Potential Application of Advanced Propulsion Systems to Civil Aircraft

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This paper identifies powerplant options for the 1990s and relates them to Airliner categories. The influence of safety, efficiency, economy, and noise is discussed in relation to obtaining the most suitable powerplant for a given application. The Advanced Feederliner is used as an example to examine effects of the introduction of open rotors on aircraft efficiency and economics.

Introduction

EVOLUTION has been a major factor in the development of airframes and powerplants. Wing design has progressed from the early empirical sections to today's fully-optimized aft-loaded supercritical sections. Civil turbine engines have progressed from turbojets through low-bypass-ratio turbofans to the current high-bypass-ratio turbofans. Propellers have advanced from fixed pitch to variable pitch and are now evolving from unswept single-rotation to counter-rotation Propfans. All these evolutionary processes have been beneficial in increasing aircraft efficiency, but the task of integrating the powerplant with the airframe has become more and more complex.

The last few years have seen a proliferation of proposals for aircraft propulsion systems which must be evaluated against aircraft requirements in order to arrive at the right choice of airframe/powerplant configuration. The choices made during the latter part of this decade will be crucial to the way in which civil transports evolve for service extending well into the next century.

In view of the vast financial investment required for any new major aircraft development, aircraft companies tend to build upon what they know rather than innovate. Aircraft configurations develop along similar lines. The rear-engine jet installation of the Caravelle was the forerunner of the BAe 111, DC9, and Fokker F28/F100. The Trident engine configuration set the style for the Boeing 727. In more recent years, wing-mounted turbofans have dominated the civil market. There is remarkable similarity between the configurations of the Boeing 757 and 767 and the A300, A310, A320, and A330 family and further configurational similarity between the A340 and the Boeing 747. Only Douglas and Fokker have stayed with the rear-engined configuration. New developments in the propulsion scene may lead to reassessment of aircraft configurations in the 1990s. Even so, the majority of commercial aircraft in service at the end of the century will have wing-mounted engines.

The major factors influencing aircraft development are *safety, efficiency, economy*, and *noise*. Safety must be paramount and, like community noise, is covered by legislation. Within these constraints, aircraft designers have the task of integrating aircraft and propulsion systems to create efficient, economic, and competitive aircraft.

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Powerplant Options

Figure 1 shows schematically the categories of advanced powerplants under development for service in the 1990s. "Open rotor" is a generic term covering all noncontained rotors, whether they are advanced propellers, swept Propfans, or unducted fans. For a given standard of core-engine technology, the geared counterrotation open rotor provides the most efficient means of propulsion.

The component parts of the *geared* open rotor—the core engine, gearbox, and propeller assembly—can be configured to provide a pusher or a tractor installation. In the pusher configuration, the gearbox lies inside the engine exhaust system, and in most configurations, the exhaust is discharged across the blade roots. Multilobe exhausts alleviate both these problems to some extent. A tractor installation avoids these problems but requires a longer overhang on a wing installation.

The *ungeared* open rotor or unducted fan (UDF) (UDF is GE proprietary concept) has the advantage of eliminating the gearbox but loses some efficiency because rotor rpm has to match turbine rpm. Rotor rpm is limited for noise reasons so that turbine rpm becomes suboptimum. Some of this lost efficiency is retrieved through the counterrotation of the turbines. The ungeared open rotor concept is based on a free turbine arrangement, which leads naturally to a pusher configuration.

Engine manufacturers are now studying advanced propulsion systems with ultrahigh-bypass-ratio-ducted (UHBR) fans. The presence of the large-diameter duct results in a weight and drag penalty which, at low speeds, is offset by a thrust increase due to the duct. The powerplant can be configured as a pusher installation with a free turbine system similar to that of the ungeared open rotor or with a geared front fan.

