllability. Ratings given were also 3 to 4. Atmospheric disturbances manifest themselves more as translational displacements than as attitude upsets to the VATOL orientation.

AH: Attitude hold was the preferred mode but did not provide a substantial advantage over the RC and RCAH systems. Pilot ratings of 2 and 3 were given. Even though this mode did not reduce the complexity or number of control inputs required for starting and stopping motions over the RC and RCAH systems, it was more precise and stable for use in controlling translational velocities.

Vertical velocity command (VVC) reduced pilot workload, as did a detent fitted to the throttle to correspond with zero vertical speed. The detent was very useful in preventing overshoots in height control by providing a reference for nominal hover thrust. VVC was not a significant control design contribution, pilot ratings differing little from manual throttle. When the translational control system gains were proper, the aircraft was not significantly more difficult to hover using manual throttle. The modeled engine is quick-reacting, and tolerable engine lags will be the subject of further study.

Transitions were simulated in a closed cockpit, as described earlier. The profiles flown were level flight, decelerating from 200 knots to zero. At the same time, cockpit tilt was activated to keep the pilot's attitude within the S.01 pitch limits while the aircraft rotated from horizontal to vertical. No difficulties were encountered, maintaining altitude to 50 ft using only the standard cockpit instrumentation shown in Fig. 2. Coordination of throttle and control stick was natural enough not to require a constant conscious thought process. Maximum pitch rate available was ± 20 deg/s with full control deflection. As the cockpit was tilted to maintain a level attitude, it was necessary to reverse the sense of the aircraft roll and yaw control systems in order for the pilot to maintain control orientation. Control phasing from the normal rate command to the attitude command mode preferred for hover was tied to the cockpit tilt angle. A linear scaling between 40 and 50 deg of cockpit angle relative to the fuselage centerline was satisfactory. Cockpit tilt, which was controlled with a switch on the throttle, normally the speed brake switch, was usually done in steps and at maximum rate. It was also easy to stop pitch rotation and to stabilize and maneuver at all intermediate speeds.

Effects of Turbulence

The principal utility of turbulence was to induce tight control and add a degree of difficulty to the tasks in order to test each control system option and gain more meaningfully. During turbulent conditions the pilots had to use more abrupt control inputs, whereas smooth-air flying had longer duration control inputs of smaller magnitude.

Although gusts were introduced in all three directions, the vertical was least affected, since the vehicle is thrust supported and has little axial aerodynamic force in hover. In the other directions, the attitudes were not affected appreciably. The primary disturbances occurred in the horizontal plane. The turbulence-induced motions were low frequency in character, with corner frequencies as great as 8.4 rad/s. Controllability was not degraded significantly with the introduction of turbulence, which was expected since control forces are generated by deflection of the propulsion exhaust and not aerodynamically. The vehicle was bounced around, making the hovering and maneuvering task more difficult. The main restriction was imposed by the confines of the simulator's range of travel. Gusty conditions made pilots reluctant to venture near the outer regions of the 20-ft cube, where sudden deviations might put the cab into the stops before countercontrols could be applied. Constant attention was required to maintain a desired hover point, but this was deemed an annoyance rather than a danger, even at the severest conditions tested, equivalent to 10-ft/s rms gusts.

Conclusions

These piloted simulation studies of a representative VATOL aircraft control system revealed that the control system requirements are not a detriment to the design, and that the displacement of the pilot above the center of rotation in hover gives a unique motion but does not adversely affect the handling characteristics. The control power provided by moderate nozzle deflections was sufficient, even abundant, compared with the requirements of horizontal attitude VTOL aircraft. And simple rate damping, usually necessary on hovering aircraft, provided sufficient stability augmentation. The moment arm created by the cockpit's remote location from the center of rotation transforms aircraft rotational motions into translational motions superimposed upon those of the aircraft at the crew station. Although adding some jerkiness, these acceleration cues provide lead information, and pilots adapted to them very readily.

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