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Application of Advanced High-Speed Turboprop Technology to Civil Short-Haul Transport Aircraft

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With an overall goal of defining the needs and requirements for short-haul transport aircraft research and development, the objective of this paper is to determine the performance and noise impact of short-haul transport aircraft designed with an advanced turboprop propulsion system. This propulsion system features high-speed propellers that have more blades and reduced diameters. Aircraft are designed for short and medium field lengths; mission block fuel and direct operating costs (DOC) are used as performance measures. The propeller diameter was optimized to minimize DOC. Two methods are employed to estimate the weight of the acoustic treatment needed to reduce interior noise to an acceptable level. Results show decreasing gross weight, block fuel, DOC, engine size, and optimum propfan diameter with increasing field length. The choice of acoustic treatment method has a significant effect on the aircraft design. Only the tuned structure aircraft have the potential of meeting of a goal of a 90 EPNL contour area of 2.6 km^2 (1.0 mile).

Introduction

THE significant increase in fuel price to commercial airlines over the past four years has shifted the emphasis in aeronautical research and technology to fuel conservation. NASA has several research and technology programs grouped under the title of Aircraft Energy Efficiency (ACEE). Projects in aerodynamics, structures, and propulsion are all ongoing within the ACEE program.

Propfan technology is one of these projects, and application of this technology represents a departure from recent transport aircraft design, in that the propulsion system is a turboshaft engine/gearbox/propeller combination rather than the turbofan that is commonplace on today's aircraft. The typical propeller design has 8-10 blades and high disk loadings, thus reduced diameter and advanced spar shell construction. At cruise, the helical tip Mach number is supersonic, thus the tips are swept back for both noise and performance reasons.

The potential performance improvements of propfan-powered air transports have been demonstrated in the Reduced Energy for Commercial Air Transportation (RECAT) studies conducted for the Ames Research Center by Boeing, Lockheed, and Douglas.[1-3] These studies showed the payoff for the propfan will be the greatest for short-haul air transports because of the greater premium on improved climb performance.

Because the propeller tips will be slightly supersonic during cruise, a particular concern is the possibility of unacceptable noise levels in the cabin. Both Boeing and Lockheed in the RECAT studies analyzed in detail the cabin noise problem and estimated weight penalties for the additional fuselage treatment required to obtain cabin noise levels equivalent to the turbofan-powered aircraft. Each company took a different approach and there are significant differences in the estimated weights of the acoustic treatment necessary to reduce cabin noise to an acceptable level.

The objective of this paper is to determine if the application of the propfan concept to a civil short-haul aircraft design represents a promising area for technology development. In this study, various design and performance parameters were determined as a function of field length for conceptual propfan aircraft. Also, the effect of the two different fuselage acoustic treatment methods, the "tuned structure"[6] and the double-wall "limp-mass"[1] concepts, was investigated for the design point aircraft. The community noise impact, in terms of the 90 EPNL contour area, was assessed, and a sensitivity analysis was performed to assess the effect of propfan diameter, tip speed, design cruise Mach number, and fuselage-to-blade tip clearance on the aircraft design.

Preliminary Design Methodology

Aircraft Configuration

The propfan aircraft were designed to carry 150 passengers on a 925 km (500 n.mi.) mission. Both aircraft had wing-mounted engines and were twin-engine, narrow-body designs with six-abreast seating, and 0.86 m (34 in.) seat pitch all tourist-class passenger cabin configurations.

The wings of both aircraft have aspect ratios of 10 and a quarter-chord sweep of 20 deg. The aircraft use leading-edge slats and double-slotted trailing-edge flaps. The propfan configuration aerodynamics included the same incremental drag and lower wing divergence Mach number penalties to account for the propfan slipstream that were used in Ref. 1. No powered lift due to slipstream effects was taken into account during the takeoff and landing. The effect of swirl upon the wing aerodynamics was not taken into account.

Aircraft Propulsion

The propulsion system selected for study was a Hamilton Standard propfan coupled with the Allison PD370-22 ad-

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vanced turbofan engine. The eight-bladed, 224 m/s (800 ft/s) tip speed propfan was chosen for the baseline configuration with performance characteristics taken from Ref. 4. The PD370-22 engine was scaled with airflow for aircraft sizing. Engine weight was scaled with shaft horsepower, and gearbox weight was computed as a function of horsepower and gear ratio, as detailed in Ref. 5. Propfan weight was computed as a function of diameter and power loading (SHP/D^2) as outlined in Ref. 4.

Acquisition cost for the propfan was based on unpublished Hamilton Standard data, with the turboshaft engine cost based on RECAT study results. For direct operating cost (DOC) calculation, the total maintenance cost of the propfan and turboshaft engine was assumed to be equal to the engine maintenance cost of an equivalent turbofan with thrust reversers.

Aircraft Sizing Method

The propfan aircraft were sized to satisfy certain cruise, takeoff, and landing field length requirements. The cruise sizing requirement consisted of a minimum cruise capability of Mach number 0.75 at an altitude of 9150 m (30,000 ft). Field lengths of 900, 1200, and 1500 m (3000, 4000, and 5000 ft) for a sea-level hot day of 308 K (90°F) were studied. The fuel price used was 7.9¢/liter (30¢/gal). Final design point cruise altitude selection was based on minimum mission DOC.

Each aircraft was sized with several propfan diameters to meet the cruise requirement at each field length. The takeoff and climb performance of the cruise-sized aircraft was then computed to determine if that aircraft could satisfy all the requirements associated with field length and climb gradients specified by FAR Part 25. If not, the aircraft was resized to satisfy the field length requirements and the cruise performance was then determined. The aircraft that yielded the lowest DOC was chosen as the final design aircraft.

