THE RELEVANCE OF THE FLEX-HUB PROP-FAN FOR FUEL-EFFICIENT AIRLINERS

ICAS-80-1.4

K. W. Sambell
Research Engineer
Arlington, Texas, USA

ABSTRACT

The Flex-Hub Prop-Fan, a variant of the rigid-hub prop-fan, is predicted to have improved performance and control characteristics for twin-engine M 0.8 airliners. In the one-engine inoperative case at take-off, the Flex-Hub Prop-Fan will have a more even thrust distribution in its tip-path plane and will develop higher propulsive efficiency and greater propulsive lift. A preliminary analysis, with a fixed engine core-size, compares payload capability of three aircraft: powered by fan-jets, rigid-hub prop-fans, and flex-hub prop-fans.

The respective design gross weights were 300,000 lbs., 320,000 lbs., and 342,000 lbs. At a range of 2,000 n.m., the passengers carried were 232, 255 and 280. The fuel economy (seat-statute miles per U.S. gallon) was 68.7, 76.5 and 79.5. Other unique characteristics of the Flex-Hub Prop-Fan are discussed, including cross-wind control, blade de-icing, and wing trailing-vortex interaction.

INTRODUCTION

The increasingly high cost of airliner fuel has stimulated research into the propeller, or prop-fan, capable of achieving high efficiency at cruise speeds of M 0.75 - M 0.80. Results have been reported by Rosen (1), Dugan (2), Conlon (3), Nored (4), and Neitzel (5). This paper concentrates on the low speed performance and investigates lifting efficiency. Combining this with the well accepted predictions for cruise, enabled an analysis to be made of aircraft payload and fuel economy.

In the one-engine-inoperative (OEI) condition at take-off, all conventional propeller aircraft operate with the propeller shaft about 5-15 degrees above the relative wind. This produces the well known " P " factor wherein the center of thrust moves laterally, 10-20 percent radius, to the down-blade side. This produces a thrust loss and also blade vibrations. The highly non-uniform wake impacts on the wing and produces only a small propulsive lift. Prop-fans are expected to show the same characteristics. In contrast, the inlet duct of a fan-jet straightens the inflow.

By adding hub flexibility, the blades are allowed to flap perpendicular to the original tip-path plane (beamwise flapping) and reach a new equilibrium position. Typically, depending on tip-speed ratio, in the OEI condition, the bottom blade would flap forward 4-6 degrees, and the top blade would flap aft 4-6 degrees. The net moment at the hub flexure would be near zero and the thrust distribution around the propeller disc would be close to uniform. This produces higher propulsive efficiency and higher propulsive lift as the wake passes over the wing. Also, in cruise, the hub flexibility provides a softer in-plane force response to vertical gusts which should also reduce the aeroelastic torsional moment on the wing. The Flex-Hub Prop-Fan has grown out of extensive research on gimbal-hub tilt rotors which have similar flapping characteristics. Tilt rotors have been predicted to be stable propulsive devices up to cruise speeds of 400 knots by Wernicke (6) and Gaffey (7). Further research is needed to assure that satisfactory stability margins (blade flapping and wing torsional damping) exist at M 0.8 cruise speed. The need to preserve blade flapping-stability tends to favor straight blades (rather than the curved scimitar type) and it is thought that the increased lifting efficiency at low speed will outweigh any small loss in propulsive efficiency at cruise.

FLEX-HUB PROP-FAN & CONTROL SYSTEM

A schematic of a typical flex-hub prop-fan is shown in Figure 1. The flexure is inboard of the blade pitch change bearings and allows flapping up to ± 12°, perpendicular to the plane of rotation. The flexure would be relatively stiff in the plane of rotation with first critical frequency above 1.3 - 1.4 per rev. The blades would be relatively stiff-in-torsion to preclude blade flutter. However, there is a preliminary indication that they will weigh substantially less than the blades of a rigid-hub prop-fan due to the lower design blade loads.

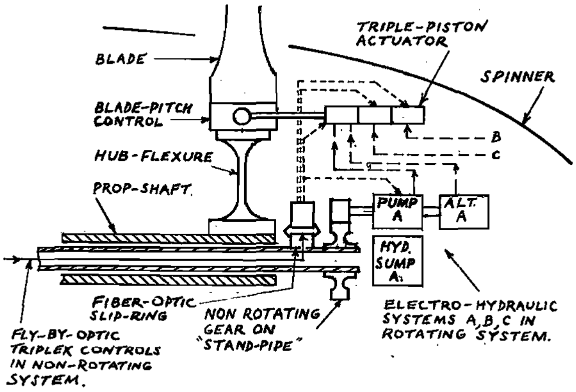

FIG. 1 SCHEMATIC OF FLEX-HUB PROP-FAN WITH "IBIS" INDIVIDUAL BLADE-PITCH CONTROL

BLADE PITCH CONTROL SYSTEM

An advanced blade pitch control system, such as "IBIS" as proposed by Guinn (8) is recommended for the flex-hub prop-fan. A schematic is shown in Figure 1. A feature of IBIS (Individual Blade Control Independent of a Swashplate) is that each blade is controlled by a triplex hydraulic actuator. Each piston of the actuator has a separate electrical, and hydraulic, power and signal supply. The hydraulic and electrical power supply is generated, and completely contained, in the rotating system. The drive is via a non-rotating "standpipe". Thus for an eight bladed prop-fan there would be eight triplex actuators (two-fail operate). Each piston is controlled and powered by one of the three electro/hydraulic systems. Command signals from the pilot could be digitized optical signals, in a fly-by-optic system, which enter the rotating system via a fiber-optic slipring. It is predicted that this system will weigh less than present systems. Also cyclic pitch of any frequency (up to 50 Herz) and phase can be added to the basic synchronized blade-pitch (or collective) control, with little weight penalty.

STUDY GROUNDRULES

The study groundrules and baseline aircraft are shown in Table 1 and Figure 2. The technology level is estimated to be typical for aircraft entering airline service in 1990, but with a limited use of composites in fuselage primary structure. The propulsion thrust s.f.c. is based on Neitzel (5) who estimated that a boosted turboprop will have an installed cruise thrust s.f.c. 12.5 percent less than a fan-jet, of the same technology level, at M 0.8, 35,000 ft. altitude.

Propulsion thrust/power characteristics versus speed are shown in Figure 3. These are based partly on Rosen (1) and Nored (4). For a constant engine core-size these data provided estimates of relative thrusts available at take-off (130 Kt) climb (250 Kt, EAS) and cruise (461 Kt, 35,000 ft.). These data are shown for axial flow conditions. However, at take-off, non-axial flow occurs and causes the rigid-hub prop-fan to have a lower propulsive efficiency than the flex-hub prop-fan, as discussed next.

PROP-FAN PROPULSIVE EFFICIENCY AT TAKE-OFF

This study investigated lifting efficiency for a baseline aircraft with a wing loading of 100 psf, a first segment climb speed (V2) of 130 Kt, VMCA = 115 Kt and a stall speed (VS) of 108.3 Kt.