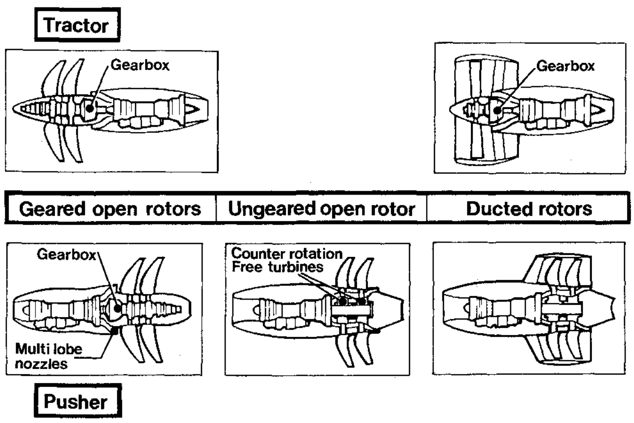

Fig. 1 Advanced powerplant categories.

Table 1 Airframe/powerplant matching

Aircraft category	No. of pass	Typical design mach no.	Typical design range nm	Preferred future powerplant option: Wing-mounted	Preferred future powerplant option: Rear fuse mounted
Small feederliners	30 - 70	0.5	700	Single rotation open rotors	
Large feederliners regional airliners	80 - 120	0.7	1200	Counter-rotation open rotors or advanced ducted rotors (UHBR)	Counter-rotation open rotors
Short/medium haul airliners	150 - 200	0.8	2000	Advanced ducted rotors (UHBR)	Counter-rotation open rotors
High capacity medium haul airliners	300 - 500	0.8	4000		
Long range airliners	250 upwards	0.85	5000– 7000+	Advanced ducted rotors (UHBR)	

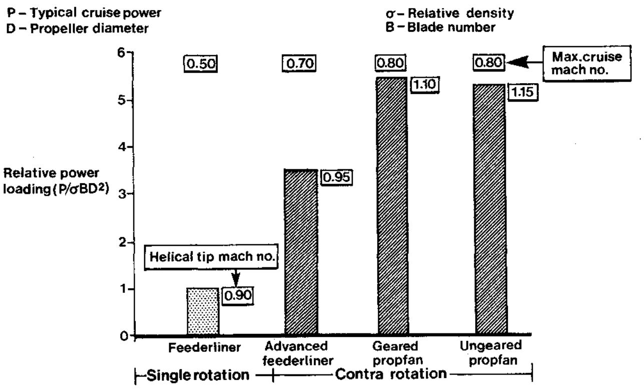

Fig. 2 Propeller power loading.

Safety

Doubts have been expressed with regard to the safety of highly-loaded open rotors operating at high cruising speeds. The safety record of modern propeller blades has been good. Dowty Rotol propellers have not experienced any loss of propeller blades or debris from propeller disintegration due to the propeller design, manufacture, or material faults during 420 million blade flight hours. Hamilton Standard propellers have not experienced any in-flight blade separations during more than 350 million blade flight hours.

Modern propellers are designed with metal or carbon fiber spars with a composite blade in the form of a sheath. With this kind of construction, detachment is generally limited to the blade sheath, which weighs only a few pounds. During an early run on the test bed, the prototype UDF engine shed a blade sheath without damage to any other blade and without any failure of the unit or mounting due to out-of-balance forces. Service experience has shown that foreign objects cause only a shredding of blade materials.

The most severe trajectories of propeller debris release can be predicted and qualitative assessments of likely damage to the aeroplane predicted. By positioning of powerplants, provision of structural redundancy, and careful layout of control systems, the effects of such damage may be alleviated such that the risk of catastrophic failure is reduced to an acceptable level. Ultrahigh-bypass-ratio-ducted rotors can be designed for rotor containment if tip speeds are limited to open-rotor values.

Influence of Noise

The main parameters determining propeller source noise are power loading and helical tip speed, both of which increase as flight speed increases (see Fig. 2). Using a typical current turboprop Feederliner as datum, a Mach 0.7 advanced Feederliner would require a doubling of power loading, whereas a Mach 0.8 Airliner would require power loadings to be increased by a factor of 4 or 5. Limiting propeller tip speeds to around 650 ft/s enables the helical tip speed of the advanced Feederliner to be kept subsonic, whereas the Mach 0.8 Airliner would produce helical tip Mach numbers of 1.1–1.15. This shows that the task of designing a Mach 0.7 aircraft with wing-mounted open rotors is significantly easier than for a Mach 0.8 Airliner, where cabin noise requirements may preclude the location of open rotors on the wing.

