Trends in Aircraft Propulsion

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Propulsion requirements for the next generation of civil aircraft are examined and some new and quite demanding needs are defined—larger engine sizes, higher takeoff thrusts, and much lower noise levels. The remarkable propulsion advances over the past two decades are charted and, from these, projections are made for the next round of improvements. All of the propulsion systems considered incorporate advanced technology gas turbine engines coupled with propulsors having a broad range of bypass ratio—from fans to propellers. This encompasses a new class of high-thrust, low-noise propulsor—the Prop-Fan—which is introduced as a needed intermediate propulsor between today's fans and propellers. This widening scope of available propulsors is shown to offer the aircraft designer much more flexibility in powerplant selection and a better opportunity to optimalize his design. Although the primary focus is on civil aviation, wherever appropriate the commonality with military requirements has been indicated.

Introduction

THE aerospace industry has been witness to some giant strides in the field of propulsion. From its very beginnings—the bent whalebone which powered George Cayley's helicopter top, Hiram Maxim's steam engine, Charles Manley's gasoline engine, the Wright Brothers' aerodynamically designed propellers, Sanford Moss's turbo supercharger, the parallel conception of the controllable pitch propeller by Frank Caldwell and Wallace Turnbull, Frank Whittle's jet engine, and Robert Goddard's rocket motors—its history has been replete with inspired breakthroughs. Each not only heralded a new era in aviation, but set an ever increasing pace for technological advances. A full perusal of this fascinating history is, unfortunately, beyond the scope of this paper, but a brief review of the accelerated propulsion developments of the past two decades does seem appropriate to set the stage for a projection of the next round of advancements.

In keeping with today's aim at improved air transport, primary consideration is directed to the propulsion needs for civil aviation. This, in itself, can span some broad categories of aircraft types ranging from the short haul to the intercontinental transports, from the few seater to the airbus, and from the subsonic, to the transonic, to the supersonic and even to the hypersonic. To maintain some reasonable bounds for the paper, the focus has been narrowed to concentrate on subsonic aircraft, and, in particular, those that appear most apt to materialize during the next 10–15 yr. They can be categorized as: a) 750–1000 passenger intercontinental transport, b) 300–500 passenger airbus, c) 150–200 passenger medium-range STOL, d) 50–100 passenger short-range STOL, and e) advanced general aviation aircraft.

Admittedly, there are other classes of aircraft such as the transonic, supersonic and VTOL transports which may be even more demanding of propulsion, but each involves rather special considerations that warrant separate treatment. However, even the five selected subsonic types call for some extreme excursions in propulsion size, type, and sophistication requirements. Yet, any consideration of developing specialized powerplants tailored to each different type and size of civil aircraft is, obviously, impractical. This, then, is the challenge to the propulsion industry, and is one which has been accepted with a confidence born of its past accomplishments.

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Requirements

The next generation of civil aircraft will certainly continue the usual demands for better thrust/weight, less fuel consumption, improved reliability and reduced cost. Each of these requirements merit varying emphasis depending on the class of vehicle: low fuel consumption for the long range aircraft; high takeoff thrust/weight for the STOL; low initial cost for general aviation. In addition to these, there are some new requirements which tend to compound the task for the propulsion designer.

One is the increasing severity of matching the vehicle thrust requirements over its full operating range. This has become more pronounced with the advent of VTOL and STOL and their inherent higher takeoff thrust needs. Thrust matching can be illustrated crudely by using a simplified parameter—the ratio of takeoff thrust/cruise thrust. In Fig. 1, the vehicle thrust requirements and the propulsor thrust available characteristics are plotted in terms of this parameter for the representative aircraft and propulsor types. Each intersection of the superimposed bands represents a good match of vehicle and powerplant. From this it is evident why turboprops have