Acoustic Treatment Methods

Propfan concept aircraft were studied by Boeing and Lockheed during recent NASA contracted studies.[1,3] In these studies, the two contractors used different acoustic treatment methods for reducing interior propeller noise to levels comparable to those of an equivalent turbofan aircraft. Boeing adopted a tuned-structure approach, and Lockheed chose a double-wall limp-mass treatment scheme. Because these two acoustic treatment methods have markedly different noise-level/frequency/weight characteristics, propfan aircraft incorporating both treatment methods were studied in this paper. One difference between the two methods is that the double-wall acoustic treatment weight estimation is a strong function of the blade-passage frequency, while the tuned structure is not. With the double-wall method, the higher the frequency the less acoustic treatment weight needed. In contrast, the tuned-structure method assumes higher acoustic weight penalties with higher sound pressure level at the fuselage exterior.

The acoustic treatment weight estimation for the tuned-structure concept is shown in Fig. 1. This curve, from Ref. 1, shows the incremental acoustic treatment weight as a function of the near-field external sound pressure level. This treatment weight represents the mass that must be added to the fuselage of the propfan aircraft in order to obtain an interior noise level environment equal to that of a comparable turbofan aircraft.

The acoustic treatment weight for the double-wall concept is also shown in Fig. 1 as a function of the fundamental blade passage frequency (FBPF) and the external sound pressure level of the blade passage tone. This correlation was computed based on the data presented in Ref. 6. Unlike the tuned structure, the double-wall acoustic treatment weight estimation is a strong function of the blade passage frequency.

The acoustic treatment weight estimation methods were incorporated into the aircraft synthesis computer program[7] using the Hamilton Standard propfan noise calculation procedures presented in Ref. 4. Knowing the propfan operating characteristics, the overall sound pressure level was computed. Corrections were made for directivity, harmonic levels, and blade tip clearance to determine the sound pressure level of the blade passage tone.

Results

Wing Loading

For the propfan aircraft, the design wing loading for a given landing field length is a function of the maximum lift coefficient and the approach speed-to-stall speed ratio, and is independent of the propulsion system size. A maximum lift coefficient of 3.4 in the landing configuration, representative of an advanced slotted flap and leading-edge device, was assumed. The approach speed was determined by the field length and a 4.57 m/s (900 ft/min) approach rate of sink constraint. Combined with an FAR Part 25 approach speed-to-stall speed ratio of 1.3 and the maximum lift coefficient of 3.4, the required wing loading was determined as a function of the field length. With the general trend of decreasing DOC's with higher wing loadings, the landing field length constrained wing loading produced the minimum DOC aircraft for a given field length. The final design wing loading as a function of field length is presented in Fig. 2. The rotation speeds corresponding to these wing loadings are also shown in Fig. 2.

Propfan Diameter

Each aircraft was sized with several propfan diameters to meet the takeoff, landing, and cruise requirements of each field length. The propfan diameter that yielded the minimum

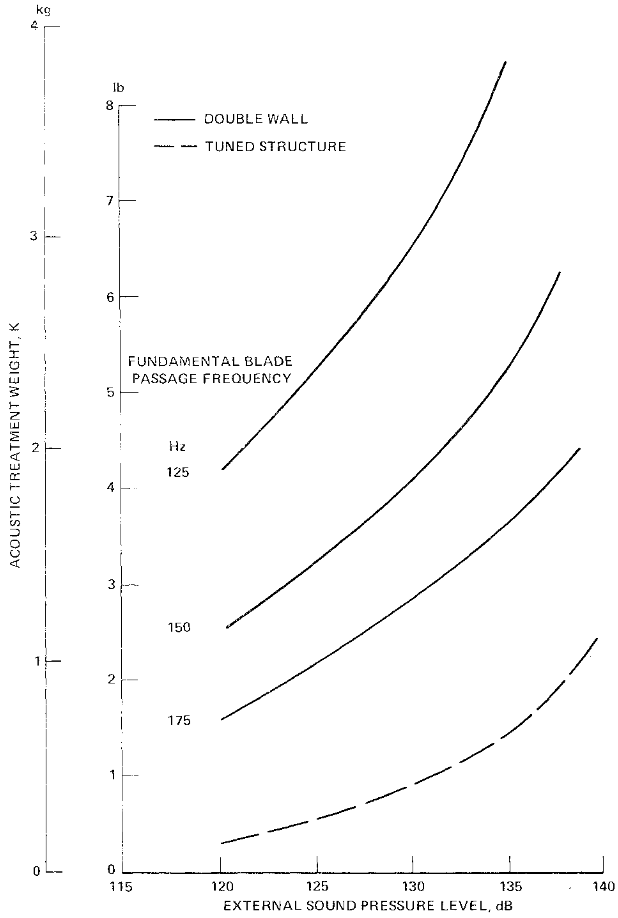

Fig. 1 Acoustic treatment weight (dB re: 0.0002 μbars, k = 1000).

