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Status of V/STOL Research and Development in the United States

JOHN P. CAMPBELL
NASA Langley Research Center, Hampton, Va.

Nomenclature

A = disk area, ft^2
$\bar{c}$ = mean aerodynamic chord, ft
C_L = lift coefficient (lift/qS)
C_m = pitching-moment coefficient (pitching moment/qSc)
C_T = thrust coefficient (thrust/qS)
D = diameter, ft
h = height above ground, ft
L = lift, lb
M = pitching moment, ft-lb
q = dynamic pressure, lb/ft^2
r = radial location of a particular station, ft
R = radius of rotor, ft
S = area, ft^2
T = thrust, lb
V = airspeed, knots or fps
W = weight, lb; or airflow, lb/sec
β = propeller blade angle, deg
γ = flight-path angle, deg
δ_f = flap deflection, deg
δ_n = nozzle deflection measured from vertical, deg
ΔT = average temperature rise in fan inlets, °F

Subscripts

j = fan efflux
rpm = fan rpm held constant
s = static condition (zero airspeed)
∞ = out of ground effect

Introduction

IT is the purpose of this paper to review the status of V/-STOL research and development in the United States with particular emphasis on significant research results obtained since the last Anglo-American Conference in 1961. Research information will be presented dealing with the helicopter, with propeller, ducted-fan, and jet V/STOL aircraft, and with the general area of V/STOL handling-qualities requirements.

Helicopter Research

During the two years since the last Anglo-American Conference, significant results have been obtained in several different areas of helicopter research and development. Some typical examples of this research are covered in Figs. 1–8. Much of the information presented in these figures has been presented in previous papers[1–16] and is presented here in summary form as an indication of the types of research that have been conducted. Subjects covered include the hingeless or nonarticulated rotor, flight measurements of rotor-blade periodic airloads, the rotor-blade stall phenomenon, and the improvement of helicopter performance by drag cleanup.

Hingeless-Rotor Helicopter

The hingeless-rotor or nonarticulated-rotor principle which has been receiving increasing attention during the last few years offers promise of providing a simpler, less expensive, and easier-to-fly helicopter. The hingeless-rotor principle has sometimes been referred to as the rigid-rotor principle, because the blades are attached directly to the hub without either flapping or lag hinges, and the hub is rigidly attached to the rotor drive shaft. The use of the term "rigid" in describing the system is not considered desirable, however, because an essential feature of a successful system of this type appears to be the incorporation of adequate flexibility into the blade itself. As shown in Ref. 1, most and perhaps all of

Mr. John P. Campbell, Associate Chief of the Flight Mechanics and Technology Division at NASA Langley Research Center, has been engaged in research at Langley since 1939, when he received his degree in aeronautical engineering from Auburn University. He has specialized in the field of dynamic stability and control research with free-flying models and has been instrumental in the development of free-flight model techniques at Langley. He has recently written an AGARDograph covering various free-flight techniques being used in this country and in Europe. For the past 15 years, he has also specialized in research on VTOL and STOL aircraft. In addition to writing numerous technical papers on the subject, he is the author of a semi-technical book on V/STOL aircraft published by The MacMillan Company, New York. He is a member of the board of Editorial Advisors to *Astronautics and Aeronautics*.

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* Associate Chief, Flight Mechanics and Technology Division.

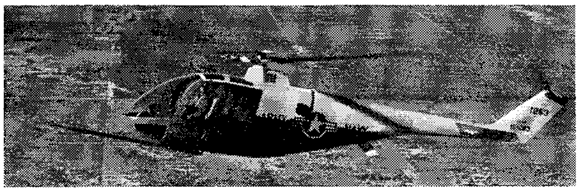

Fig. 1 Lockheed XH-51A hingeless-rotor helicopter.

the past failures with "rigid" rotor systems involved attempts to increase the rigidity of the blade as well as its attachment to the rotor shaft. On the other hand, the success of current hingeless-rotor systems results from the fact that no attempt is made to eliminate flexibility but rather that varying amounts of flexibility are utilized to alleviate the high-stress levels in the rotor system.

Most of the recent research and development on the hingeless-rotor principle has been carried out by Lockheed Aircraft Corporation, Bell Helicopter Company, and NASA. Lockheed, which has chosen the hingeless-rotor helicopter as its entry into the helicopter field, is involved in the development of what is intended to be an optimized operational aircraft of this type. After initial work with a simplified machine starting in 1959, Lockheed built the XH-51A shown in Fig. 1 under a joint Army-Navy contract and has completed the contractor's flight tests. Service evaluations of the helicopter are now under way. In addition, as part of this program, wind-tunnel research on a full-scale rotor system has been conducted in cooperation with NASA in the Ames Research Center's 40- × 80-ft tunnel.[3, 4]

Bell's work on the hingeless-rotor principle[5] has involved special rotor systems installed on existing helicopters to provide research information. One of these hingeless-rotor systems was obtained by NASA Langley Research Center and installed on an Army H-13 helicopter for some exploratory research on the hingeless rotor at Langley. A photograph of this machine is presented in Fig. 2. It should be noted that this particular hingeless-rotor arrangement does not appear to be very clean and simple, because it was fabricated from off-the-shelf components and experimental hub components which were overdesigned to provide generous margins of safety.

Some of the research results obtained with the helicopter shown in Fig. 2 are presented in Fig. 3. The left-hand plot of this figure consists of a time history of the pitching velocity produced by a longitudinal-control step input in hovering flight for the hingeless-rotor helicopter of Fig. 2 compared with a typical response for a conventional hinged-rotor helicopter. The response for the hingeless rotor is much more rapid than that for the hinged rotor. As a result of this "tight" response, the pilot of the hingeless-rotor machine receives early and clear evidence of the angular velocity

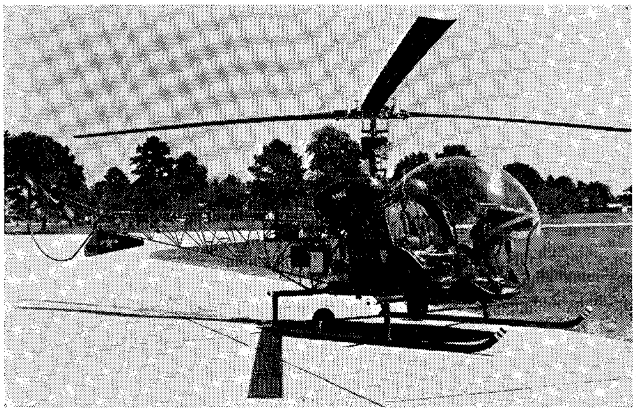

Fig. 2 NASA research helicopter with Bell hingeless rotor installed.

