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V/STOL HANDLING QUALITIES AS DETERMINED BY FLIGHT TEST AND SIMULATION TECHNIQUES

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INTRODUCTION

V/STOL aircraft are emerging from the stage of being interesting curiosities to the hard realities of operational aircraft. They have posed a challenging set of engineering problems including the severe requirement for high installed thrust-to-weight ratios, the need for high performance in forward flight as well as the ability to hover, and in many cases the need for complex shafting and gearing in order to interconnect multiple engines and rotors. In addition, control power for maneuvering has been difficult to provide below the speed at which conventional flapped control surfaces are effective. The test-bed aircraft programs in various countries have also demonstrated a need for stability augmentation devices in several instances. All these demands tend to make the aircraft overly complex. To reduce some of the demands, many studies have been made to determine the minimum control power and stability requirements for this class of aircraft. One of the first studies is reported in Ref. 1. Further investigation of these variables was made at the NASA Ames Research Center with a simulator having two rotary degrees of freedom and with several fixed simulators. The results of these tests are presented in Refs. 2 and 3. The pilots used for these tests were simultaneously flying various test-bed aircraft which were also programed on the simulator in several cases to test the validity of the results and to suggest improvements to the simulator apparatus.

In an attempt to determine in flight the control-power and damping relationship for a hovering VTOL airplane, the NASA conducted research programs on the majority of the VTOL test beds. Unfortunately, these test beds were blessed

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with low control powers, with little or no damping, so their contributions to resolving the requirements were small. Subsequently, to enable a systematic investigation of the control-power and damping requirements, the Bell X-14 was modified to provide variable control power and variable damping. Figure 1 shows this aircraft in hovering flight in front of a hangar at Ames Research Center in California. Flight tests of this aircraft have provided additional handling qualities data which can be used to determine the desirable and limiting stability and control characteristics for a visual hovering task. The results are presented in Ref. 4. The present paper will discuss data obtained with the X-14 and compare that study with other flight and simulator studies including recent information obtained from the Lockheed C-130 BLC aircraft and the Ryan VZ-3 deflected slipstream V/STOL aircraft.

VTOL RESEARCH—BELL X-14A

DESCRIPTION

The X-14A VTOL test vehicle used in this investigation was constructed by the Bell Aircraft Corporation under U.S. Air Force contract. The X-14 as shown in Fig. 1 is a low-winged jet-propelled aircraft which derives its vertical lift ability from the jet exhaust of two turbojet engines. A cascade diverter mounted at the tail-pipe exit enables the pilot to direct the thrust either vertically for hovering flight, horizontally for conventional flight, or at an intermediate angle for transition. During hovering and at low speeds, control of the airplane is maintained by jet reaction nozzles, while aerodynamic surfaces serve this function during conventional flight.

As illustrated in Fig. 2, the airplane has seven reaction nozzles. The pilot has direct control over three, and the variable-stability system operates four nozzles.

Fig. 1. X-14A VTOL test vehicle.

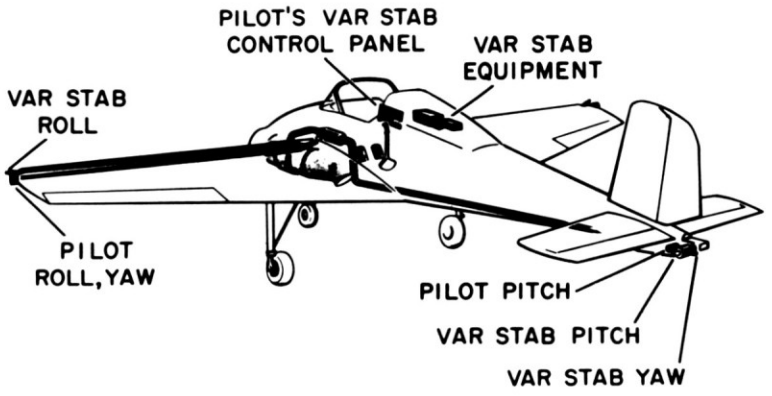

Fig. 2. Variable-stability VTOL vehicle.

Each of the two-nozzle systems has its own set of air ducts. This parallel arrangement of nozzles was used to provide an effective margin of safety. Since the nozzles controlled by the pilot are supplied a greater amount of bleed air than those controlled by the variable-stability system, the pilot has a direct overriding capability.

The variable-stability nozzles are driven by electric servomotors and are capable of being positioned by the sum of six inputs. Each input signal is controlled by a potentiometer which enables the pilot to select the magnitude and sign of the signals. In this investigation, angular rate signals were used to position the nozzles to oppose airplane motion in direct proportion to the angular velocity, thus creating rate damping, while the response from the pilot's control signal either supplemented or opposed the basic airplane reaction nozzles, thus changing the amount of control power. Details of the airplane and equipment are described in Ref. 4.