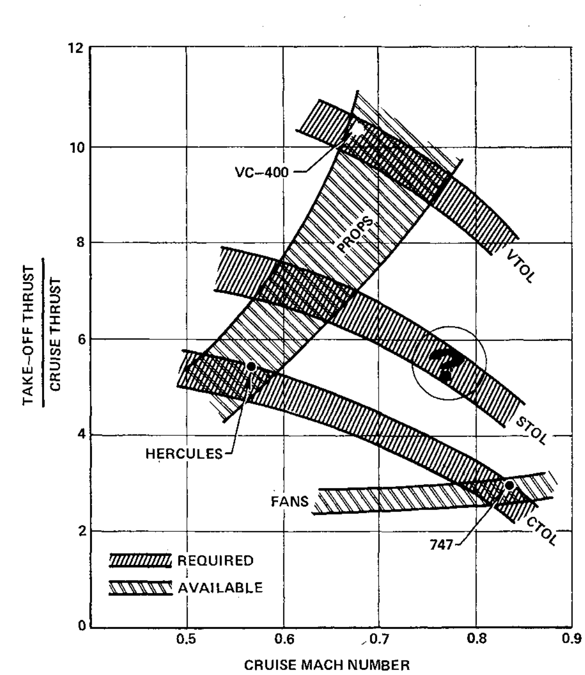

Fig. 1 Propulsor matching (transports).

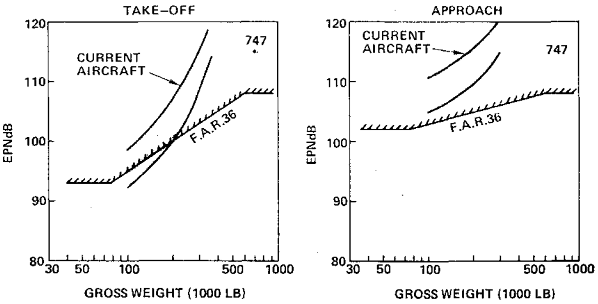

Fig. 2 Civil transport noise levels.

been effective for the 0.5–0.6 M conventional take-off and landing (CTOL) aircraft and why it was necessary to go to turbofans for the 0.8–0.85 M CTOL's.

In looking at the STOL case, it is also clear that the turboprop can still provide a good fit for the short-haul STOL with cruise speeds up to M = 0.65. However, for the medium-haul STOL, which may want to cruise at M = 0.75–0.80, neither prop nor fan seem to fit, and there is an apparent need for a new class of intermediate propulsor. It is interesting to observe that there is another potentially good match for this intermediate propulsor—the future 0.85–0.90 M VTOL.

Such performance requirements have added a new dimension to propulsion design, but there are also other novel demands on the designer. To keep up with the times, he has found it necessary to add a new word to his vocabulary—ecology. Much like the automobile, the growth of air traffic has raised the specter of untenable atmospheric pollution due to engine emissions. However, it is acoustic pollution that is, potentially an even more restrictive concern. Although good progress is being made toward the "clean engine" by improved combustion, noise generation could become a serious deterent to the growth of aviation if nothing were done to offset the trend of increasing noise level with powerplant size. Thus to assure some measure of acoustic control, the civil regulatory authorities have set definite certification limits for CTOL aircraft (Fig. 2) and are considering much tighter limits for V/STOL. To meet these requirements will take more drastic measures than merely trying to suppress the noise generated by today's high performance powerplants. There is no doubt, from the foregoing, that we are facing a widening and more demanding set of propulsion requirements for civil aviation. Thus it seems appropriate to scrutinize the recent trends in propulsion and, from these, to try to project the potentials for the next decade.

Propulsion Trends

Aircraft propulsion can be subdivided into two prime elements: the basic engine to generate power and the propulsor to convert the power to useful thrust. It is generally conceded that, for the subsonic transports, the gas turbine offers the most attractive power source by virtue of its compactness, reliability, efficiency, and favorable power-to-weight ratio. Its only drawback appears in the smaller-sized general aviation applications where its high initial cost relative to the simple reciprocating engine becomes prohibitive. Even this limitation may be removed if current efforts aimed at design simplification and the application of new production processes with high-volume tooling to the small gas turbine engine should prove successful.

