Investigation of the Use of Vectored Thrust during Carrier Landings

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Analytical and piloted-flight-simulator studies were conducted to investigate the use of vectored thrust for improving controllability during carrier landings. For study purposes, an aircraft having the aerodynamic and control characteristics of the Vought F-8A Crusader with a hypothetical vectored-thrust turbofan engine was assumed; thrust-vector angles ranging from 1.0° to 76.5° were investigated. The results show that vectored thrust offers substantial reductions in approach airspeed and sink rate, improvements in flight path control, and improvements in wave-off performance. It was found that the most satisfactory configurations, considering over-all performance of the landing task, will have thrust-vector angles in the neighborhood of 45° to 50° and will utilize approach power compensators, i.e., automatic throttles. On the basis of these studies, it appears that vectored-thrust turbofan engines that are being developed for VTOL applications may be advantageously used also in non-VTOL carrier-based aircraft to provide improved landing characteristics.

Nomenclature

a_h = longitudinal acceleration at end of catapult, ft/sec^2
$C_{L\max}$ = maximum lift coefficient
d_T = distance from center of gravity to resultant thrust line (see Fig. 1b), ft
g = gravitational constant, 32.2 ft/sec^2
h = altitude, ft
h_D = height of datum bar above deck (see Fig. 3b), ft
h_ϵ = aircraft altitude error from nominal approach flight path (see Fig. 3b), ft
I_y = moment of inertia in pitch, slug-ft^2
K_N, K_α, K_γ = approach power compensator gains, Eq. (1)
m = mass of aircraft, slugs
M = pitching moment (positive nose-up), ft-lb
n_z = acceleration normal to aircraft centerline, g's
PR = Cooper pilot rating[5,6]
R = distance from aircraft to mirror (see Fig. 3b), ft
s = Laplace transform operator, per sec
T = total thrust, lb
$T_{\max}$ = military thrust rating (standard day), lb
T_0 = nominal approach thrust, lb
V_A = nominal approach airspeed, knots
V_S = stall speed in level flight, knots
V_W = mean head wind, knots
V_{WOD} = wind-over-deck (mean head wind plus carrier speed), knots
W = landing weight of aircraft, lb
x_m = distance between light source and mirror (see Fig. 3b), ft
x, z = longitudinal and normal aircraft body axes, ft
X_M = distance traveled relative to carrier from point of applying military thrust to point of minimum altitude, ft
X_R = distance traveled relative to carrier following change in throttle setting, ft
α = angle of attack, deg
α_ϵ = angle-of-attack error from nominal approach angle of attack, deg
γ_g = nominal approach flight path angle with respect to the horizontal, deg
δ_e = elevator deflection angle, deg
δ_0 = angle between resultant thrust vector and centerline of fuselage (see Fig. 1b), deg
Δh = altitude change following change in throttle setting, ft
$\Delta h_{\max}$ = maximum altitude loss following advance of throttle to military thrust, ft
ΔT = change in thrust from nominal approach thrust, lb
ΔV_A = change in air speed from nominal approach air speed, knots
ϵ = angular error between the reflected light and the datum bar as viewed by the pilot (see Fig. 3b), rad
θ = pitch attitude perturbation from nominal approach attitude, rad
$\sigma_{\dot h}$ = standard deviation of sink rate at ramp, fps
σ_{V_A} = standard deviation of air speed at ramp, knots
τ_e = engine thrust response time constant, sec
τ_N, τ_α = approach power compensator time constants, Eq. (1), sec

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Introduction

ONE of the most important considerations in the design of a new high-performance carrier-based aircraft is its controllability during carrier landings. New aerodynamic and mechanical methods are being sought continually which would provide lower approach air speeds, improved flight path control during the approach, and improved wave-off performance. The most familiar of these methods are high-lift leading-edge and trailing-edge flaps, boundary-layer control by suction or blowing, and variable-sweep wings. Another promising method that has been evaluated in flight tests is the direct-lift-control (DLC) concept,[1] in which fast-acting wing flaps are used for flight path control.

At the present time, consideration is being given to the development of lift-cruise turbofan engines for VTOL aircraft. These engines will have thrust-deflecting devices that will permit the direction of the thrust vector to be rotated from along the centerline of the engine, as in conventional engines, to angles as large as 90° with respect to the centerline. With such engines to be available, the possibility of using vectored thrust to improve the controllability of non-VTOL carrier-based aircraft during landings should be considered. Figure 1a illustrates this concept. The engine would be sized on the basis of the catapult-launch requirement or the most severe mission requirement, as is presently done; thus, the maximum thrust available without after-burning would be between 45 and 65% of the landing weight of the aircraft and would consequently be much less than the thrust that would be required for VTOL operation. However, since the thrust vector could be rotated as shown in Fig. 1a, part of the weight of the aircraft could be supported by engine thrust, thereby reducing the lift required from the wing and allowing a decrease in approach airspeed. Furthermore, because a component of thrust would be normal to the flight path, the throttle would be an effective means for controlling vertical acceleration and hence sink rate, and a large vertical force would be available when the throttle is advanced to military thrust setting for a wave-off.

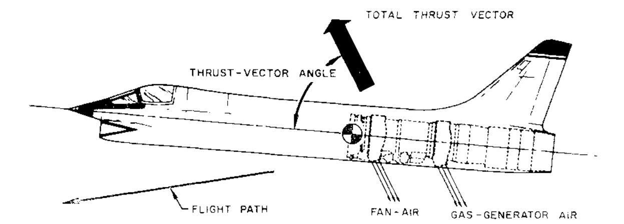
Before detailed designs can be considered, it is necessary to obtain preliminary information on the carrier landing characteristics of vectored-thrust aircraft and to demonstrate the feasibility of the concept with the pilot in the control loop. In the studies discussed in this paper, it was desired to determine the approximate range of thrust-vector angles which would result in best over-all performance considering approach conditions, flight path control, and wave-off performance. Information also was sought on the effects of pitching moment due to thrust-line offset and thrust available for flight path control on performance of the landing task. Finally, it was desired to determine whether an approach power compensator (i.e., automatic throttle) of the type currently used in some Navy aircraft could be used in combination with vectored thrust.

