NASA TECHNICAL
MEMORANDUM

NASA TM X–62,086

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AERODYNAMICS OF LIFT FAN V/STOL AIRCRAFT

by Jerry V. Kirk, Leo P. Hall, and Brent K. Hodder
Ames Research Center
and
U.S. Army Air Mobility Research and Development Laboratory

September 1971

FACILITY FORM 602

N71-35204	
(ACCESSION NUMBER)	(THRU)
8	63
(PAGES)	(CODE)
TMX-62086	02
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

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Jerry V. Kirk, Leo P. Hall, and Brent K. Hodder
Ames Research Center, NASA, and U.S. Army Air Mobility Research and Development Laboratory

Abstract

Lift fans have been shown to be effective for providing direct lift for V/STOL aircraft. Recent efforts at Ames Research Center have been directed toward determining the aerodynamic characteristics of podded lift fans located fore and aft of the wing to allow higher wing loading and reduce constraints on wing design. The more important results are summarized, and the induced aerodynamic effects of various pod locations are shown. Because efficient use of the propulsion system may dictate that the fans also be used for high-speed cruise, the effectiveness of various methods for vectoring the fan flow from the cruise to the lift direction for low-speed transition is presented.

Most existing design studies in which lift fans were used for direct lift show that on the basis of installed thrust to weight and thrust to volume, a fan pressure ratio of about 1.3 is optimum while an augmentation ratio of 2.5 is maintained. For this reason an investigation was made of the aerodynamic characteristics of a 1.3 pressure ratio lift fan; the results are discussed in this paper. Noise constraints were not placed on the design and construction of the fan, but subsequent modifications were incorporated to alleviate noise. Measurements of sound are given for the modified and the original fan operating in crossflow.

Results show that podded lift-fan configurations can produce induced lift approaching the magnitude of the better fan-in-wing configurations while reducing significantly the variation of pitching moment with forward speed. Variable camber exit louvers and hooded exhaust deflectors can vector cruise fan exhaust with losses under 10%. The 1.3 pressure ratio lift fan performs well in crossflow and research is being conducted to reduce lift-fan noise.

Notation

A_f	fan area, sq ft
b	half-span of wing, ft
C	local wing chord, ft
C_L	lift coefficient, L/qS
D	fan diameter, ft
D_e	effective fan diameter $(4A_f/\pi)^{1/2}$, ft
L	lift of the model, lb
ℓ	overall cruise fan nacelle and duct length
M	pitching moment, ft-lb
PNL	perceived noise level, PNdB
PWL	sound power level, dB re 10^{-13}, W
p_o	standard atmospheric pressure, 2116 psf
p_s	free-stream static pressure, psf
q	free-stream dynamic pressure, psf
R	fan radius, ft
RPM	fan rotational speed, revolutions/min
S	wing area, sq ft
SPL	sound pressure level, dB re 0.0002 dyne/cm^2
T	fan gross thrust, lb
V_o	airspeed, knots
V_j	airspeed of the fan exhaust, knots
W	aircraft gross weight, lb
α	angle of attack, deg
β_v	angle of exit louvers from the vertical, deg
θ_v	turning angle for cruise fan vectoring, 0° in cruise direction, deg
ΔL_i	lift induced by lift-fan operation, lb
δ	relative static pressure, p_s/p_o
$(\ )_s$	static operation

Introduction

As part of a continuing study of the most promising methods for accomplishing the transition from powered lift to wing supported flight, Ames Research Center has been pursuing lift-fan research for use in short haul V/STOL transports. Previous investigations[1-4] of large-scale fan-in-wing models have shown the aerodynamic interference between the fans and airframe; transition performance; stability and control; and installation problems.

This paper presents similar aerodynamic results for fans located in pods or on the sides of the fuselage remote from the wing. Efficient use of the propulsion system may dictate, in some designs, that the fans also be used during high-speed cruise. With this in mind, the effectiveness of different methods for turning the cruise fan exhaust for transition flight will be shown for both 1.1 and 1.3 pressure ratio lift fans.

Noise standards tentatively being advanced for V/STOL aircraft will require considerable improvement in means of quieting lift fans. Research is being conducted to reduce lift-fan noise.[5,6] Some results recently obtained in crossflow in the Ames 40- by 80-Foot Wind Tunnel with a 1.3 pressure ratio fan mounted in a semispan fan-in-wing model are presented. Comparison is made between the original fan, which was designed by performance criteria with no noise constraints, and the modified fan, which incorporated noise reducing techniques.