Gas Turbine

Many technological advances have been made in the gas turbine during its short life span. One measure of this progress is the trend in specific power or thrust (SHP/Wa or T/Wa) as plotted in Fig. 3. The 50% improvement over the past 15–20 yrs has come, primarily, as a result of continuing refinement in thermodynamic efficiency through higher turbine inlet temperature (T.I.T.) and over-all pressure ratio (O.P.R.). Thus, it is most encouraging to observe that the engine designer can still project an additional 65% improvement for the 1980 engine. The attainment of this target does take some doing, however. It calls for T.I.T. ~ 2700°F and O.P.R. ~ 30 : 1 but these appear feasible with the use of the new metallic and fiber composite materials combined with new cooling techniques in the critical engine components. Such technology advances are currently under development for military engines and should be available for the civil market in the time frame plotted in Fig. 3.

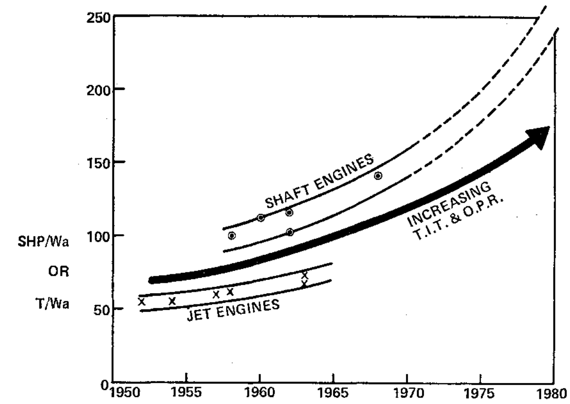

Fig. 3 Gas turbine technology trend.

Propulsor

To derive the full benefit from this advancing engine technology requires a parallel effort in propulsor technology. The several categories of propulsors which are potential candidates all depend on the principle of accelerating a mass of air to produce thrust and, therefore, can be considered parts of a single continuous spectrum (Fig. 4) of air propulsors. Yet, they each have unique configuration and operational differences, best suited to their individual operating regimes, and thus do not tend to overlap. Until quite recently there have been two significant gaps in this spectrum—one between rotors and propellers and the other between propellers and fans. The former is of specific interest for VTOL and thus will not be discussed here.

It is the region between propellers and fans that demands our attention, since some of the new civil aircraft types, such as the advanced STOL, seem to have thrust requirements (Fig. 1)

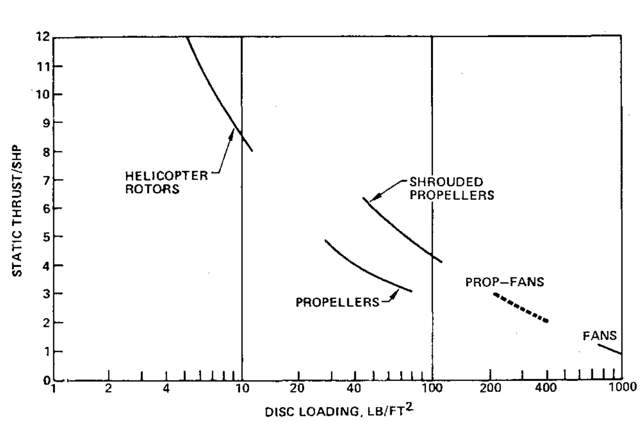

Fig. 4 Propulsion spectrum.

which tend to fall in this area. This requirement began to surface several years ago and led to the conception of a new propulsor type—the Prop-Fan.[1] As its name implies, the Prop-Fan offers a synthesis of the best features of its progenitors. It is aimed at combining the good noise and takeoff thrust characteristics of the turboprop with the good high-speed cruise performance and compactness of the turbofan.