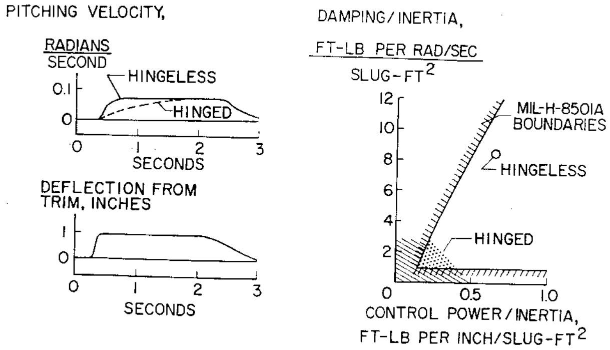

Fig. 3 Control-response and handling-qualities comparison of hingeless-rotor helicopter and conventional hinged-rotor helicopter in hovering flight (figure taken from Ref. 7).

developed by the control. In contrast, the much slower response for the hinged-rotor case requires that the pilot wait much longer before he can judge the resulting steady-state angular velocity.

In the right-hand plot of Fig. 3, the control power and damping of the hingeless-rotor helicopter are shown together with the military handling-qualities boundaries. Also shown for comparison, in the lower left-hand corner of the plot, are the combinations of control power and damping of conventional hinged-rotor helicopters used in previous NASA flight investigations. It is apparent that the hingeless-rotor helicopter meets the minimum requirements and also that it possesses values of control power and damping several times greater than values for conventional helicopters.

In the NASA hingeless-rotor flight study, the structural loading problem of most concern proved to be the "in-plane" or chordwise bending moments induced in the rotor blade. A promising method of solving this problem was indicated in the results of a wind-tunnel program on a 10-ft-diam hingeless-rotor dynamic model conducted at NASA Langley Research Center, as a cooperative effort of NASA, Lockheed, and the Army. This program included a study of the influence of blade-stiffness ratio on blade-structural loads. The blade-stiffness ratio refers to the ratio of the blade-bending stiffness in the chordwise direction to that in the flapwise direction. Conventional blades, which are very stiff in the chordwise direction and quite flexible in the vertical direction, have a very high stiffness ratio, which results in the coupling of blade-bending deflections with blade twist. This coupling can be reduced by reducing the blade-chordwise stiffness and can be theoretically eliminated by matching the chordwise stiffness to the flapwise stiffness. Figure 4 presents wind-tunnel data indicating that the reduction of blade-chordwise stiffness can lead to a significant reduction in chordwise structural loadings. The data show a large increase in chordwise cyclic load with increasing speed for the conventional blade (that is, for the blade with high chordwise stiffness and low flapwise stiffness). By modifying the attachment of the blade at the root to reduce the chordwise stiffness to equal the flapwise stiffness, a large reduction in the chordwise cyclic loads over the entire speed range was

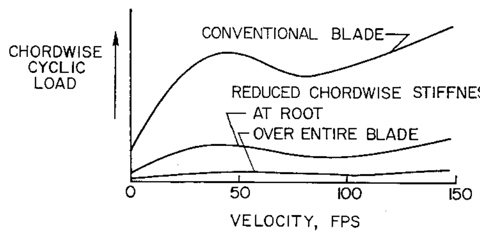

Fig. 4 Hingeless-rotor wind-tunnel data showing effect of blade chordwise stiffness on chordwise cyclic blade loads.

obtained. An even greater reduction in loads was obtained by matching the chordwise and bending stiffness at all points along the blade radius. The results presented in Fig. 4 are for steady 1-g flight. Similar improvements in chordwise cyclic loads were obtained in tests in which the load factor was increased to about 2.

In general, the wind-tunnel and flight research carried out to date on the hingeless-rotor principle has been very encouraging and has indicated definite promise of improvements to be obtained by application of the principle.

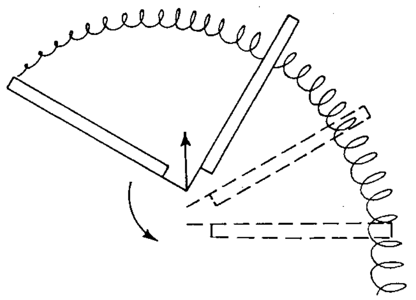

Fig. 6 Illustration of manner in which tip vortex from one blade is hit by next blade (figure taken from Ref. 1).

Rotor-Blade Periodic Airloads

Some interesting information regarding rotor-blade periodic airloads has been obtained recently in a flight investigation carried out at NASA Langley Research Center with an H-34 helicopter instrumented to measure rotor-blade pressure distributions.[1, 2, 8, 9] A sample of the data obtained is presented in Fig. 5. Measured blade loads for different azimuth positions are shown, and the theoretical variation of the blade loads for the same test condition is also presented for comparison. It is apparent that there are definite disagreements between experiment and simple theory, particularly in the existence of "jumps" or abrupt changes in the experimental data. These jumps appear in the data for all conditions except at the higher speeds and are generally most pronounced in the vibration-critical flight conditions. Thus, an understanding of the source of these jumps may lead to a better understanding of the basic problem of helicopter vibration and periodic airloads.

A simple physical picture of the probable source of the jumps in the experimental data is presented in Fig. 6. The sketch shows how a given blade, in three successive positions, encounters the tip vortex generated by the preceding blade and does so at successively smaller radii through this portion of each revolution. The azimuth values predicted for the load jumps by this simple geometrical relationship are shown by the ticks in Fig. 5. The fact that the ticks are somewhat closer together than the measured jumps is attributed to a rolling-up and inward shift of the tip vortex (whereas Fig. 6 was drawn on the basis that the vortex center stays on the line traced by the path of the tip). Several organizations are now studying possible methods for predicting the magnitude and location of these jumps.