X-14A TESTS

All three pilots who participated in the flight tests had experience in a variety of V/STOL aircraft types including helicopters. The tests consisted of hovering the aircraft out of the ground effect with specific combinations of control power and damping adjusted. (The variable stability apparatus was set to cancel the gyroscopic moments.) The pilots disturbed the aircraft with control steps, pulses, and normal control action, usually remaining within about $\pm 10°$ in pitch and $\pm 20°$ in roll. Yawing turns of 360° were made, and accelerations and quick stops up to 20 knots both forward and reversed were performed. The winds were below 10 knots during all evaluation testing and below 5 knots most of the time so that the pilot could more readily compare stability characteristics. The pilots rated variation in stability and control about each axis separately and their comments were tape recorded immediately following each flight. Transition maneuvers were performed by all of the pilots, and hovering was accomplished at altitudes up to 3,000 ft where more abrupt control inputs could be made with correspondingly larger changes in attitude than would be prudent when close to the ground.

RESULTS AND DISCUSSION

Each pilot rated a series of prescribed conditions using a Pilot Opinion Rating System composed of numerical ratings from 1 to 10 in which 1 represents ideal conditions and 10 catastrophic characteristics.

From the numerical rating assigned by the pilots to the control power and damping configuration investigated, a set of boundaries was estimated for each of the aircraft axes. The boundaries as determined for the pitch axis are presented in Fig. 3. The rating of 3½ separates the region of satisfactory and unsatisfactory control characteristics while the 6½ boundary separates the unsatisfactory and unacceptable. A reasonable interpretation of these boundaries is that the control system of a VTOL airplane must be designed to fall within the satisfactory area regardless of the number of artificial augmentation devices necessary. However, failure of an augmentation device must not result in a control system that falls outside of the unsatisfactory region into the unacceptable region. Two items to note here are (1) the pilot is willing to accept near-zero pitch damping if the control power is above about 0.75 radian per sec^2, and (2) raising the damping above about 0.3 per sec does not affect the pilot's rating of the aircraft. The shaded area in Fig. 3 is the range of control power and damping investigated.

Figure 4 shows the similar set of boundaries established for the roll axis. These boundaries when compared with the pitch boundaries show that the pilots considered the lateral motion of the airplane more critical in that large amounts of control power and damping are required for this axis. The pilots would not accept a low value of damping for a satisfactory rating for the roll axis.

Figure 5 presents the satisfactory and unacceptable boundaries for the yaw axis. Here, again, as in the case for the pitch axis, the pilot considered zero damping satisfactory if he had control power in the order of 1 radian per second

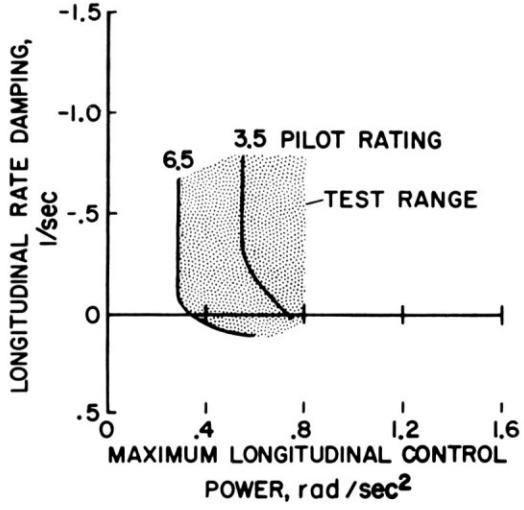

Fig. 3. Pitch-control boundaries.

per second. With these low values of damping at the higher control powers, the pilot uses the excess control power to supply manual, pilot-induced damping.

Although the ranges of the control power and damping which could be investigated were less than covered by either the variable-stability helicopter or the angular-motion simulator, the amount of control power and damping available was sufficient to obtain a pilot rating of less than 3, thereby covering the areas of greatest interest from the designers' standpoint. It was not possible, however, with the present capabilities in the X-14A to derive values for optimum control power about any axis.

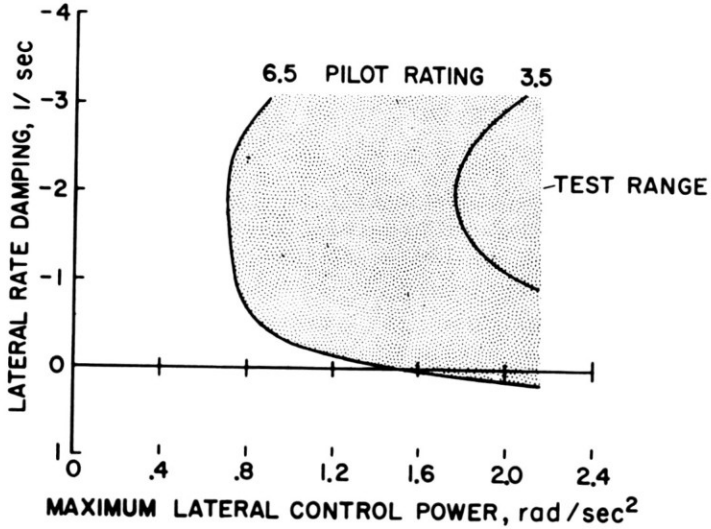

Fig. 4. Roll-control boundaries.

