Problems Unique to VTOL Automatic Flight Control

LEO J. MUELLER*
Honeywell Inc., Minneapolis, Minn.

The automatic flight control system is a desirable aid to the handling qualities, stability augmentation, and safety of the present day VTOL aircraft. This has been verified in recent flight tests of the VJ101C VTOL built for the German Defense Ministry. Flight and simulator experience gained on this program emphasizes the need for stability augmentation in at least the pitch and roll axes. Other features, such as control stick steering and engine failure protection, were also provided. Since some of the flights were performed on a telescopic simulator, the range of control parameters could be expanded to permit a wider range and better separation of the control variables. All three phases of the VJ101 program as well as three distinct prototypes are described.

Introduction

VERTICAL take-off and landing of an aircraft has a number of inherent problems: low stability, insufficient control power and stick sensitivity, and an unrealistically high task load on the pilot, all of which can be mitigated by an automatic flight control system. Providing such a flight control system for a VTOL aircraft, however, presents its own problems, and it is with the solutions to these problems that this paper is primarily concerned. The discussion is based on Honeywell's participation in the development of a VTOL jet fighter, the VJ101C, for the German Defense Ministry.

The firm Entwicklungsring-Süd (EWR), a combination of Messerschmitt, Heinkel, and Bölkow, was formed to develop the VJ101C. Honeywell was selected by EWR to provide the automatic flight control systems for several VTOL aircraft in various stages of the VJ101C development. This project demonstrated both the feasibility of an automatic flight control system for VTOL aircraft and the fact that aircraft safety, stability, and handling qualities can be greatly improved by its use.

Program Description

Four prototypes were developed during this program, starting about 1959. The first prototype, "Die Wippe," was used to determine the feasibility of controlling the aircraft in the hover phase by engine thrust alone. It consisted of a horizontal beam pivoted at one end and with a RB108 Rolls Royce jet engine and a cockpit at the other end. As shown in Fig. 1, the pitch axis was simulated, although the pilot's seat could be turned for roll axis simulation. The static moment and inertia of the vehicle were varied to simulate the same characteristics as the aircraft. Under normal circumstances, the horizontal attitude or pitch angle was held by varying the thrust of the engine. The autopilot for this vehicle used a vertical gyro, rate gyro, and accelerometer as sensors and a series hydraulic servo for thrust control. This system proved the feasibility of thrust modulation as a means of attitude control.

The next prototype, the "Bedstead," was built to have six degrees of freedom and more nearly represent the final configuration. Three RB108 lift jet engines were installed, one at the end of each boom and one in back of the cockpit, as shown in Fig. 2. The uncovered fuselage was made of steel tubing with the engines located on booms equidistant from the center of gravity to simulate the aircraft.

Control was by thrust modulation of the three engines for pitch and roll and by differential tilt of the wing-tip engines for yaw. For this prototype, a four-axis autopilot was developed that controlled roll, pitch, yaw, and altitude. For early tests, the "Bedstead" was tethered at the vehicle center of gravity before free flight was attempted.

The final prototypes, designated the X-1 and X-2, have a pair of RB145 jet engines in rotating pods on each wing tip and two lift engines in the fuselage behind the cockpit (see Fig. 3). The four wing-tip engines are located aft of the center of gravity, and the two forward lift engines are forward of this point just aft of the cockpit. All six engines are directed downward during take-off until an altitude of about 50 feet is reached; then the wing-tip pods are rotated toward the horizontal. Each of the six engines is controlled by a separate throttle for the start, checkout, and idling phase. After start and prior to take-off, the engines are controlled by a single throttle.

Mechanical connections from the control stick to the engine throttle linkages control the free aircraft in the roll and pitch axes during hover. The controls are designed to alter throttle settings between engine pods as a function of control stick position and to produce roll or pitch moments. As the wing pods rotate toward the horizontal and the aircraft forward velocity increases, the mechanical linkage gain to the engines decreases, and aircraft control reverts to control surfaces (ailerons and elevator). Engine-pod rotation is controlled by two switches on the single throttle. One switch is used to select the direction of pod tilt, whereas the other has a center detent for off, fast, and slow pod rotation. Hydraulic actuators (tilt actuators) rotate the wing engines between vertical and horizontal. During hover, yaw moments are produced by tilting the right and left engine pods in opposite directions.

