Agility Performance of Several V/STOL and STOL Aircraft

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A comparison of five V/STOL and STOL aircraft designs was conducted to determine the effect of their configuration characteristics on agility performance. Agility was defined as the combination of performance and maneuverability that determines how rapidly any aircraft can accelerate, decelerate, and turn at specified rates of climb and airspeed. As such, agility performance may be as important a design consideration as range, payload, and cruise performance for many V/STOL aircraft missions. The five configurations considered were as follows: 1) pure helicopter, 2) winged helicopter, 3) tilt-wing propeller V/STOL aircraft, 4) fixed-wing, tilt propeller V/STOL aircraft, and 5) fixed-wing direct-control STOL aircraft. Maneuvers considered were horizontal acceleration and deceleration performance, normal load factor capability, turning performance, and an attack maneuver that combines a decelerating turn with straight-line acceleration. Because of its high deceleration capability, the winged helicopter was found to have the best agility performance up to its top speed of 180 knots. Of the propeller-driven designs, the tilt-wing propeller has the best acceleration and normal load factor capability, due primarily to the favorable effect of the propeller slipstream on wing airflow at low speeds. For the attack maneuver described, deceleration was generally more important than acceleration or normal load factor. Although the data presented are directly applicable only to the specific designs studied, it is felt that the conclusions may be extended to compare agility performance of the five configurations for any mission.

Introduction

IDEALLY, V/STOL aircraft differ from conventional aircraft in that they are capable of operation from unprepared or closely confined sites and controlled flight at extremely low speeds. In military operations, such aircraft rely on maneuverability and nap-of-earth flight to reduce vulnerability to enemy fire. For searching tasks, such as search and rescue or reconnaissance, low-speed flight is used to enhance detection probability. For assault transport missions, close terrain following is desirable at high cruise speeds, with capability for rapidly descending and decelerating into landing areas that come into view only a short distance ahead. For battleground fire support, good flight conditions for target identification and rapid target acquisition and tracking in the nap of the earth are essential. Commercial VTOL transports should possess similar capabilities in some types of operations, so that they may move in and out of restricted areas in the minimum time and at lowest noise levels without compromising passenger safety.

Classically, aircraft performance is measured by such factors as range, payload, endurance, and maximum speed. Maneuvering response and stability and control are measured by such factors as time varying rates of roll, pitch, and yaw of the aircraft following control inputs or external disturbances. However, in some of the flight modes encountered in the missions just discussed, behavior in terms of acceleration, deceleration, normal load factor capability, and time and distance to turn is of paramount interest. Such behavior involves a combination of performance, maneuvering response, and stability and control in conventional aircraft. Since these characteristics are closely interrelated in V/STOL aircraft, it is desired to introduce the term agility with the following definition: agility is the combination of performance and maneuverability that determines how rapidly an aircraft can accelerate, decelerate, and turn at specified rates of climb and airspeed.

Acceleration and deceleration result, of course, in certain speed changing and turning performance in terms of time and distance for all bodies. Since these relationships are primary to the concept of agility, a set of such data is presented in Figs. 1 and 2. To demonstrate the importance of these data, Fig. 1 shows that an aircraft possessing 10 knots/sec deceleration capability will require 15 sec and a distance of nearly 2000 ft to slow down to a stop from 150 knots initial airspeed. An aircraft possessing only 3 knots/sec deceleration capability will require 50 sec and over 5000 ft to accomplish the same task. In Fig. 2, an aircraft with a normal load factor of 2.0 at 150 knots is seen to turn 180° in 14 sec with a radius of turn of about 1250 ft. An aircraft with a normal load factor capability of 1.25 at the same speed will require 33 sec and a radius of about 2700 ft to accomplish the same turn. A second look at both figures reveals the large effect of speed on such performance at given rates of acceleration or load factors, a strong argument for high agility at low

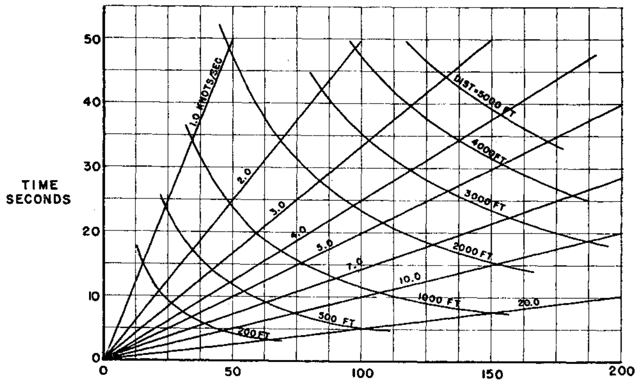

Fig. 1 Horizontal acceleration: time and distance required.