Rotor-Blade Stall Phenomena

A wind-tunnel investigation has recently been completed at NASA Langley Research Center in which a 15-ft-diam rotor was operated at extreme thrust coefficients and high tip-speed ratios to provide information on rotor-blade stall phenomena in high-speed flight.[10] The results indicated that the loss in rotor lift for conditions in which large regions of blade stall were expected was much less than anticipated for the range of conditions covered. The data of Fig. 7 were taken from Ref. 10 illustrate this point. Measured rotor thrust, in terms of hovering mean lift coefficient, is compared with calculated values of thrust based on a simple theory using constant lift-curve slope and on a more refined theory utilizing two-dimensional section characteristics of the rotor blade. It can be seen that both calculations agree with the theory up to the point at which the stall is theoretically predicted. At the higher lift coefficients, the simple theory overpredicts the lift whereas the refined theory underpredicts it, with the simple theory giving the closer agreement.

In the past, somewhat similar cases of disagreement between experimental data and the refined theory have been noted, but usually with smaller models and at much lower Reynolds numbers. The 15-ft-diam rotor used in these tests should be expected to provide results generally applicable to small helicopters, and analysis has indicated that similar trends should also be expected in varying degrees with larger helicopters.[10]

Helicopter-Drag Cleanup

In an effort to obtain increased performance from existing and proposed helicopters, a number of helicopter-drag cleanup investigations have been conducted recently by the Army, Navy, NASA, and industry.[12–16] In one example of this work, Bell Heliocopter conducted an investigation on a UH-1B helicopter under an Army contract, with NASA providing research support by testing the helicopter in the Ames Research Center 40- × 80-ft wind tunnel. Major modifications to reduce the drag of the helicopter included using a tilting pylon, adjustable in flight, to keep the fuselage in a minimum drag attitude; installing fairings around the pylon, on the landing gear, and just aft of the cargo compartment on the fuselage; installing improved engine inlets; and increasing the vertical fin area and adding camber to the surface. The effect of these changes on performance as determined in flight is shown in Fig. 8, which was taken from Ref. 15. The top speed was increased from about 120 to 155 knots. In addition, the range was increased by 30%, and the vibratory stresses were appreciably reduced. These pro-

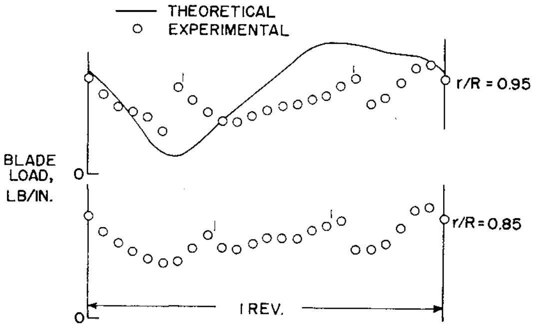

Fig. 5 Comparison of experimental and theoretical blade loads for a single-rotor helicopter in forward flight (figure taken from Ref. 1).

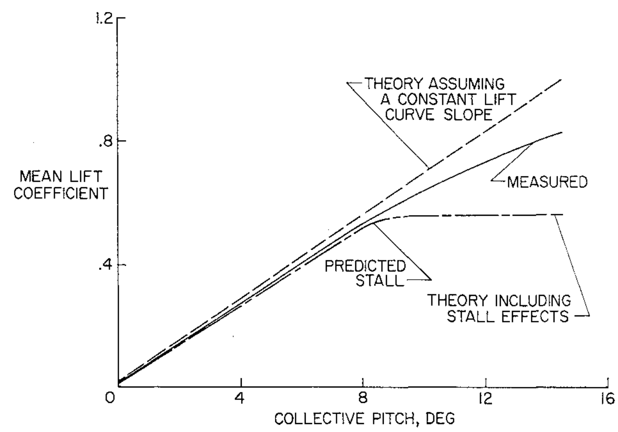

Fig. 7 Comparison of rotor thrust (in terms of hovering mean lift coefficient) with simple and refined theory (figure taken from Ref. 10).

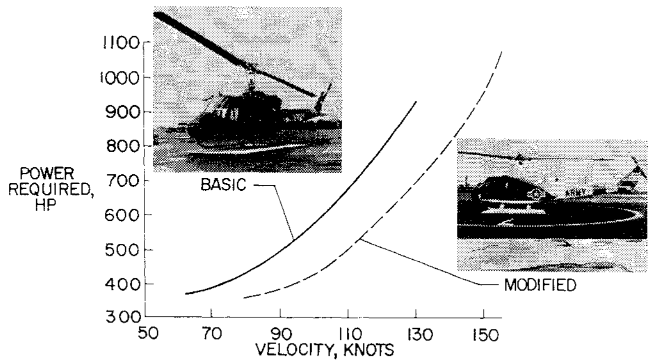

Fig. 8 Effect of drag cleanup on performance of UH-1B helicopter (figure taken from Ref. 15).

nounced improvements in performance and reduction in vibration problems obtained by modifying an existing helicopter certainly suggest that increased attention to these items in the initial helicopter design would pay substantial dividends.

Propeller V/STOL and STOL Aircraft Research

A substantial research effort in the propeller V/STOL and STOL area has continued during the past two years[17–32] with much of the research being directed toward the wing stall and related problems encountered in transition or low-speed flight. The awarding of a contract for the construction of the XC-142 Tri-Service V/STOL airplane shortly before the 1961 Anglo-American Conference marked a turning point in the development of the tilt-wing V/STOL aircraft type. The research and development effort in this general area took on more significance, and much of the effort was oriented to provide direct support for the XC-142. An extensive wind-tunnel program was undertaken by the contractor (Vought-Hiller-Ryan) and NASA to provide detailed information on the configuration and to refine the design. Photographs of two of the models used by NASA in this work are presented in Fig. 9.

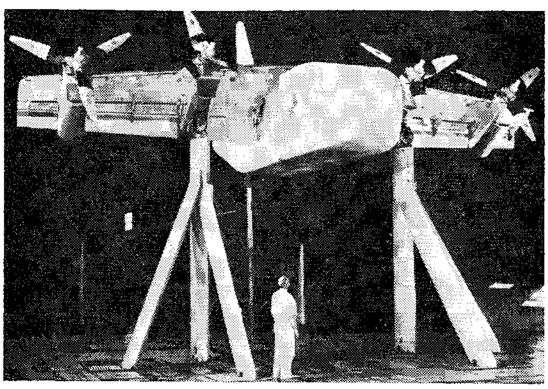

Fig. 9a Large-scale model of XC-142 tri-service VTOL airplane in NASA Ames Research Center 40- × 80-ft wind tunnel.