Yaw-axis control of the free aircraft is by mechanical con-

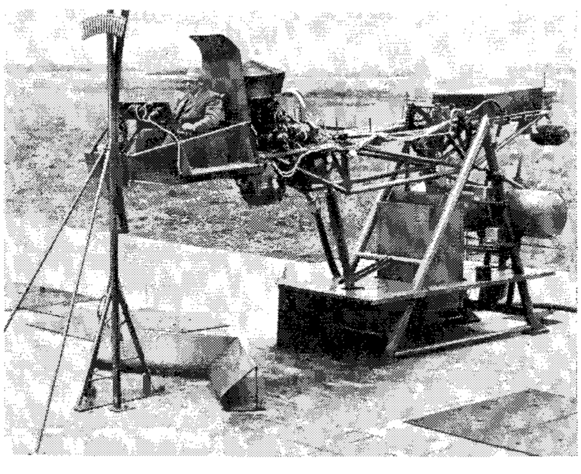

Fig. 1 "Die Wippe" test rig.

Presented as Preprint 64-774 at the Military Aircraft Systems and Technology Meeting, Washington, D. C., September 21–23, 1964; revision received March 11, 1965.
* Senior Development Engineer. Member AIAA.

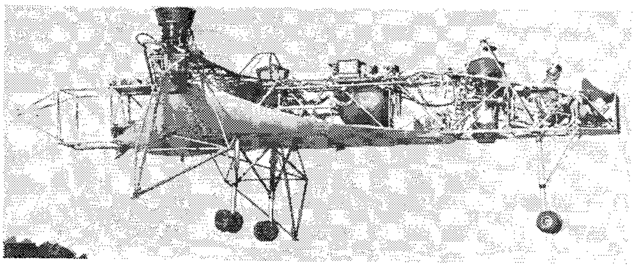

Fig. 2 VJ101C "Bedstead."

nections from the rudder pedals to the tilt actuator. As the engines rotate toward the horizontal, linkage gain to these actuators decreases, and mechanical linkage gain is introduced to the rear engine throttles. Yaw moments are then produced by thrust modulation as commanded from the rudder pedals.

In conventional flight, the forward engines are shut down, the inlet scoop door is closed, and the stick and rudder command aerodynamic surface deflections. The scoop door insures adequate flow to the forward lift engines during the transition and hover phase. Four spring-loaded, slotted flaps are installed in the air intake cover to open when the pressure over the rear engine drops below a set point.

Some of the X-1 flight tests were conducted on a fixture called the telescope, as shown in Fig. 4. This telescope permitted limited freedom of the aircraft in pitch, roll, yaw, and altitude. In operation, it resembles a telescoped system of linkages attached to the aircraft to provide angular and linear restraint. This fixture afforded a completely safe method of system verification as well as an opportunity for pilot familiarization. The X-2 is similar to the X-1 except that the RB145 engines have afterburners installed to increase speed capability.

Aircraft Operation

After the engines are started and the usual checkout is finished, the collective throttle is advanced to the fully open position in 3 to 4 sec to reduce the ground erosion and recirculation effects. Recirculation causes a loss of thrust as the hot exhaust gases are drawn into the intake. This usually occurs whenever the aircraft is within 15 ft of the ground and normally takes 4 to 5 sec to build up its circulating path.

After the throttles are advanced, the aircraft lifts off vertically to a height of about 50 ft, after which the pilot commands a nose-down attitude. The nose-down attitude of 4° or 5° rotates the thrust vectors of the lift engines and causes the aircraft to gain forward speed. Shortly thereafter the pilot reduces throttle and begins the engine-pod rotation toward the horizontal. A slow pod rotation is used until about a 45° position is reached, after which a faster rate may be used. As the forward speed increases, the aerodynamic lift increases, and the aerodynamic controls become more effective. As the engines approach the horizontal, the stick control is mechanically changed from fuel control to aerodynamic surface control. At the end of the transition, the angle of attack is about 10° and the forward speed is about 185 knots. A take-off transition may be accomplished in as little as 60 sec and a horizontal distance of 5300 ft.