Models and Apparatus

Three remote tip turbine driven lift-fan systems were used: the X-353-5B, the X-376B, and the LF-336. The X-376B and LF-336 lift fans have a diameter of 36 in. and design pressure ratios of 1.1 and 1.3, respectively. The X-353-5B lift fan has a rotor diameter of 62.5 in. and a design pressure ratio of 1.1. The fans were driven by either J-85 or T-58 turbojets. One T-58 propelled one X-376B fan. One J-85 propelled one X-353-5B, one LF-336, or four X-376B lift fans.

Pertinent characteristics of the podded lift fan and fuselage mounted fan models tested are shown in Fig. 1 while representative photographs of the models are shown in Fig. 2. Models 1 through 5 used the X-376B lift fans. Model 5 was the only model tested with a low wing.

Four different sets of exit louvers (Fig. 3a) were used with the X-353-5B lift fan.

Turning of the exhaust of fans mounted in cruise fan nacelles was accomplished with two devices: a cascade of variable camber louvers and hooded type deflectors (Fig. 3(b)). The louver system consisted of a cascade of 18 louvers mounted at a 45° angle behind the X-376B lift fan in a cruise nacelle. The hooded deflector used with the X-376B lift-cruise fan was a simple four-segment circular shell that allowed geometric turning angles up to 138°; it had a radius-to-diameter ratio of 0.54. A segmented, telescoping hood was used with the 1.3 pressure ratio fan. The hood had a D-shaped cross section, the flat side making the floor of the duct. An area ratio of 1.63 with a total equivalent cone angle of 19° was provided in the duct prior to turning to allow for flow diffusion to approximately 0.4 Mach number. The total hood and duct assembly was sized for a cruise nacelle with an $\ell/D = 1.75$ and a duct $R/D = 0.78$.

Noise was measured on a semispan wing model with the LF-336/A (original design) and the LF-336/C (quiet version) lift fans mounted in the wing (Fig. 4). The original fan was not designed as a quiet fan. It has 42 rotor blades, 45 stator vanes with a rotor/stator axial spacing of 0.15c. The blade passing frequency is 4230 Hz at 100% RPM. Modifications that caused the greatest noise reduction were:

1. A 90 vane stator with 30° of lean in the direction of rotation.
2. Increasing the rotor/stator spacing to two chords
3. Placing acoustic material at the hub and tip walls and adding an acoustic splitter.

All results presented in this paper were obtained in the Ames 40- by 80-Foot Wind Tunnel with the exception of the 1.3 pressure ratio fan hooded deflector results, which were obtained on an outdoor static test facility.

Results and Discussion

Large-scale lift-fan aircraft research at Ames Research Center was initially directed to fan-in-fuselage and fan-in-wing configurations. Research for the past 6 years has been devoted to podded fan configurations. This research has been conducted for at least two major reasons. Fan-in-wing designs usually require undesired contour modifications to basic airfoils in order to make the fan fit the wing. The second and probably most important reason is that podded fan configurations remove wing area restrictions and allow higher wing loading. Figure 5 is a table of fan-in-wing aircraft and studies dating back to the XV5A/B, CX-6, and NASA short-haul study. Included in the table are podded configurations from the short-haul study and presently proposed designs. The fan-in-wing configurations had wing loadings of 45-60 psf while the podded configurations show wing loadings of 100-125 psf. A higher wing loading provides more efficient high-speed cruise coupled with better ride quality and offers weight saving advantages.

Aerodynamic Considerations

Induced Lift. An interesting and valuable attribute of lift-fan aircraft is the induced aerodynamic effects on overall aircraft performance generated by the large masses of air set in motion by fan operation. A significant increase in payload can be realized from induced lift if an aircraft is designed for VTOL operation and is allowed to operate overloaded in the STOL configuration. This overload capability can be as much as 15 to 20% of the aircraft gross weight. If the aircraft is not operated overloaded in the STOL configuration, noise is reduced because lower power settings are used during transition.

Induced lift is defined in Fig. 6. Power-off lift and fan thrust variation with forward speed are summed for a typical lift-fan configuration. The difference between the summed value and the corresponding value measured with power on is termed induced lift. Induced lift can be positive or negative, depending on fan placement. Negative induced lift has been measured without exception over a part of the velocity ratio range representative of transition for all configurations with lift fans forward of the wing (Fig. 7). Results have shown that to minimize the detrimental effect, the fans ahead of the wing should be located away from the fuselage, at least at mid-semispan. Fans placed aft of the wing (Fig. 8) have without exception produced positive induced lift throughout the transition envelope. The optimum location for fans aft of the wing appears to be near the wing root where the fan flow produces results similar to that of a jet-flapped airfoil.