Discussion of Aircraft, Simulation, and Test Procedures

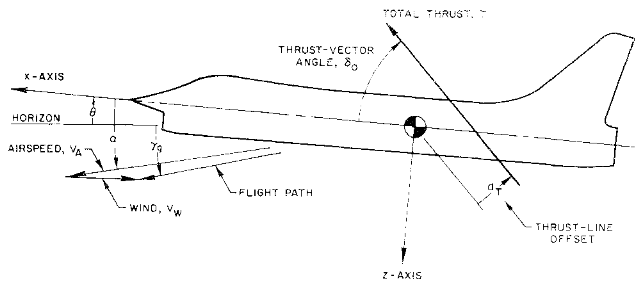
Description of Aircraft Simulated

For study purposes, an aircraft having the aerodynamic and control characteristics of the Vought F-8A Crusader with a hypothetical vectored-thrust turbofan engine was assumed. The F-8A is one of several currently operational aircraft having landing characteristics similar to those expected for future high-performance carrier-based aircraft. In addition, it is an aircraft for which ample aerodynamic data for the landing configuration are available.[2]

Equilibrium approach airspeeds were calculated for several thrust-vector angles, and the corresponding total-force stability derivatives were derived. The principal physical characteristics of the aircraft in the landing configuration were a landing weight of 20,000 lb, a pitch moment of inertia of 89,000 slug-ft^2, and a wing area of 375 ft^2. The principal aerodynamic characteristics of the aircraft were a nominal approach lift coefficient of 0.778, a nominal approach lift-to-drag ratio of 5.32, and a maximum lift coefficient of 1.17. The nominal approach angle of attack was 5.03° for all thrust-vector angles. This value was determined by calculation to be the angle of attack required to trim the aircraft on a mirror-landing-aid glide slope of 4° at the Fleet-average approach airspeed[2] of 141 knots, assuming a mean head wind of 15 knots and a carrier speed of 20 knots. At this angle of attack, the approach airspeed for the basic aircraft without thrust vectoring was 128% of stall airspeed. A summary of nominal approach conditions for all thrust-vector angles investigated is presented in Table 1.



a) Vought F-8A Crusader with hypothetical vectored-thrust engine



b) Schematic of aircraft showing nomenclature

Fig. 1 Characteristics of simulated aircraft.

The hypothetical engine was assumed to have a standard-day military thrust rating of 13,000 lb, so that at the aircraft landing weight of 20,000 lb the maximum available thrust-to-weight ratio was 0.65. The thrust magnitude T and thrust vector angle δ_0 were assumed to represent the vector sum of the deflected engine thrust and the inlet ram drag. Moreover, the military thrust was assumed to be independent of thrust-vector angle. The engine thrust response to throttle changes was approximated by a first-order time lag. The assumed variation of engine thrust response time constant τ_e with percent maximum thrust was representative of current two-spool turbofan engines; the values that were used at each of the nominal approach conditions are included in Table 1.

The simulated approach power compensator was of the angle-of-attack-sensing type and had dynamic characteristics similar to those units in operational use on F-8A aircraft.[3] The engine thrust change response to the sensed angle-of-attack error α_ϵ and normal acceleration n_z was described by the transfer function

$$\Delta T = \left(\frac{1}{1 + \tau_e s}\right)\left[\left(\frac{K_\alpha}{1 + \tau_\alpha s} + \frac{K_\gamma}{s}\right)\alpha_\epsilon + \frac{K_N}{1 + \tau_N s}\, n_z\right] \qquad (1)$$

The values of the gains K_α, K_γ, and K_N and the time constants τ_α and τ_N which were used for the basic aircraft without thrust vectoring were as follows: K_α = 1670 lb/deg, K_γ = 190 lb/(deg-sec), K_N = 19,400 lb/g, τ_α = 0.75 sec, and τ_N = 1.0 sec. As mentioned later, these gains were reduced subsequently by a factor of 4 to provide satisfactory operation in combination with vectored thrust.

Table 1 Summary of nominal approach conditions

Thrust-vector angle δ_0, deg	Aircraft weight W, lb	Approach speed V_A, knots	Sink rate $\dot{h}$, fps	Flight path angle γ_g, deg	Trim thrust-to-weight T_0/W	Engine time constant τ_e, sec
1.0	20,000	141.0	−12.32	3.36	0.138	0.901
27.9	20,000	136.2	−11.93	3.34	0.149	0.892
50.0	20,000	130.3	−11.23	3.31	0.195	0.855
69.1	20,000	118.4	−9.83	3.23	0.318	0.759
76.5	20,000	106.6	−8.44	3.13	0.442	0.662
50.0	23,412	141.0	−12.32	3.36	0.193	0.856

Fig. 2 United Aircraft flight simulator with contact analog display.

Description of Carrier Approach Simulation

The experimental program was conducted in the United Aircraft flight simulator (Fig. 2). This facility consists of a full-scale, fixed-base Sikorsky S-61 helicopter cockpit, a Norden contact analog display system, and a variety of flight controls and flight instruments. Flight controls used in the present three-degree-of-freedom simulation included the longitudinal (elevator) control stick and the throttle; yaw, roll, and sideslip degrees of freedom were not simulated. The longitudinal control stick had no control force gradient, although a small amount of inherent friction was present. The pilot could adjust the friction force on the throttle. Flight instruments used in the simulation included an airspeed indicator, an altimeter, a throttle setting indicator, and a rate-of-climb indicator having a first-order lag time constant of 2.0 sec.