In the landing transition, the scoop door is opened, the vertical lift engines are started, and flap and gear are lowered. The pilot then increases the angle of attack to 5° or 10° to increase drag and reduces the wing engine thrust to about 50%. At the same time, he starts the slow engine rotation from horizontal to vertical. The nose-up attitude is still held as the aircraft loses speed and the throttles are advanced. The approach speed can be anywhere from about a minimum of 140 knots to 220 knots as a maximum for lowering the gear. The pods are held at about 45° down to about 90 to 100 knots, and, as speed decreases further, the pods are then rotated toward the vertical. By adjustment of angle of attack, sink rate, and thrust control, the final touchdown spot can be selected. Landing transition can be accomplished in about 2 min and in a horizontal distance of about 7500 ft.

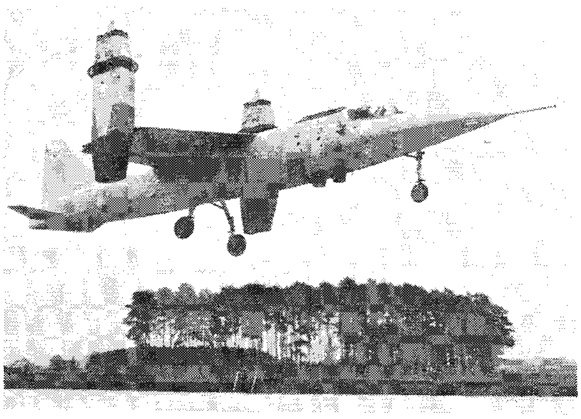

Fig. 3 VJ101C-X1 in vertical ascent.

Autopilot Description

The autopilot in "Die Wippe" was used primarily to prove the feasibility of hover control through thrust modulation. Attitude, rate, and acceleration signals were used to provide stability augmentation and attitude feedback. In addition, a stick-position signal was used for the control stick steering mode.

The second prototype (Bedstead) had a four-axis autopilot with fixed gain for stabilization in roll, pitch, yaw, and altitude. The control stick steering mode, with its stick-position signal, improved stick power and sensitivity. This system proved the feasibility of the approach and was the basis for the next phase of the program.

The autopilots for the X-1 and X-2 (Figs. 5 and 6) incorporate many of the features previously described. The series servo controls the differential thrust for the roll and pitch axes and differential tilt in the yaw axis. The stick-position signal and attitude and rate signals provide the inputs to the

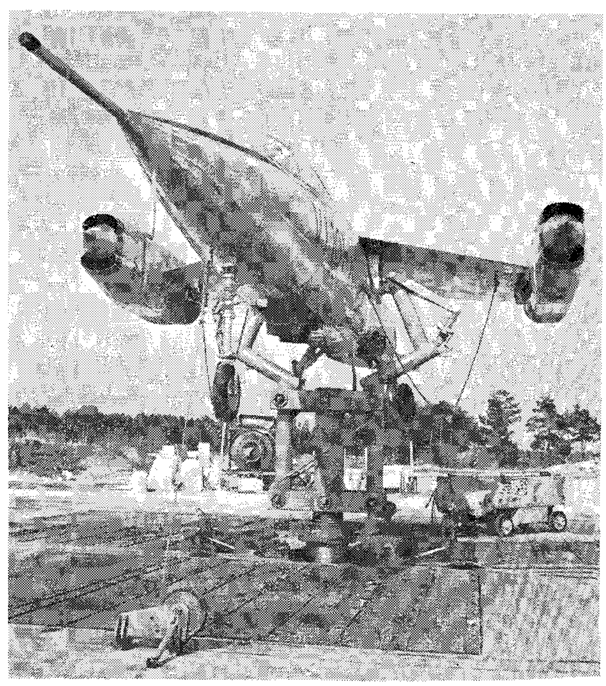

Fig. 4 VJ101C-X1 on the "telescope."