The induced lift results for the complete configurations (front and rear fans operating) are shown in Fig. 9. Examination of the experimental results from models 1 through 4 plus theoretical calculations[7] on induced lift for rear fans operating near the wing trailing edge led to the investigation with model 5. Of the podded configurations examined, model 5 produced the highest induced lift even though the rear fans alone showed less induced lift than the rear fan only configuration from model 2. The low wing arrangement on model 5 probably reduced the induced lift carryover of the fuselage (this is a common occurrence with trailing-edge flaps). Theoretical calculations based on two-dimensional jet flap theory and three-dimensional wing theory do not adequately predict the induced lift carryover, and this approach does not predict induced effects from fans located remote from the wing. Improved theoretical approaches need to be developed and a better understanding of the phenomena involved is needed.

Results of Ref. 7 indicated that maximum induced lift would probably be obtained from a fan-in-wing configuration with many small fans spaced spanwise near the wing trailing edge. These results have been placed on Fig. 9 along with the podded configuration results. Induced lift for the fan-in-wing configuration is not significantly greater than that obtained from model 5.

Moment Variation. Turning of the airflow by lift fans causes a nose-up pitching moment as forward speed is increased, and past results, especially those of fan-in-wing configurations, have indicated that high induced lift usually generates large moments. With the podded configurations tested the moment variation with forward speed (as shown in Fig. 10) was much less than that with the fan-in-wing configuration shown and should be trimmable throughout transition.

Lift-Fan Vectoring. Efficient turning of the lift-fan exhaust is required for successful transition from direct lift to wing supported flight. Continuing research is needed to find effective ways for turning the lift-fan exhaust. Some of the results of large-scale research in this area are indicated on Fig. 11. Four sets of exit louver cascades were tested with the X-353-5B lift fan at constant RPM. On the XV-5 aircraft were 7-in. chord louvers. The 14-in. chord louver used the same airfoil as the 7-in. louver, and was flapped at mid-chord (see Fig. 3(a)) in an attempt to reduce back pressure of the fan at the higher deflection angles. The swept vane was also designed to relieve the fan back pressure by providing an open area in the center of the fan at the higher deflection angles. The results of the static tests are indicated on the figure. The dashed lines indicate the geometric turning angles from the hover or maximum lift position. Beyond 30° deflection, the effectiveness of all louver systems started to deteriorate, rapidly becoming less effective at 40° and above. The 14-in. chord vanes were superior at the higher deflection angles, and the trailing-edge flap provided some benefits above 30° of vectoring. The results in crossflow produced the same trends as indicated during static operation.

As fan pressure ratio is increased, the fan performance should be more sensitive to back pressure. To explore this, limited testing has been accomplished with the 1.3 pressure ratio LF-336A lift fan. A set of fixed camber exit vanes of 6.1-in. chord were placed in the fan flowpath immediately below the wing. The vanes were then dropped 1 louver vane chord (6.1 in.) below the wing undersurface. Both positions were examined throughout the velocity ratio range indicated on Fig. 12. To obtain the same lift the dropped cascade required an average of 3° more deflection than the louvers against the wing. Fan exit total-pressure measurements did not indicate any unloading tendencies with exit louver position; however, with the exit louvers close against the fan flowpath, RPM tended to hunt ±0.5%.

Cruise-Fan Vectoring. Many current lift-fan STOL and VTOL designs propose using the fan for high-speed cruise to reduce the number of propulsion units required for the mission. Efficient use of the system then dictates some means of vectoring the thrust to the lift direction for transition. One of the obvious methods proposed is to rotate the entire propulsion package. Some testing of this concept has been accomplished and was reported.[9] Two other methods have been examined by large-scale testing at Ames. Results from the first system (the variable camber louvers) are presented in Fig. 13. The louvers were deflected to six geometric angles and the fan was run over the RPM range shown on the figure. The data band shows a maximum loss in lift of less than 8% at 82° turning angle regardless of the fan RPM. This system is complex and could have fatigue problems if left in the fan efflux. To reduce cruise thrust loss, the system should be retracted which would further increase complexity. Another method studied, the hooded deflector, has been used with both the 1.1 and 1.3 pressure ratio 36-in. lift fans. The hooded deflector will probably be large and could be heavy, which might restrict its use on a particular aircraft design. The radius-to-diameter ratio of the 1.1 pressure ratio fan hooded deflector was low (0.54), and no attempt was made to optimize the area ratio for controlled diffusion prior to turning. The results in Fig. 14 are for the static case and are somewhat better than would be predicted from pipe flow theory. However, they are well below what would be considered satisfactory for an aircraft installation. The segmented exhaust hood used with the 1.3 pressure ratio fan had a more generous radius-to-diameter ratio (0.78) and allowed for flow diffusion prior to turning. Results with this deflector are very encouraging (Fig. 15). For the three fan RPM's tested the turning losses were very low – less than 10% at all vector angles.