At V2 the average wing lift coefficient is 1.75 and the local airstream inflow relative to the prop-shaft axis

TABLE 1. STUDY GROUNDRULES

DESIGN PARAMETERS		FAN-JET AIRCRAFT (BASELINE)	PROP-FAN AIRCRAFT
DESIGN GROSS WEIGHT	LB	300,000	AS CALCULATED
PROPULSION, S.L.S. STATIC	LBF	2 X 46,500	2 X 51,000
PROPULSION, DIAMETER	FT	8	20
ENGINE CORE SIZE	LB/SEC	110	SAME
WING AREA	SQ FT	3,000	SAME
WING ASPECT RATIO	ND	8.0	SAME
FUSELAGE EXT. DIA.	FT.	16.7	SAME
NO. PASSENGERS	NO.	232	AS CALCULATED
RANGE, WITH RESERVES	NM	2,000	SAME
THRUST SFC, CRUISE, INSTALLED	LB/HR/LB	0.57	0.499

PERFORMANCE CRITERIA

(A) TAKEOFF: 1.2% GRADIENT AT V2, OEI

(B) CRUISE: INITIAL CRUISE, M 0.8 35,000 FT AT ≤ 90% MAX. CONTINUOUS RATING

GOAL: COMPARE FUEL ECONOMY

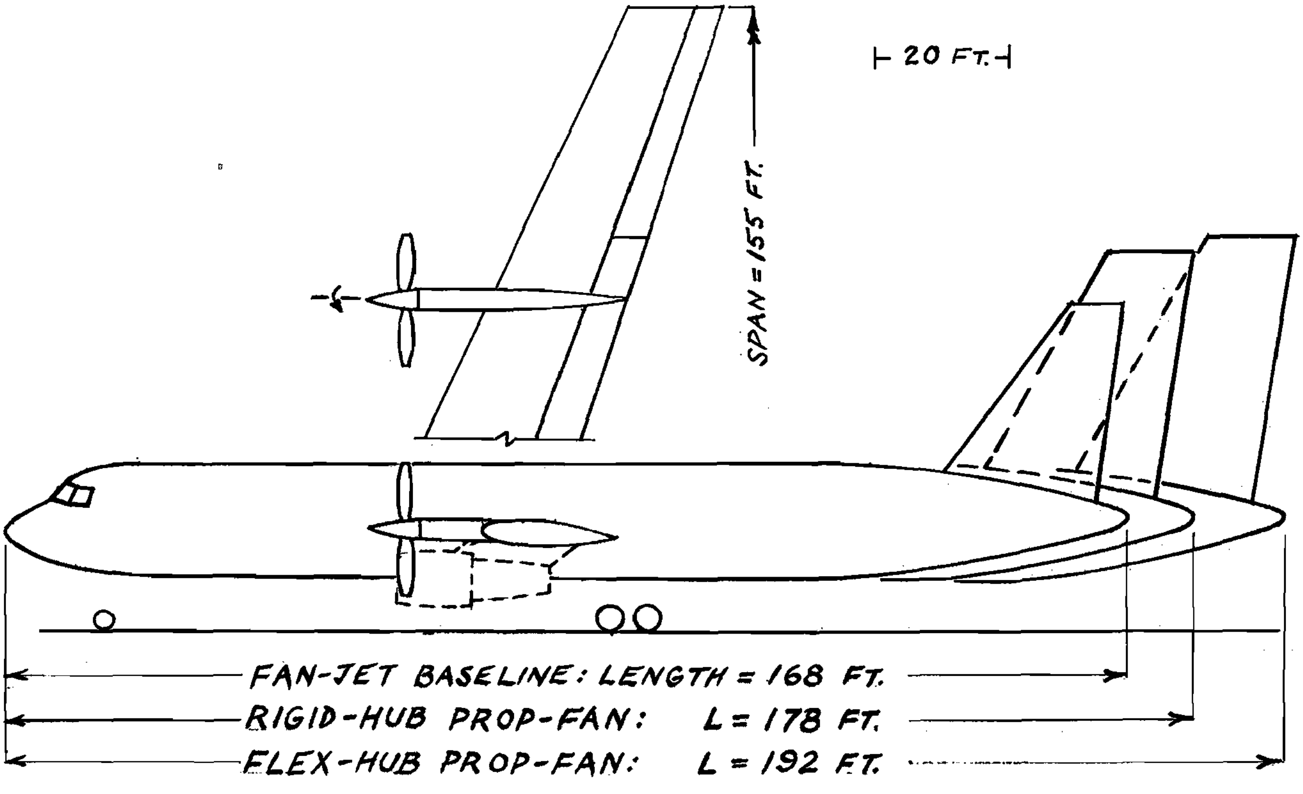

FIG. 2 BASELINE FAN-JET AIRCRAFT AND PROP-FAN DERIVATIVE AIRCRAFT

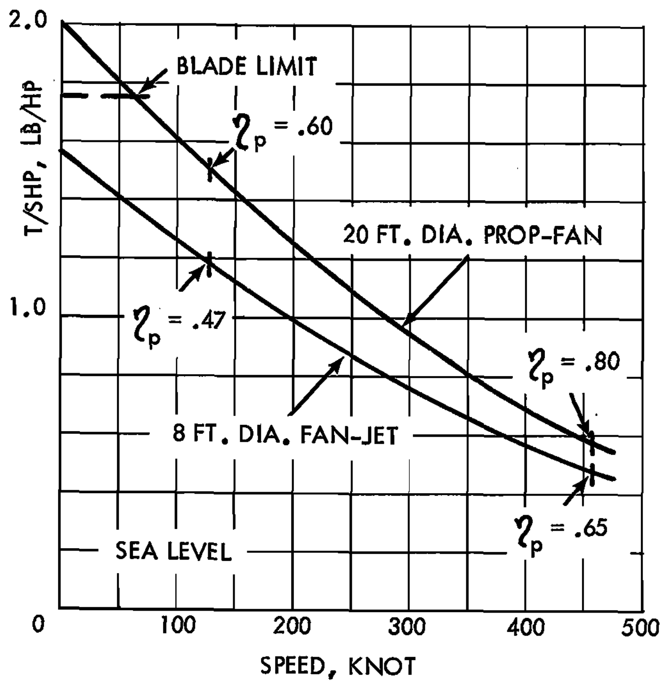

FIG. 3 PROPULSION CHARACTERISTICS, 30,000 SHP CORE-SIZE

at the tip-path plane is 8-12 degrees, Figure 4. A value of 10 degrees was selected as typical. This non-axial flow produces losses which, up to now, have not been significant. But with prop-fans being proposed with powers of 10-30,000 shp, this loss is now of interest.

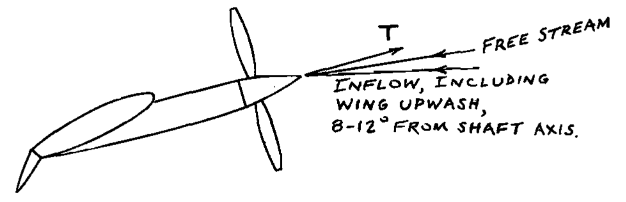

FIG. 4 TYPICAL INFLOW ANGLE AT TAKE-OFF. V2 = 130 Kt, C_L = 1.75, WING LOADING 100 PSF

PROPULSIVE EFFICIENCY DIFFERENCE BETWEEN RIGID-HUB AND FLAPPING PROPELLERS WITH UNIFORM, NON-AXIAL INFLOW

A computerized analysis examined propulsive efficiency of a rigid-hub propeller and a flapping propeller at non-axial flows up to 15 degrees. The program assumed uniform induced velocity across each propeller disc, which is an error but nevertheless a convenient starting point. At each shaft angle, blade pitch was adjusted to hold power constant. The loci of the resultant vectors are shown in Figure 5. At any non-axial shaft angle the flapping propeller produced more thrust than the rigid-hub propeller. At 10 degrees shaft angle the flapping propeller produced 4.4 percent greater horizontal thrust than that for the rigid-hub propeller. The latter did produce a larger vertical component but that is not considered significant when the wing does that so well.