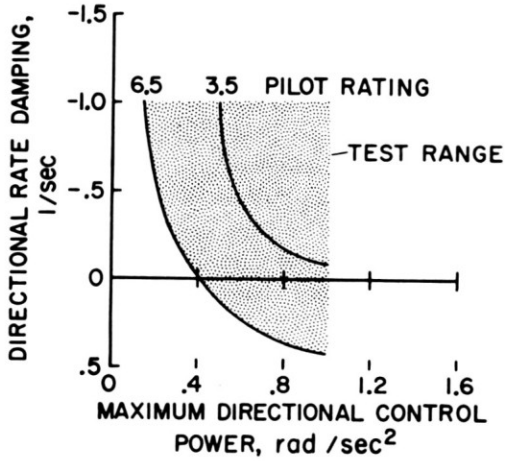

Fig. 5. Yaw-control boundaries.

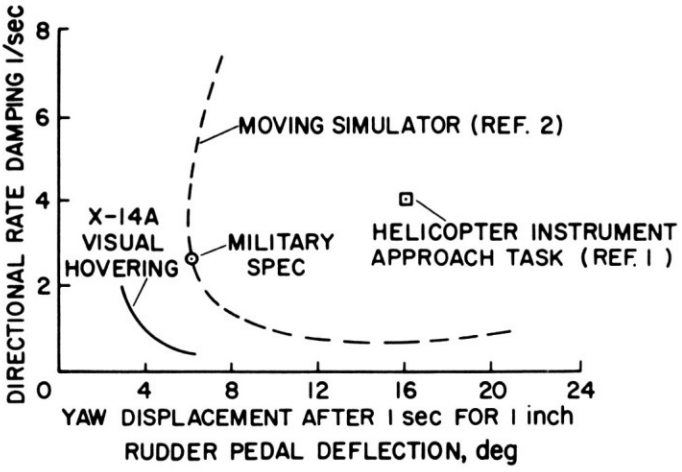

Fig. 6. Comparison of satisfactory control power and damping requirements for the yaw axis.

Although the X-14 flight test data agree well with previously published flight and simulator results in pitch and roll, the yaw axis boundaries show considerable deviation. A comparison is given in Fig. 6 of the yaw control power and damping requirements obtained from the simulator tests of Ref. 2, the variable stability helicopter instrument flight tests of Ref. 1, the United States Military Specification H-8501A, and the X-14A visual hovering tests of Ref. 4.

The results are compared on the basis of the angular displacement of the vehicle after 1 second for 1 inch of rudder pedal deflection. This comparison is made for the minimum satisfactory control power ($3\frac{1}{2}$ boundary); similar results would be obtained on the basis of minimum acceptable characteristics ($6\frac{1}{2}$ boundary). The symbol representing the amount of control power and damping a machine the size of the X-14A would require if it were to satisfy the present military specifications for helicopters indicates a much greater control power and damping than the flight tests of the X-14A. The reason is, in part, that the specifications require a high degree of damping for a small light helicopter, which would be sensitive to gust disturbances. Such high damping requires a commensurately higher control power to obtain the maneuvering capability desired. During these tests the pilots felt that the X-14A exhibited a high degree of hovering steadiness and an insensitivity to gust disturbances, thus it did not require large amounts of damping. Consequently, they rated the lower amounts of control power and damping as satisfactory. The variable-stability helicopter data taken from an ILS approach indicate a desire for values of control power and damping considerably in excess of the other results. These results are influenced greatly by the task being performed and they indicate that directional stability and control requirements for the low speed instrument approach are more stringent than for the visual hovering task.

Application of these data to other vehicles will be influenced by the hovering steadiness of the vehicle under consideration. The present investigation was

conducted on a deflected jet VTOL aircraft which is a very steady hovering machine, and not affected by self-generated disturbances. When control power and damping requirements are considered for other types of VTOL aircraft, such as tilt wing or deflected slipstream, which have been shown to be self-disturbing during hovering, some adjustment to these boundaries should be made. In such cases, the boundaries derived in this report would be considered maneuvering boundaries and this much control power and damping should be supplied over and above the control power required to cope with the self-induced disturbances.

JET LIFT V/STOL AIRCRAFT PERFORMANCE

Although measurements and calculations of conventional aircraft performance can be used for jet lift V/STOL aircraft during high-speed and cruise flight, the takeoff, transition, and landing data present a unique case. Certain missions, for example, may require that the aircraft be loaded so that the thrust-to-weight ratio is less than 1 and VTO is not possible, and in some cases landings may also be required with the same thrust weight limitations.