Fan Performance. Studies[10] on the basis of installed thrust to weight and thrust to volume have shown that 1.3 pressure ratio lift fans are about optimum for maintaining an augmentation ratio of 2.5. To determine the crossflow performance of the 1.3 pressure ratio fan, a model was selected and the fan was placed in the same location as a previously tested 1.1 pressure ratio fan. The tests were conducted at equivalent velocity ratios to ensure comparable results. Figure 16 presents the ratio of fan thrust with forward speed to static thrust (measured by fan exit total pressure) as a function of velocity ratio. The 1.3 pressure ratio fan thrust did not decay significantly with forward speed and performed slightly better than the 1.1 pressure ratio fan over the entire velocity ratio range shown.

The highly loaded 1.3 pressure ratio fan was tested over a large velocity ratio range and model angle-of-attack ranges and stalled only once. This was during a test specifically programmed to induce stall, and the stall occurred well beyond velocity ratio ranges typical of transition. Figure 17 compares the 1.1 and 1.3 pressure ratio fans on an absolute speed scale. The 1.3 pressure ratio fan stall shown falls well outside the 1.1 pressure ratio fan boundaries. Thin fan-in-wing installation and, in some designs, thin pod installation mean short inlets and low distortion during transition. Studies[11] conducted prior to the design of the 1.3 pressure ratio fan resulted in a specially designed elliptic inlet to delay flow separation at the rotor tip during crossflow operation.

Sound Measurements. Results have been published[5] describing modifications incorporated in the LF-336 lift fan to reduce noise. These modifications reduced the fundamental tone PWL by 19.6 dB, the second harmonic PWL by 10.7 dB, and the 150-ft arc PNL by 13.5 dB during static testing in free-field conditions.[5]

The two configurations (base fan and quiet fan) were tested in crossflow in the Ames 40- by 80-Foot Wind Tunnel. Results from 6% bandwidth frequency spectrums were obtained at four microphone positions on a 20-ft radius with respect to the center of the fan exhaust; three microphones were on the upstream side of the fan with respect to tunnel flow and one was downstream. Figure 18 shows the relative change in blade passing frequency SPL versus tunnel forward speed for the base fan and quiet fan configurations, and Fig. 19 shows the relative change in average SPL for jet noise in the 200-630 Hz bandwidth. At the blade passing frequency the SPL increased with forward speed for both the base and quiet fan configurations with a definite separation of levels between the two configurations. In the 200-630 Hz bandwidth both configurations produced about the same SPL increases with forward speed, the largest increase occurring at the downstream microphone position because of the bending of the jet wake with increasing forward speed. At the highest speed shown, the wake begins to cover the microphone position.

Concluding Remarks

Recent research on large-scale lift-fan transports at Ames Research Center has been devoted to podded lift-fan configurations. Podded fan configurations remove wing contour and wing area restrictions and allow higher wing loading designs. Properly placed, podd[illegible]tions have induced lift values approaching those of [illegible] configurations. The variation in pitching momen[illegible] is significantly less for podded configurations than [illegible] designs having high induced lift.

Lift and lift cruise fan vectoring systems have [illegible]

1. Lift-fan vectoring deteriorates rapidly beyond 30° for the four louver systems shown.

2. The variable camber louver system used with the 1.1 pressure ratio fan had turning losses of less than 8% but the system is complex and installation on an aircraft could increase this complexity.

3. The hooded deflector used with the 1.1 pressure ratio fan had a low radius-to-diameter ratio (R/D = 0.54), and no attempt was made to diffuse the flow prior to turning. Losses on the order of 30% were recorded. The deflector used with the 1.3 pressure ratio fan had a more generous radius-to-diameter ratio (R/D = 0.78), and provisions were made for flow diffusion. Turning losses were low (less than 10%) with this system. Hooded deflectors will probably be large and heavy, which might influence their selection for an aircraft installation.

The 1.3 pressure ratio lift fan performed well in crossflow. Fan thrust did not deteriorate significantly over the velocity ratio range representative of transition. Stall boundaries indicated for the 1.1 pressure ratio fan appear satisfactory except possibly at high angles of attack at lower speeds. The 1.3 pressure ratio fan stalled well outside the 1.1 pressure ratio fan, and if the boundaries follow the same trend, the stall margin should be adequate for transition.