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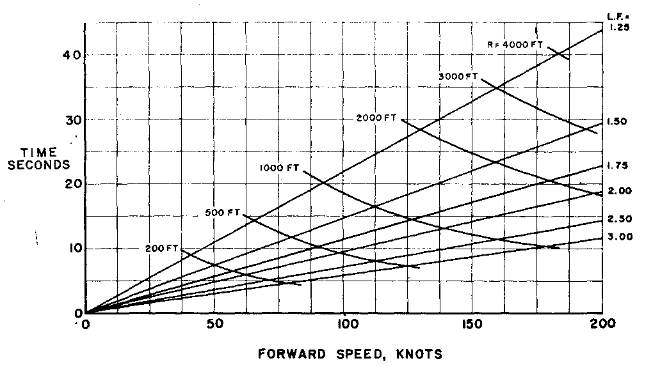

Fig. 2 Turning performance: time required for 180° turn and turn radius.

speeds if minimum distances and times are required for these basic maneuvers.

Studies of a number of V/STOL aircraft in the performance of their intended missions have indicated that, depending on their particular configurations, there are wide differences in agility characteristics. A mission that will particularly illustrate this point is the tactical support mission, where not only the basic maneuvers shown in Figs. 1 and 2 are constantly required, but also various combinations of these. For the purposes of this paper, five configuration designs that might be suited to this mission are selected for comparison as follows: 1) high-performance pure helicopter, later referred to as "helicopter," 2) high-performance helicopter with a wing, referred to later as "winged helicopter," 3) tilt-wing propeller V/STOL aircraft, referred to later as "tilt wing," 4) fixed-wing, tilt-propeller V/STOL aircraft, referred to later as "tilt prop," and 5) direct-control fixed-wing STOL aircraft equipped with pitch and yaw fans, referred to later as "STOL."

Although the results presented in this paper are directly applicable only to the tactical support mission for which these aircraft were designed, it is believed that they are generally applicable to all missions requiring similar performance. It is hoped that this study will stimulate application of the concept of agility performance to the design of V/STOL aircraft for the variety of missions now contemplated for such aircraft.

Figure 3 shows the mission criteria to which the aircraft were designed. Power installation was governed by the hover requirement, so that maximum speed varied from 175–375 knots, depending on aircraft configuration. Duration of the mission varied from 1.7–2.2 hr, depending on the cruise speed of the aircraft. Since the mission chosen was for a tactical support aircraft, one maneuver for the agility study was that used in attacking a ground target.

The aircraft are described in Fig. 4. The winged helicopter is similar to the helicopter, since rotor downwash effects in hover can be minimized with large (40% chord) full span flaps. The wing accounts for the 600-lb gross weight difference. The tilt propeller and tilt-wing designs are of comparable size. The effects of propeller downwash in hover on the tilt-propeller design dictate larger propellers for the same hover performance as the tilt-wing design. For this tilt-propeller design, the larger propellers are less efficient at high speeds and require more fuel to be carried for the cruise requirement, resulting in the higher gross weight of the tilt propeller design. For comparison purposes, a STOL design was prepared, similar to the tilt-wing design but with fixed wings and enough power and control to clear a 50-ft obstacle in 500 ft of runway. This design, of course, would not meet the requirement for hover, but represents a cheaper, less complicated approach to tactical support.

Artists' conceptions of three of these aircraft are presented in Figs. 5–7. The helicopter, not shown, is similar to the winged helicopter but without wings. The STOL design is similar to the tilt wing.

The tilt propeller, tilt wing, and STOL designs are equipped with pitch and yaw fans for direct control at low speeds. The tilt propeller and tilt-wing aircraft use differential propeller pitch for roll control at low speeds, whereas the STOL depends on large aileron surfaces operating in the slipstream of the propellers. All the V/STOL configurations meet or exceed the flying qualities requirements of MIL SPEC-H-8501A.