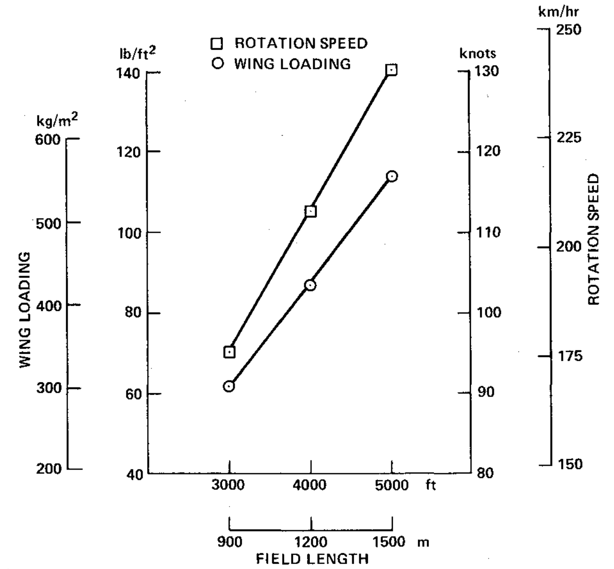

Fig. 2 Design wing loading and rotation speed vs field length.

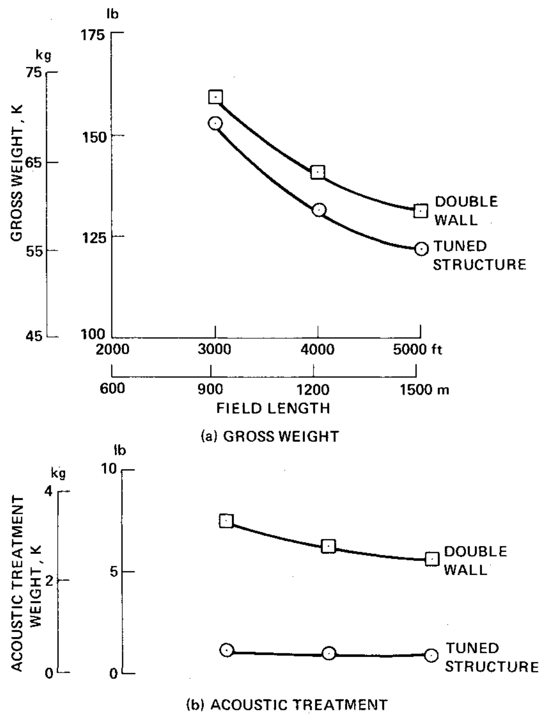

Fig. 3 Gross weight and acoustic treatment weight vs field length.

DOC at each field length was then determined. The sensitivity of DOC to propfan diameter will be discussed in another section of the paper. The optimum propfan diameters were 5.33, 5.03, and 4.88 m (17.5, 16.5, and 16 ft) for the tuned-structure aircraft, and 4.88, 4.57, and 4.42 m (16, 15, and 14.5 ft) for the double-wall aircraft for the respective field lengths of 900, 1200, and 1500 m (3000, 4000, and 5000 ft). The tuned-structure aircraft was sized by the cruise requirement at all field lengths and easily met the takeoff field length requirement with the optimum cruise-sized propfans. However, this was not true for the aircraft using the double-wall treatment method. These aircraft were sized by a combination of the cruise requirement and the takeoff field length constraint. This is because the double-wall treatment method favors smaller propfan diameters.

The trend for both the tuned-structure and double-wall aircraft is decreasing propfan diameter with increasing field length. As the field length increases, less thrust is needed and,

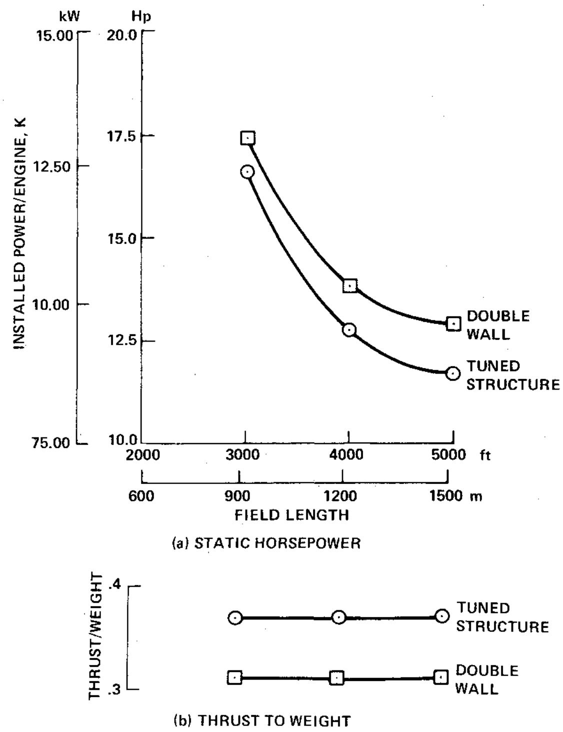

Fig. 4 Static horsepower and thrust-to-weight ratio vs field length.

therefore, the propfan diameter decreases. At all field lengths, the tuned-structure aircraft have a larger propfan diameter than the double-wall aircraft. This difference is due to the fact that the acoustic treatment weight of the double-wall treatment method is highly frequency-dependent—the higher the frequency, the less acoustic treatment weight required. Therefore, for a fixed tip speed, the smaller propfan diameter results in a higher frequency which leads to lower acoustic treatment weight and lower gross weight. This causes the double-wall aircraft to favor smaller propfan diameters than the tuned-structure aircraft.

Cruise Point

Presented in Table 1 are the cruise Mach number and cruise altitude for the design point aircraft that result in minimum design-mission DOC. All aircraft cruise at normal cruise power setting. The cruise Mach number associated with this power setting yielded the lowest DOC.