The noise measurements recorded in crossflow for the quiet fan have shown an SPL reduction of 8-11 dB over that of the base fan at the fundamental blade passing frequency for the quiet fan. At the blade passing frequency the SPL increased with forward speed for both configurations. The broadband (200-630 Hz) noise also increased with forward speed, but both fan configurations produced about the same SPL increase. The largest increase in broadband noise occurred at the downstream microphone partly because of the bending of the jet wake with increased forward speed.

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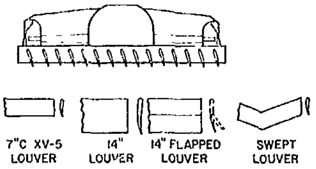
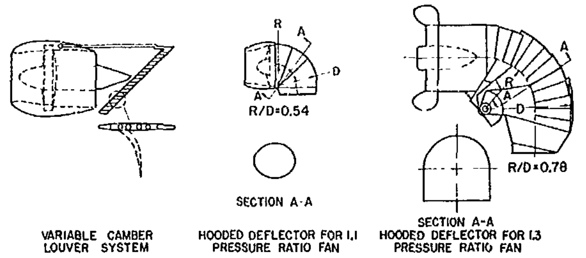
MODEL	TYPE		WING ASPECT RATIO	WING LOC.	SWEEP OF QUARTER CHORD LINE	TAPER	$\frac{A_f}{S}$	$\frac{D}{C}$	$\frac{D}{b}$	REFERENCE
1	FOLDING LIFT FAN ROTATING CRUISE FAN		5.8	HIGH	35°	.3	.123			7,9
2	TANDEM LIFT FAN - NEAR FUSELAGE		5.8 (BASIC) 3.44 (GROSS)	HIGH	35°	.3	.073	.161	.164	7,9
3	TANDEM LIFT FAN - MID - SEMISPAN		5.8 (BASIC) 4.04 (GROSS)	HIGH	35°	.3	.086	.169	.164	10
4	PODDED FRONT LIFT FANS LIFT - CRUISE FANS AFT		5.8 (BASIC) 4.51 (GROSS)	HIGH	35°	.3	.096	.208	.164	
5	FRONT FANS MID - SEMISPAN AFT FANS NEAR FUSELAGE		5.65 (BASIC) 3.73 (GROSS)	LOW	35°	.3	.080		.165	

Fig. 1. Model geometry.



(a) X-353-5B lift fan and exit cascade with four sets of exit louvers.



(b) Variable camber louvers and hooded deflectors.

Fig. 3. Turning devices used for vectoring lift-fan and lift-cruise fan exhaust.