British Aerospace are involved in a comprehensive acoustic research program, including flight research, to investigate cabin noise and to demonstrate means of providing an acceptable cabin environment for Mach 0.7 airliners with wing-mounted open rotors. Placing a duct around the rotor to provide source noise containment would enable wing-mounted powerplants to be used on aircraft operating at Mach numbers of 0.8 or higher.

Airframe/Powerplant Matching

Table 1 divides Airliners into categories and identifies the most suitable advanced powerplant configurations for the next new generation of developed aircraft. Small Feederliners with operating speeds up to Mach 0.5 have traditionally been propelled by open rotors, and this trend is continued with aircraft such as the BAe ATP, the Fokker F50, and the Aerospatiale ATR 42. These aircraft have relatively low blade loadings, and slipstream swirl is not a major problem; consequently, the additional complexity of counterrotation is not justified. Blade sweep is not required at these operating speeds.

Larger, faster Feederliners/Regional Airliners currently typified by the turbofan powered BAe 146 may lead in the 1990s to aircraft family developments powered by open rotors or ultrahigh-bypass-ratio-ducted (UHBR) fans. At these speeds, counterrotation begins to show significant benefits in terms of propeller efficiency and lower interference losses due to the virtual elimination of slipstream swirl. Gearboxes become more compact, lighter, and more efficient with reduced cooling requirements. However, blade pitch control systems become more complex.

Short/Medium-haul Airliners and high-capacity medium-haul airliners with cruise Mach numbers up to 0.8 require either open rotor powerplants with swept counterrotation Propfans or advanced turbofans such as the ultrahigh-bypass-ratio-ducted fan. Cabin noise considerations lead to a natural division between rear-engined pusher open rotors and wing-mounted advanced turbofans in this aircraft category. The

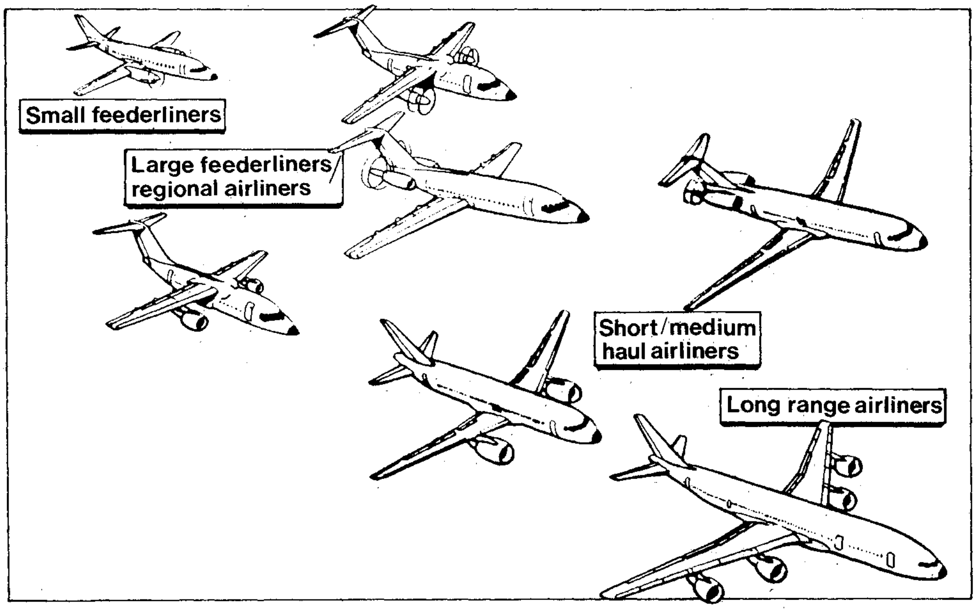

Fig. 3 Likely powerplant airframe options the 1990s.