The tilt-propeller aircraft is equipped with single-slotted 40% chord flaps. In transition to and from low-speed flight, flaps for both aircraft are automatically controlled as a function of nacelle or wing tilt angle. Stores cannot be carried in or on the wing of the tilt-wing design, and must be carried in or outside the fuselage. Consequently this configuration had more parasite drag than the tilt-propeller aircraft, and a slightly lower maximum speed.

It is shown in Fig. 3 that maximum speed of the helicopter can be extended by addition of a wing to unload the rotor at higher speeds, resulting in a winged helicopter. For this mission, the tilt wing and tilt-propeller designs will have about 140% the weight, 500% the installed horsepower, and twice the maximum speed of the helicopter design.

Since the tilt-wing aircraft encounters high wing angles of attack at low speeds, it must be controlled so that the wing angle of attack does not exceed 5° below the stall angle. This

POWER REQUIRED	HOVER AT 6000' O G E 95°F
PAYLOAD	1500 POUNDS
MISSION RADIUS	100 NAUTICAL MILES
HOVER	5 MINUTES
LOITER TIME	30 MINUTES
FUEL RESERVE	10 PER CENT
RESULTING PERFORMANCE	
MAXIMUM SPEED	175 - 375 KNOTS
ENDURANCE	1.7 - 2.2 HOURS

Fig. 3 Mission requirements.

	WEIGHT LBS	WING AREA SQ FT	MAXIMUM HP	MAXIMUM SPEED KNOTS	ROTOR RADIUS FEET	DISC LOADING LBS/SQ FT
HELICOPTER	11,900	-	1500	175	28	4.8
WINGED HELICOPTER	12,500	100	1500	180	28	5.1
TILT PROPELLER	17,320	235	7500	375	-	38.2
TILT WING	16,300	255	7500	360	-	43.3
STOL	16,300	255	5100	275	-	-

Fig. 4 Aircraft data.

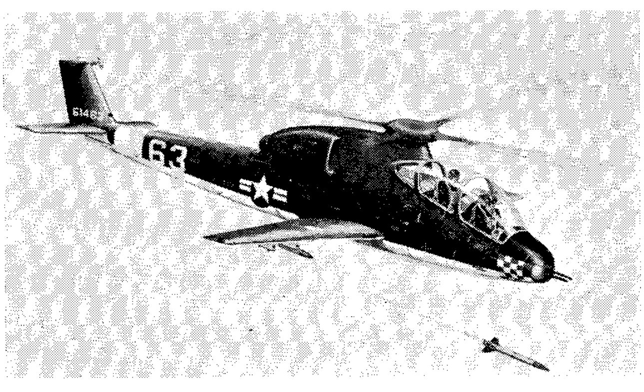

Fig. 5 Winged helicopter.

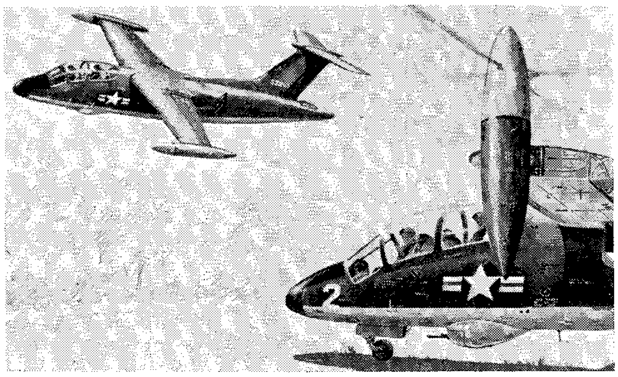

Fig. 6 Tilt-propeller V/STOL aircraft.

is accomplished for this design by automatically programing extension of the double-slotted flaps at low speeds.

Technical Approach

The agility performance data presented in this paper were calculated from total force simulations of the V/STOL aircraft designs considered, using the hybrid analog-digital computer and flight simulator shown in Figs. 8 and 9.

For the helicopter and winged helicopter, a generalized rotor-performance program was developed which computed rotor performance in real time. In this program, no limitations are imposed by the magnitude of advance ratio, inflow angle, or Mach number. Airfoil section data measured as a function of angle of attack and Mach number were taken from wind-tunnel tests of CH-37 rotor blades and stored in the PDP-1 Digital Computer component of the hybrid computer system. Differential equations of flapping motion and rotor rotation were programed and integrated in the Berkeley Ease 2133 Analog Computer Component of the computer system. Equations of motion of the aircraft in six degrees of freedom were programed in the computer system, so that the differential equations were integrated in the analog computer and algebraic and function generation operations were performed in the digital computer. By using such a computing system, computing accuracy was better than was possible in pure analog computation and faster than was possible in pure digital computation.