servo. During hover, attitude is proportional to stick position for both roll and pitch, but, as the transition progresses, pitch rate is proportional to stick position. The stick gain and shaping networks were selected to provide fast response to stick inputs. The high-pass network in the servo feedback path provides a proportional-plus-integral feedback that eliminates "droop" in the system. The lateral axis autopilot, as shown in Fig. 6, is similar in many respects to the pitch axis. The attitude and rate signals are summed with stick position, whereas yaw rate is summed with rudder pedal position. The yaw rate summed with roll stick position reduces the yaw coupling during roll stick input.

The autopilot also includes an engine failure monitoring system that is operative at all times during forward flight. The system is unique in that it senses the effects of the failure rather than monitoring the failure itself. In the forward flight phase, if an engine fails, the thrust of the remaining engines is adjusted through the series servos to equalize the forces. With the aircraft fully stabilized, the pilot can attempt a landing or eject if the situation warrants it.

Angular and lateral acceleration resulting from engine failure is sensed by two accelerometers located fore and aft of the center of gravity. The system also compensates for the attitude and rate deviation by essentially increasing the rate damping during this period. If an engine failure occurs in the hover mode, the series servos have sufficient authority to cope with the failure.

Design Considerations

Many design analysis considerations were made before the X-1 and X-2 systems evolved. Some of these considerations are reflected in the design of the aircraft, others in the autopilot. The trend in VTOL aircraft is toward the use of multiple engines rather than a single power source. With most designs, the loss of one engine, in addition to reducing over-all lift, will cause a roll, pitch, or yaw angular rate. To reduce this rate, sufficient control must be present or the corresponding engine thrust must be reduced. There are several methods of sensing the engine failure and initiating proper action. If the pilot initiates the action, he must first detect the engine malfunction and then throttle back the corresponding engine. This time delay may be sufficient to allow the aircraft to reach a dangerous attitude before recovery is accomplished. The type of failure may be hard to determine, since it could be fuel, fuel control, compressor stall, or some type of mechanical failure. To instrument these types of failure could require multiple sensors with a high degree of reliability.

The approach taken on the VJ101C was to sense the angular acceleration and initiate recovery. This has the advantage of eliminating individual failure sensors and, instead, detecting the effect of the failure on the aircraft. It has the disadvantage of "nuisance" type engagements from gust disturbances or rapid stick inputs. However, this problem can be minimized through proper design of phasing networks. If the system engages accidentally, the response is virtually unchanged, and the thrust of the engines is not reduced.

VTOL aircraft, like helicopters, are intended to take off and land in such a way that forward speed is maintained as long as possible. If the aircraft has a reasonable forward velocity, the pilot can make a flare-type landing or eject if the engine should fail. Actually the time span in the hover phase is short in comparison to the total flight time, and engine failure is not much more serious than that for conventional aircraft. The engine failure monitor and the hover augmentation system are very useful in the reduction of the danger associated with an engine failure.

Flight parameter variations and flight conditions during the various stages of the transition were another consideration. Flight conditions on the extreme of the "flight corridor" in the hover and transition were selected for analysis. Variations in inertia, angle of attack, and other characteristics are quite linear and can be simulated by discrete flight conditions. This situation may not hold true for VTOL with a tilt wing where variations in slipstream play an important part in control. The equations used in the analysis are typical aircraft equations with additional terms due to thrust. Although aerodynamic effects are small, they were included in the simulation together with inertia, angle of attack, and other parameters.

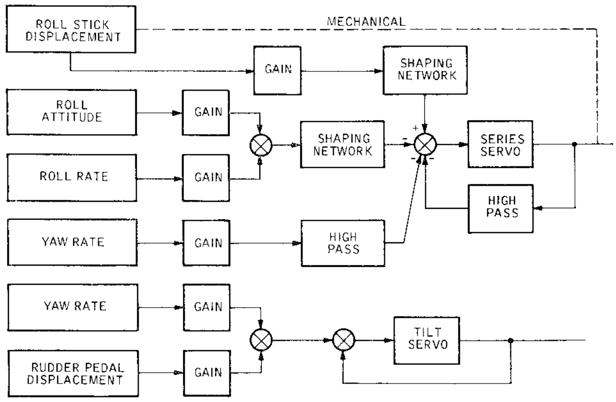

Fig. 5 Lateral axis block diagram.