Figure 3a shows the contact analog display that was used for the simulation. The pathway element was used to simulate the deck of the carrier; its size and position with respect to the horizon were programed as a function of the instantaneous distance from the aircraft to the ramp (the aft end of the deck) and the altitude of the aircraft. Figure 3b shows the geometry of the mirror-landing-aid system.[4] The cross and square elements in the contact analog display were used to simulate the mirror-landing-aid system, with the cross representing the reflected light (the "meatball") and the square representing the datum bar. The cross vanished when the aircraft deviated outside of a $\pm 0.75°$ angle about the nominal flight path (Fig. 3b) to simulate "loss of the meatball," which occurs in the actual-landing-aid system.

The equations of motion governing the pitch, longitudinal, and vertical degrees of freedom were linearized and described perturbed motion about the nominal trimmed approach flight condition at each thrust-vector angle. The equations were similar in form to those used by other investigators,[4] except for the terms that were added to account for the force and pitching-moment perturbations due to thrust changes and to introduce the effects of the vertical component of turbulence. This simulated turbulence was generated by passing the output of a random-noise generator through a first-order filter having a breakpoint frequency of 0.40 rad/sec. The root-mean-square value of simulated turbulence was 1.55 fps.

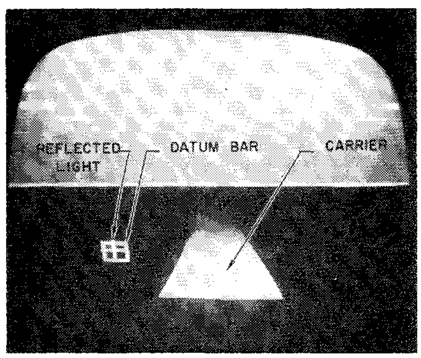
Description of Test Procedures

The approaches were initiated with the aircraft on the nominal 4° glide slope at a range of 5000 ft from the ramp. The aircraft was initially in equilibrium flight except for the instantaneous effects of turbulence. At the ramp, altitude error from the nominal flight path, sink rate, and approach speed were recorded to provide a quantitative measure of performance for the landing task. The data represent mean values of these quantities for 40 approaches (20 by each of two pilots). During the preliminary practice period and while performing the 20 approaches for a given configuration, each pilot qualitatively assessed handling qualities and independently assigned a Cooper pilot rating[5,6] to the configuration. The principal factors considered in assigning the pilot rating were 1) ability to perform consistent and accurate approaches, 2) amount of control effort required, 3) amount of concentration and anticipation required, and 4) level of confidence in performing approaches.

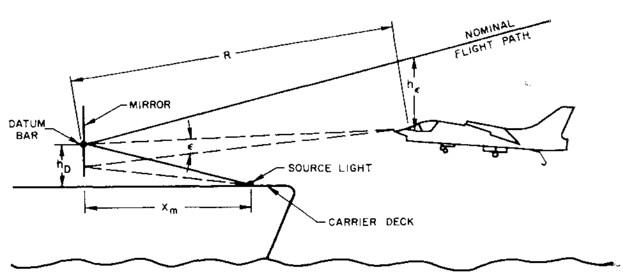
The criterion used for determining successful approaches was based on a set of boundaries on plots of sink rate vs altitude error from the nominal flight path, where both quantities are the measured values at the ramp. The boundaries define the limits of combinations of sink rate and altitude error at the ramp which will result in the arresting hook engaging a cable, assuming that the aircraft continues in equilibrium flight from the ramp to touchdown. Because of the assumption of equilibrium flight, this method provides at best a relatively crude indication of successful landings. Therefore, the curves of percent wave-offs plus unsuccessful approaches which are presented should be used only to indicate the trend of this parameter and should not be expected to correlate on an absolute scale with Fleet experience.

Discussion of Results

For clarity of presentation, the discussion of results has been separated into three major subject areas: 1) results pertaining to approach conditions (nominal approach air



a) Contact analog showing display for aircraft in high approach



b) Schematic of mirror-landing-aid system

Fig. 3 Display for carrier approach simulation.

speed and sink rate, etc.); 2) results pertaining to flight path control; and 3) results pertaining to wave-off performance. Selection of a thrust-vector angle that would offer the best over-all performance for the landing task must be based on a compromise in which all three of these subject areas are considered.

Results Pertaining to Approach Conditions

Approach airspeed and sink rate

The upper portion of Fig. 4 shows the predicted and measured variations of approach airspeed at the ramp with thrust-vector angle. Note that the static trim (i.e., equilibrium of aerodynamic, thrust, and gravity forces) calculations predicted reductions in both approach speed and stall speed, so that a stall-speed margin of approximately 20 knots was maintained to thrust-vector angles as large as 76.5°. The measured flight simulator data points (means based on 40 approaches at each thrust-vector angle) are quite close to the predicted curve and indicate that the predicted reductions in airspeed can be achieved with the pilot in the control loop. A reduction in approach speed of 11 knots was obtained at an angle of 50.0°, and a reduction of 34 knots was obtained at an angle of 76.5°. The predicted and measured reductions in sink rate at the ramp with increasing thrust-vector angle are shown in the lower portion of Fig. 4. The results show that the predicted reductions in sink rate can be achieved in piloted approaches.