The maneuvers desired were commanded to the simulation by means of high-gain autopilots used in an implicit synthesis approach. This method uses circuits external to the aircraft dynamics which apply controls to the aircraft as they are required. The computed results can be the control requirements for the flight paths or any other performance parameters monitored or unmonitored by the autopilots. For example, in the determination of deceleration performance, at an initial condition of $V_{\max}$ level flight trim, normal load factor

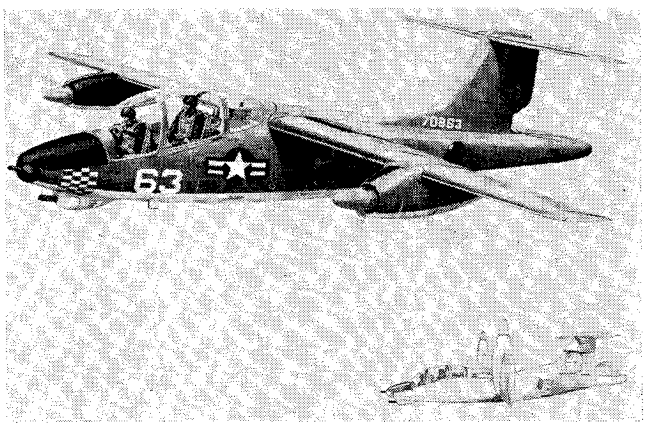

Fig. 7 Tilt-wing V/STOL aircraft.

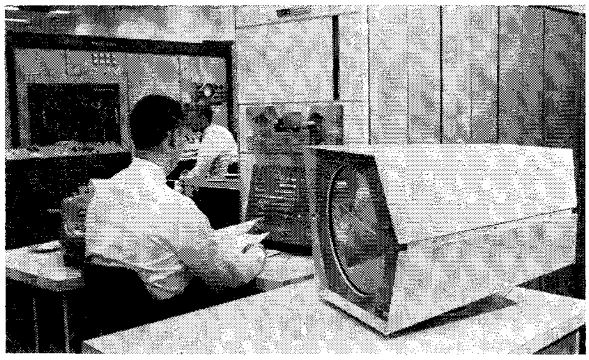

Fig. 8 UAC hybrid computer system.

was commanded to a value of 1.0 and shaft torque was set to zero. The autopilots drive cyclic, collective, and tail rotor pitch angles to values causing maximum decelerating force without exceeding rotor blade limit angles-of-attack of 16° anywhere on the retreating blade, a wing angle-of-attack of 15° above 50 knots airspeed, and a rotor speed of not more than 110% nor less than 90% normal. Below 50 knots, shaft power was made available as required to satisfy the load-factor requirement.

Control of the program was maintained through the digital computer. The simulator was used to check general flying qualities of the designs only. The actual desired maneuvers were not flown in the simulator by human pilots; such study is planned in the future. It is believed that introducing the performance of human pilots in the study instead of high-gain autopilots will reduce the agility performance of the aircraft to some extent.

Agility performance for the tilt-wing, tilt-prop, and STOL aircraft was obtained in a similar manner. However, Hamilton-Standard propeller theory was substituted for the generalized rotor performance method. The computer also simulated automatic extension of the flaps for the tilt-wing design.

Discussion

Horizontal Acceleration Performance

Horizontal acceleration performance for each configuration design, shown by plots of airspeed vs time, is presented in Fig. 10. The tilt wing has the highest acceleration performance at all airspeeds, because it has an over-all good lift-drag ratio, and high-power installation. The tilt propeller, though similar in performance above transition speed, 80 knots, has poor lift-drag characteristics below 80 knots, where propeller slipstream effects produce down-load conditions on the wing. These differences in the wing loading conditions existing between the tilt wing and tilt propeller are further emphasized in Fig. 11, where nacelle tilt angles, wing angles of attack, and power required are shown for static trim conditions.