Gross Weight and Acoustic Treatment Weight

Presented in Fig. 3a is a plot of gross weight for the minimum DOC configurations as a function of field length. Both aircraft show decreasing gross weight with increasing field length, due to the higher wing loadings at the longer field lengths. The difference in gross weight between the two aircraft is caused by the higher acoustic treatment weight needed for the double-wall aircraft. Approximately one-half the difference in gross weight is attributable to the difference in acoustic treatment weight between the two aircraft. The remaining difference in gross weight is the result of the increased fuel weight, additional airframe weight, and larger engines needed for the heavier aircraft.

Figure 3b shows the acoustic treatment weight vs field length. The acoustic treatment weight for the tuned-structure aircraft remains relatively constant with field length. However, for the double-wall aircraft, the trend is toward decreasing acoustic treatment weight with increasing field length. As discussed before, the weight of the acoustic treatment when the double-wall treatment method is used is dependent on frequency—the higher the frequency, the less the acoustic treatment needed. Therefore, as the design propeller diameter decreases with field length, the fundamental blade passing frequency increases (with fixed tip speed); hence, the amount of acoustic treatment weight decreases.

Static Horsepower and Thrust Loading

Shown in Fig. 4a is the variation of static horsepower with field length. Both aircraft show the same relationship of decreasing field length. Because of its greater gross weight, the double-wall aircraft requires more horsepower than the tuned-structure aircraft. For all the tuned-structure aircraft, the required horsepower was determined by the cruise requirement of a cruise Mach number of 0.75 at an altitude of 9150 m (30,000 ft). The horsepower required for the double-wall aircraft, however, is determined by the takeoff field length constraint and the cruise Mach number requirement.

The maximum thrust-to-weight ratio of the aircraft vs field length is shown in Fig. 4b. The thrust-to-weight ratio for both aircraft remains relatively constant with field length. This characteristic is due to the propeller diameter decreasing with field length, and thus tends to reduce the thrust from the propeller in the same proportions as the reduction in gross weight. The thrust-to-weight ratio of the double-wall aircraft is shown to be less than that of the tuned-structure aircraft, even though the double-wall aircraft requires more power. This is because the smaller propeller diameters of the double-wall aircraft yield less thrust.

Block Fuel and Direct Operating Cost

The variation of DOC with field length for the two aircraft is presented in Fig. 5a. The trend for both aircraft is decreasing DOC with increasing field length, which stems directly from the lower gross weight and block fuel of the aircraft associated with the longer field lengths. The double-wall aircraft shows higher DOC's than the tuned-structure aircraft due to the higher gross weight and block fuel of the double-wall aircraft.

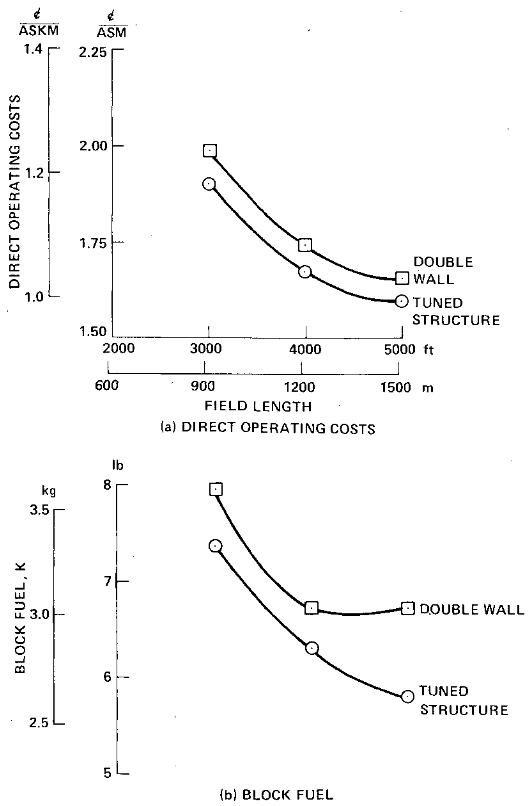

Fig. 5 DOC and block fuel vs field length (ASM - available seat mile, ASKM - available seat kilometer).

Presented in Fig. 5b is the variation of block fuel with field length. Both aircraft show decreasing block fuel with increasing field length due to the decrease in gross weight and required horsepower with increasing field length. The higher block fuel of the double-wall aircraft, compared to that of the tuned-structure aircraft, is due to the larger engines required by the heavier double-wall aircraft.

Aircraft Noise

Community noise impact is an important consideration in aircraft design, especially for aircraft operating into and out of short-haul community airports. As a goal, it is desirable that the 90 effective perceived noise level (EPNL) noise contour be less than 2.6 km^2 (1.0 $mile^2$) in area. This constraint will insure little community noise impact with the 90 EPNL contour possibly flying within the airport boundary.

The noise characteristics of the propfan aircraft were computed using the methods presented in Ref. 4. The perceived noise level (PNL) was computed as a function of propfan diameter and tip speed, horsepower input, helical Mach number, and distance to the observer. A tone correction factor of 2.0 dB was assumed for computing the tone-corrected perceived noise level (PNLT) for both the takeoff and landing power setting. This 2.0 dB factor represents an upper bound for the tone correction in data presented in Ref. 8 for a large turboprop transport. The tone correction was also assumed to be independent of aircraft/observer distance, since the correction factor occurs in the low-frequency region and hence will propagate to the far field, relatively unattenuated by atmospheric absorption effects. Conversion of PNLT to EPNL was made using duration correction data taken from Ref. 8. The duration factor, a function of the slant range distance, was also corrected for different aircraft velocities.