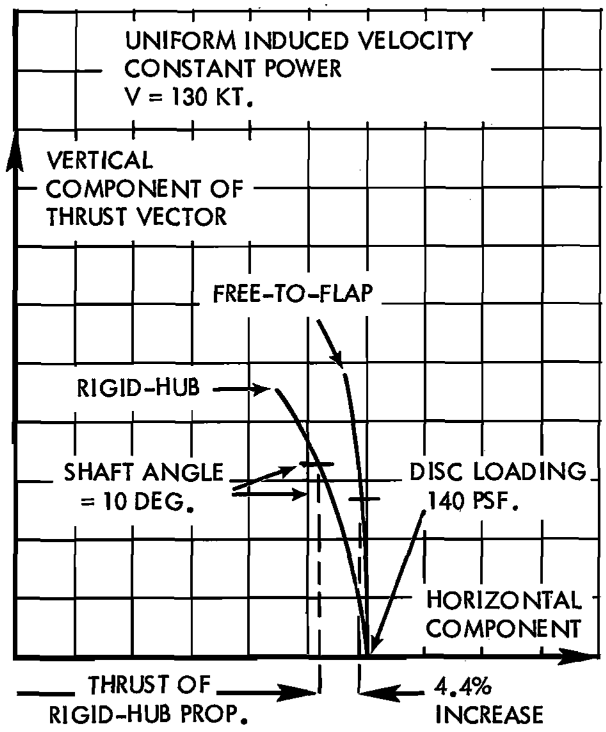

FIG. 5 THRUST INCREASE FOR A FREE-TO-FLAP PROPELLER, 10 DEGREES NON AXIAL INFLOW.

Thus the analysis proceeded to the next step -- the analysis with a non-uniform induced velocity. This is a much tougher analytical problem and a preliminary method was selected which served to outline the potential of the flex-hub prop-fan. Development of more complete methods using realistic prescribed wake lifting-surface analyses are proceeding within the industry, but are still several years away from completion.

PROPULSIVE EFFICIENCY DIFFERENCE WITH NON-UNIFORM, NON-AXIAL INFLOW

A computerized analysis was used to analyze the distribution of thrust around the tip-path plane of rigid propeller, while holding the overall average disc loading at 140 psf. Each blade was analyzed at 20 radial stations, every 15 degrees around the tip-path plane. Local induced velocity at each blade element was iterated versus local angle of attack until they were balanced. The disc loading (thrust divided by area) for the down-blade quadrant (45 degrees of azimuth, either side of the wing) and the up-blade quadrant was then calculated. This ratio is shown in Figure 6. At a shaft angle of 15°, a ratio of 2.3 : 1 was calculated. This compares reasonably well with the "feeling" of several propeller designers that "for rigid-hub propellers the ratio is 2 - 3 : 1 at shaft angles of 15-20°, with blade flapping of about 2 degrees." At an angle of 10 degrees, the curve predicts the ratio is 1.65 : 1. The author feels that this is on the low or conservative side. This ratio was then applied to estimate the

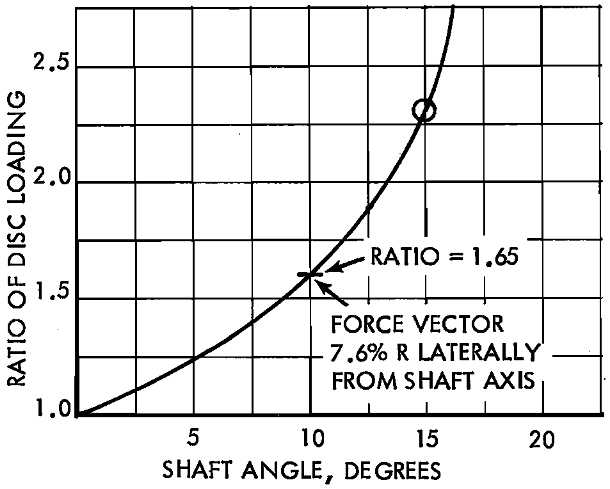

FIG. 6 RATIO OF DISC LOADING,
DOWN-BLADE QUADRANT
UP-BLADE QUADRANT

difference in overall thrust between a flex-hub prop-fan (wherein the disc loading is estimated to remain uniform at 140 psf) and a rigid-hub prop-fan. A typical propeller efficiency curve, Figure 7, was used in this iteration.

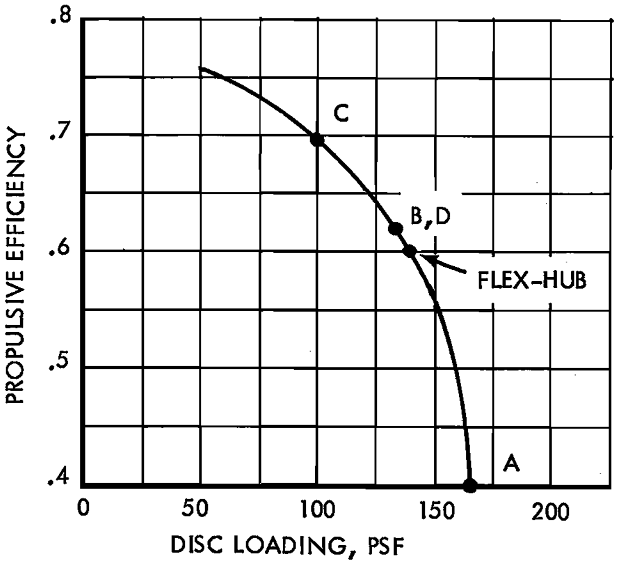

FIG. 7 PROPULSIVE EFFICIENCY 130 KT.,
TIPSPEED = 800 FT/SEC.
AXIAL FLOW

The resulting disc loading distribution is shown in Figure 8. The down-blade quadrant A, increased its disc loading to 165 psf from the basic 140 psf. To maintain constant power the collective blade pitch was reduced from that of the flex-hub, and quadrants B and D have a disc loading of 132 psf (essentially equal since upwash does not change their blade angles-of-attack). The up-blade quadrant reduced its disc loading to 100 psf. Each quadrant's propulsive efficiency is shown in Figure 7. The overall power is the same and the flex-hub prop-fan is estimated to develop 5.7 percent higher thrust than a rigid-hub prop-fan, flapping about 2°. The thrust center for the rigid prop-fan is offset 7.6% radius laterally, on the down-blade side. This is also thought to be conservative. The disc loading in quadrants A and C were also used to estimate the slipstream dynamic pressure over the wing. Quadrants B and D, theoretically, do not touch the wing and their effect was neglected.