The description and development status of the Prop-Fan was presented in Ref. 1 and need not be detailed here. It can be defined, in terms of its basic geometry, as a controllable pitch fan with 8–12 blades, 1.10–1.20 pressure ratio, and 700–750 fps tip speed. Its performance and acoustic characteristics have been substantiated by model tests, and sufficient design concepting has been completed to establish its mechanical feasibility and to provide generalized weight data. Other potential advantages of the Prop-Fan are low drag for engine-out, fast thrust response (forward and reverse) and elimination of flow reversers on the ducting.

It is worthy of note that these higher bypass ratios are much more feasible, today, due to less weight penalties associated with their trend toward larger fans. This is attributable to two factors—the large weight gain achieved with controllable pitch reversing compared to flow reversers, and the much more favorable blade weight trends afforded by recent developments of durable, lightweight blade structures. A new blade design technology has evolved which not only utilizes advanced materials such as fiber composites, but designs the blade structure to derive the maximum benefit of the physical properties of each material. One attractive construction which has been developed is a hollow blade comprised of a metal spar and a fiber composite shell. This blade technology can be applied effectively to all propulsors but does offer increasing advantages as blades get larger. It has been the availability of this new technology which has made it possible to introduce the Prop-Fan as a new and important member of the family of propulsors for subsonic aircraft.

At this point it may be well to clarify the parameter, bypass ratio, since there is a tendency to misuse it for propulsor classification. In truth, pressure ratio is the more exact classifier of propulsors. Bypass ratio rather describes the complete powerplant package since it is defined as the ratio of propulsor flow divided by gas generator flow. This makes it a function of fan pressure ratio (P.R.) and engine specific power (*SHP*/*Wa*). Since the latter term varies with level of engine technology, there can be no unique value of bypass ratio for a given propulsor configuration. The trend curve of SHP/Wa from Fig. 3 was used in preparing the bypass ratio chart presented in Fig. 5. This chart will serve to define the general bounds of bypass ratio for the different propulsor types. In the following, all of these—the propeller, the Prop-Fan and the fan—will be evaluated comparatively for the several pertinent classes of civil aviation but with somewhat more emphasis on the STOL transport.

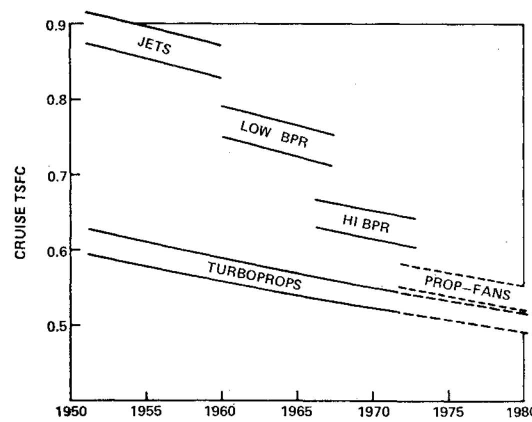

Fig. 6 Specific fuel consumption trend.

Specific Fuel Consumption

For moderate and long-range transports, fuel consumption is the most important factor affecting aircraft DOC. Thus the trend of specific fuel consumption shown in Fig. 6 is very provocative. Starting with turboprops in the mid-fifties at a comfortable level of around 0.60 tsfc, the change to the pure jet engines increased the fuel consumption by nearly 50%. This was a steep price to pay for speed, and it is not surprising that the turbojets were quickly replaced by the more efficient low-bypass fans (B.P.R. ~ 1 : 1), and more recently by the high-bypass fans (B.P.R. ~ 6 : 1).

The next logical step is to go to the even higher bypass Prop-Fan (B.P.R. 20 : 1—30 : 1), for which another sizeable gain in fuel consumption of about 15% can be projected. However, the turboprop has also been profitting from the continuing improvement in thermal efficiency of the gas turbine and this has enabled it to maintain a modest advantage in tsfc. Thus, for short stage length transports where high cruising speed is not needed, the turboprop must still be considered an attractive propulsor candidate.