When an aircraft of this type becomes operational, it will be necessary for the pilot to be able to determine optimum takeoff conditions of speed and distance as a function of thrust-to-weight ratio available and of diverter angle by referring to charts. The flight test experience with the X-14 has indicated a way in which these variables may be presented to the pilot so that he can determine takeoff and landing conditions. Figure 7 shows takeoff speed plotted against ground-run time for values of T/W and diverter angles. Takeoff distance is also shown so that the pilot can select either minimum takeoff speed or distance and determine the best diverter angle for each condition. First we note that if the

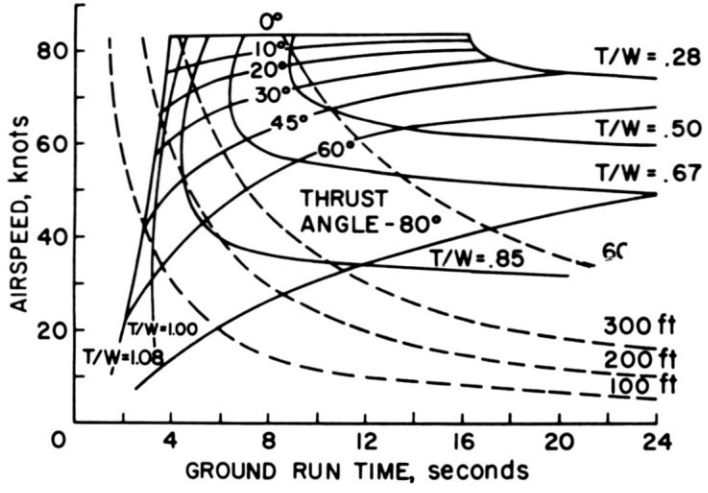

Fig. 7. Lift-off conditions for the X-14 jet VSTOL aircraft.

T/W is 1 or greater, vertical takeoff can be made with the thrust vector at 90° to the fuselage and zero ground-run time is involved. If the T/W is slightly less than 1, then infinite time would be required at 90° thrust angle or, in other words, VTO is not possible. Let us take an example of how the pilot might use performance data presented in this manner. First of all, the gross weight of the loaded aircraft must be known accurately. Engine performance charts would be used to determine takeoff thrust as a function of temperature and pressure altitude, and the chart of Fig. 7 would be entered with a known T/W. Let us say that a T/W of 0.85 has been determined as the takeoff condition and that the pilot would like to take off in the minimum distance. Lines of constant takeoff distance appear as a function of ground-run time and takeoff speed. The possible takeoff conditions for a T/W of 0.85 are indicated on the constant T/W lines and the minimum takeoff distance is indicated by the point on the T/W curve nearest the minimum distance line. For the case of $T/W = 0.85$, we see that the minimum takeoff distance would be about 180 ft. The diverter angle should be approximately 55° and the takeoff speed will be 46 knots which includes an arbitrary margin from the wing stall angle of attack. The effects of deviations from these conditions can also be seen. It is interesting to note that the takeoff distance and ground-run time at $T/W = 0.85$ are not greatly affected by thrust-diverter angle but that the takeoff speed increases almost directly with decreases in diverter angle. Higher diverter angles than optimum have a direct effect on takeoff distance and ground-run time, but very little decrease in takeoff speed is obtained. It should be noted at this point that the curves for the values of thrust-vector angle, and T/W ratio are quite general for vectored thrust jet lift V/STOL aircraft. Only the time, speed, and distance scales are specific to the X-14.

At low values of T/W corresponding to a more conventional aircraft loading, it can be seen that little is to be gained by vectoring the thrust below horizontal. At $T/W = 0.28$, for example, the optimum takeoff distance would be obtained at about 30° thrust angle, but the difference in takeoff speed would be negligible. The takeoff speed would be reduced by about 10 knots for the X-14 and would be less for aircraft having higher wing loadings.

Although landing figures are not presented, the reduction in approach speed possible at each T/W can also be determined from this figure. Again, if we assume that the angle of attack stall margin for the lift-off is the same as for landing in the STOL condition, the same method of determining speed performance can be used. The charted speed values would be touchdown speeds, and the ground-run distance curves would be changed to indicate braking rather than forward acceleration.

The climb-out angle is an important consideration for obstacle clearance and calculations of this parameter are readily made for a vectored thrust V/STOL aircraft. Actual takeoffs and climb-outs have been made at angles from 90° with the vertical force supplied entirely by engine thrust to more conventional aircraft takeoff angles with the vertical force produced primarily by wing lift. It appears that the diverter angles and airspeeds for maximum climb angle at a given thrust-weight ratio will be the same as for the minimum speed takeoff

condition and therefore they can also be determined from data presented in the form of Fig. 7.

The curves presented in Fig. 7 are calculated and were used as a starting point for flight-test performance measurements. The only area where significant deviations occurred was in the region of high T/W and low diverter angles where the brakes had to be released prior to reaching full power. Since the times and distances are so short, a great deal of scatter was present in the flight measured data in this area. Flight measured performance data did indicate that, in general, this was a useful form in which to present performance data to the pilot.