Thrust and elevator angle required to trim

As thrust-vector angle is increased and wing lift is reduced, increasing amounts of thrust are required to support the weight of the aircraft. The upper portion of Fig. 5 shows the variation with thrust-vector angle of thrust-to-weight ratio required for trimmed equilibrium flight on the nominal approach flight path. Thrust-to-weight ratio required increases sharply for thrust-vector angles greater than about 50° to 60°, with the result that the thrust margin available for wave-off diminishes rapidly. As discussed later, provision of adequate thrust margin for flight path control and wave-off is an important consideration in determining the maximum usable thrust-vector angle.

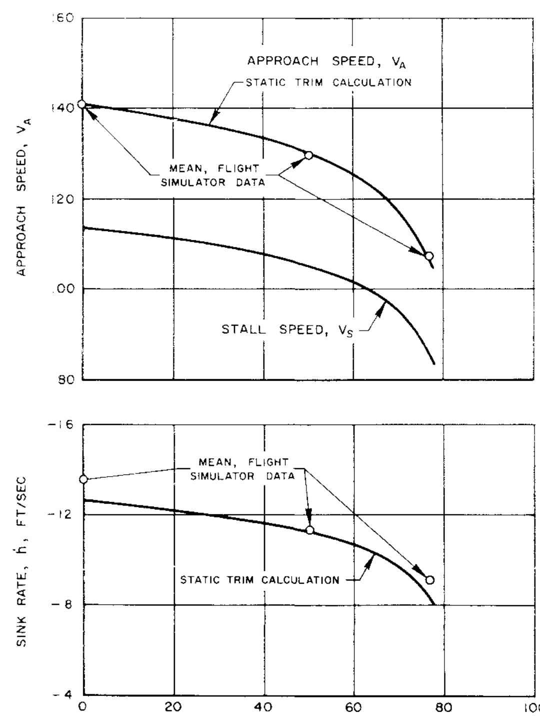


Fig. 4 Effect of thrust-vector angle on mean approach conditions at ramp.

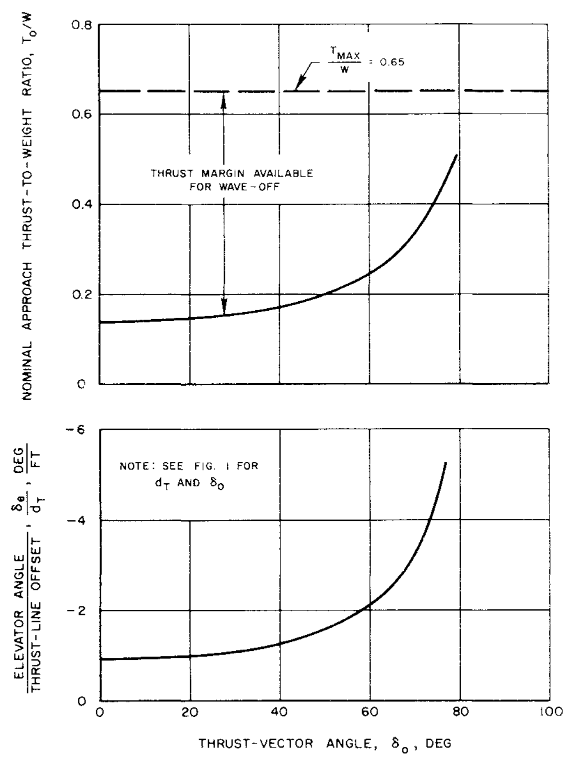


Fig. 5 Effect of thrust-vector angle on approach thrust and elevator angle.

A second limitation arises when the total thrust vector is displaced from the center of gravity by an offset distance d_T (Fig. 1b). Pitching moments will be produced by both the thrust required to trim the aircraft on the approach and by changes in thrust introduced by the pilot for flight path control purposes. The lower portion of Fig. 5 shows the variation with thrust-vector angle of elevator angle required to trim divided by thrust-line offset distance, δ_e/d_T. This elevator trim parameter increases only slightly up to thrust-vector angles of 50° to 60°, but then increases rapidly because of the combined effects of increased thrust for trim (upper portion of Fig. 5) and decreased elevator effectiveness because of reduced airspeed (upper portion of Fig. 4). Thus, the elevator angle required to trim is also an important consideration in determining the maximum usable thrust-vector angle in a practical engine installation.

Comparison of calculated sink rate and approach speed responses

Figure 6 shows the variations with time of the changes in sink rate and approach speed from the trimmed values following a step change in throttle setting (aircraft initially on nominal flight path and pitch attitude held constant). The curves are for thrust-vector angles of 1.0°, 50.0°, and 76.5° and include the effects of engine thrust response lags. The large differences in sink rate and approach speed responses between the basic aircraft (δ_0 = 1.0°) and the vectored-thrust configurations for a given thrust change ΔT are due to the relative magnitudes of the incremental thrust components normal to and parallel to the flight path, respectively. For example, 1.0 sec following step throttle changes, the 50° thrust-angle configuration experienced a change in sink rate 4.8 times greater and a change in approach speed 1.8 times less than the basic aircraft for the same thrust change ΔT. This much more rapid sink rate response with only small attendant changes in air speed is the primary factor that ac-

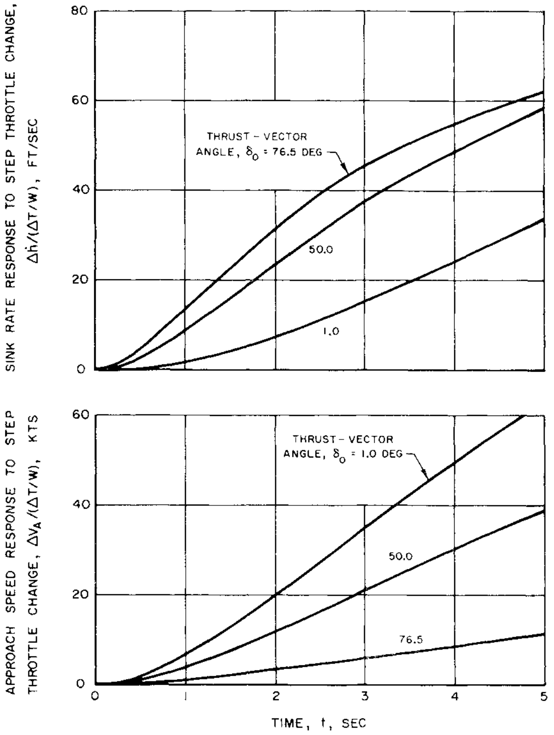


Fig. 6 Sink rate and approach speed responses for step change in throttle setting.

counts for the improved flight path control characteristics of vectored-thrust aircraft.