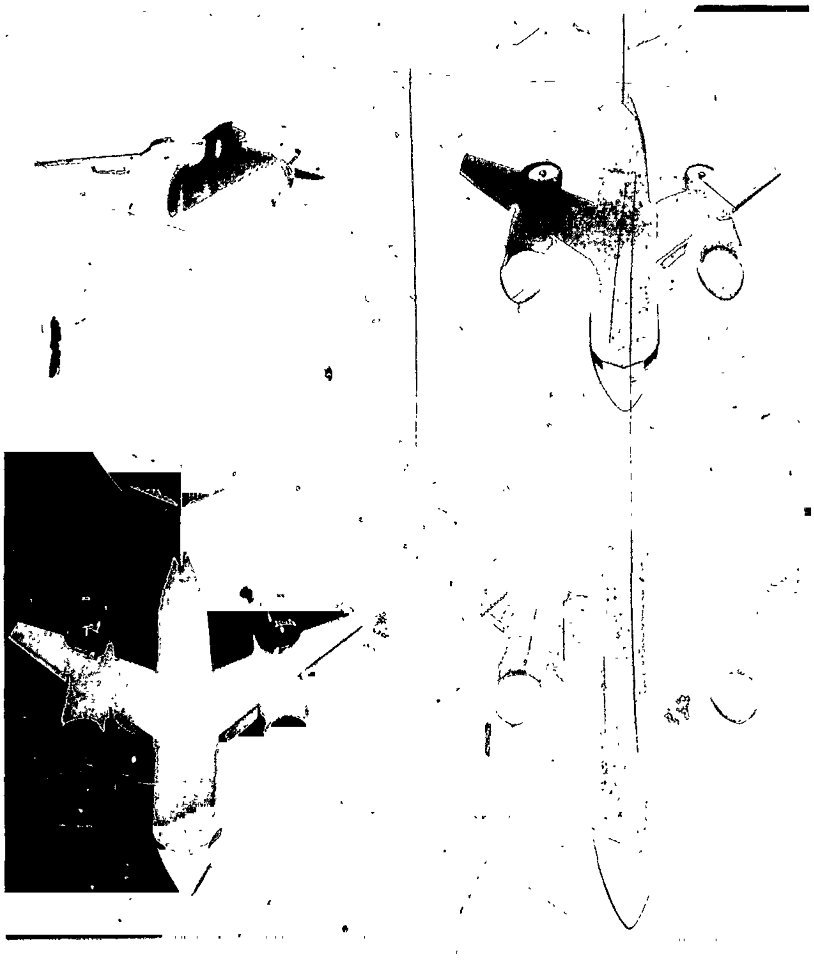


Fig. 2. Lift fan models mounted in the Ames Research Center 40- by 80-Foot Wind Tunnel.

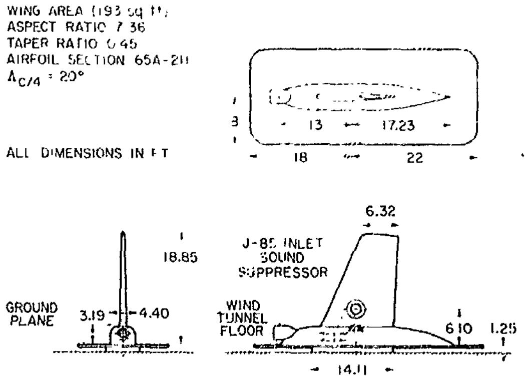


Fig. 4. Geometric details of the semispan model with high pressure ratio lift fan.

AIRCRAFT/STUDY	W/S FAN-IN-WING	W/S PODDED
XV5A/B	45	
CX-6	60	
NASA SHORT-HAUL	60	100
NORTH AMERICAN ROCKWELL		125

Fig. 5. Wing loadings for respective lift-fan configurations.

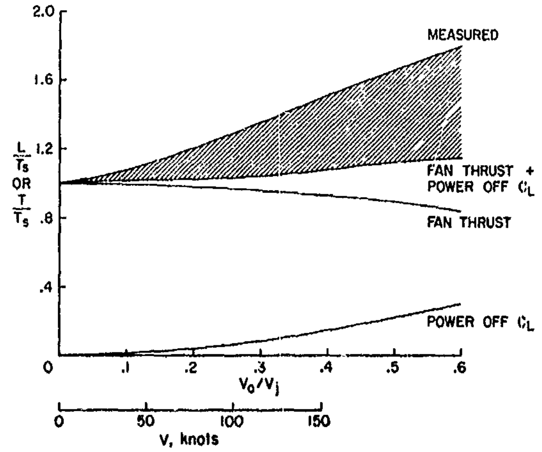


Fig. 6. Induced lift for typical lift-fan model.

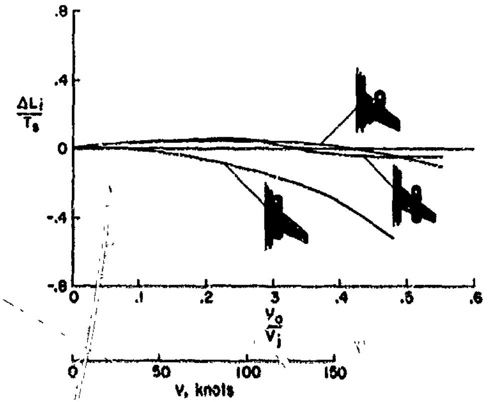


Fig. 7. The variation in induced lift with front fan operation for representative podded configurations; $\alpha = 0°$, $\delta_f = 0°$.

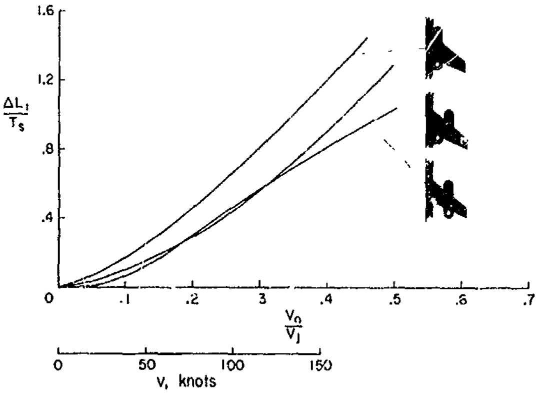


Fig. 8. The variation in induced lift with aft fan operation for representative podded configurations; $\alpha = 0°$, $\delta_f = 0°$.