STOL RESEARCH

In addition to the jet lift VTO X-14, recent tests at the Ames Research Center have been conducted using the deflected slipstream Ryan VZ-3 shown in Fig. 8 and the boundary-layer control Lockheed C-130B shown in Fig. 9. These

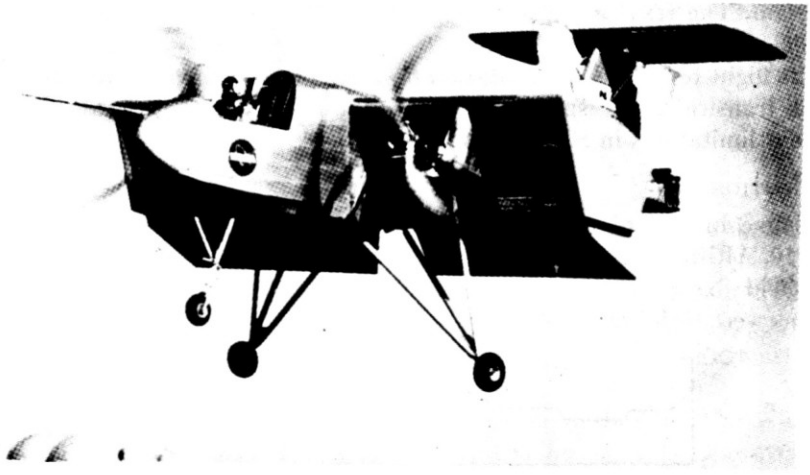

Fig. 8. VZ-3 airplane.

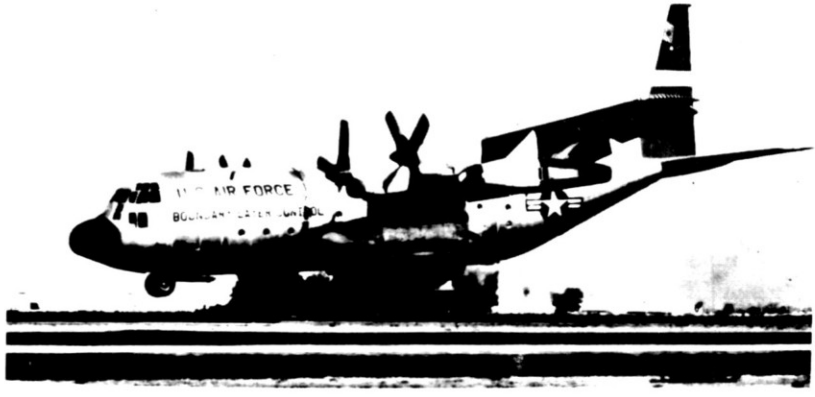

Fig. 9. C-130 airplane.

aircraft have been used to investigate the stability, control, and operating problems of propeller-driven V/STOL aircraft at low speeds.

RYAN VZ-3RY

The VZ-3 was built as a research tool for investigating the characteristics of the deflected slipstream concept for V/STOL aircraft. It weighs 2,925 lb and is powered by one Lycoming YT-53 turboprop free-turbine engine which develops 785 hp. Two propellers are driven through gear boxes, and the engine residual thrust is passed through a diverter on the tail which is mechanically linked to the rudder and elevator in order to provide pitch and yaw control at low speeds and in hovering flight. Slot lip spoilers provide roll control at high speed and differential propeller pitch control is phased in as the flaps go down so that maximum differential propeller deflection is obtained with 70° of flap. The aircraft has flown over a speed range from 0 to 90 knots and both wind tunnel and moving-based simulator testing were used as a guide to the flight test program. The results of the wind tunnel and simulator tests are presented in Ref. 5.

The flight tests have concentrated on three primary areas of interest, the level flight transition, low speed flight in ground effect, and the rate or angle of descent limitations in STOL flight.

Transition

A time history of a typical level flight transition in the VZ-3 is shown in Fig. 10. Altitude was held constant at about 30 ft, and the trimmable stabilizer was held fixed. Previous flight data had indicated that stabilized flight conditions were satisfactory over the speed range and at all flap deflections. During

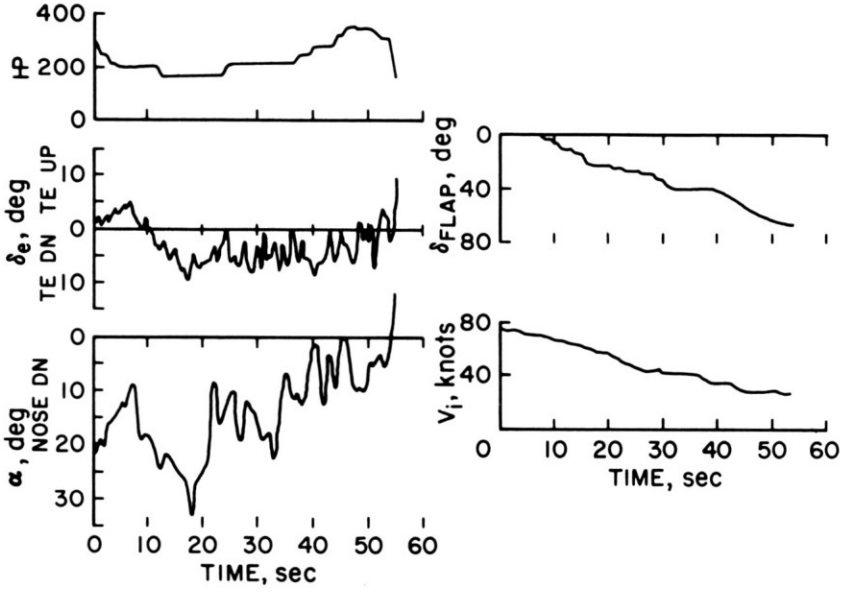

Fig. 10. Transition of the VZ-3RY level flight.