Optimum stick handling characteristics are difficult to provide in some VTOL aircraft. The design aim of the control stick steering mode was to provide better stick handling and to provide a natural feel to the pilot. As a consequence, the first autopilot system had provision for wide gain variation on attitude and rate.

System performance specifications are similar in many respects to conventional aircraft. The design aim was to obtain response times as low as one second to 90% final value. Optimum overshoot should be 5% with some variation on either side of this value. With the series servo, automatic trim is a desirable feature, since it would keep the servo operating about a center position. Trim rates should be kept to a low value consistent with adequate servo authority and manual trim rates. A "beep" trim feature was added to permit the pilot to command trim changes through the servo. The pilot used the trim for a nose-heavy condition for the initial phase of the land transition until just prior to final touchdown.

Results

Analog computer results have generally been verified in flight tests. Much of this can be attributed to the complete aerodynamic data available from Entwicklungsring (EWR) wind-tunnel tests. Some typical responses to a stick input are shown in Fig. 7 for the pitch autopilot. Various phases of the transition are shown with all the variations in acceleration, velocity, and displacement. Responses vary from 1 sec for the take-off condition to about 5 sec for the 60° engine-pod position.

Stick augmentation is a feature that found pilot acceptance since it improved handling qualities. As shown in the

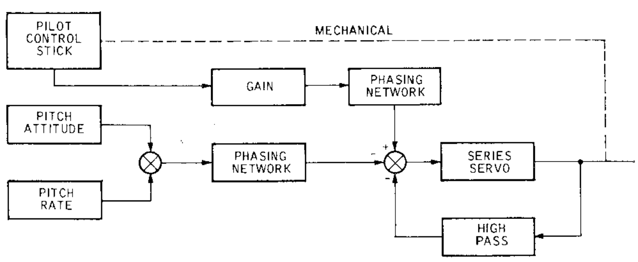

Fig. 6 Pitch axis block diagram.

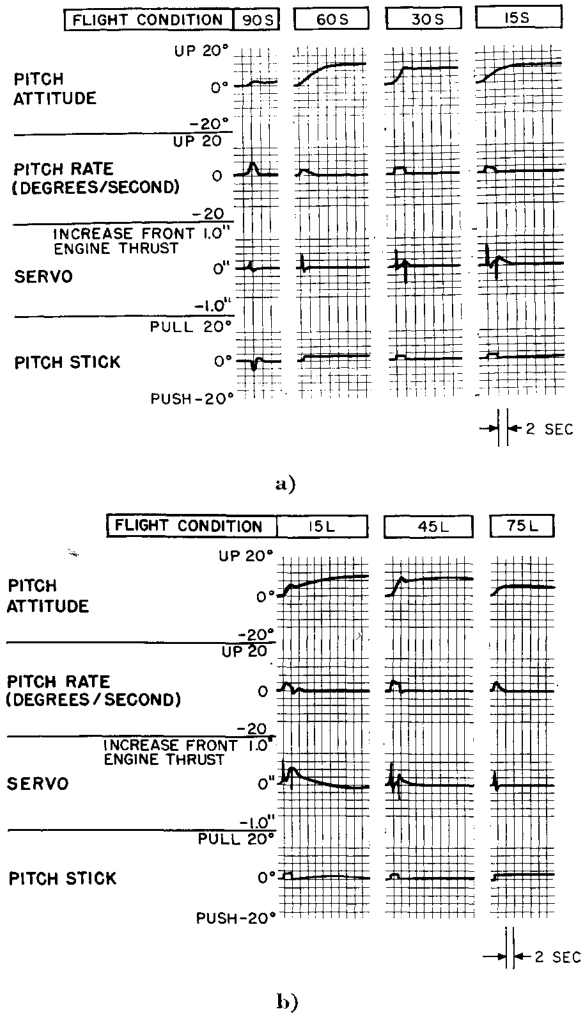

Fig. 7 Autopilot pitch axis responses to control stick commands.