Comparison of flight path control techniques

Before discussing the flight simulator results, it is important to distinguish between the widely different flight path control techniques used by the pilots for the basic aircraft with manual throttle, the vectored-thrust configurations with manual throttle, and the basic aircraft and vectored-thrust configurations with approach power compensator.

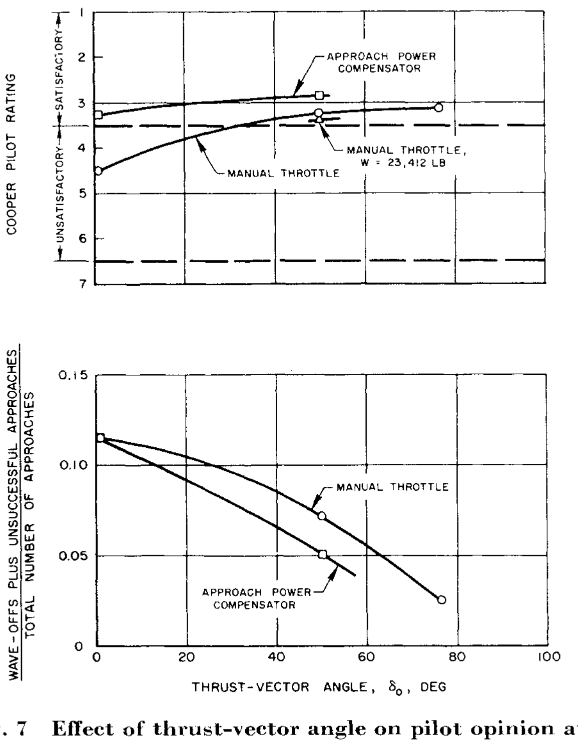


Fig. 7 Effect of thrust-vector angle on pilot opinion and performance.

Flight path control of the basic aircraft with manual throttle was achieved by coordinated throttle and small pitch attitude changes. This required the pilot to monitor the airspeed and rate-of-climb instruments closely. Because of the complex interactions of airspeed, attitude, and rate of climb and because of the slow response of these quantities to changes in control stick and throttle setting, flight path control using this technique has long been regarded as an extremely difficult closed-loop control task requiring a high degree of concentration and coordination.[7] For vectored-thrust configurations with manual throttle, the control technique was to use the throttle to control normal acceleration directly (not indirectly through airspeed) while maintaining essentially constant pitch attitude. Since throttle changes had a relatively small effect on airspeed, the airspeed indicator was read only infrequently and was not a consideration in introducing control inputs. For both the basic aircraft and the vectored-thrust configurations with an approach power compensator, the standard APC technique of controlling flight path by means of pitch attitude was used. Complete flight path control was obtained using the longitudinal control stick, since the APC controlled thrust.

Pilot opinion of handling qualities

Flight simulator experiments were conducted to investigate the effects of thrust-vector angle on the ability of the pilot to control the flight path. For this series of tests, the thrust-line offset d_T was set at zero. A summary of the effects of thrust-vector angle on Cooper pilot rating of handling qualities is shown in the upper portion of Fig. 7. The results show that the use of vectored thrust with manual throttle resulted in handling qualities that were much more satisfactory than those of the basic aircraft ($\delta_0 = 1.0°$) with manual throttle, and that handling qualities with thrust-vector angles greater than about 40° and manual throttle were essentially as satisfactory as those of the basic aircraft with an approach power compensator. Pilot comments indicated that, as a result of the reduction in approach speed with increasing thrust-vector angle, more time was available for making flight path corrections, and less anticipation was required for making flight path corrections and for initiating wave-off maneuvers on poor approaches. The reduced levels of dynamic pressure at the lower vectored-thrust approach speeds had very little effect on the oscillatory dynamics, and adequate longitudinal control effectiveness was available at all thrust-vector angles. As approach speed decreased with increasing thrust-vector angle, less attention was required for holding precise attitude, since sink rate was less sensitive to angle-of-attack errors. Although all of these factors were important, the most important benefit of vectored thrust was the improved sink rate control made possible by having a controllable component of thrust normal to the flight path. Although this improvement was quite substantial when the thrust-vector angle was increased to 50°, there was no significant additional improvement in controllability as thrust-vector angle was further increased to 76.5°.

The results presented in Fig. 7 also show that, for the two thrust-vector angles that were investigated (basic aircraft and 50.0°), handling qualities with an approach power compensator were found to be more satisfactory than with a manual throttle. This general improvement is a result of a reduction in the over-all levels of effort and concentration required, since there is only one longitudinal control loop for the pilot to close (sink rate controlled using longitudinal control stick). Operation of the angle-of-attack-sensing APC [Eq. (1)] was found to be quite compatible with vectored thrust; the only modification required was to reduce the APC gains to 25% of their values for the basic aircraft [listed after Eq. (1)] in order to reduce sink rate response sensitivity to angle-of-attack errors caused by turbulence and unintentional control inputs.