the actual transition, airspeed decreases and power is reduced at least at the start so deviations from stabilized conditions are encountered, depending on the rate at which the transition is attempted. The transition presented in Fig. 10 was done slowly taking approximately 56 sec to go from 73 to 27 knots, so the power, airspeed, and flap deflections are not greatly different from the stabilized flight conditions at each point. The time history indicates that elevator deflection changes were small over the conditions covered and no abrupt changes in power were required.

The rate at which the transition can be accomplished is limited primarily by the structural limits of the flap and the flap deflection rate, and the lightweight flap structure of the VZ-3 did not allow its full use as a speed brake or drag device. Transitions have been made from 80 to 30 knots at rates which exceeded the capability of the light helicopter chase aircraft with no change in the trim requirements. It should be noted, however, that the pilot, if given the choice, generally maintained speeds in excess of 60 knots in the approach to about 50 ft and then he would slow the aircraft to whatever touchdown speeds were required. To the pilot, the remarkable things about the transition are the negligible change in trim required from 0° to 70° flap with minor power changes, and the ease with which speed was maintained even though static stability measurements indicate neutral stability at 30° flap or greater.

Steep Descents

For most STOL approach conditions, the descent rate capability of the aircraft exceeded that desired by the pilot and in fact a single rotor helicopter flying chase in autorotation could not descend as rapidly. Quantitative data are being obtained on the descent conditions over the airspeed range from 0 speed to 85 knots. At speeds above 40 knots, adequate flare capability was demonstrated without the addition of power. At lower speeds, power was added much as would be done with a helicopter. No short period longitudinal or directional oscillations could be excited at transition speeds because of the low stability; however, the damping in yaw was high and caused a very sluggish feeling because of the low control power available.

Ground Effect

Although this aircraft has been flown at zero forward speed at altitude, it cannot reasonably ascend or descend through ground effect at speeds less than about 20 knots. Specific measurements other than tuft pictures of the changes in flow have not been made, so only the subjective effects can be mentioned. The presumed flow patterns in free air and close to the ground are shown in Fig. 11. Out of ground effect, the aircraft is steady and responds normally to controls over the speed range. When in ground effect below about 6 feet and slowing to less than 20–25 knots, the aircraft settles abruptly with some yawing and rolling motions encountered. Usually about this time a slapping noise comes from either or both propellers and continues as long as high power and forward speed is maintained while rolling out on the runway. It appears that low velocity turbulent air is recirculated forward through the propellers and upsets the

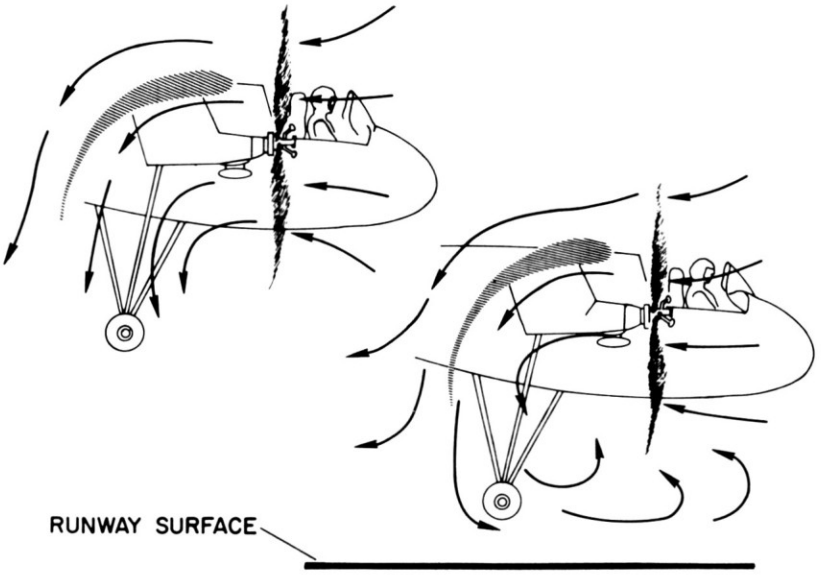

Fig. 11. Recirculation produced by ground effect for the deflected slipstream VZ-3RY.

turning efficiency of the wing. No solution to this problem is apparent; however, it occurs at so low an airspeed that it probably does not compromise the STOL capabilities of this type of aircraft. The changes in pitching moment in ground effect which were predicted by wind-tunnel tests have not been noticed; however, each period of flight at less than 20 knots in ground effect has been brief.