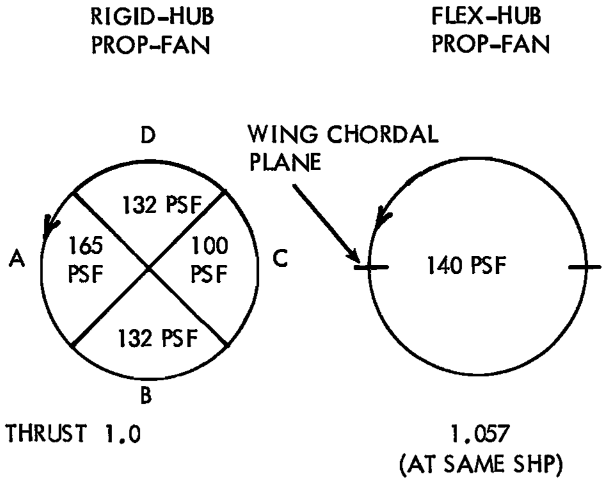

FIG. 8 DISC LOADING DISTRIBUTION,
SHAFT ANGLE = 10 DEGREES
V = 130 KT.

Thus this preliminary method was used to estimate the difference in propulsive efficiency between flex-hub prop-fans and rigid-hub prop-fans for non-axial flow at take-off. Results are shown in Figure 9, which shows an "ideal" propeller, a flex-hub propeller, a rigid-hub propeller of conventional rigidity, and an infinitely rigid propeller. The propulsive efficiency is based on resolving axial and in-plane forces on an axis halfway between the shaft and the angle of inflow. All four curves begin at a propulsive efficiency of 0.6 in axial flow. This is taken from Figure 3 and is considered to be typical for disc loadings of 140-150 psf, a tipspeed of 800 ft/sec, and airfoils and blade twist capable of meeting the M 0.8 cruise efficiency requirement of 80 percent. The "ideal" rotor is assumed to have, for shaft angles up to 20 degrees: uniform induced velocity, no increase in profile power from axial flow, no in-plane force.

Its propulsive efficiency (along half the shaft angle) actually increases slightly. This hypothetical result comes from the above assumptions and is due to the reduced axial velocity component through the propeller disc. However it does provide an upper limit to claims of improved performance! The propeller, with actual rigidity, is shown with its propulsive efficiency falling quite steeply to 0.537 at 15 degrees. At 20 degrees, propeller designers find that the oscillatory loads typically reach high values which usually force the design of blade-stiffness and blade-weight. Blade flapping is about 2°, which provides some relief from the infinitely rigid case. The free-to-flap or flex-hub propeller flaps 4-6 degrees (depending on blade Lock No. for a hub-flexure offset from the shaft axis) at a shaft angle of

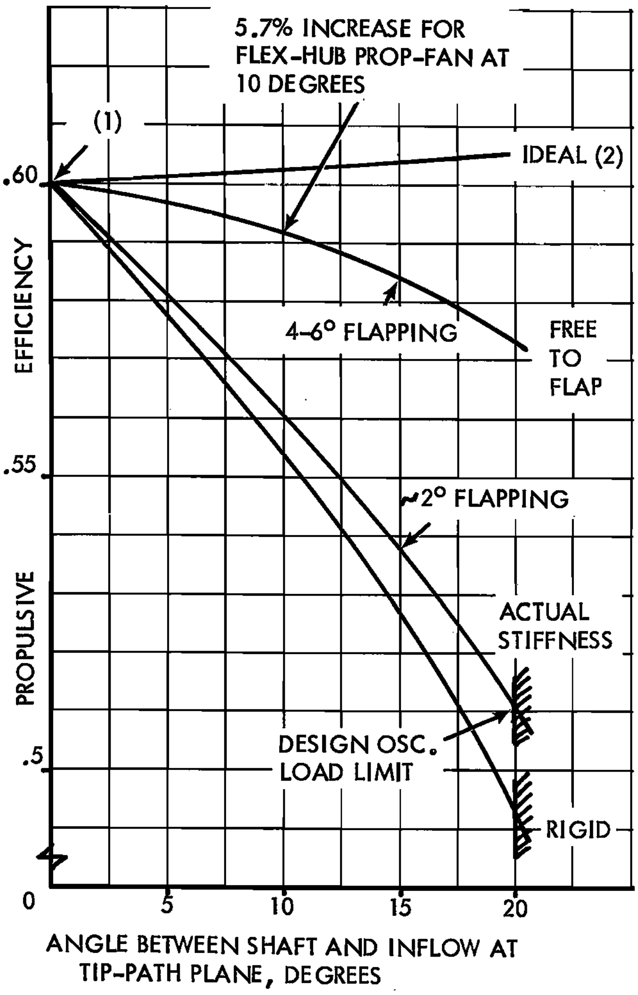

FIG. 9 PROPULSIVE EFFICIENCY FOR FLEXIBLE-HUB AND RIGID-HUB PROP-FANS

NOTES: 1. V = 130 KNOT, DISC LOADING 140-150 PSF, TIPSPEED 800 FT/SEC.
2. THRUST RESOLVED MIDWAY BETWEEN SHAFT AND INFLOW

15 degrees and improves propulsive efficiency by 8.75 percent, and by 5.7 percent at a shaft angle of 10 degrees, substantially approaching the "ideal" propeller. There is some debate over predictions of flapping angle in the presence of wing upwash -- it is by no means a precise science. However, should the flex-hub prop-fan fail to develop this beneficial flapping (by for instance, some unforeseen design requirement which forces blade-weight up) then longitudinal cyclic pitch can be introduced to achieve the desired condition of unloading the advancing blade and loading up the retreating blade. The hub flexure would then provide tolerance to the required cyclic pitch and provide a "softer" prop-fan over a given range of non-axial flow.

Thus at the selected shaft angle of 10 degrees, the flex-hub prop-fan is predicted to have a propulsive efficiency along the flight path of 0.592 at take-off thrust, versus 0.56 for a conventional rigid-hub prop-fan. This relatively small difference has never been noticed (or searched-for) in the past. But at power levels of 30,000 shp it provides a significant thrust difference and a significant propulsive lift difference, as discussed next.

PROPULSIVE LIFT AND DRAG

The combination of a prop-fan, with disc loadings of 140-150 psf at 130 Kt, and a swept-back wing at a wing loading of 100 psf, is new. There are many unknowns which force many assumptions in the most detailed analysis. As Nored (4) points out "(a) the prop-fan is operating in the wing upwash which produces a one-per-rev. oscillatory loading and (b) the wing sweep-back produces a two-per-rev oscillatory loading." However when operating in highly disturbed conditions always go back to basics! Thus, the 1937 propulsive lift method of Smelt and Davies (9) was reviewed and modified by the addition of propeller swirl as per Glauert (10) of 1926. The propulsive lift method was thus: (a) the fully developed propeller induced velocity (and contracted wake) was assumed to exist across the total wing chord; (b) the performance results of Figure 8 were used, with the rigid prop-fan having a disc loading of 165 psf (slipstream dynamic pressure of 165 + 57 = 222 psf) immersing the wing on the down-blade side, and a disc loading of 100 psf (slipstream dynamic pressure of 100 + 57 = 157 psf) on the up-blade side; (c) propeller swirl calculated, treating the up-side and down-side separately, and assuming that the swirl at 0.75 blade radius acts from 0.2 radius to the edge of the contracted wake at 0.95 radius; (d) the wing immersed in the wake, at the angle-of-attack as calculated in (c), develops its basic lift and drag coefficients and deflects the slipstream downwards at the average downwash for the whole wing.