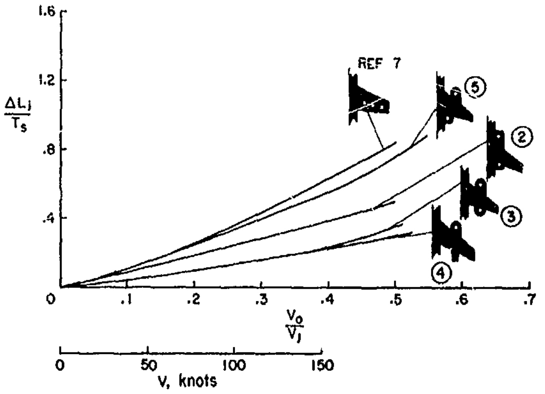


Fig. 9. The variation in induced lift for the complete podded lift-fan configurations; $\alpha = 0°$, $\delta_f = 0°$.

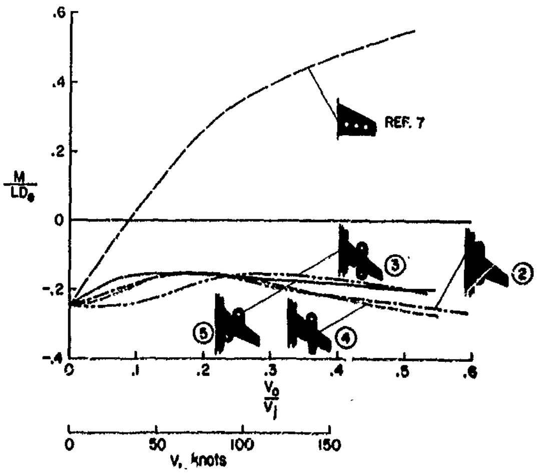


Fig. 10. The variation in pitching moment for podded lift-fan configurations; $\alpha = 0°$, $\delta_f = 0°$.

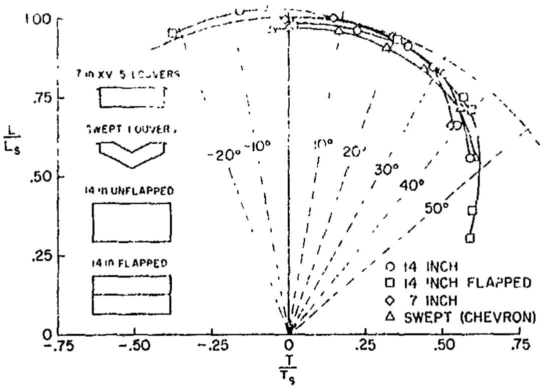


Fig. 11. Static turning effectiveness of four exit louver systems beneath the X-353-5B lift fan.

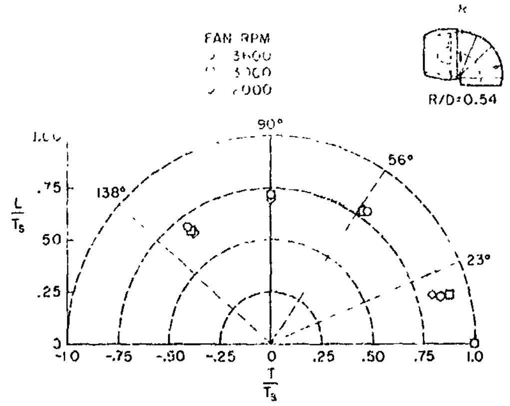


Fig. 14. Vectoring cruise fan exhaust with a hooded deflector; 1.1 pressure ratio fan.

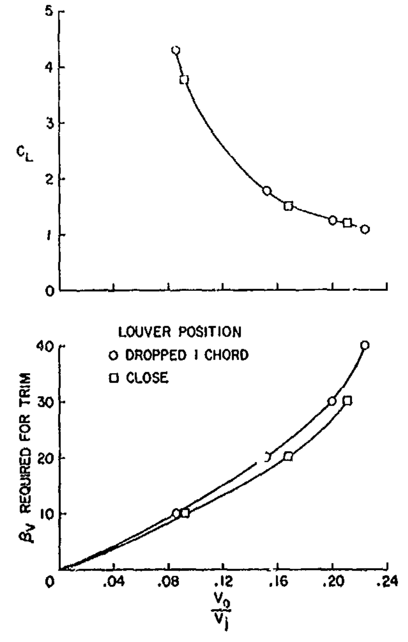


Fig. 12. Effect of dropping exit louver cascade on turning effectiveness; 1.3 pressure ratio fan.