One adverse pilot comment associated with APC control at all thrust-vector angles was that sink rate and flight path corrections were somewhat limited near the ramp, since proper pitch attitude had to be maintained for engaging the cable. Although not studied in the flight simulator experiments, this problem could be resolved in vectored-thrust aircraft by providing a manual throttle override of the APC so that near the ramp the pilot could make sink rate corrections manually using the throttle while holding pitch attitude constant. It is believed that the inclusion of such a throttle override on the APC would result in Cooper pilot ratings slightly better than those shown in Fig. 7.

Experiments also were conducted for a thrust-vector angle of 50.0° and a landing weight of 23,412 lb. This combination of thrust-vector angle and increased landing weight required the same 141-knot approach speed as the basic aircraft at a landing weight of 20,000 lb. Figure 7 shows that a slightly poorer Cooper pilot rating was assigned to this configuration than to the 20,000-lb aircraft for the same 50.0° thrust-vector angle. Small decreases in longitudinal control stick and throttle sensitivities were evident for the heavier aircraft, but the primary reason for the slightly poorer rating was its higher closure rate with the carrier.

Quantitative data on flight path control

The quantitative flight simulator data also show that improved flight path control results using vectored thrust. The lower plot in Fig. 7 shows that when thrust-vector angle was increased to 50.0° a reduction of about 50% was obtained in the frequency of wave-offs plus unsuccessful approaches for control using both manual throttle and approach power compensator. The improvements in control also resulted in reductions in the standard deviation of sink rate at the ramp for both manual throttle and APC control (upper portion of Fig. 8). These reductions in standard deviation of sink rate, when combined with the lower mean sink rates and approach speeds (Fig. 4), reduce the probability of hard landings and indicate possible savings in the weight of the landing gear and arresting gear. Figure 8 (lower portion) also shows that substantial percentage reductions in the standard deviation of approach speed result with increasing thrust-vector angle, particularly with an APC.

Maximum thrust change requirements

Experiments were conducted to determine the maximum change in thrust about the nominal approach thrust setting which is required by the pilot for satisfactory control of sink rate with vectored thrust and a manual throttle. In Fig. 9a, Cooper pilot rating is plotted vs bandwidth of thrust-to-weight ratio available for flight path control. The results show that, as the bandwidth of thrust-to-weight ratio available was reduced from its maximum to ±0.10, there was no appreciable change in pilot rating. However, a bandwidth of ±0.03 was found to be insufficient for normal operation, as shown by the unsatisfactory pilot ratings. On the basis of these results, it can be concluded that a bandwidth of thrust-to-weight ratio available of more than ±0.05 but not more than ±0.10 is required for satisfactory flight path control. These results appear to be compatible with the normal acceleration requirements of aircraft using the fast-acting-flap, direct-lift-control (DLC) concept.[1, 8]

Effects of pitching moments due to thrust changes

For a thrust-vector angle of 50.0°, the effects of pitching moments due to changes in thrust for flight path control were investigated also. An important effect is the influence of pitch attitude disturbances caused by thrust changes on the ability of the pilot to control the flight path. The parameter $(M/I_y)/(\Delta T/m)$, which expresses the ratio of pitching acceleration to linear acceleration of the aircraft, was used

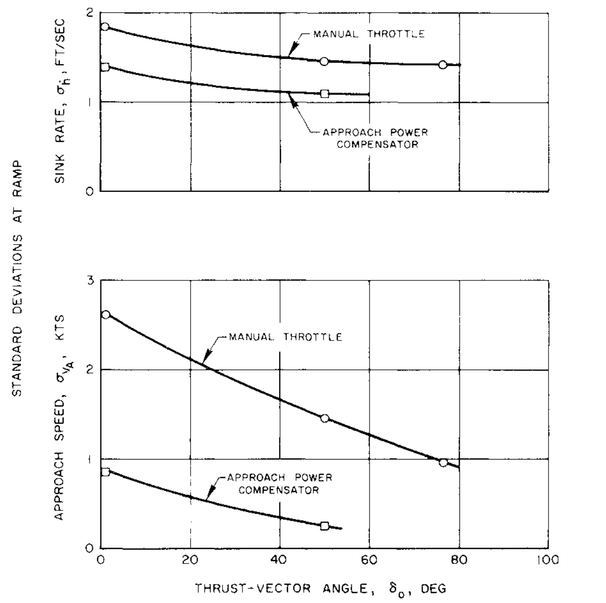


Fig. 8 Standard deviations of sink rate and approach speed at ramp.

in the flight simulator experiments. A plot of Cooper pilot rating vs pitching-moment parameter is presented in Fig. 9b. All results shown in this figure are for manual-throttle approaches.

It can be seen that satisfactory handling qualities resulted for values of this parameter within the range ±0.02. For the mass and moment of inertia of the F-8A aircraft, the corresponding thrust-line-offset distances d_T are approximately ±3 ft. At a parameter value of −0.035 (thrust-line offset of 5 ft), the attitude-throttle interaction was annoying particularly near the ramp, where precise attitude control was most needed. This interaction and the unnatural aft-stick