Thrust/Weight

An equally dramatic trend in thrust/weight ratio for powerplants is plotted in Fig. 7. Again we see a progression of stepped improvements over the years. The basic slope has been due primarily to the weight reductions achieved by refined design and better materials, whereas each step change has come as a result of the improved takeoff thrusts associated with the successive increases in bypass ratio. VTOL lift engines are not included in this comparison because of their

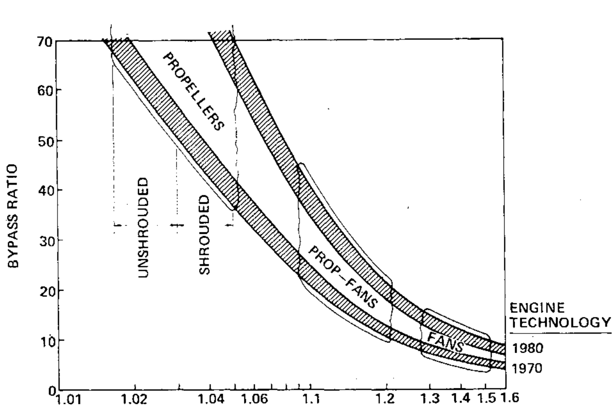

Fig. 5 Bypass ratio trend.

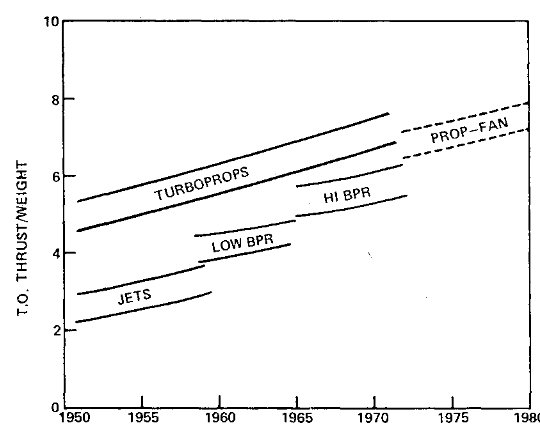

Fig. 7 Specific thrust trend.

specialized requirements. The projection of this trend to show another 25% increase in thrust/weight ratio for the Prop-Fan represents a reasonable extension of the advanced technology programs currently under development.

Operating Costs

The favorable trends in powerplant thrust/weight and fuel consumption have contributed substantially to the continually improving transport operating costs (Fig. 8) which have paced the growth of civil aviation. These gains in D.O.C. are even more remarkable when viewed against more than a 2 : 1 monetary inflation over the past 20 yr.

Based on the previous projected powerplant improvements it appears reasonable to forecast another 20% reduction in D.O.C. for the conventional transport of the next decade. STOL's will, of course, have higher D.O.C. due to their smaller aircraft, shorter stage lengths and relatively higher installed power. This should improve quickly, however, as larger, faster STOL aircraft are developed. The STOL curve shown on Fig. 8 represents a correlation of recent industry estimates of several turboprop and Prop-Fan STOL transports.

Noise

Fortunately, the trend toward the more lightly loaded, higher bypass propulsors has been consistent with reduced noise generation. When examined on the basis of total thrust produced, it can be seen in Fig. 9 that jets and high tip speed propellers both started high on the annoyance scale. With the progression toward more lightly loaded propulsors and correspondingly lower tip speeds has come an improvement of about 20 PNdB in noise level. High bypass ratio has been an important adjunct to these achievements, by virtue of its reduced jet energy. Comparable reductions in jet noise to those attained in the propulsor were needed to produce a balanced low noise generation from both the front and rear of the powerplant.