A typical high-lift wing was selected with lift and drag characteristics as shown in Figure 10.

Resulting propulsive lift and drag characteristics are shown in Tables 2 and 3. For the rigid-hub prop-fan the high swirl of the down blade produced zero lift over its wing area. The up blade produced a wing lift of 52970 lbs. for a net increase (over the power-off lift) or 23870 lbs., (8 percent of baseline GW). In contrast the more-even wake distribution behind the flex-hub prop-fan produced a net increase (over the power-off lift) of 57650 lbs., (19% of baseline GW). Also the incremental (lift/drag) ratios both exceeded that of the basic wing operating at the same percentage increased lift. The drag associated with this propulsive lift is shown in Table 3.

Thus the analysis predicts that the 5.7 percent thrust increase of the flex-hub prop-fan produces an 11 percent gross weight increase in propulsive lift compared to the rigid-hub prop-fan. These results were then applied to the conceptual design of three aircraft; powered respectively by fan-jets, rigid-hub prop-fans and flex-hub prop-fans as discussed next.

CONCEPTUAL DESIGN OF TWO PROP-FAN AIRCRAFT RELATIVE TO BASELINE FAN-JET AIRCRAFT

The propulsive lift and drag of the preceding section was applied to the prop-fan aircraft designs as per the study groundrules of Table 1. The major changes were:

(a) removing fan-jets and adding prop-fans raised the thrust line by 6 feet. The additional tail download to trim, was allowed for.

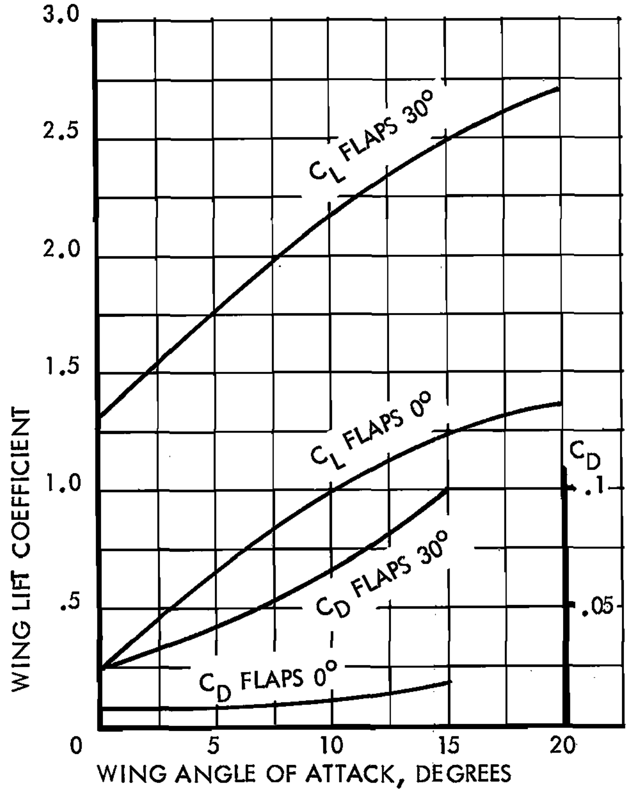

FIG. 10 WING LIFT & DRAG, ASPECT RATIO = 8.0

TABLE 2. PROPULSIVE-LIFT, GW = 300,000 LB OEI, 130 Kt, FLAPS 30 DEG.

PORTION OF SLIPSTREAM (1)		RIGID - HUB DOWN-BLADE	RIGID - HUB UP-BLADE	FLEX - HUB DOWN-BLADE	FLEX - HUB UP-BLADE
DISC LOADING	PSF	165	100	140	140
SLIPSTREAM DYN. PRESS	PSF	222	157	197	197
WING ANGLE OF ATTACK (AT 3/4 BLADE RADIUS)	DEG	-11.9	+12	-6.7	+15.9
C_L IN SLIPSTREAM	ND	0	2.3	.53	2.52
WING AREA	SQ FT	145	147	146	144
LIFT (PROPULSIVE)	LBF	0	52970	15260	71290
TOTAL LIFT (PROPULSIVE)	LBF	52970		86550	
BASIC WING LIFT (T=0) (2)	LBF	29100		28900	
INCREASE OVER BASIC LIFT	LBF	23870 (7.96% GW)		57650 (19.2% GW)	
INCREASED DRAG (SEE TABLE 3)	LBF	4300		7490	
$\frac{\text{PROPULSIVE LIFT}}{\text{PROPULSIVE DRAG}}$	ND	5.5		7.7	
IF BASIC WING C_L INCREASED SAME PERCENTAGE					
$\frac{\text{INCREASE IN } C_L}{\text{INCREASE IN } C_D}$		4.7		4.4	
THUS BOTH PROP-FANS OFFER SUPERIOR INCREMENTAL L/D					

NOTES: 1. SLIPSTREAM QUADRANT EXTENDS ± 45 DEGREES OF AZIMUTH, EITHER SIDE OF WING CHORDAL PLANE
2. BASIC WING C_L = 1.75

TABLE 3. DRAG OF WING IN SLIPSTREAM, OEI, 130 Kt, FLAPS 30 DEG.

		RIGID-HUB DOWN	RIGID-HUB UP	FLEX-HUB DOWN	FLEX-HUB UP
DISC LOADING	PSF	165	100	140	140
C_{D_o} IN SLIPSTREAM	ND	.04	.08	.022	.108
DRAG, PROFILE	LBF	1290	1840	630	3060
DRAG, INDUCED	LBF	0	4080	1200	5490
TOTAL DRAG (PER SIDE)	LBF	1290	5920	1830	8550
TOTAL DRAG (PER PROP)	LBF	7210		10380	
BASIC WING DRAG	LBF	2910		2890	
INCREASE OVER BASIC DRAG	LBF	4300		7490	

(b) the prop-fan was installed with a fuselage to blade-tip clearance of 0.75 D (15 feet). The propulsive lift, with OEI, thus had to be balanced by larger ailerons (spoilers were not considered in this study). The down-aileron trim requirement was checked to ensure that the original VMCA of 115 Kt could be maintained. See Table 4.