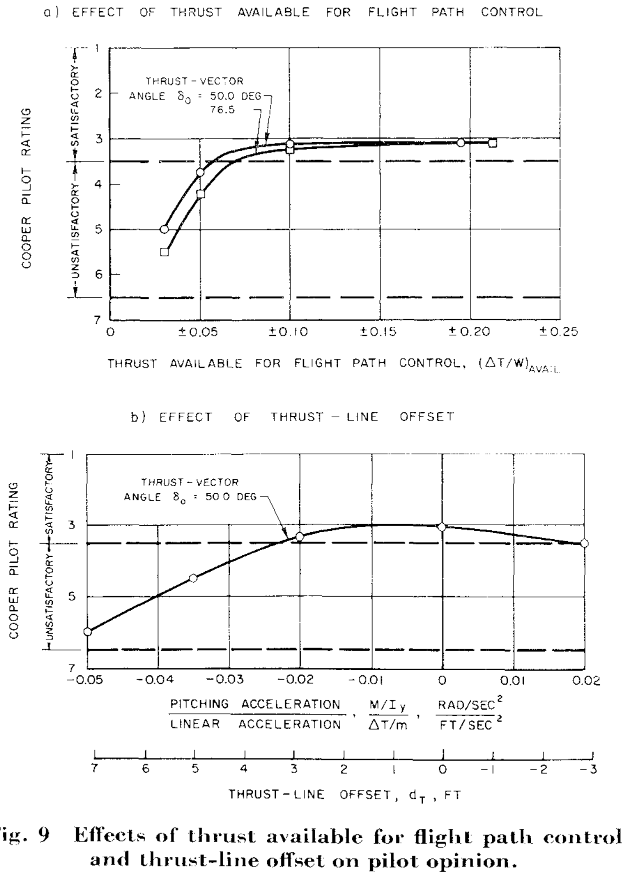


Fig. 9 Effects of thrust available for flight path control and thrust-line offset on pilot opinion.

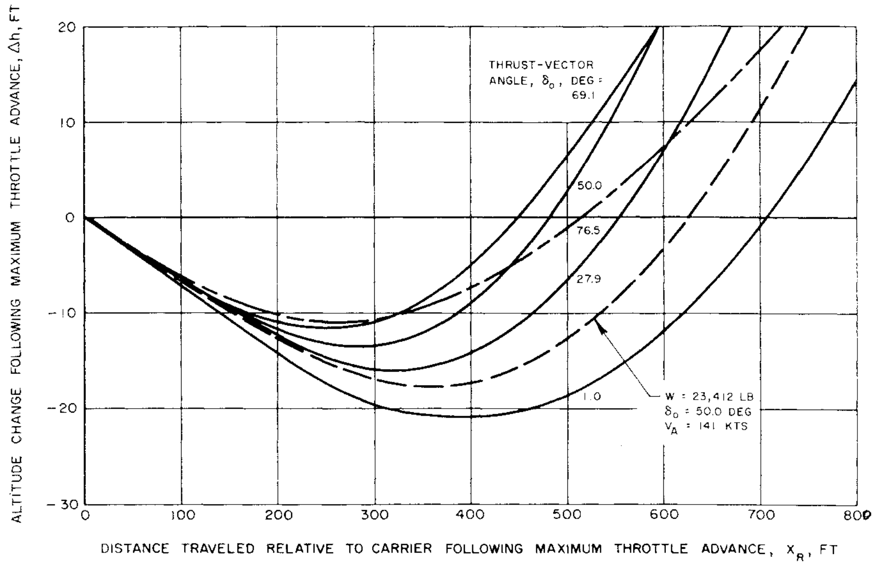


Fig. 10 Effect of thrust-vector angle on wave-off performance.

motion required with increasing throttle displacement would make this amount of pitching moment greater than the practical limit for normal operation with a manual throttle.

Although no quantitative data were recorded, it was found that, with a thrust-vector angle of 50.0° and an approach power compensator, the effects of pitching moments due to thrust changes could be tolerated with thrust-line-offset distances up to ±5 ft. These larger allowable offset distances with APC result because the pilot is able to devote more attention to controlling pitch attitude, and the thrust changes commanded by the APC are smaller and more gradual than those introduced by the pilot using manual throttle.

Results Pertaining to Wave-Off Performance

The prime objective in improving wave-off performance is to minimize the loss in altitude and the distance traveled to the point of minimum altitude. This maneuver must be performed without reducing the stall-speed margin.

Unpiloted analog-computer calculations were made to examine the effects of thrust-vector angle on the flight profiles during wave-off maneuvers. It was assumed that the aircraft was initially in a nominal approach condition (Table 1). The throttle was advanced in a step from the approach setting to the military thrust setting. An automatic controller on the computer was used to rotate the aircraft to 0.90 $C_{L_{max}}$ and to control angle of attack and airspeed during the maneuver. If airspeed decreased below the nominal approach speed, the controller reduced angle of attack to hold airspeed at or slightly above the nominal approach speed.

Flight profiles are shown in Fig. 10 on a plot of altitude change vs distance traveled relative to the carrier (i.e., with effects of wind and carrier speed included) following the change in throttle setting. The substantial improvements in wave-off performance which are shown with vectored thrust result from having a component of excess thrust normal to the flight path. The reductions in altitude loss and dis-

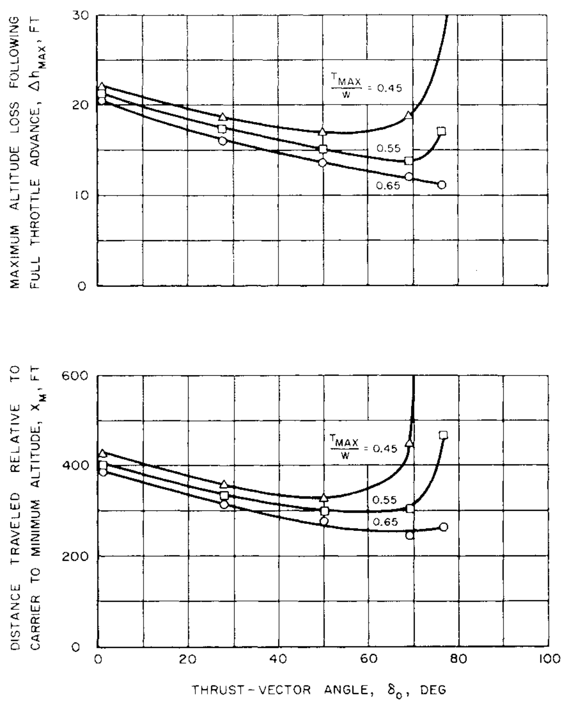


Fig. 11 Effect of maximum thrust available on wave-off performance.