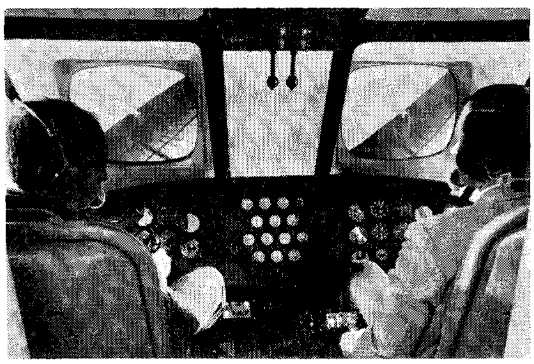

Fig. 9 Sikorsky aircraft flight simulator.

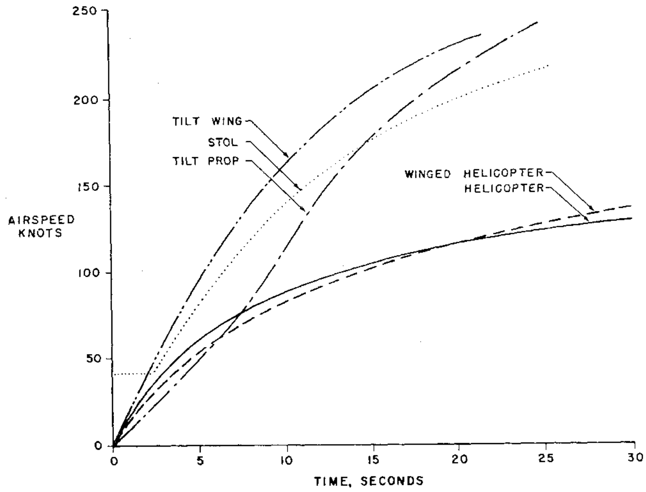

Fig. 10 Level flight acceleration performance.

In Fig. 10, the helicopter exhibits somewhat superior acceleration to the winged helicopter below 100 knots, primarily because unfavorable wing angle of attack due to rotor downwash in the compound reduces its lift-drag ratio to below that of the helicopter. However, above 100 knots, the winged helicopter begins to show better performance with increased rotor unloading by the wing. When compared to the tilt-wing and tilt-propeller configurations, the rotary wing configurations are inferior above 100 knots. This is caused by high rotor drag and lower power installed in the latter configurations.

Figure 10 shows that the STOL aircraft has no operational capability below 40 knots, as this is the minimum speed at which it is airborne. Acceleration performance is similar to but less than that of the tilt wing, primarily because less power is installed. However, its performance is greater than that of the tilt prop below 80 knots because of the wing down-load on the tilt prop.

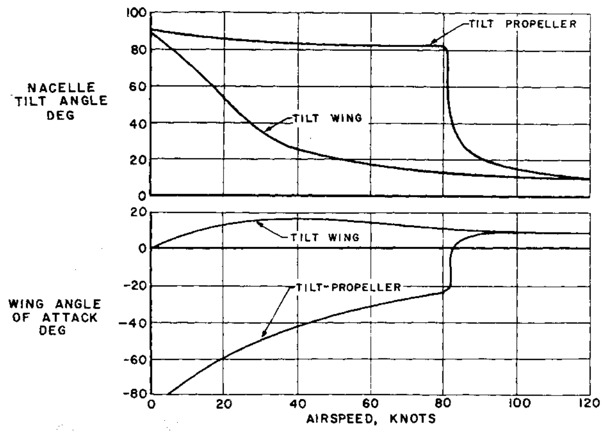

Fig. 11a Tilt-propeller and tilt-wing level attitude performance.

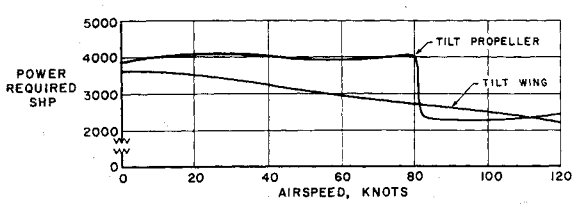

Fig. 11b Tilt-propeller and tilt-wing level attitude power required.