Fig. 4 BAe 146.

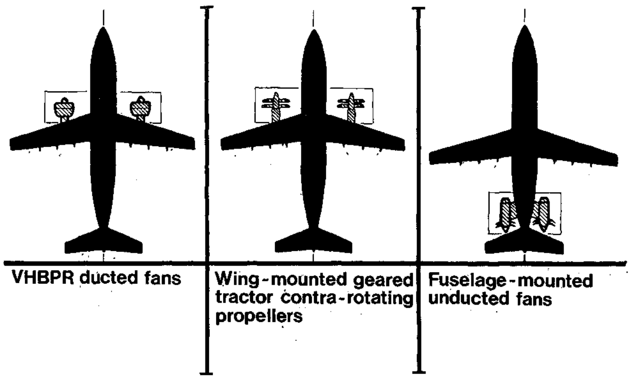

Fig. 5 New propulsion options for mid 1990s.

high-capacity airliners require larger engines where escalation of gearbox size and weight may begin to make geared engines less attractive.

The Mach 0.85 long-range Airliner poses a more severe set of propulsion requirements resulting from the combination of high-speed and high-weight due to the large amount of fuel carried. At Mach 0.85, wing-mounted Propfans become even less viable due to cabin noise constraints, and the propulsion field becomes limited to advanced turbofans, unless acceptable three-engined aircraft configurations can be found. Figure 3 illustrates some of the possible aircraft configurations under study for service in the 1990s.

Advanced Feederliner

Each category of aircraft generates it own set of powerplant requirements. For the purpose of this paper we will examine one category in more detail—that of the advanced Feederliner/Regional Airliner. For this kind of operation, field performance is an important parameter. With stage lengths averaging 200 nm, a high proportion of flying time is spent in climb and descent. This obviously has a bearing on powerplant characteristics as well as the aircraft configuration.

It is worth examining the design philosophy behind the BAe 146 (see Fig. 4), which was designed specifically to fulfill this role. The BAe 146 is powered by four high-bypass-ratio turbofan engines. Development of the turbofan engines and further aircraft stretch will enable the 146 to remain competitive well into the 1990s.

The high wing location is beneficial in providing good field performance. Continuity of the lifting surface across the fuselage coupled with continuous flaps extending out to 70% of the span accounts for the high $C_L$max (3.4) achieved by the BAe 146 without leading edge devices. The high wing enables engines to be mounted under the wing with a good ground clearance. Location of the fuselage close to the ground facilitates quick loading and unloading of passengers or freight with good access to aircraft services for a quick turnaround. The high wing and high tail combination enables the installation of ultrahigh-bypass-turbofan or open-rotor powerplants to provide further improvements in fuel efficiency in the longer term.

Figure 5 shows some of the aircraft configuration options suitable for an Advanced Feederliner/Regional Airliner. The first two powerplant options suit the characteristics of the BAe 146 airframe. The pusher open-rotor powerplant is more suited to a rear-engined installation, as shown in the figure.

For this class of aircraft, the building blocks will be available to develop tractor or pusher open-rotor powerplants for service in the early 1990s. There is currently no firm proposal for an ultrahigh-bypass-turbofan at this size. Table 2 compares the characteristics of aircraft configured with wing-mounted open rotors with aircraft configured with rear-mounted open rotors.

Figure 6[1] shows an aircraft development with wing-mounted counterrotating open rotors based upon a BAe 146 Airframe. The engine installation is illustrated in Fig. 7.

Coaxial counterrotating open rotors offer significant advantage to the airframe designer compared with single rotation: 1) higher rotor propulsive efficiency, 2) reduction in disc diameter with less loss of efficiency, 3) lighter, more compact, more efficient gearbox, and 4) reduction in gearbox oil cooling requirements. In the particular case of a wing-mounted, tractor engine installation for a derivative aircraft cruising at M0.65, there are three further advantages: 1) fewer blades per disc—less intake blockage, 2) elimination of need to contour the wing to remove slipstream swirl; no requirement for handing gearboxes, and 3) possibility of lowering tip speed to reduce source noise without loss of propeller efficiency.