LOCKHEED C-130 BLC AIRCRAFT

Description

AC-130 aircraft shown in Fig. 9 was modified by Lockheed Aircraft Corporation under USAF contract to investigate the effects of boundary-layer control on a large aircraft. Plain flaps were installed with a maximum deflection of 90° and provision was made to droop the ailerons 30°. Full span blowing type BLC was installed at the flap and aileron leading edges and the leading edges of the rudder and elevator. The engine-compressor units for the BLC system were mounted on wing pods as shown in Fig. 9. The primary areas of interest during the first flight tests of this aircraft were the stability and control characteristics at the very low approach speeds obtainable with the BLC installation.

STOL Stability and Control

The effectiveness of the BLC system may be illustrated briefly by the reductions in approach and stall speeds obtained. At 100,000 lb gross weight, the conventional C-130 minimum approach speed is 106 knots with the stall at 80 knots. The BLC equipped C-130 stalled at 56 knots, and the approach speeds used for the tests were between 67 and 75 knots at a lift coefficient of about 3.0. At these speeds the maneuvering capability of the aircraft was severely limited

by the reduced control power (particularly roll and yaw), the negligible directional stability, and the sideslip angles induced by bank angle, aileron deflection, and side force changes with power. Flight records of an aileron pulse and the resulting controls fixed motions (Fig. 12) illustrate the objectionable aircraft behavior that also occurs to some extent on the STOL VZ-3 previously discussed

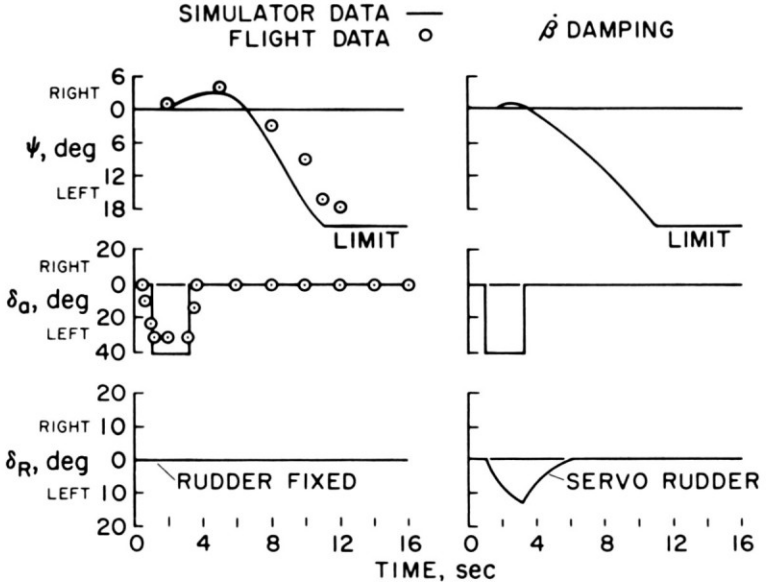

Fig. 12*a*. C-130 BLC airplane response to lateral control.

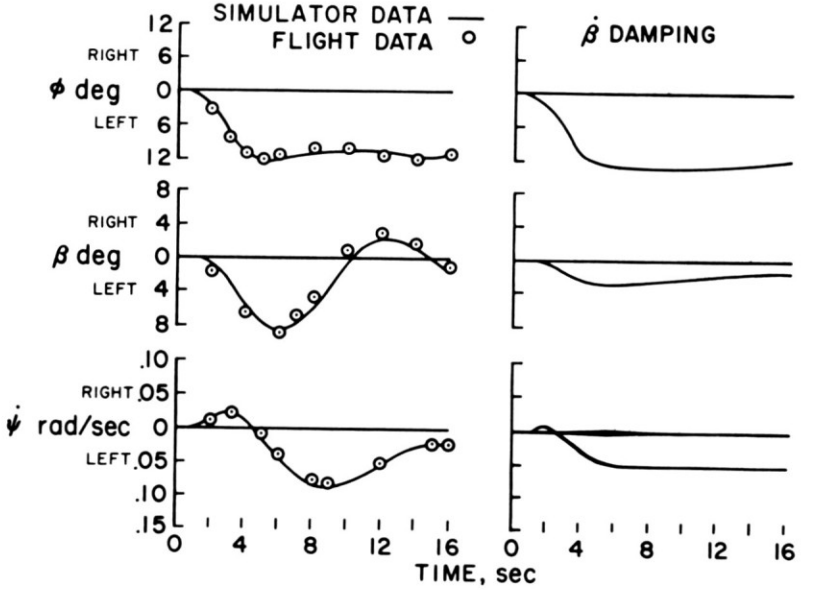

Fig. 12*b*. C-130 BLC airplane response to lateral control.