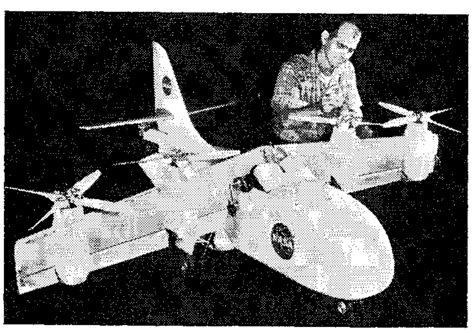

Fig. 9b Free-flying model of XC-142 airplane used in dynamic stability and control research at NASA Langley Research Center.

Another interesting propeller V/STOL development is the Curtiss-Wright X-19 tandem four-propeller airplane (Fig. 10) which has been built as part of the Tri-Service V/STOL transport program and which is now undergoing testing by the contractor. Only a limited amount of research has been carried out on this tilt-propeller type, much of it having been done by Curtiss-Wright while the airplane was a company project intended for development as a civil transport. The NASA Langley Research Center has recently conducted a general research wind-tunnel study to provide some basic aerodynamic information on the tilt-propeller type.[17, 29] Results of this study indicate rather poor STOL performance for the tilt-propeller type compared to that of a well-designed tilt-wing configuration. On the other hand, the tilt-propeller type appears to have a less serious wing-stall problem in transition than does the tilt-wing type.

In order to provide flight information more directly applicable to the XC-142, the Vertol VZ-2 tilt-wing research airplane that has been used in research at NASA Langley Research Center for several years[18] has been modified to incorporate full-span flaps and ailerons.[19] Research is now in progress with these modifications. Results to date indicate a substantial improvement in the wing-stall problem in transition flight with the full-span flap programed to deflect with changes in wing incidence. This result is illustrated in Fig. 11, which compares the pilot's opinion of the flying qualities of the VZ-2 (with flap installed) with previous results obtained (with plain wing and leading-edge droop). The leading-edge droop had been found to provide a definite improvement in flight characteristics, as indicated by the upper and lower left plots of Fig. 11 which show the greater permissible rates of descent with the droop. An even more pronounced improvement was obtained with the trailing-edge flaps (leading-edge droop removed), as shown by the plot at the lower right. The improvement was especially noticeable at the higher speeds (50–70 knots). Although the permissible rate of descent was greatly increased at these higher speeds when the flaps were installed (as indicated by the lower position of the boundary), there was a mild buffet problem for some conditions falling on the acceptable side of the boundary. The use of leading-edge droop in conjunction with the flaps tended to alleviate this buffet problem.

One method of alleviating the stall problem in transition or landing approach for propeller V/STOL and STOL airplanes having four propellers involves the use of differential blade pitch between the inboard and outboard propellers. This feature, which was proposed several years ago by Breguet in conjunction with their STOL airplane development, was investigated on the XC-142 model shown in Fig. 9.[20] Some results of this study are presented in Fig. 12. Boundaries are shown for the normal case of 10° blade pitch on all propellers and for the case of differential pitch with the in-

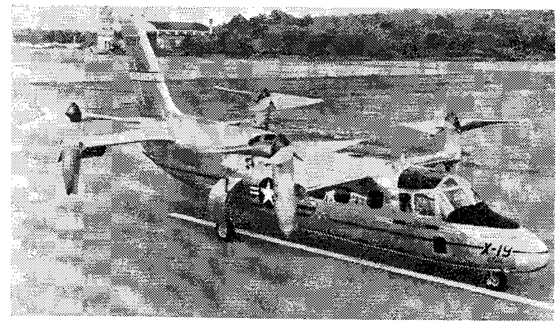

Fig. 10 Curtiss-Wright X-19 tilt-propeller research airplane.

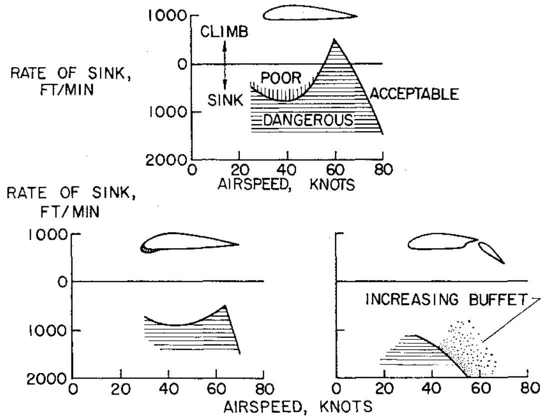

Fig. 11 Effect of leading-edge droop and trailing-edge flaps on flying qualities of VZ-2 research airplane in transition.

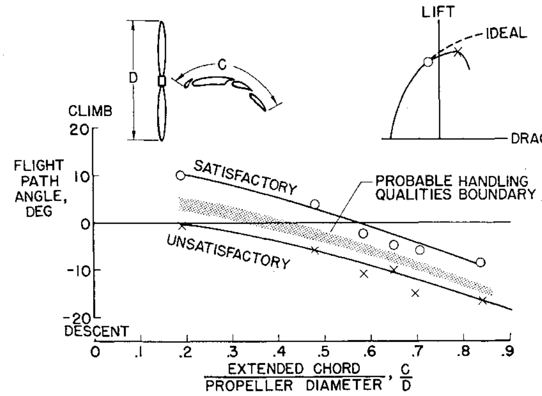

Fig. 13 Effect of chord-diameter ratio on permissible angle of descent for satisfactory handling qualities (figure taken from Ref. 21).

board propellers at 14° and the outboard propellers at 0°. The shift in the boundaries indicates a pronounced beneficial effect of differential thrust which amounts to approximately a 700-ft/min greater permissible rate of descent at a given speed or to a 10-knot decrease in stall speed at a given rate of descent. Despite the fact that the outboard propeller was producing a net negative thrust in the differential pitch case, the outboard portion of the wing did not stall prematurely. Apparently, the inner portion of the outboard propeller was actually producing positive thrust and therefore an increment of positive slip-stream velocity over most of the outboard portion of the wing. Although the outer portion of the propeller was producing negative thrust, the regions of negative thrust occurred either where the propellers overlap or where the propeller extends beyond the wing tip.[20]

Past research has established the importance of wing size and flap effectiveness on the wing stall of propeller V/STOL aircraft in transition and, particularly, in descent conditions. The amount of wing and flap required to avoid stalling has not been clearly established, however, and no satisfactory method of analysis of the wing-stall problem has been developed.[21] An analysis of existing wind-tunnel and flight data has been made in an effort to provide at least a first approximation to the proper wing size in order to avoid wing stalling, and the relationships obtained are shown in Fig. 13. This figure, which was taken from Ref. 21, shows the effect of wing-chord to propeller-diameter ratio on the permissible angle of descent for propeller V/STOL aircraft. This chart admittedly is an oversimplification of the problem and applies only to wings with a fairly large and elaborate flap system. The explanation for the data points is given by the powered-model lift-drag sketch at the upper right of the figure. A broad-brush handling-qualities boundary has been drawn between the two sets of data which are based partly on results obtained with the VZ-2 airplane and partly on the assumption that some local wing stalling could be tolerated but that complete wing stall could not. The plot indicates that satisfactory conditions in level-flight transition could be obtained with an extended chord-diameter ratio of about 0.3–0.5 but that a 10° descent requirement calls for an extended chord-diameter ratio of about 0.6–0.8.