Incentives

Aeronautical engineers are continually striving for improvements in efficiency. The performance of the powerplant is the largest single factor contributing to aircraft efficiency. Powerplant efficiency relates directly to fuel that needs to be carried. Improved powerplant efficiency not only reduces fuel consumption but results in a lighter aircraft to perform the same task or in increased range for the same fuel capacity.

The main incentive is fuel economy. Figure 8 compares fuel breakdowns for the Feederliner shown in Fig. 6 powered by upswept contraprops driven by derivative turboshaft engines with a similar airframe powered by the best proposed turbofan derivatives. Block fuel savings of 27% are predicted over a typical stage length of 200 nm. Currently this class of aircraft makes the equivalent of 3,500 such flights a year. With fuel at $1.00 per U.S. gallon, this would represent a saving of $4.5 million per year for an operator with a fleet of ten aircraft.

For a derivative aircraft, savings in block fuel and reserve fuel can be used to increase payload or range. The fuel savings shown in Fig. 8 would enable design range to be increased by around 45% for equal fuel capacity.

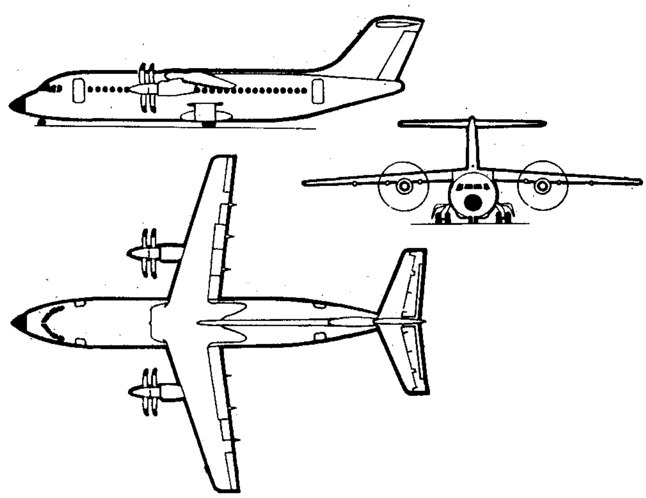

Fig. 6 120-seater advanced open-rotor Feederliner/regional airliner.

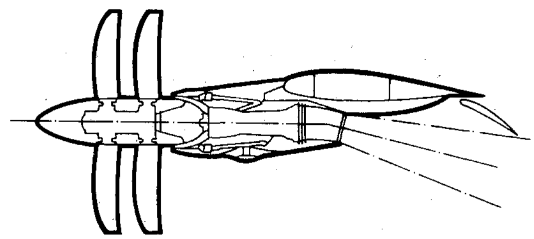

Fig. 7 Wing-mounted open-rotor powerplant installation.

Table 2 Wing vs rear fuselage-mounted rotors

	Wing-mounted open rotors	Rear-fuselage-mounted open rotors
Preferred wing location	High	Low
Preferred propeller configuration	Tractor contrarotating	Pusher contrarotating
Propeller environment	Clean air entering Props but high upwash at high incidence	Props in wing downwash and pylon wake fields. High probability of EOD.
Thrust line/trim drag	Thrust line on center of drag—no trim drag penalty	High thrust line required to provide Prop/Ground clearance—trim drag penalty
Cabin noise and vibration	Need to minimize source noise and provide additional cabin soundproofing or active or active noise control	Alleviation of airborne transmitted cabin noise. Structural-borne noise and vibration at rear of cabin could be worse
Community noise	Measures to limit source noise should avoid a community noise problem	Could be a community noise problem, particularly with high tip speed required by gearless option
Wing design	Design constrained due to presence of engines	Clean wing with more design flexibility
Flexibility for other roles	Suitable for two or four engine layouts. Same powerplant could be used for military applications requiring four engines	Rear fuselage installation limits configuration to two (or three) engines—precludes four engined solution