Recent efforts to effect further improvements have been reasonably productive. In the case of propellers, new criteria have been derived for quieter STOL propellers and have been demonstrated in full scale. For fan engines, the attention has been directed to improved techniques of suppressing the fan, compressor and jet noise by duct wall treatment, suppressor rings and choked inlets. These are quite effective but do involve varying degrees of performance, weight and cost penalties which the aircraft designer must assess in his tradeoff studies.

A new noise consideration has been introduced by the externally-blown flap configuration which is currently favored for civil STOL transport. Recent investigations[2] have indicated that there is a significant noise source from the jet

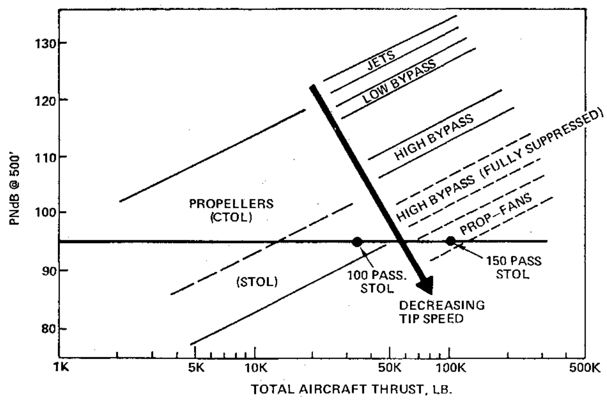

Fig. 9 Sideline noise trend.

stream impinging on the large deflected flaps. This interaction noise has been found to be a function of fan pressure ratio and this trend has been plotted in Fig. 10 for comparison with fan noise. This indicates that, for fan pressure ratios above 1.3, additional treatment over and above the "wall treatment only," aimed at further suppressing the fan noise, is not warranted, since the interaction noise would then become dominant. Thus it appears that, for the example of the 100,000 lb. STOL shown in Fig. 10, it would not be possible to attain a sideline noise level less than 105 PNdb for pressure ratios above 1.3. However, in the range of pressure ratios between 1.1 and 1.2 the interaction noise is sufficiently depressed, that levels of 95–100 PNdb are attainable with current techniques of moderate duct wall treatment.

It does indeed appear that sufficient progress has been made to meet the current targets for CTOL and STOL community noise levels. Furthermore, these reductions in powerplant noise generation should also help the airframe designer obtain comfortable cabin noise levels with a minimum of soundproofing. This success should not be construed, however, to indicate that the propulsion industry can now rest on its acoustic laurels. It is quite likely that more stringent noise limits will be imposed in the future, to cope with increasing airport traffic densities and more congested airport locations. Perhaps we must next look to the theoreticians to produce a more fundamental understanding of the detailed phenomena of noise generation which could lead to better criteria for low noise design.

Powerplant Selection

The designer of tomorrow's advanced civil aircraft is faced with a formidable task. He is called upon to meet more stringent performance requirements; he has to satisfy new

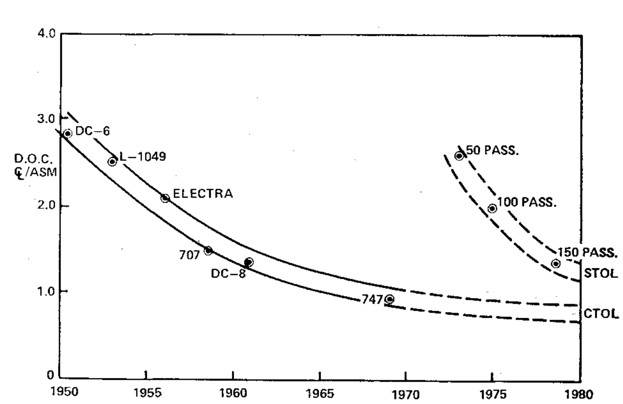

Fig. 8 Direct operating cost trend.