and, therefore, that may be considered a more general characteristic of STOL aircraft. The data points are from the flight records, and the solid curves are the simulator response to the same inputs. Normal left bank angle response to aileron input is achieved, and with rudder fixed, an initial small yaw to the right results from the adverse yaw produced by the ailerons. The undesirable response is indicated by the buildup in left sideslip with bank angle. An analog computer analysis indicated that the same sideslip motion occurs in the absence of an aileron-produced yawing moment and that the sideslip occurs because of the low side force and low directional stability. The flight tests indicated that although the pilot can use visual reference and apply rudder control to balance the initial adverse yaw, he must rely on a dial presentation of sideslip angle in order to even determine the sideslip direction once the bank angle has been established. The rudder-fixed response in Fig. 12 shows that a large amplitude sideslip oscillation occurs with a period of about 12 sec. The frequency of this oscillation was so low that even with reference to a sideslip indicator the pilot could not control sideslip and establish a balanced turn at the lower approach speeds. The rudder power was high in terms of the ability to produce sideslip angles, but this concept of rudder power only appears to apply for those conditions when the pilot relies on the static stability to return the airplane toward zero sideslip. It is evident that when the directional stability is very low and the pilot must continually use rudder control to reduce the sideslip then some other measure of rudder power should be used. The experience with control-power requirements for hovering would indicate that the yaw angular acceleration response to rudder should be considered. It would be impossible to meet the hovering requirements for yaw-control power with any reasonable increase in the rudder size or effectiveness so a simulator study was initiated to determine whether a satisfactory method of providing stability augmentation could be found.

The simulator used consisted of a fixed transport aircraft cockpit, an instrument panel, and flight controls which were connected to an analog computer adjusted to provide the aerodynamic response of the test airplane in six degrees of freedom. Visual reference for the landing approach below 400 ft was provided by a television projection system which included a servo-driven camera looking at a moving belt runway.

The solid lines in Fig. 12 show how the simulator response was matched to the actual airplane response to a pulse aileron input. Flights in the simulator indicated the same problems as reported in flight. The next step was to change the stability through the analog computer using those parameters which could reasonably be changed on the actual airplane. Large increases in directional stability and yaw damping kept sideslip angles to a minimum, but the rudder also acted to cancel the turn rate which was a desired response. The most promising parameter to use was sideslip rate rather than yaw rate as a damping signal, and the results of this input are also shown in Fig. 12. With practical values of rudder response to sideslip rate, the sideslip angle is maintained at very low values without slowing the turn rate and the large amplitude yaw oscillation is damped at the start. The pilots have indicated from simulator

flights that this should provide a satisfactory solution to the lateral-directional control problems during an STOL approach with the C-130B airplane. The hydraulic servo-driven rudder actuator on the airplane could be modified to accept signals from a sideslip rate sensor, and if this is accomplished, flight tests will be conducted as a final step in the solution of this particular problem.

CONCLUDING REMARKS

A flight investigation using the variable stability and control Bell X-14A test vehicle has provided a set of control power and damping boundaries for a visual hovering task. Comparison of the flight data, with the results of a piloted motion simulator, resulted in fair agreement for the pitch and roll axes. However, the satisfactory boundaries determined in flight for the yaw axis indicate a control power roughly one-third of the simulator values.

STOL flight tests using the Ryan VZ-3 deflected slipstream airplane have shown that level transitions from maximum speed to about 20 knots are accomplished with a negligible change in longitudinal trim and at rates comparable to those done with a helicopter. The STOL descent angles are about the same as an autorotating helicopter at speeds above 35 knots. Low-energy turbulent air recirculating through the propellers when in ground effect has limited the takeoff and touchdown speeds to greater than 20 knots even though the airplane has been flown at zero speed at altitude.

STOL flight and simulator tests of the Lockheed C-130B airplane have shown that at low approach speeds, large sideslip angles are produced when banking the aircraft even when the aileron adverse yaw is neglected. Analytically, this condition appears to be a general effect in STOL flight. Simulator results indicate that directional damping augmentation as a function of sideslip rate as opposed to yaw rate may be a promising solution.

NOTATION

T/W = thrust to weight ratio
V_i = indicated airspeed, knots
α = angle of attack, deg
β = angle of sideslip, deg
δ_a = aileron position, deg
δ_e = elevator position, deg
δ_{flap} = flap position, deg
δ_R = rudder position, deg
φ = roll angle, deg
ψ = yaw angle, deg
$\dot{\psi}$ = yaw rate, rad/sec

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DISCUSSION

Author: Fred J. Drinkwater, III

Discussor: E. D. Keen, Director and Chief Engineer, Wilinorth Glosten Aircraft, Ltd.

The speaker laid considerable emphasis on handling qualities in the event of failure of the autostabilizing system. However, there was another approach to the VTOL control problem as described in Foody's paper at the last Anglo-American conference in which it was assumed that control was impossible except through an autostabilizing system which consequently needed to be completely reliable and, therefore, had to be triplicated or even quadruplicated. Would the speaker please give his views on this alternative approach?

(*Author did not reply.*)