Most propeller STOL and V/STOL aircraft have experienced some form of lateral-directional problem in low-speed flight which has been considered objectionable or unsatisfactory by the pilot. In some cases, poor lateral-directional characteristics at approach speeds have reduced the controllability and therefore limited the usefulness of the aircraft. In Ref. 20 it is pointed out that such problems have been encountered with the YC-134, BLC-130, and Ryan VZ-3 in flight research at NASA Ames Research Center. An example of this type of problem with the BLC-130, in which reduced controllability was exhibited during STOL approaches by large sideslip excursions when maneuvering, is illustrated in Fig. 14, taken from Ref. 20. The solid lines represent flight data for the BLC-130 during a banked turn at 65 knots. The data show that when the airplane is banked to initiate a turn, large sideslip angles build up prior to the development of a rate of turn. Actually, the airplane turns initially in the wrong direction because of adverse aileron yawing moments. A simulator study was undertaken to determine the important parameters involved in this case and to seek practical solutions.[22] This study indicated that satisfactory characteristics could be obtained when the static directional stability was increased fourfold and the damping in yaw sixfold, but such large changes would be very difficult to obtain on the BLC-130. A more practical solution indicated by the simulator study was to add damping proportional to rate of sideslip $C_{n\dot{\beta}}$ in addition to doubling the static directional stability. The dotted curve of Fig. 14 shows the beneficial effect of such a change on the response

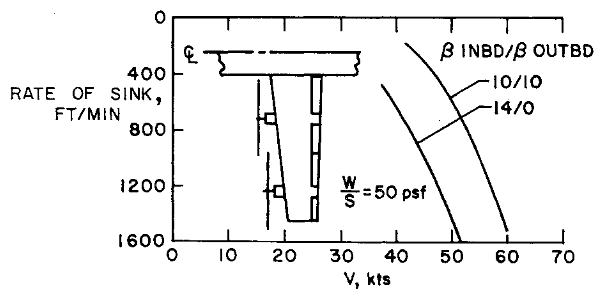

Fig. 12 Effect of differential blade pitch between inboard and outboard propellers on stall speed of a four-propeller configuration with large-chord double-slotted flaps (figure taken from Ref. 20).

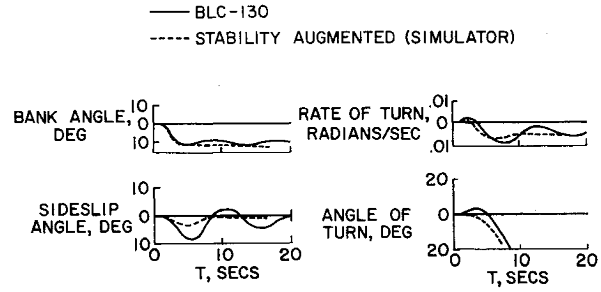

Fig. 14 Effect of stability augmentation (increased directional stability $C_{n\beta}$ and sideslipping acceleration damping $C_{n\dot{\beta}}$ on lateral controllability of BLC-130 (figure taken from Ref. 20).

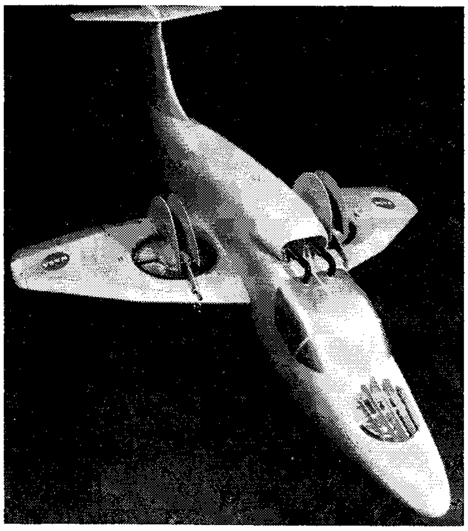

Fig. 15 Small-scale flying model of General Electric-Ryan XV-5A fan-in-wing research airplane.

of the BLC-130 to an aileron input. The sideslipping was greatly reduced, and the lag in developing a turn in the proper direction was cut down. Flight tests of the BLC-130 with this modification are now being made to verify the results of the simulator study.

Research on Ducted-Fan V/STOL Aircraft

Most of the recent research on ducted-fan V/STOL aircraft has been directed toward the fan-in-wing and tilt-duct types, and advanced research aircraft of these two types are now under construction. The XV-5A fan-in-wing research airplane (Fig. 15) is being built for the Army by General Electric and Ryan, and the X-22A quad-duct airplane (Fig. 16) is being built by Bell Aerosystems as part of the Tri-Service V/STOL program.

Fan-in-Wing and Fan-in-Fuselage Research

Extensive large-scale research on fan-in-wing and fan-in-fuselage configurations has been conducted as joint NASA-General Electric projects in the NASA Ames 40- × 80-ft wind tunnel during the last few years.[33–40] Some of the more significant results of this research are summarized in Fig. 17 (taken from Ref. 35), Fig. 18, and Fig. 19 (taken from Ref. 36). Data are presented for the three configurations in Fig. 17: a fan-in-fuselage type (model 1) and two fan-in-wing types (models 2 and 3). Model 3 was intended to provide a fairly close approximation to the XV-5A fan-in-wing research airplane.