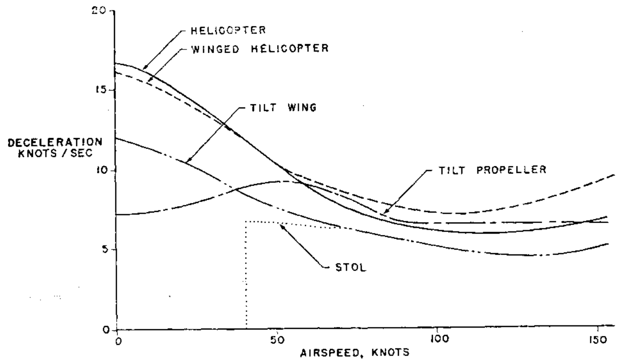

Fig. 12 Level flight deceleration performance.

Horizontal Deceleration Performance

Deceleration performance in level flight is shown in Fig. 12. With the tilt-wing configuration, high wing-nacelle tilt angles are required to decelerate under conditions of little or no propeller slipstream velocity. Thus, the limitation that the wing not be stalled results in poorer deceleration for this configuration than for the other designs. The tilt propeller with its fixed wing incurs favorable wing angles of attack in this mode and possesses better over-all deceleration performance.

Below 150 knots, the helicopter and winged helicopter are capable of better decelerating performance than the other designs. The rotors of these configurations operated in the autorotative flare mode serve as excellent brakes without easily incurring stall conditions.

Since decelerating performance is independent of power installed—that is, the engines are idling—at other than very low airspeeds, the tilt-wing and the STOL designs have almost identical decelerating performance. The STOL must be trimmed out at nose-up attitudes corresponding to maximum permissible wing angle of attack to accomplish this performance, requiring direct control in the low-speed flight regime.

Aerodynamic brakes were not investigated for the propeller-driven designs, but they would be effective only in the high-speed range, whereas the turning and attack maneuvers presented in this paper are considered primarily in the low-speed range.

Normal Load Factor

Figure 13 is a plot of the sustained normal load factor capability of the designs in steady level flight. This is, therefore, dependent on power available. Shown also is the maximum short-duration load-factor capability of the helicopter and winged helicopter. Since the helicopter has

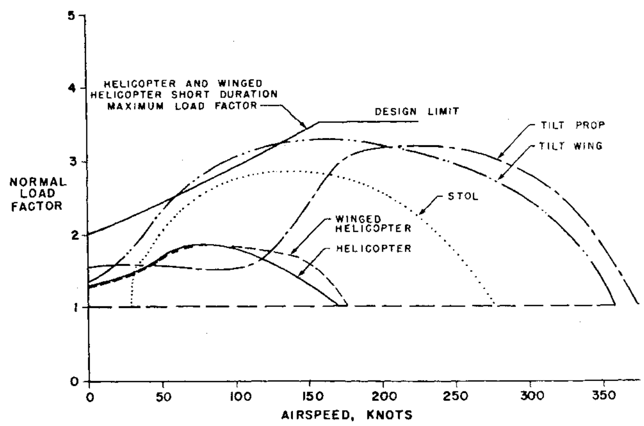

Fig. 13 Maximum normal load factor: steady flight.

considerable stored energy in its rotor system, its maximum short-duration load-factor capability is much greater than its sustained normal load-factor capability. Therefore, for maneuvers requiring a few seconds to perform, such as small angle turns, the maximum short-duration load-factor capability can be used. This is not true of the propeller-driven VTOL that have little stored energy capability. The favorable wing angle-of-attack of the tilt-wing design is demonstrated by increased load-factor capability over the tilt-propeller design at low speed. The effect of the wing on improving the load-factor capability of the winged helicopter over the helicopter is evident above 100 knots when long duration normal load-factor capability is of interest.

Turning Performance

As previously seen in Fig. 2, turning performance is dependent on normal load factor and airspeed for any aircraft.

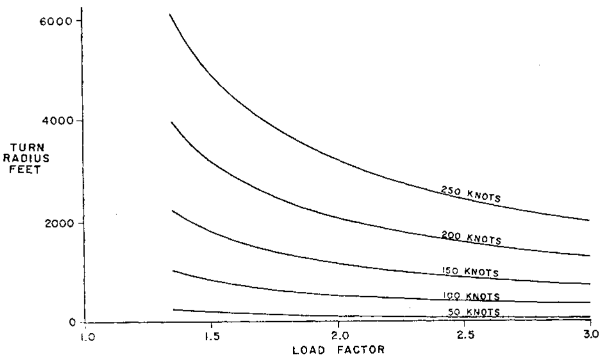

Fig. 14 Turning performance: turn radius.