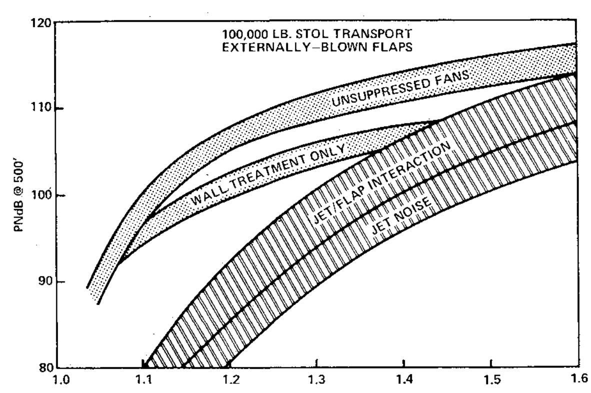

Fig. 10 Comparative noise sources.

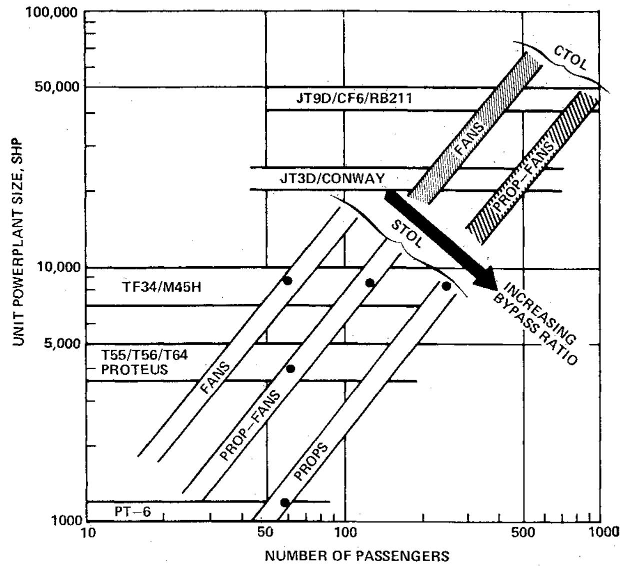

Fig. 11 Powerplant sizing (4-engine aircraft).

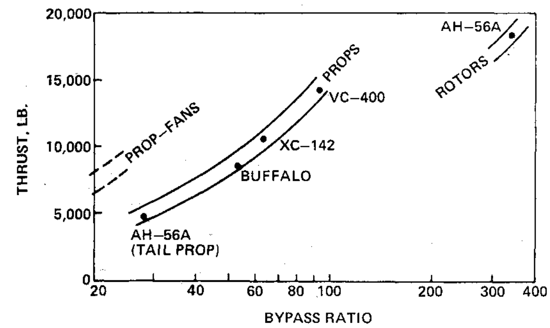

Fig. 12 Propulsion flexibility.

noise restrictions; he must achieve lower operating costs without jeopardizing reliability; and he is forced, by practical economics, to try to accommodate these conflicting requirements within the framework of existing or planned engines. He does, however, have one powerful tool at his disposal, a wider range of propulsors which can be adapted to the available gas turbines.

This is illustrated in a very general sense in Fig. 11, where some of the major size categories of available gas turbine engines are plotted in the horizontal bands, and power requirements, as affected by propulsor type, are plotted in the diagonal bands. Using the STOL category as an example, two sets of points have been marked. One is to show the potential for reduced engine size with increase in bypass ratio for a given vehicle size. The other indicates the prospect of increasing vehicle size with a given engine by going to higher bypass propulsors. It must be recognized, however, that there is a price to pay for these gains with higher bypass ratio. It generally means a reduced cruise speed due to the relatively lower installed power.

The aircraft designer must look at all the trade-offs of initial cost, DOC, noise, passenger appeal, etc., in making his ultimate power-plant selection. It may be of interest, however, to try to list, in Table 1, some of the probable propulsion candidates for the several categories of the future civil aircraft. These are not intended to be exact descriptions of the best candidates in each case, since this can come only from a detailed aircraft study. They are merely a representation of the broad scope of propulsion selection available to the designer.