Typical variations of lift-thrust ratio with flight-velocity ratio at zero louver angle for the three models are presented in Fig. 17. The total lift increased with increasing speed for all configurations. The variation of fan thrust with velocity

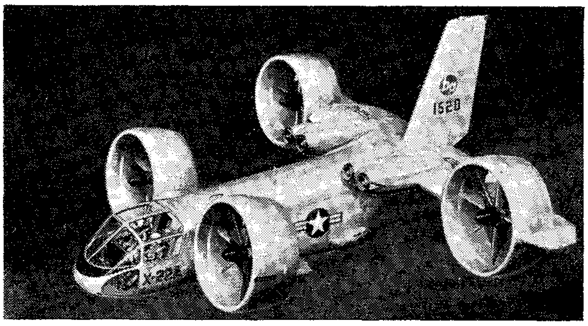

Fig. 16 Artist's drawing of Bell X-22A quad-duct V/STOL airplane.

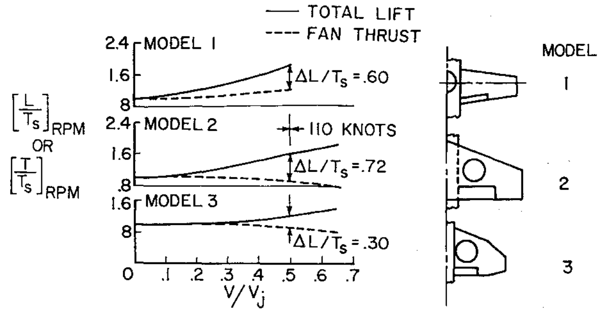

Fig. 17 Variation of lift and thrust with velocity ratio for three ducted-fan configurations; $\alpha = 0°$ (figure taken from Ref. 35).

ratio is also shown in Fig. 17. The increment between fan thrust and model lift shown in the three cases is about 80% induced lift due to fan operation and 20% due to wing camber. The fact that the induced lift for model 3 is much less than that for models 1 and 2 indicates that an increasing ratio of fan area to wing area results in smaller induced lift. The data presented in Fig. 17 are for flaps retracted. Data of Ref. 35 show that trailing-edge flaps behind the fans provide a further increase in lifting capability.

The increasing lift with increasing speed shown by the data of Fig. 17 gives an indication of the STOL capability of the lift-fan configurations. In order to give a better indication of the STOL capability of the fan-in-wing models 2 and 3 and to compare them with a propeller V/STOL configuration, data of this type have been replotted in Fig. 18. This figure shows the increase in lift with increasing speed for three hypothetical airplanes having the same wing loading and wing area. Two of the airplanes are lift-fan configurations having the wing and fan geometry of models 2 and 3. The data in this case are for louver angles that provide the necessary thrust for forward flight. The other airplane is a tilt-wing configuration geometrically similar to the XC-142. The model 3 configuration shows very little STOL capability. Model 2 has more STOL capability, apparently because of its greater ratio of wing area to fan area. The tilt-wing configuration has even greater STOL capability, because its wing is immersed in the propeller slipstream and therefore produces substantial lift even at low speeds.

The problem of reingestion of hot exhaust gases proved to be a definite problem with model 3 when hovering in light wings or in forward flight. The flow patterns involved in these cases are illustrated in Fig. 19a, in which the shaded areas represent the hot exhaust gas from the turbine. The sketch at the top shows the flow pattern in hovering flight with the model headed into a light wind. In this case, the hot gas was blown back into the vicinity of the model, resulting in a small temperature rise (less than 10°F) in both the fan and gas-generator inlets. For the forward-speed case, representing the ground run on a short takeoff, the hot-gas ingestion problem became more severe because, as the sketch at the lower left of Fig. 19a indicates, there was a shorter path of the hot gases from the turbine exit to the inlet and

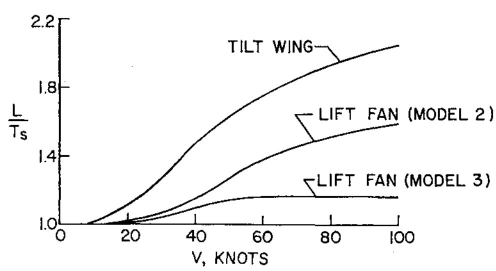

Fig. 18 Comparison of STOL capability of lift-fan and tilt-wing V/STOL configurations.

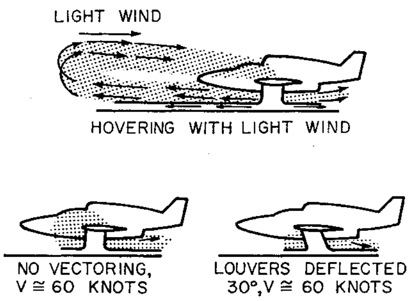

Fig. 19a Flow patterns in ground effect for a fan-in-wing model (model 3) (figure taken from Ref. 36).

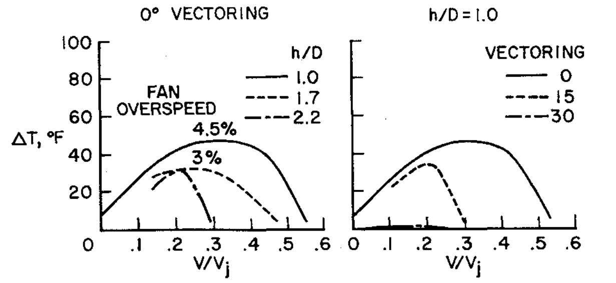

Fig. 19b Effect of ground height and slipstream vectoring on the temperature rise in the fan inlets of a fan-in-wing model (model 3) (figure taken from Reference 36).

therefore less time for the exhaust to cool. For the 60-knot airspeed condition, a temperature rise of 50°F occurred in the fan inlet. When louvers were used to deflect the fan turbine exhaust 30° rearward, the reingestion of exhaust gases was eliminated, as indicated by the flow pattern at the lower right of Fig. 19a. Experimental data showing the average temperature rise in the fan inlets for several ground heights and vector angles as a function of velocity ratio are presented in Fig. 19b. It can be seen from the left-hand plot that increasing the height above the ground decreased the velocity range for ingestion but did not greatly change the maximum temperature rise. The largest temperature rise shown produced a thrust loss that would require a 4.5% increase in fan speed to offset. The right-hand plot shows the pronounced beneficial effect of vectoring the fan turbine exhaust rearward. The data shown in Fig. 19b are for temperature rise in the fan inlet. The gas-generator inlets on top of the fuselage experienced less ingestion with a maximum temperature rise of 20°F being measured. Additional information on ground effect phenomena with fan-in wing and fan-in fuselage configuration is given in Ref. 41.