TABLE 4. ROLL TRIM ANALYSIS OEI AT V2 (130 Kt), CLIMB GRADIENT 1.2%

		FAN JET BASELINE	RIGID-HUB PROP-FAN	FLEX-HUB PROP-FAN
WING LOADING	PSF	100	106.7	114
PROPULSIVE LIFT	LBF	0	23900	45800
LATERAL ARM	FT	—	38.2	38.2
ROLL MOMENT	10^6 FT.LB.	—	.913	1.750
FIN SIDE FORCE	LBF	14285	21470	24980
VERTICAL ARM	FT	13.0	16.0	17.2
FIN ROLL MOMENT	10^6 FT.LB.	.186	.344	.430
FAN TORQUE	10^6 FT.LB.	+.077 (1)	-.22 (2)	-.22 (2)
TOTAL ROLL MT.	10^6 FT.LB.	.263	1.037	1.960
AILERON ΔC_L REQD.	ND	.062	.245	.463
C_L REQD. AT V2 (ON DOWN-AILERON SIDE)	ND	1.812 (3)	1.995 (3)	2.213 (3)
C_L MAX. REQD. AT VMCA (4) (ON DOWN-AILERON SIDE)	ND	2.32	2.55	2.83 (5)
C_L MAX. REQD. AT VS (4) (POWER OFF)	ND	2.46	2.62	2.80

NOTES: 1. CRITICAL ENGINE, TORQUE ADDITIVE
2. PROP-FANS COUNTER ROTATING, TORQUE SUBTRACTS FROM ROLL MOMENT
3. BASIC WING C_L REQUIRED = 1.75
4. VMCA = 115 Kt, STALL SPEED (VS) = 108.3 Kt
5. THIS CASE SIZES AILERONS AND FLAPS

(c) the large asymmetric thrust, OEI, and the asymmetric aileron drag forced the adoption of a T-tail and a larger fin. The drag and weight of these was allowed for. Also the rolling moment produced by the fin side-force was included.

GROSS WEIGHT AT TAKE-OFF, 130 Kt AT SEA LEVEL

Analysis of the baseline fan-jet indicated that at Design Gross Weight, OEI, sea level standard day, at V2 (130 Kt), the 1.2% climb gradient was critical and required the operative engine to develop 110 percent of the standard take-off thrust, Table 5. Water/methanol injection would be required at higher altitudes.

TABLE 5. DRAG ANALYSIS AT TAKE-OFF OEI AT 1.2 VS (130 Kt SLS)

		FAN JET (BASELINE)	RIGID HUB PROP-FAN	FLEX-HUB PROP-FAN
GROSS WEIGHT	LB	300,000	320,000	342,000
TAIL DOWNLOAD (1), REL. TO BASELINE	LBF	0	3,900 (2)	3,800 (2)
GROSS WING LIFT REQD.	LBF	300,000	323,900 (3)	345,800 (4)
PROPULSIVE LIFT	LBF	0	23,900	45,800
PROPULSIVE DRAG	LBF	0	4,345	5,948
BASIC WING LIFT REQD.	LBF	300,000	300,000	300,000
BASIC WING DRAG (5)	LBF	30,000	30,000	30,000
FUSELAGE, H-TAIL, LANDING GEAR	LBF	2,850	2,950	3,055
DEAD FAN OR PROP	LBF	220	285	285
FIN DRAG	LBF	2,496	2,900	3,326
AILERON DRAG	LBF	0	300	894
CLIMB DRAG (1.2% GRADIENT)	LBF	3,600	3,840	4,104
TOTAL DRAG	LBF	39,166	44,620	47,612
SHP AVAIL., INSTALLED (@1.1 T.O.P., SLS, 130 Kt)	SHP	33,000	33,000	33,000
PROPULSIVE EFFICIENCY	ND	.472	.560	.592
TRANSMISSION EFFICIENCY	ND	1.0	0.97	0.97
THRUST AVAILABLE (@1.1 T.O.P.,SLS, 130 Kt)	LBF	39,166	45,039	47,612

NOTES: 1. THRUST LINE RAISED 6 FT RELATIVE TO BASELINE
2. TAIL ARM INCREASED WITH FUSELAGE STRETCH
3. WING LIFT LIMIT
4. LIMITED BY THRUST AVAILABLE
5. EXCLUDES TRIM DRAG

Converting the baseline aircraft to rigid-hub prop-fans allowed the Design Gross Weight to grow to 320,000 lbs. At this weight the wing lift was critical while there was about 1% of prop-fan thrust in reserve. To preserve the same stall speed, the increase in wing loading called for the maximum wing lift coefficient at take-off (CLMTO) to be increased from 2.46 to 2.62. This was achieved by changing from a single slotted flap to a double slotted flap. A final iteration would be to extend the wing span slightly but that was outside the scope of this study.

Converting from rigid-hub to flex-hub prop-fans allowed the Design Gross Weight to increase from 320,000 lb. to 342,000 lbs. At this weight the thrust-available was limiting, while only 82% of the OEI propulsive lift could be used. The OEI roll moment also forced the CLMTO up to 2.83 (probably calling for triple slotted flaps). A final iteration would be to investigate a smaller prop-fan diameter or to extend the wing span. These were also outside the groundrules of the study.

However, the increases in Design Gross Weight, for the same engine core-size, were substantial and the next step was to examine cruise performance.

DRAG ANALYSIS AT INITIAL CRUISE, M 0.8 AT 35,000 FT.

Analysis of the baseline aircraft indicated, Table 6, that at initial cruise it had an L/D of 14.9 and a thrust requirement of 19673 lbs. By the study groundrules, this was achieved at 90 percent Maximum Continuous Power (MCP). This thrust was also reasonable when compared with the E3 turbofan data of ref. (5).

TABLE 6. DRAG ANALYSIS AT INITIAL CRUISE M 0.8 AT 35,000 FT

		FAN-JET (BASELINE)	RIGID-HUB PROP-FAN	FLEX-HUB PROP-FAN
DESIGN GROSS WEIGHT	LB	300,000	320,000	342,000
GROSS WEIGHT, INITIAL CRUISE	LB	294,000	314,000	336,000
PROPULSIVE LIFT	LBF	0	15,000	15,000
PROPULSIVE DRAG	LBF	0	1,500	1,500
BASIC WING DRAG	LBF	10,737	10,998	12,043
FUSELAGE & REMAINDER	LBF	8,936	9,651	10,299
TOTAL DRAG	LBF	19,673	22,149	23,842
L/D	ND	14.9	14.2	14.1
PROPULSIVE EFFICIENCY	ND	.65	.8	.8
TRANSMISSION EFFICIENCY	ND	1.00	.97	.97
THRUST AVAILABLE MCP (1)	LBF	21,859	26,096	26,096
INITIAL CRUISE, % MCP	ND	90.0	84.9	91.4

1. MAXIMUM CONTINUOUS POWER, BOTH ENGINES, INSTALLED

For the prop-fan aircraft, the propulsive lift and drag was obtained by the same method as for take-off. The thrust available was obtained by ratioing the propulsive efficiencies, from the baseline aircraft.

Thus, the rigid-hub prop-fan aircraft was found to achieve initial cruise at 84.9 percent MCP at 320,000 lb. TOGW. The flex-hub prop-fan aircraft achieved initial cruise at 91.4 percent MCP at 342,000 lbs. TOGW. Both were considered to be close enough to 90 percent for mission analysis to proceed.

MISSION ANALYSIS, RANGE = 2000 nm

The mission analysis, Table 7, compared aircraft performance in three mission segments: climb, cruise and hold/divert.

The climb segment analyzed performance for the three aircraft at 250 Kt EAS at 15,000 ft., (315 Kt TAS).