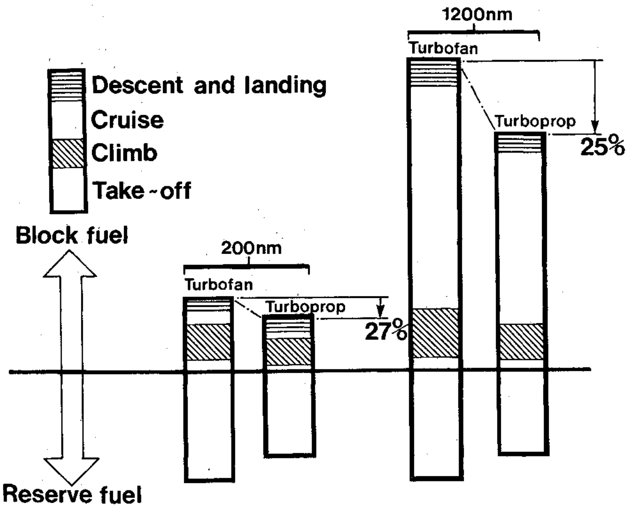

Fig. 8 High-speed Feederliners fuel breakdowns.

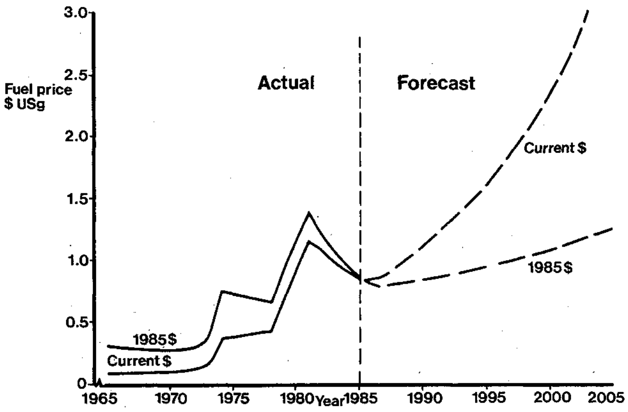

Fig. 9 Jet kerosene prices (U.S. international operators).

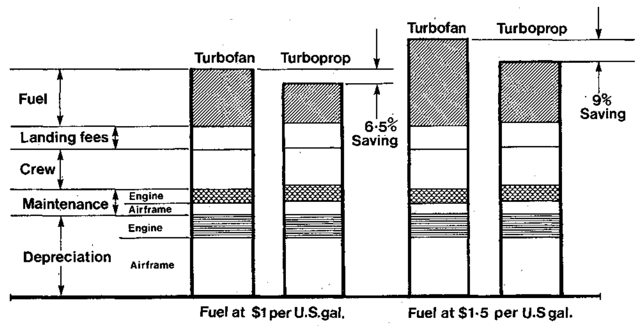

Fig. 10 120-seat Feederliner DOC breakdowns 200-nm stage, including interest fees and cabin crew, for equal powerplant price.

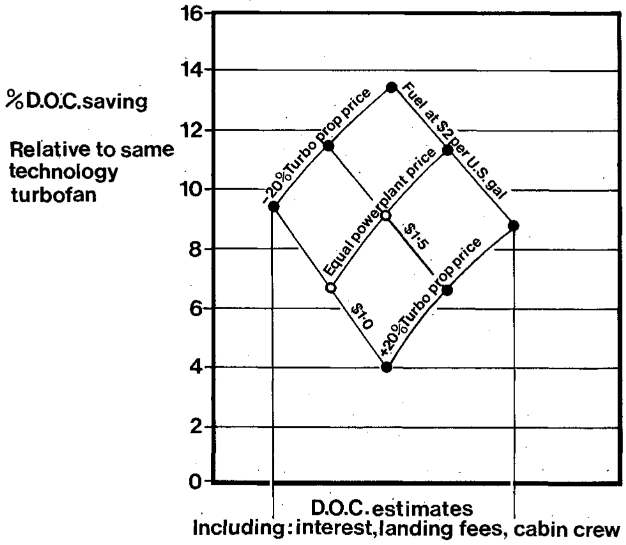

Fig. 11 120-seat Feederliner/regional airliner DOC sensitivity over 200-nm stage.