The noise calculations were made using the engine shaft horsepower, optimum propfan diameter, and tip speed determined by the aircraft sizing method for minimum DOC. For all aircraft, a tip speed of 244 m/s (800 ft/s) produced the

Table 1 Cruise Performance

Aircraft acoustics field length, ft	Cruise Mach no.	Cruise[a] altitude, m (ft)
Tuned-structure		
3000	0.761	10,400 (34,000)
4000	0.750	9150 (30,000)
5000	0.750	9150 (30,000)
Double wall		
3000	0.777	10,400 (34,000)
4000	0.768	9150 (30,000)
5000	0.765	7600 (25,000)

[a] Selected for minimum DOC.

Table 2 Noise levels, EPNdB

Aircraft acoustics field length, ft	FAR 36 takeoff	FAR 36 approach	FAR 36 sideline	Takeoff, 500 ft sideline
Tuned structure				
3000	84.8	90.9	92.3	100.3
4000	85.4	93.1	91.5	99.5
5000	85.7	93.7	90.8	99.1
Double wall				
3000	87.6	92.5	93.7	100.8
4000	87.2	94.6	92.4	100.3
5000	88.8	95.3	92.8	100.8

lowest DOC. The sensitivity of DOC of tip speed will be discussed in another section of the paper.

The takeoff profiles were computed for each aircraft for a 100% power all-engine climbout. Power cutbacks on takeoff were not considered. The climbout portion of the takeoff profile was optimized by permitting the flaps to be retracted from the takeoff setting to a value that resulted in the maximum climbout flight path angle when the aircraft had attained an altitude of 120 m (400 ft). The approach flight path angle was determined by the approach speed and the 4.57 m/s (900 ft/min) rate of sink constraint. With the approach speed increasing with increasing field length, the resulting approach flight path angle decreased with field length. The noise levels at the FAR Part 36 measuring points, a 152 m (500 ft) sideline point, and the noise contours were then computed using the calculated EPNL vs slant range curves and the takeoff and landing flight profiles for each design point aircraft.

Presented in Table 2 are the EPNL values at the FAR Part 36 measuring points and at a 152 m (500 ft) sideline takeoff point. All aircraft are below the FAR Part 36, "stage 3" noise levels by a range of 2-9 EPNdB.

Presented in Fig. 6 are the 90 EPNL noise contour areas as a function of field length for the design point aircraft. For both the tuned-structure and double-wall propfans, the contour area increases slightly with longer field length, due mainly to the better climb performance of the shorter field length aircraft which tends to offset the higher noise levels associated with the larger engines of the shorter field length aircraft. The double-wall propfan aircraft exhibited larger contour areas due to their higher gross weights, requiring larger and hence noisier engines and resulting in lower takeoff/climbout flight path angles. None of the final design aircraft meet the desired noise goal of a 90 EPNL contour area of 2.6 km^2 (1.0 $mile^2$).

All the tuned-structure, cruise-sized aircraft had engines larger than necessary to meet the field length requirement. As a result, the takeoff field length of the design point aircraft at full power is less than the required design field length. Because of this extra performance capability, a study was conducted to determine the effect of throttling the engines during takeoff. Throttling the engines would result in lower propfan tip speeds and engine power output, and hence, lower noise levels. This benefit would be offset by longer takeoff ground roll and lower climbout flight path angles associated with the lower thrust level of the throttled engine.

With the engines sized by the cruise requirement, and the optimum tip speed determined by minimum mission DOC considerations, the engine horsepower and gear ratio are fixed. With the engine horsepower fixed, the propfan thrust level cannot be maintained at the lower tip speeds by using higher blade angles. With the gear ratio fixed, throttling the engines results in operating at an off-design condition, hence lower power output. The throttled condition was modeled assuming a constant turbine stage-loading parameter, resulting in power output proportional to the square of the engine speed. This result agrees well for both fixed- and free-shaft turbines over a modest range of engine speed reduction.

For each design point aircraft, the minimum takeoff tip speed which resulted in the all-engine and critical engine-out takeoff distance equal to the design field length was determined. For the engine-out takeoff, the throttle on the remaining engine was advanced to full power after the other engine had failed.

For the 900 and 1200 m (3000 and 4000 ft) aircraft, the noise goal of 2.6 km^2 (1.0 mile) can be met. The takeoff and landing could be performed at about 218 m/s (715 ft/s) tip speed. This corresponds to 89.4% engine speed, which would give adequate engine response time for an emergency or go-around condition. For the 1500 m (5000 ft) aircraft, takeoff tip speed at the required minimum value of 214 m/s (702 ft/s), coupled with an approach tip speed of 207 m/s (680 ft/s), would meet the desired noise goal.

In addition to the noise impact on the community surrounding the airport, there is also the potential noise impact on the enroute community. However, the far-field noise levels due to the supersonic blade tip during cruise and its impact on the enroute community were not determined in this study.