For the baseline aircraft, fan-jet data for a bypass ratio of 7, ref. 11, indicated that the climb thrust available would be 40420 lbs. for both engines, at an s.f.c. of 0.552 lb/hr/lb. Since the core size was the same, the fuel flow was held constant for all three aircraft. Thrust available was ratiod by the propulsive efficiencies from Figure 3. Resulting climb rates and fuel required are shown in Table 7.

The cruise segment was calculated at one average weight for the remainder of the 2000 nm mission. Cruise drag was calculated with the same approach as for take-off drag. An installed thrust s.f.c. of 0.57 lb/hr/lb was selected for the baseline aircraft as being typical of 1990 technology. The prop-fan thrust s.f.c. was considered to be 12.5 percent less, per ref. 5.

The hold/divert/reserves part of the mission was considered to be equivalent to 2 hours at 225 Kt at 10,000 ft. The baseline aircraft thrust s.f.c. was 0.531 lb/hr/lb,

TABLE 7. MISSION ANALYSIS

		FAN-JET BASELINE	RIGID-HUB PROP-FAN	FLEX-HUB PROP-FAN
TO GW	LB	300,000	320,000	342,000
1. CLIMB, SL TO 35,000 FT				
GW, AVERAGE	LB	297,000	317,000	339,000
SPEED, TRUE (1)	Kt	315	315	315
L/D	ND	15.0	13.2	13.6
DRAG	LB	19,995	23,982	24,868
THRUST	LBF	40,420	51,740	51,740
FUEL FLOW (2)	LB/HR	22,304	22,304	22,304
RATE OF CLIMB	FT/MIN	2,195	2,794	2,517
FUEL	LB	5,933	4,662	5,169
DISTANCE	NM	84	66	73
2. CRUISE M0.8, 35,000 FT				
GW, AVERAGE	LB	272,000	293,000	313,000
L/D	ND	14.4	13.6	13.7
DRAG	LB	18,850	21,560	22,830
THRUST SFC	LB/HR/LB	.57	.499(3)	.499 (3)
FUEL	LB	44,615	45,105	47,580
DISTANCE	NM	1,916	1,934	1,927
MISSION FUEL BURNT	LB	50,548	49,767	52,749
RANGE	NM	2,000	2,000	2,000
3. HOLD & DIVERT, 2 HRS AT 225 KT, 10,000 FT				
GW, AVERAGE	LB	241,100	263,100	281,400
L/D	ND	15.4	14.6	14.3
DRAG	LB	15,650	18,010	19,690
THRUST SFC	LB/HR/LB	.531	.398 (4)	.398 (4)
FUEL	LB	16,624	14,336	15,676
TOTAL FUEL CARRIED	LB	67,172	64,103	68,425

NOTES
1. CLIMB PERFORMANCE SHOWN AT 15,000 FT. ALTITUDE
2. SAME CORE-SIZE, SAME FUEL FLOW
3. 12.5 PERCENT REDUCTION FROM FAN-JET
4. 25 PERCENT REDUCTION FROM FAN-JET

ref. 11, and the prop-fan aircraft were considered to have a 25 percent reduction in thrust s.f.c. to .398 lb/hr/lb.

The mission fuel burnt, and fuel carried, are shown in Table 7.

EMPTY WEIGHT ESTIMATE

The airframe weight estimate, Table 8, was based heavily on the baseline aircraft which is considered typical for airliners entering service in 1982-1983. Thus the empty weights do not reflect a large use of advanced composites. The propulsion systems were estimated to be of the same design technology level, if design for each began in 1980-81.

TABLE 8. EMPTY WEIGHT ESTIMATE

		FAN-JET BASELINE	RIGID-HUB PROP-FAN	FLEX-HUB PROP-FAN
DESIGN PARAMETERS				
DESIGN GROSS WEIGHT	LB	300,000	320,000	342,000
C_L MAX. AT TAKE OFF		2.46	2.62	2.80
THRUST/ENGINE, IRP,SLS	LBF	46,500	51,000	51,000
NO. OF SEATS	NO	232	255	280
GROUP WEIGHTS				
PROPULSION, INSTALLED	LB	18,600	23,400	23,400
FUSELAGE	LB	60,000	64,000	70,000
WING	LB	31,810	33,000	34,200
FIN	LB	1,800	3,700	4,300
H-TAIL	LB	3,600	3,800	4,100
LANDING GEAR	LB	15,000	16,000	17,100
FUEL SYSTEM	LB	6,720	6,410	6,845
REMAINING SYSTEMS	LB	29,350	30,350	31,350
FURNISHINGS & BASIC ACOUSTICS	LB	9,600	10,200	11,250
EXTRA ACOUSTICS, PROP-FAN	LB	0	3,200	3,200
OPERATING WEIGHT EMPTY		176,480	194,060	205,745
OWE/GW		.588	.606	.602
FUEL CARRIED	LB	67,172	64,103	68,425
PASSENGERS @ 235 LB (1)	LB	54,520	59,925	65,800
CREW, COCKPIT @ 250 LB EACH	LB	750	750	750
CREW, CABIN @ 200 LB EACH	LB	1,000	1,200	1,200
TAKE-OFF GROSS WEIGHT	LB	299,922	320,038	341,920

NOTE: 1. INCLUDES PASSENGER, BAGGAGE, FOOD, WATER, SAFETY EGUIPMENT.

The rigid-hub and flex-hub propulsion group weights were estimated to be the same. There is a possibility that the flex-hub prop-fans will have a substantially lower blade weight, which will balance the more complex control system.

The ratios, for operating weight empty, for the three aircraft were .588, .606, and .602. These allowed substantial increases in useful load for each of the prop-fan aircraft.

SUMMARY OF AIRCRAFT PERFORMANCE

The prop-fan aircraft both carried substantially increased passenger payloads, Table 9. The rigid-hub prop-fan, even though heavier than the fan-jet, burnt slightly less fuel than the fan-jet. The flex-hub prop-fan payload was 21 percent greater than that for the fan-jet but it burnt only 4.3 percent more fuel. The fuel used (U.S. gallons per available seat-statute mile) was 68.7, 76.5 and 79.5. A brief analysis of direct operating costs (U.S. cents per available seat-statute mile) indicated that the rigid-hub prop-fan aircraft would be 6.3 percent less than the baseline aircraft, and the flex-hub prop-fan aircraft would be 9.4 percent less than the baseline aircraft.

TABLE 9. SUMMARY: AIRCRAFT & MISSION

COMMON:	TWO ENGINES	30,000	E SHP (EACH)
	WING AREA	3,000	SQ FT
	SPAN	155	FT
	CRUISE M 0.8 AT	35,000	FT
	RANGE	2,000	NMI
	FUEL COST	$1.50	US GALLON

		FAN-JET BASELINE	RIGID-HUB PROP-FAN	FLEX-HUB PROP-FAN
WING- LOADING	PSF	100	106.7	114
TAKE OFF C_L MAX	ND	2.46	2.62	2.80
PROP/FAN DIA.	FT	8	20	20
DGW	LB	300,000	320,000	342,000
OWE, LB	LB	176,480	194,060	205,745
OWE/DGW	ND	.588	.606	.602
FUEL BURNT	US GALLON	7,777	7,656	8,115
PASSENGERS	NO	232	255	280
FUEL INDEX	SSMPG	68.7	76.5	79.5
DOC ¢/SEAT MILE		BASE	BASE-6.3%	BASE-9.4%

It is felt that the flex-hub prop-fan aircraft has sufficient potential to justify further research. Also there are some additional interesting features as described next.