Economics of Change

The tradeoff between efficiency and cost is the determining factor influencing the economics of change. Fuel price is a key factor. In 1986, a dramatic fall in the price of oil occurred due to the collective failure of the world's oil producers to conserve their resources and balance supply and demand. But the situation is unlikely to continue indefinitely. Figure 9[2] indicates that fuel prices are likely to return to around $1.00 per U.S. gallon in real terms by 1995. From then on, fuel prices might be expected to rise again due to the increased cost of obtaining oil from less accessible fields or from resorting to synthetic fuels. Oil demand for nonaeronautical purposes appears to be on the decline, which may place a premium on the small proportion of the barrel suitable for aeroengines. However, predictions can be upset if there are more oil crises similar to those that forced oil prices through the roof in the late 1970s.

If an economic case can be made for aircraft entering service in the mid 1990s powered by new fuel-efficient propulsion systems with fuel at $1.00 per U.S. gallon, the economic advantage can be expected to increase during the service life, which will extend into the next century. Studies have shown that for short/medium haul aircraft, a 20% change in fuel consumption has the same effect on operating cost as a 10% change in aircraft price or a 40% change in powerplant cost if engine price comprises 25% of aircraft cost.

Figure 10 compares the DOC breakdown over a typical 200-nm stage for turboprop and the turbofan-powered Feederliners using the fuel savings shown in Fig. 8. The effects of interest, fees, and cabin crew are included, and the total powerplant cost per aircraft is assumed to be equal. On this basis, a DOC saving of 6.5% is predicted with fuel at $1.00 per U.S. gallon rising to 9% with fuel at $1.50 per U.S. gallon.

Powerplant depreciation can account for as much as 11% of the aircraft DOC on a 200-nm stage. Figure 11 shows sensitivity of DOC to fuel price and powerplant price.

A 20% increase in turboprop price relative to the turbofan would result in the DOC advantage being reduced by around 3%. For study purposes, it has been assumed that half the maintenance costs are proportional to first cost, and half proportional to engine size, with maintenance costs for the turboprop increased by 10% relative to the turbofan. A 20% change in maintenance costs changes DOC by 1%.

For this class of aircraft, a lower engine price resulting from the saving in development costs consequent upon using an existing engine core could outweigh the DOC advantage resulting from the greater fuel efficiency of a higher priced all-new powerplant. Development costs of all-new powerplants might, however, be alleviated by the use of a new engine core having multiple applications.

Conclusions

1) Contrarotating open rotors provide the most efficient known means of propulsion for aircraft cruising at Mach numbers between 0.6 and 0.8.

2) Considerations of safety, efficiency, economy, and noise determine the best match of powerplant and airframe for a given aircraft configuration. There is no universal powerplant configuration that will suit all needs.

3) An Advanced Feederliner can show a block fuel advan-

tage of 27% and a range increase of 45% by replacing turbofan engines with counterrotating open-rotor powerplants. DOC savings of 6.5% are predicted for equal powerplant costs and fuel at $1.00 per U.S. gallon.

4) Efficiency has to be balanced against cost. The DOC advantage of a 20% reduction in fuel usage can be cancelled out by a 10% increase in aircraft price or a 40% increase in powerplant price.

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References

[1]Blythe, A.A. and Smith, P., "Prospects and Problems of Advanced Open Rotors for Commercial Aircraft," AIAA Paper 85-1191, July 1985.

[2]Smith, P., "Designing for Competitiveness in Civil Aircraft," paper for British Aviation Exhibition Seminar at Dehli/Bangalore, India, Nov. 1985.