Sensitivity Analyses

Cruise Mach Number

Several cruise Mach numbers, other than the design cruise Mach number, were studied to determine the change in DOC and block fuel with change in cruise Mach number. This was done for both the tuned-structure and the double-wall aircraft for a wing loading of 554 kg/m^2 (113.4 lb/ft^2), which corresponds to the 1500 m (5000 ft) field length. However the takeoff field length requirement was not imposed on either aircraft. Both aircraft were resized to cruise at the particular Mach number at an altitude of 9150 m (30,000 ft). Shown in Fig. 7 are DOC and block fuel as a function of cruise Mach number for the tuned-structure and the double-wall aircraft. Both aircraft show increasing block fuel with increasing cruise

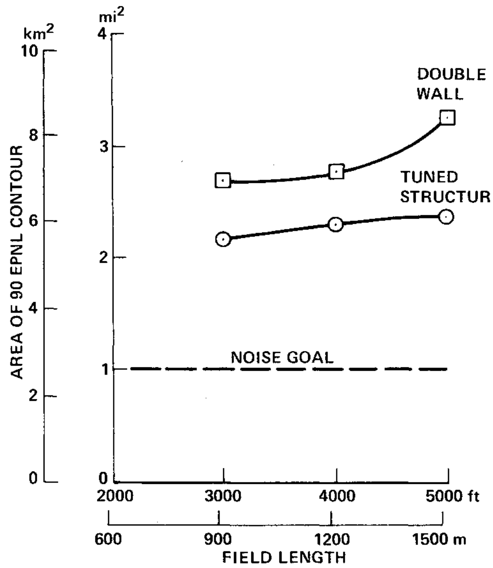

Fig. 6 EPNL contour area vs field length.

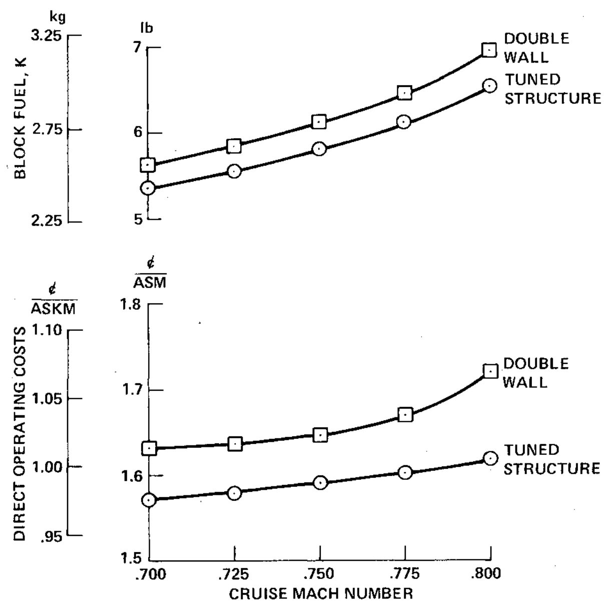

Fig. 7 DOC and block fuel vs cruise Mach number.

Mach number due to the increase in drag. The DOC for both aircraft also increased with increasing cruise Mach number because the increase in aircraft productivity with speed does not compensate for the increase in block fuel. The tuned-structure aircraft yielded lower block fuel and DOC throughout the cruise Mach number range, due mainly to its lower gross weight.

Propeller Tip Speed and Diameter

To determine the effect of tip speed on DOC and block fuel, three different tip speeds were studied: 244, 213, and 198 m/s (800, 700, and 650 ft/s). Again, both the tuned-structure and double-wall aircraft had wing loadings of 554 km/m^2 (113.4 lb/ft^2), which corresponds to the 1500 m (5000 ft) field length aircraft. Although the takeoff field length requirement was not imposed on either aircraft, they were required to meet the cruise requirement of a cruise Mach number of 0.75 at an altitude of 9150 m (30,000 ft). The results are shown in Fig. 8 for the tuned-structure aircraft and in Fig. 9 for the double-wall aircraft. In sizing the aircraft for different tip speeds, the change in propfan weight due to change in tip speed was taken into account.

Presented in Fig. 8 are the changes in block fuel and DOC vs propfan diameter at the three tip speeds for the tuned-structure aircraft. There is no significant variation in DOC or block fuel with propfan diameter. As shown in Fig. 8a, the tip speed of 244 m/s (800 ft/s) yields the lowest DOC. However, there is no significant difference in DOC at the lower tip speeds shown. This tip speed also showed the lowest block fuel of the three tip speeds at all the diameters studied (Fig. 8b). The lower block fuel at the 244 m/s (800 ft/s) tip speed is due simply to the higher efficiency of the propfan at the higher tip speed.

In general all trends with propeller diameter in the range investigated, 4.6-5.5 m (15-18 ft), are quite flat. The optimum is at a diameter of 4.9 m (16 ft), but very little penalty would be incurred with either a slightly smaller or slightly larger propeller diameter.

The change in DOC and block fuel with the change in propeller diameter at the three tip speeds for the double-wall aircraft are shown in Fig. 9. As with the tuned-structure aircraft, the higher tip speeds yield the lowest DOC's and also the lowest block fuels.

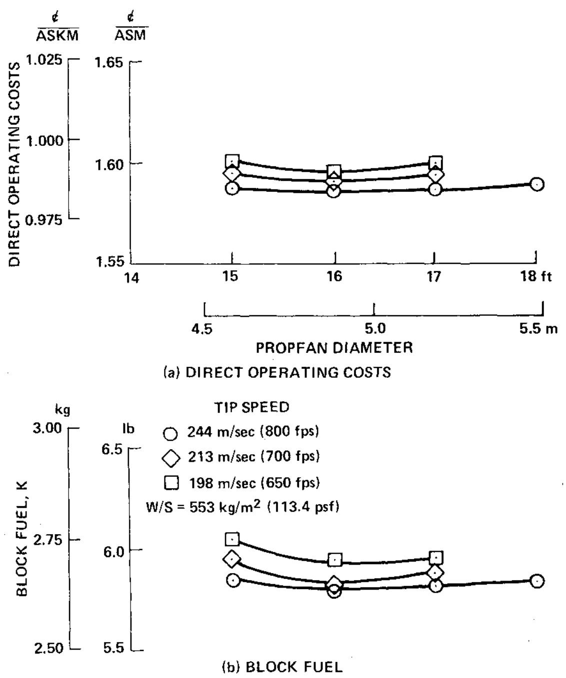

Fig. 8 DOC and block fuel vs propfan diameter for tuned-structure aircraft.