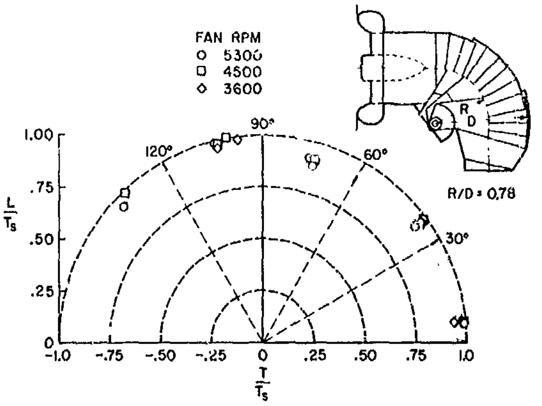


Fig. 15. Vectoring cruise fan exhaust with a segmented hood deflector; 1.3 pressure ratio fan.

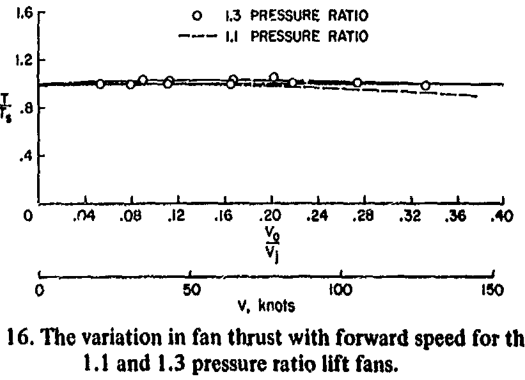


Fig. 16. The variation in fan thrust with forward speed for the 1.1 and 1.3 pressure ratio lift fans.

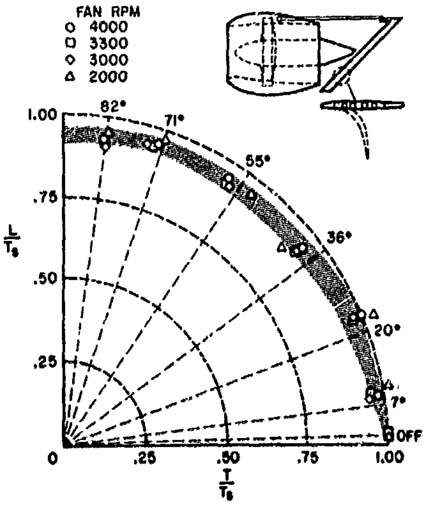


Fig. 13. Vectoring cruise fan exhaust with variable camber exit louvers; 1.1 pressure ratio fan.

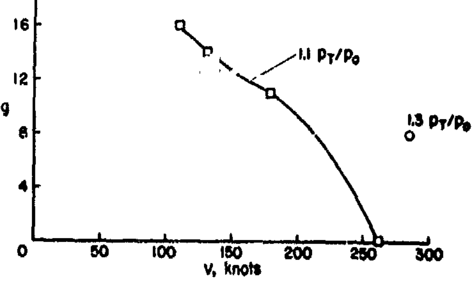


Fig. 17. Fan stall margin for 1.1 and 1.3 pressure ratio lift fans.

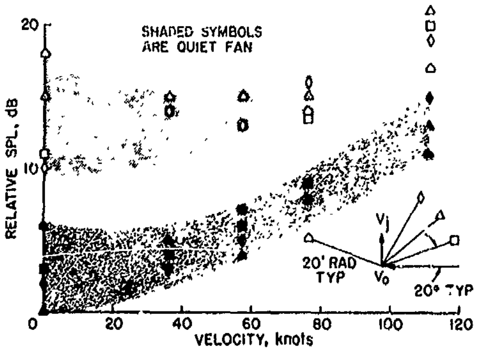


Fig. 18. Effect of tunnel forward speed on blade passing frequency noise; 6% narrow-band analysis.

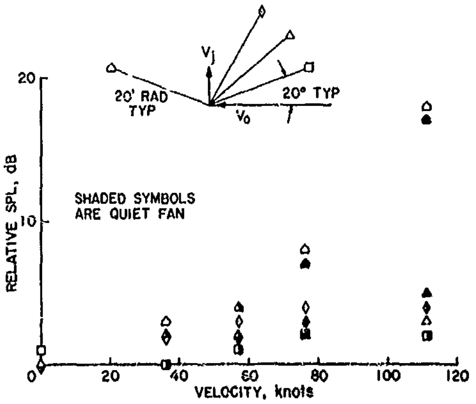


Fig. 19. Effect of tunnel forward speed on 200-630 Hz broadband noise; 6% narrow-band analysis.