Tilt-Duct Research

Research on tilt-duct V/STOL aircraft has, during the past two or three years, shifted from two-duct configurations, such as the Doak VZ-4 research airplane, to tandem four-duct configurations, such as the Bell X-22A airplane.[42–50] Much of the research at present is in direct support of the X-22A. NASA is providing some of this support with static wind-tunnel investigations of small-scale and large-scale models and with dynamic stability and control studies with a free-flying model.

An investigation of operational downwash impingement problems of the tandem four-duct type is being carried out by Kellett Aircraft Corporation under contract to the Navy. In this investigation, a large semispan test setup (approximately a full-scale model of the X-22A) is being tested over various types of terrain and water at disk loadings up to 60 psf. In general, the results to date indicate some rather serious impingement and recirculation problems. A sketch of the basic recirculation flow field in hovering determined in the Kellett investigation is presented in Fig. 20. One area of flow of particular concern is the upwash area between the front and rear

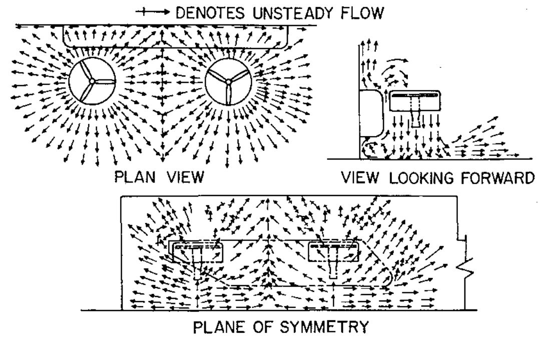

Fig. 20 Basic flow field created by the slipstreams of a four-duct tandem V/STOL configuration at a height of 1 diam above the ground.

ducts near the sides of the fuselage. This upflow can cause debris to be blown up above the fuselage and thereby lead to particle ingestion problems. Research to alleviate these problems is in progress.

Turobjet V/STOL Aircraft Research

The United States' effort in the turbojet V/STOL area has been overshadowed during recent years by the progress in Europe toward the development of operational turbojet V/STOL aircraft. The early lead in research and development in this area resulting from the work associated with the Ryan X-13 and Bell X-14 research airplanes was soon lost when work on the Bell D-188A fighter airplane was discontinued in 1959 and no work on other operational turbojet V/STOL aircraft was started.[51] The only new turbojet V/-STOL aircraft in this country is the Lockheed XV-4A (Fig. 21), a small research aircraft making use of the jet-ejector principle;[52] also known as the Hummingbird, the XV-4A is now being flight tested by the contractor. The Bell X-14A is still being used in research at NASA Ames Research Center, but this work is in the general area of handling-qualities requirements and not directed specifically toward turbojet V/-STOL aircraft.

Although a number of small-scale wind-tunnel studies have been carried out on turbojet V/STOL configurations, much of this work has been classified or proprietary. References 53–56 cover the results of some unclassified research in the general area of induced interference effects, and Figs. 22 and 23 present some results of more recent research in this area.

Figure 22 shows the effect of nozzle configuration on the lift and pitching moment of a turbojet V/STOL model in the transition range of flight. Nondimensionalized lift- and pitching-moment data are plotted against velocity ratio for three nozzle configurations: a single large nozzle and two arrangements of four small nozzles. All three configurations show the typical lift loss at zero angle of attack and nose-up pitching moments resulting from negative pressures induced on the lower surface of the fuselage and wing behind the jets. It should be noted that the data in Fig. 22 were obtained with a model having compressed air jets supplied from an external source. The effects of an inlet on lift and pitching moment are therefore not included. The lift forces at an inlet are

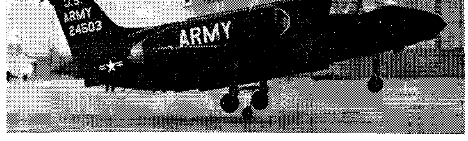

Fig. 21 Lockheed XV-4A (Hummingbird) turbojet-ejector V/STOL research airplane.

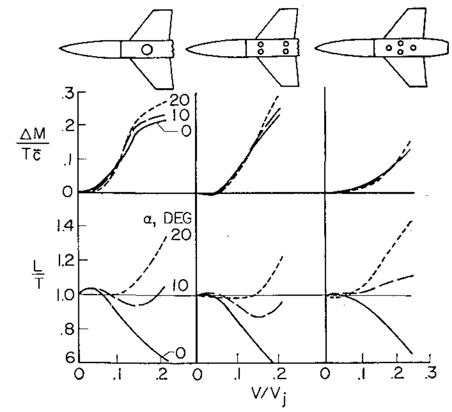

Fig. 22 Effect of nozzle configuration on the lift and pitching moment of a jet V/STOL model in transition flight.

positive and tend to counteract the lift loss at the exit. In some cases, such as for the ducted-fan configurations of Fig. 17, the effect of the inlet is large enough to eliminate the lift loss and produce an increasing lift with increasing airspeed. The configuration at the right in Fig. 22, with the four nozzles arranged in a diamond pattern, appears to be the best of the three, since it produces smaller nose-up pitching moments and greater lift for a given angle of attack and velocity ratio. The better characteristics of this configuration are attributed to the more effective "streamlining" of the jet-exhaust pattern with the diamond arrangement; therefore, smaller negative pressures are induced on the lower surface of the fuselage and wing behind the jets. It has been shown in related research[56] that jet exhausts issuing perpendicularly from the lower surface of a plate produce induced interference effects similar to those produced by solid cylinders having the same diameter as the jets. It is therefore reasoned that a more streamlined arrangement of these effective cylinders should produce less obstruction to the flow and therefore less induced effect on the airframe of the model.

An example of jet-induced effects on a different type of V/STOL configuration is presented in Fig. 23. Pitching-moment data are shown for a vectored-thrust turbofan V/STOL model for various horizontal-tail arrangements and thrust conditions. The left-hand plot shows data for the power-off condition with tail off and with the tail in a high and low position. It can be seen that the model is unstable (positive slope of pitching-moment curve) with the tail off and that the instability increases with increasing angle of attack. Addition of the tail in the high position does not entirely eliminate the instability, but moving the tail to the low position (and into a more favorable downwash field) does provide stability over the entire lift range. The plot on the right, which presents data for the power-on condition with the low tail position, shows that large changes in trim and reductions in stability occur when thrust is added with the nozzles in the intermediate angle range (30° and 60°). A highly unstable condition results for the 60° nozzle setting. Analysis has indicated that the detrimental effects of power are caused by a change in the flow field at the horizontal tail. Apparently, the favorable downwash field existing at the low horizontal-tail position for the power-off condition is shifted downward away from the tail by the strong jet exhaust flow from the deflected nozzles. The problem illustrated by these data appears to be a basic one for vectored-thrust or lift-engine V/STOL fighter configurations having horizontal-tail surfaces. Careful attention must be given to the arrangement of the wing, tail, and nozzles to achieve acceptable longitudinal-stability characteristics for all flight conditions.