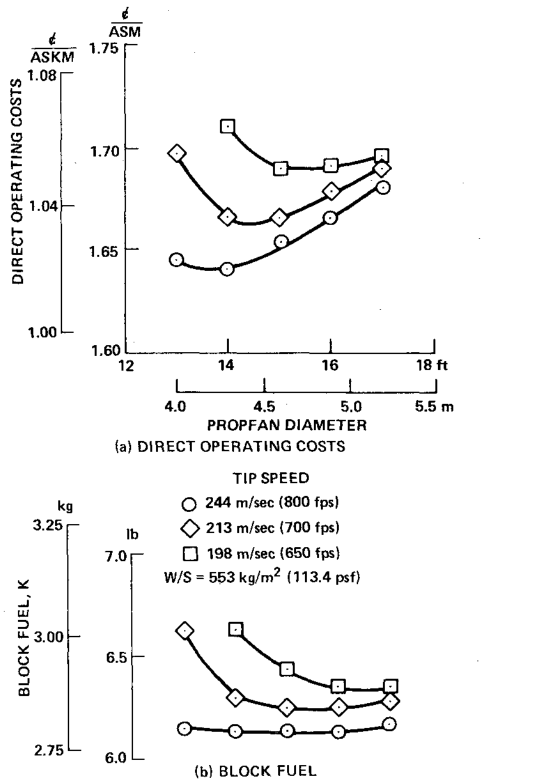

Fig. 9 DOC and block fuel vs propfan diameter for double-wall aircraft.

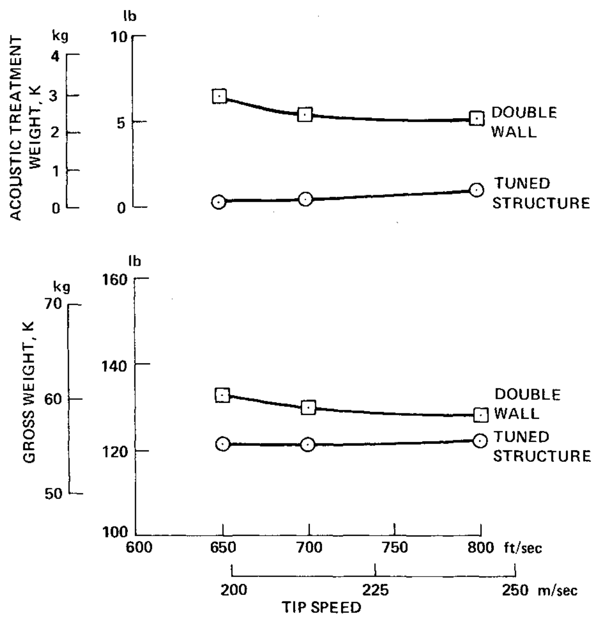

Fig. 10 Gross weight and acoustic treatment weight vs tip speed.

In contrast to the tuned-structure aircraft, the double-wall aircraft shows more pronounced trends with change in propeller diameters. This is because the acoustic treatment weight is dependent on the blade passage frequency and, therefore, the blade tip speed. The optimum, based on minimum DOC, is at a propeller diameter of 4.3 m (14 ft) for a tip speed of 244 m/s (800 ft/s).

Figure 10 shows a plot of the minimum gross weight and acoustic treatment at each tip speed for both the tuned-structure and double-wall aircraft. The double-wall aircraft shows decreasing gross weight with increasing tip speed due to the decrease in acoustic weight. The tuned-structure aircraft shows both lower gross weight and lower acoustic treatment

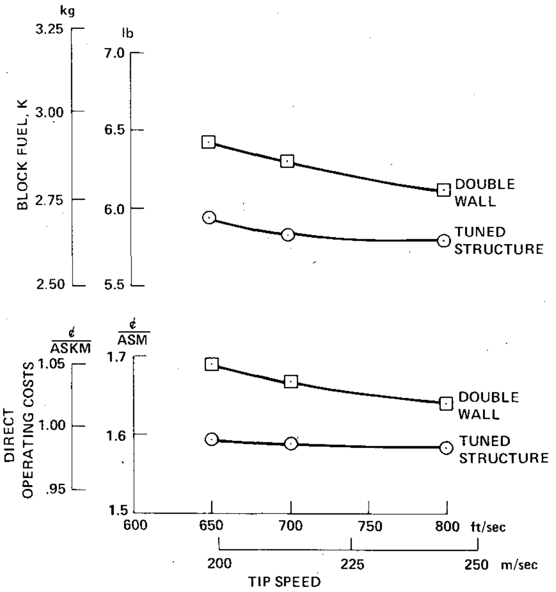

Fig. 11 DOC and block fuel vs tip speed.