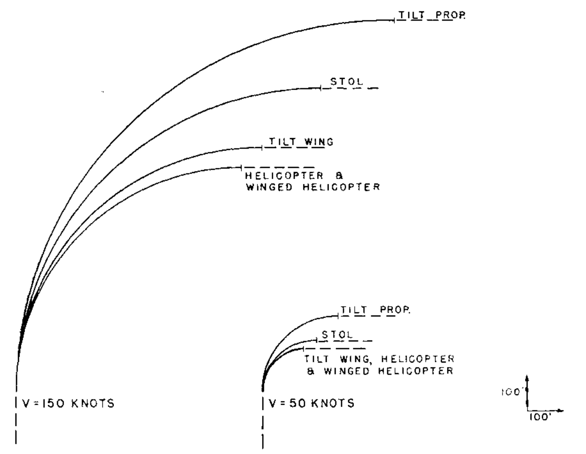

Fig. 15 Ninety degree turns: 50 knots and 150 knots.

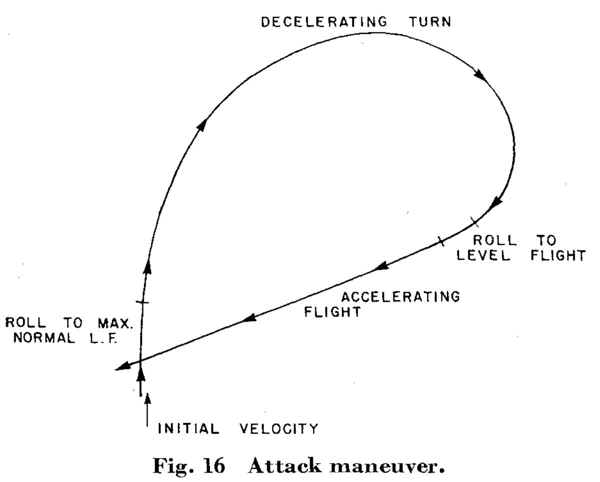

Fig. 16 Attack maneuver.

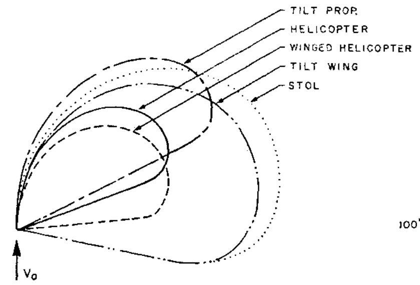

Fig. 17 Attack maneuver: 100 knots initial airspeed.

Figure 14 shows the effect of load factor and airspeed on turn radius. It is evident that low-speed flight is very desirable for turns in a confined space, since turn radius increases as the square of the airspeed. To illustrate this, Fig. 15 presents constant speed turn capability of the five V/STOL and STOL designs at 50 and 150 knots for a 90° turn. The superior short-duration load-factor capability of the helicopter designs is evident. However, as the turn angle and corresponding time required to complete the turn increases, the long-term load-factor curves shown on Fig. 13 become applicable. This results in a rapid improvement in turning performance for the propeller-driven V/STOL aircraft.

At 50 knots, normal load-factor capability has little effect on turning performance of the aircraft. The STOL is considered marginal for sustained flight at 50 knots because of lack of altitude control and proximity to stall.

Attack Maneuver

Figure 16 illustrates a maneuver that would return an aircraft over a given point in the shortest possible time. Since it would typically be used in a tactical support mission to attack a target of opportunity, the maneuver is termed an attack maneuver. It consists of a decelerating turn, followed by a straight-line horizontal acceleration. If the acceleration portion were replaced by decelerating descent to hover, this maneuver would represent a landing approach in a confined space.

The flight paths followed by the various V/STOL and STOL designs are shown in Fig. 17 for an initial airspeed of 100 knots and, to the same scale, in Fig. 18 for an initial airspeed of 150 knots. At either speed, the helicopter and winged helicopter are seen to require less space than the other configurations, due to their higher deceleration capability. The better performance of the tilt prop at 100 knots, compared to the tilt-wing design, is also due to higher decelerating capability.