block diagram (Fig. 5), an attitude or rate signal is summed with a stick displacement plus the manual stick input. Thus, the series servo can be used to augment or neutralize stick sensitivity and feel characteristics. At present, a stick sensitivity of about 0.6° alt/deg of stick is used in pitch and roll.[1] Since this sensitivity can vary over the transition, the gain can also be varied to compensate for it. In the transition region, the aerodynamic controls become more effective, and the aircraft is more responsive. The gain selected for this application seemed optimum and felt "natural" to the pilot. As the chief test pilot stated, the system has the ability to maintain zero attitude much more closely than can the pilot.

The engine failure mode was primarily evaluated on a ground pedestal or "telescope," since an engine failure in flight is hard to simulate. This mode was also extensively checked on the analog computer with a pilot's control stick and scope presentation. These studies and the checks on the telescope all predicted the system would perform as indicated.

Stability augmentation is the most useful mode of the VTOL automatic flight control system. During the critical hover and transition phase, the aircraft is almost perfectly inert and, therefore, very unstable. The pilot work load at this time is also heavy, and any unusual disturbances can increase it to the critical point. The pilot is also manipulating the maximum number of controls (five) recommended for safe flight. The effects of gust disturbances and recirculation all aggravate the stability problem. Simulator, telescope, and flight tests all verified the need for stability augmentation in two or more axes. For the yaw axis, the pilot is capable of providing the necessary damping, but the yaw attitude variations are greater. Under conditions where the steady-state side velocity is high in the landing phase, this yaw attitude drift may become a problem. It has been the experience on the VJ101C that it is desirable to have three axes of stability augmentation with the potential of failure in the yaw axis. With at least three axes of augmentation, the pilot is greatly relieved and can concentrate on the other tasks needed for the transition. The augmentation also provides damping for the other modes, such as attitude and stick steering. As the transition progresses toward forward flight, the pilot is capable of flying all three axes without augmentation in emergency conditions. This requirement for augmentation was checked on telescopic tests in which one, two, or three degrees of freedom were permissible by adding or removing linkages.

The use of attitude and attitude rate feedback summed with stick position was also thoroughly checked. With a rate feedback, the pilot commands a position and then returns the stick toward neutral when the desired attitude is achieved. This normally is satisfactory for the forward flight regime when the pilot is interested in controlling attitude rate or flight-path rate. However, the pilot, when positioning the aircraft over a spot on the ground at altitudes of about 150 ft or less, prefers an attitude feedback. If the pilot commands a stick deflection, the servo will provide and maintain an aircraft attitude proportional to stick deflection. The rate signal provides the necessary damping to the pilot stick inputs. During the transition, the summing signal changes from an attitude signal for the hover phase to a rate signal for forward flight. By stick deflection, the pilot commands aircraft attitude, and, when the desired translatory velocity is reached, he recenters the stick. This system is so natural to the pilot that he is unaware most of the time that the system has changed from rate to attitude. The change is scheduled as a function of pod position as the engines change from horizontal to vertical.

Experiences on the flight-test program verified analog computer studies for the various modes. The telescope used with the X-1 provided a valuable assist in determining the problems associated with VTOL control. It also permitted pilot familiarization and training and was a useful tool for checking single-axis operation. Since this telescope had angular and height restraints, it was possible to check items that could never be checked in actual flight.

The importance of the autopilot in augmentation of the stability of the aircraft and the improvement of the handling qualities during hover cannot be stressed too much. The use of attitude feedback for the stick signal in the hover phase is also important. At present, the VJ101C has completed over 100 flights, and the experience gained on this program will benefit many future VTOL projects.

Reference

[1] Bright, G. L., "Mach 2 V/STOL (VJ101) flight test program," Society of Experimental Test Pilots Paper, pp. 101–110 (September 27–28, 1963).