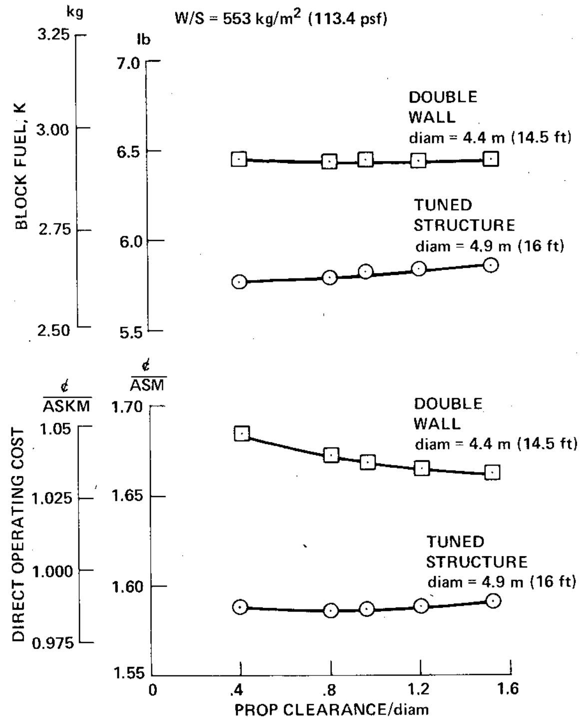

Fig. 12 DOC and block fuel vs fuselage-tip clearance ratio.

weight than the double-wall aircraft, due to the difference in acoustic treatment methods. Unlike the double-wall aircraft, the tuned-structure aircraft shows a slight increase in gross weight with tip speed because of the increase in acoustic treatment weight with tip speed (i.e., higher sound pressure level).

The minimum DOC's and block fuels of both aircraft for each tip speed is shown in Fig. 11. Both aircraft show decreasing DOC and block fuel with increasing tip speed due to the higher propfan efficiencies at the higher tip speeds. The tuned-structure aircraft has both lower DOC and block fuel than the double-wall aircraft. Again, this is due to the lower acoustic treatment required by the tuned-structure acoustic treatment method.

Fuselage-Tip Clearance

Depending on where the engines are positioned on the wing, there will be a tradeoff between the additional weight and drag of the larger vertical tail, which is required as the engine is moved outboard, vs the increase in acoustic treatment weight as the engine is moved inboard. To determine the effect of the engine placement, the DOC and block fuel for the 1500 m (5000 ft) tuned-structure and double-wall aircraft were determined at several fuselage-tip clearance ratios. The clearance ratio is defined as the ratio of the distance between the fuselage and the propeller tip to the diameter of propeller. DOC and block fuels are shown in Fig. 12.

For the tuned-structure aircraft, the block fuel increases slightly with the increase in clearance ratio. This is due to the increase in drag of the larger tail needed as the propfan is moved farther outboard. However, the weight of the additional block fuel and the larger tail is offset by the decrease in acoustic treatment weight with the increase in clearance ratio. Because of this tradeoff in weight, the effect of increasing clearance ratio on DOC is slight.

For the double-wall aircraft, the increase in clearance ratio has no effect on block fuel. This is due to the fact that along with an increase in the size of the vertical tail, there is also a large decrease in acoustic treatment weight with increasing clearance ratio. This decrease in acoustic treatment weight more than compensates for the increase in tail size and results in a decrease in gross weight. This decreased gross weight also results in a decrease in DOC with an increase in clearance ratio.

Conclusions

The RECAT studies have demonstrated both fuel and operating cost savings potential for propfan-powered aircraft compared with conventional turbofan aircraft. These studies addressed civil transport aircraft designed for either medium or long range with cruise Mach numbers greater than 0.75.

With studies providing excellent reference points for both the technology and performance levels, this paper has addressed the propfan concept for short-haul transport aircraft with cruise Mach numbers as low as 0.70. Emphasis has been placed on the problem of reducing cabin noise at cruise, which is severe due to the supersonic Mach numbers at the propeller blade tips. Noise treatment of the fuselage is mandatory to reduce the near-field noise level, and the two methods evaluated—tuned-structure and limp-mass double wall—have surprisingly different impacts on the resulting performance of the aircraft.

For the range of field lengths studied, the gross weight, block fuel, DOC, engine size, and optimum propfan diameter decrease with increasing field length. For optimum propfan diameters, the tuned-structure acoustic treatment method yields lower aircraft gross weight, block fuel, and DOC than the limp-mass, double-wall method. At the field lengths studied, the optimum design was based on lowest DOC. Only the tuned-structure aircraft have the potential of meeting the 90 EPNL contour area goal of 2.6 km^2 (1.0 $mile^2$).

Because of the propfan cruise efficiency and acoustic treatment weight considerations, the 244 m/s (800 ft/s) tip speed produced the minimum DOC aircraft. Lower cruise Mach numbers gave lower block fuel consumption for both aircraft. Finally, a fuselage-to-propfan tip clearance ratio of 0.80 seems near optimum for DOC for the tuned-structure aircraft; the double-wall aircraft showed a continued decrease in DOC with increasing clearance ratio.

The driving factor in almost all trends shown in this study is the acoustic weight penalties. There is an obvious need for experimental research to determine which of the acoustic treatment methods will solve the problem of interior noise and whether the estimates for weight penalties are accurate. The two methods presented here yielded two very different aircraft. The limp-wall method, because of its dependence on high blade passage frequency, leads to smaller, less efficient propellers, larger gross weight, and larger engines than the aircraft designed using the tuned-structure method.

This study demonstrates clearly that the problem the propfan propulsion concept will result in excellent performance for short-haul aircraft. Thus, the trends established in the RECAT studies also existed for short-haul aircraft. For this performance to be realized, continued coordinated research and development efforts must be pursued in the following areas: cabin noise reduction; engine airframe integration; turboprop engine cycle definition; gearbox weight and cost reductions; isolated propeller performance; and far-field noise.

Work is underway in each of these areas to a varying degree. Cabin noise may be the most serious concern and the most difficult problem to solve because of the need for flight testing.

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