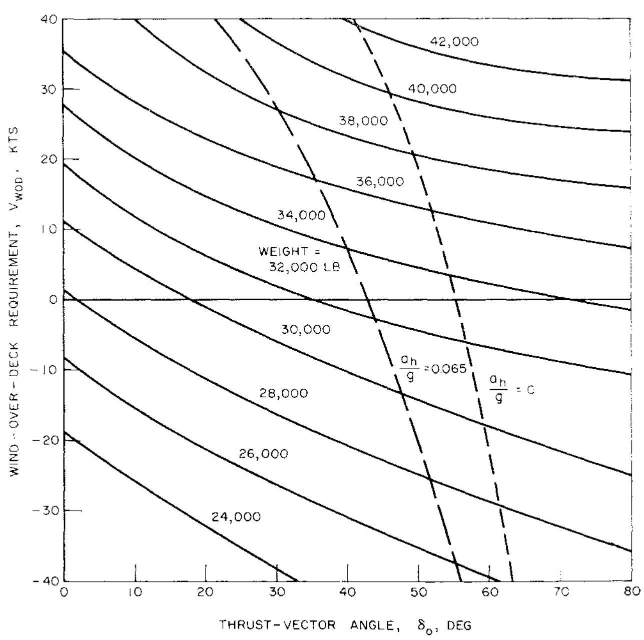


Fig. 12 Effect of thrust-vector angle on wind-over-deck requirements for catapult-launched takeoff.

tance traveled to the point of minimum altitude indicate that, with vectored thrust, successful wave-off maneuvers may be initiated much closer to the ramp than with the basic aircraft.

The results shown in Fig. 10 indicate that, at thrust-vector angles above approximately 50.0°, the performance gained by having the thrust vector more nearly normal to the flight path is offset by the rapidly diminishing excess thrust available for the wave-off maneuver (see upper portion of Fig. 5). The effect of reducing the thrust margin available for wave-off is further shown in Fig. 11 on plots of maximum altitude loss and distance traveled to minimum altitude vs thrust-vector angle for values of maximum thrust-to-weight ratio of 0.65, 0.55, and 0.45. The optimum thrust-vector angle from the standpoint of minimum loss of altitude is seen to be dependent upon the installed maximum thrust-to-weight ratio. The smaller this ratio, the smaller the optimum thrust-vector angle.

Conclusions

This investigation has provided preliminary information on the carrier landing characteristics of vectored-thrust aircraft. Piloted flight simulator studies have shown that the concept of controlling the flight path using vectored thrust is feasible. The results also show that reductions in approach airspeed and sink rate are obtained with vectored thrust, and that substantial improvements in flight path control and wave-off performance are obtained. The results indicate that moderate thrust-vector angles (in the neighborhood of 45° to 50°) appear to offer the best over-all performance considering approach conditions, flight path control, and wave-off performance. In addition to these results for the landing task, preliminary calculations (discussed in the Appendix) indicate that important improvements in catapult takeoff performance also can be obtained using vectored thrust.

Appendix: Catapult Takeoff Performance with Vectored Thrust

Catapult takeoff performance is another important factor in the design of carrier-based aircraft, since it determines the maximum takeoff weight (and therefore the payload capability) of the aircraft and the wind-over-deck requirements. Two essential conditions that must be met at the end of the catapult are 1) sufficient airspeed to sustain flight, and 2) adequate longitudinal acceleration for climb-out. Factors that most directly affect takeoff performance are the performance characteristics of the catapult (catapult end speed vs takeoff weight of the aircraft), the wind-over-deck conditions, and the amount of pitch attitude rotation which is required to attain the lift coefficient for climb-out.

Calculations were performed to examine the effects of thrust-vector angle and aircraft gross weight on wind-over-deck requirements. It was assumed that the aircraft attitude at the end of the catapult was equal to the climb-out angle of attack (corresponding to a lift coefficient of 0.85 $C_{L_{max}}$). It was required that the airspeed at the end of the catapult be equal to the minimum flight speed of the configuration (i.e., lift plus vertical component of thrust equal to weight).

Results of these calculations are shown in Fig. 12 on a plot of wind-over-deck requirement V_{WOD} vs thrust-vector angle for the F-8A for a takeoff thrust of 12,390 lb and hot-day conditions (89.6°F). The catapult performance assumed was representative of the large steam-driven catapults on modern carriers. Figure 12 shows a significant reduction in the wind-over-deck requirement with increasing thrust-vector angle at a given gross weight. It can be seen, however, that the requirement to meet the Navy's minimum longitudinal acceleration criterion (0.065 g) places a limitation on the maximum usable thrust-vector angle. For this particular aircraft-catapult combination, the thrust-vector angle at which the longitudinal acceleration is reduced to 0.065 g increases from about 30° at a weight of 38,000 lb to about 55° at a weight of 26,000 lb. This increase is due to the smaller drag forces associated with the lower airspeeds required to sustain flight at lower gross weights. The results show that, by increasing the thrust-vector angle to the 0.065-g acceleration limit, the takeoff gross weight can be increased by about 4000 lb at a given wind-over-deck, or the wind-over-deck requirement can be decreased about 20 knots at a given takeoff gross weight.

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