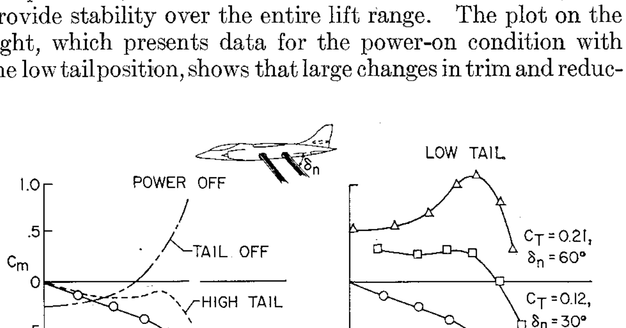

Fig. 23 Effect of horizontal-tail position and thrust on the longitudinal stability and trim of a vectored-thrust turbojet V/STOL configuration.

Research on Handling-Qualities Requirements

Several research studies directed toward the determination of rational handling-qualities requirements for V/STOL aircraft have been conducted during recent years, and this work is continuing.[57–71] Research in this area has been carried out with V/STOL aircraft (usually with variable-stability and control features) and with simulators of various types. A large portion of the handling-qualities research has been carried out by NASA at the Ames and the Langley Research Centers. Langley has used helicopters in most of its flight research along this line and is presently making use of a YHC-1A twin-turbine tandem helicopter equipped with very elaborate variable-stability-and-control equipment and with provisions for conducting research on the problem of making steep approaches under instrument flight conditions. Ames is using the X-14A turbojet V/STOL variable-stability-and-control research aircraft for its flight work in this area. Other research organizations, such as Cornell Aeronautical Laboratory, Princeton University, and a number of companies, have also carried out research on handling-qualities requirements using either helicopters or simulators.

An important point regarding the interpretation of results of flight and simulator studies of V/STOL handling-qualities requirements is brought out in Fig. 24. The upper portion of the figure presents typical handling-qualities boundaries for hovering flight of V/STOL aircraft on a plot of damping vs control power. The 3.5 and 6.5 Cooper flight rating boundaries divide the plot into three areas—combinations of control power and damping which are considered satisfactory, acceptable for only limited operation, and completely unacceptable. Extensive use has been made of figures such as this to present flight and simulator results dealing with handling qualities about each of the three aircraft axes. In some cases there have been discrepancies between sets of data which should have been comparable, apparently because the control power has been specified in different ways. In some studies it has been specified as aircraft angular acceleration per inch of stick displacement which may be thought of as control sensitivity. In other studies, the maximum control power obtained with full control deflection has been used. Although each of these means of specifying control power is valid for certain applications, experience now indicates that care must be used in the selection of the one appropriate for the case at hand. The two plots at the bottom of the figure illustrate what now appears to be the proper use of the two control power designations.

First, at the lower left, the 6.5 Cooper rating boundary is shown on a plot of damping vs maximum control power to indicate that when a V/STOL aircraft has inadequate or marginal control and low damping, the pilot must use control up to or near the stops in his evaluation maneuvers and, therefore, tends to evaluate the aircraft on the basis of maximum control power. This situation applies for Cooper ratings of perhaps 5 and greater.

The plot at the lower right, on the other hand, applies to Cooper ratings of perhaps 4 and smaller (that is, for the better combinations of control power and damping). The 3.5 rating

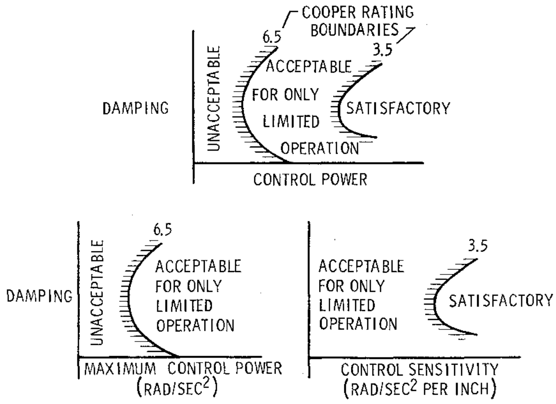

Fig. 24 Illustrative plots indicating significant factors determining boundaries for V/STOL handling qualities requirements.

boundary is shown on this plot of damping vs control sensitivity to indicate that, in evaluating the better V/STOL control systems, the pilot does not generally need to use full control and, therefore, tends to rate the aircraft on the ease, quickness, and precision of control, which is closely related to control power per inch of stick travel (or control sensitivity). This illustration is based on the assumption that the maximum control throws available are of normal magnitude. If the control throws available are abnormally large, it is possible to obtain control ratings of 5 or greater without the pilot using maximum control. In such cases, control sensitivity would also appear to be a factor in establishing the 6.5 Cooper rating boundary. Although Fig. 24 admittedly oversimplifies a problem which has many ramifications, it is believed to provide a correct indication of the basic nature of the problem.

Concluding Remarks

The status of V/STOL research and development in the United States has been reviewed and a summary of significant recent research results presented. It is apparent from this review that the helicopter continues to be a subject of strong research interest and that propeller and ducted-fan V/STOL aircraft are also receiving increasing attention, because aircraft of these types are now being built as part of the Tri-Service V/STOL transport program and other programs. The United States still lags, however, in work on turbojet V/STOL types. Studies of these types are being conducted by research organizations, the services, and industry, but research development in this area cannot accelerate without firm plans for operational turbojet V/STOL aircraft. Perhaps in the near future this impetus will be provided by service requirements for turbojet V/STOL aircraft to be used in close support operations.

Another area of research and development in the V/STOL field in which the United States is lagging is the propulsion area. Although some development work on turbojet lift engines has been started since the last Anglo-American Conference, there is still an inadequate research and development program for V/STOL aircraft engines in this country. Since significant advances in V/STOL aircraft performance in the future will depend on improvements in propulsion systems, there is obviously an urgent need for increased research and development effort in this area.

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