The time required to accomplish the attack maneuver is plotted in Fig. 19. This figure clearly illustrates the im-

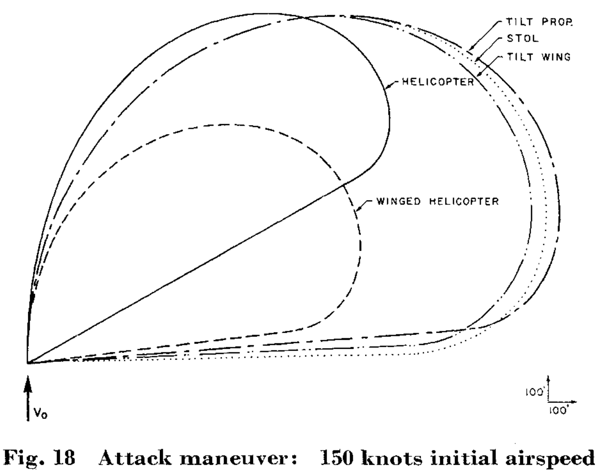

Fig. 18 Attack maneuver: 150 knots initial airspeed.

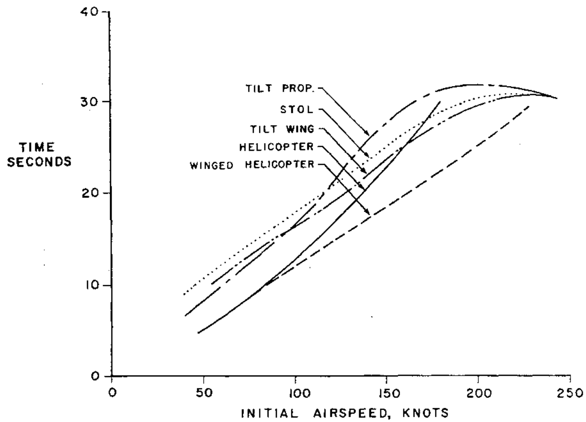

Fig. 19 Time required for attack maneuver.

portance of decelerating capability for this maneuver. Except for the helicopter near its maximum speed, where it has only marginal long-duration load-factor capability, required by this particular maneuver, the configurations with the best decelerating capability require the least time to accomplish the attack maneuver.

Conclusions

The following conclusions are presented as a result of this study.

The design and selection process of V/STOL aircraft for any mission should include consideration of agility performance, measured as the ability to execute maneuvers required for the mission.

Of the designs compared, the tilt wing possesses the best horizontal acceleration characteristics because of high installed power, whereas the tilt propeller possesses the poorest acceleration performance below 100 knots, due to the adverse effect of the propeller slipstream.

The helicopter and winged helicopter are superior in deceleration below 150 knots, where the rotor acts as an efficient brake; however, aerodynamic brakes were not investigated on the propeller-driven designs. The tilt-propeller design achieves good decelerating performance below 150 knots by upward tilt of the nacelles, whereas, in this speed range, the tilt-wing configuration cannot rapidly decelerate without incurring wing stall.

Normal load-factor capability of the tilt propeller is severely limited below 150 knots by the unfavorable airflow over the wing when the nacelle is tilted upward. The helicopter configurations have high short-duration load-factor capability due to rotor stored energy.

One measure of agility for the mission considered is performance of a decelerating turn maneuver and subsequent acceleration. For this maneuver, decelerating capability is generally more important than normal factor or accelerating capability. Thus, the helicopter and winged helicopter perform best, up to their maximum speeds, whereas the tilt-propeller design performs better than the tilt wing below 100 knots and poorer above 100 knots.

If the top speed limitation of the winged helicopter does not prevent it from performing the mission, it has the best over-all agility performance of the configurations studied. This is particularly significant when the propeller-driven designs require 140% the weight and 500% of the installed power of the compound for the mission considered. No over-all conclusions applicable throughout the speed range can be reached in comparing the propeller-driven V/STOL designs. Where vertical takeoff and flight below 50 knots are not required for the mission, the STOL design has agility performance similar to but slightly poorer than that of the tilt wing.

When performed by actual pilots, the attack and other maneuvers will probably require somewhat more time and space than shown in this paper, due to the pilot's inability to establish continually optimum controls.

Although the conclusions presented in this paper apply directly only to the designs prepared for the tactical support mission, it is believed that the comparisons may be extended to different designs of the same configurations for other missions.