ADDITIONAL FEATURES OF FLEX-HUB PROP-FAN

LATERAL CYCLIC TO REDUCE INDUCED DRAG

Lateral cyclic blade-pitch, in combination with a hub flexure, has the capability to deflect the "full circle" of slipstream, laterally outwards, towards the wing-tip trailing vortices (Figure 11). The possibility exists of moving the trailing vortices outwards, or even destroying them, and thereby reducing the induced drag. It is beyond the state-of-the-art to calculate this effect closely, but a simple analysis indicated that a 5 percent reduction in induced drag (similar to the effect of winglets) may be possible in climb, and during loiter, at high wing lift

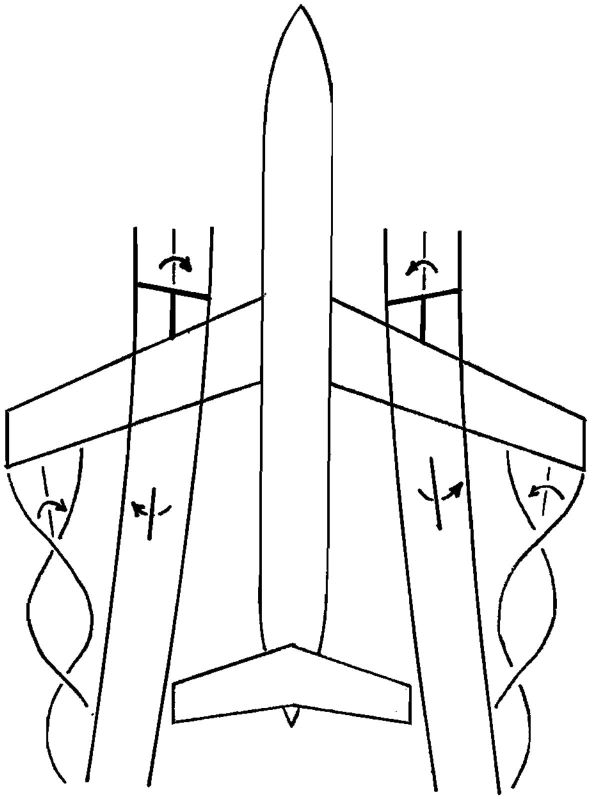

FIG. 11 LATERAL CYCLIC PITCH MAY DEFLECT WING-TIP VORTICES OUTWARDS

coefficients. The value of a 5% reduction in induced drag was calculated, Table 10, and is shown to have a life cycle value for a fleet of 100 aircraft of $134 million. This effect should be researched, with carefully Froude-scaled flight hardware. It should be noted that lateral cyclic pitch applied to a rigid-hub prop-fan would produce only a "semi-circle" of slipstream, of higher velocity, but less outward lateral deflection. The difference is thought to be significant.

TABLE 10. LIFETIME VALUE OF A 5% REDUCTION IN INDUCED DRAG IN CLIMB & HOLD

FUEL SAVING IN CLIMB	45	LB
FUEL SAVING IN HOLD & DIVERT	386	LB
TOTAL FUEL SAVING	431	LB (1)
LIFETIME VALUE	$1.34	M/AIRCRAFT
FLEET LIFETIME VALUE	$134	M/100 AIRCRAFT

NOTE: 1. EQUIV. TO 90.7% OF ONE EXTRA PASSENGER (& RELATED STRUCTURE)

2. REVENUE $.08/SEAT MILE, LOAD FACTOR 60%, BLOCK SPEED 400 MPH, UTILIZATION 3500 HRS/YEAR FOR 20 YEARS

LATERAL CYCLIC TO IMPROVE CROSS-WIND CONTROL

By deflecting the prop-fan thrust vectors into the cross-wind on final approach, a side force can be developed which should significantly reduce the angle of bank or crab, and ease pilot workload.

BLADE DE-ICING WITH LATERAL CYCLIC

A high frequency (30-50 Herz) lateral cyclic "buzz" could set up a progression of anti-nodes, from the tip to the root of the blade, to progressively shed ice in small fragments. This could eliminate the need for electrical deicing. A typical duty cycle in heavy icing could be 10 seconds of cyclic "buzz" every 1-2 minutes. The passengers would possibly never feel the vibration. Again, this effect needs to be researched.

SOFTER IN-PLANE GUST RESPONSE WITH A FLEX-HUB

During a vertical gust the flex-hub prop-fan begins to flap to relieve asymmetric moments. The rate of build-up of in-plane force is about half that of a rigid-hub prop-fan. This will reduce the aeroelastic torsional moments on the wing and improve ride quality.

APPLICATION TO M 0.8 STOL AIRCRAFT

Inflow angles exceeding 20 degrees are experienced on STOL aircraft, such as the YC-14 and YC-15, when developing wing lift coefficients around 5, at take-off, at 80-100 Kt. The flex-hub prop-fan's ability to produce high propulsive efficiency and propulsive lift, in these conditions, make it a candidate. At these take-off speeds, a trade study should investigate an interconnect shaft between the prop-fans to eliminate asymmetric lift and thrust. Substantial increases in payload are predicted.

CONCLUSIONS

This paper has outlined the quantitive and qualitative advantages of the flex-hub prop-fan. The discussion of many of the features is intended to stimulate research into this interesting and potentially cost-effective propulsion system. It is felt that the combination of performance and control features will justify the additional complexity compared to the conventional rigid-hub prop-fan.

REFERENCES

1. Rosen, G., "Prop-Fan, A High Thrust, Low Noise Propulsor." SAE Paper 710470, U.S.A., May 1971.
2. Dugan, J.F., et al, "Advanced Turboprop Technology Development." AIAA Paper 77-1223, U.S.A., August 1977.
3. Conlon, J.A., et al, "Application of Advanced High Speed Turboprop Technology." AIAA Paper 78-1487, U.S.A., August 1978.
4. Nored, D.L., Conference on Propeller Propulsion, NASA-Lewis Research Center, U.S.A., April 1980.
5. Neitzel, R.E., et al, "Basic Engine Considerations for Turboprop Propulsion Systems." Ibid, April 1980.
6. Wernicke, K.G., "Tilt-Proprotor Composite Aircraft, Design State of the Art." American Helicopter Society Paper, May 1968.
7. Gaffey, T.M., "Effect of Positive Pitch-Flap Coupling on Rotor Blade Motion." American Helicopter Society Paper, May 1968.
8. Guinn, K.F., "A Preliminary Investigation of Individual Blade Control Independent of a Swashplate." Rotor Systems Design Specialists Meeting, American

Helicopter Society, Philadelphia, U.S.A., October 1980.

9. Smelt, R., et al, "Estimation of Increase in Lift Due to Slipstream." Aeronautical Research Council, England, R & M 1788, 1937.
10. Glauert, H.,. "Elements of Aerofoil and Airscrew Theory." Textbook, Cambridge University Press, U.K., 1948.
11. General Electric Company, "Preliminary T64-F1B Turbofan Performance Data, Bypass Ratio 7 : 1." U.S.A., May 1965.