The fan engine will, most likely, remain the choice for the long range intercontinental transports because of the premium on high cruise speed, even though this is going to require the development of a new, larger engine. In the case of the shorter range airbus, the choice is less clear and will require a careful evaluation of the trade between higher utilization and better fuel consumption for representative route structures, and an assessment of the ability to meet new noise limit requirements. The Prop-Fan appears to be favored for the medium-haul STOL and the turbo-prop for the short-haul STOL where improved fuel consumption should out-weigh cruise speed in effecting low DOC.

Another important consideration is the commonality between these civil aircraft requirements and the propulsion needs for new military aircraft. Fortunately there appear to be some good match-ups. The new large 80–100,000 SHP engine indicated for the intercontinental transport seems to be of the right size for such potential military requirements as a second generation C-5 or an advanced AWACS. The probable payload and range requirements for the USAF MST (Medium STOL Transport) seem to be quite comparable to its civil counterpart and could thus justify another engine development in the 12,000–14,000 SHP range. Subsequently, this powerplant size might find other applications such as a smaller civil or military VTOL transport, an advanced AX with VTOL capability, or a new class of ASW aircraft.

It is the flexibility afforded by mating a relatively few advanced gas turbine engines with a wide range of propulsors that provides the assurance of handling the differing propulsion requirements of such a variety of aircraft types. This has been well exemplified by the diverse applications of the G.E. T64 engine. In Fig. 12 it is shown that, with this one basic engine, it has been possible to fit nearly a 4 : 1 ratio of thrust requirements by varying the bypass ratio through choice of propulsor. The addition of the Prop-Fan has served to further expand the latitude of propulsor selection.

Table 1 Candidate propulsion systems

	Size	Propulsors	Engines	Gross Weight	V_{cruise}
Intercontinental Transport	750 pass.	1.2 P.R. prop-fan 1.5 P.R. fan	4 × 50,000 hp 4 × 100,000 hp	1,200,000# 1,500,000#	0.85 M 0.95 M
Airbus	500 pass.	1.15 P.R. prop-fan 1.4 P.R. fan	4 × 22,000 hp 4 × 50,000 hp	600,000# 750,000#	0.80 M 0.85 M
Medium-haul STOL	150 pass.	1.1 P.R. prop-fan 1.3 P.R. fan	4 × 11,000 hp 4 × 18,000 hp	150,000# 175,000#	0.75 M 0.75 M
Short-haul STOL	60 pass.	1.02 P.R. propeller 1.08 P.R. prop-fan	4 × 1,100 hp 4 × 3,000 hp	50,000# 65,000#	0.40 M 0.55 M

Concluding Remarks

The subject of propulsion for civil aviation, even as limited here to the subsonic types, is quite broad in scope and, thus, has to be treated in terms of rather gross generalizations. Some new dimensions of the propulsion problem, such as broader thrust matching requirements and more stringent noise restrictions were defined. With these in mind, the full spectrum of propulsors was examined and a new, promising candidate was introduced—the Prop-Fan.

Based on the propulsion trends of the past 15–20 yr and with due consideration of current advanced technology programs, it was possible to make attractive projections of the improved specific fuel consumption, thrust/weight, DOC and noise levels for the next decade. Also indicated was the greater flexibility afforded the aircraft designer by the wider range of bypass ratio propulsors adapted to the current family of gas turbines. Propulsion commonality with potential military requirements provides further assurance of the availability of a new generation of advanced propulsion systems. It now remains for the airframe industry to conduct the more comprehensive propulsion studies needed to make the powerplant selections and to formulate their specifications. The propulsion industry is in a position to provide effective support for such studies and to assist in mapping the propulsion goals for this widening aspect of civil aviation.

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