MATCHED PROPULSION FOR ADVANCED VEHICLES

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ABSTRACT

Increasing demands for improved transportation in the face of today's fuel and environmental constraints calls for advanced vehicles with better matching of propulsion to their specialized needs. The very high bypass variable pitch fan is described as a new and effective means to this end. It offers good low speed performance, low fuel consumption, and low noise level in a compact, light weight propulsion package. Representative advanced commercial and military aircraft are examined to show the potential benefits from the marriage of optimum higher bypass fans with existing core engines.

INTRODUCTION

The matching of propulsion to vehicle requirements is not a new practice. The whole history of transportation is replete with examples. It has been particularly prevalent in the aerospace field, where the remarkable chain of achievements in our generation certainly has attested to the benefits to be derived from proper propulsion matching.

It is the impact of the new and more demanding requirements posed by the next generation of transport vehicles that puts added emphasis on the need for even more exact tailoring of propulsion to vehicle needs. No longer can the aircraft designer satisfy his customer with a vehicle that merely performs the desired mission at minimum cost. He must now work the further miracle of accomplishing this without polluting the atmosphere, without creating any noise, and without consuming any fuel.

Over the past several years there has been an active mutual effort by the aircraft and engine designers to keep pace with the progressively more stringent environmental regulations. Some new noise abatement techniques have already been effected in the wide-body transports, but there is continuing pressure for further improvements. Now with the primary focus shifted to fuel conservation, there is much concern that this could cause a retrogression in the progress toward reduced noise and emissions, and also could adversely effect the profitability of the resulting vehicles.

These concerns have instigated much study by all sectors of the aerospace industry and fuel conservation was the subject of a major Workshop sponsored by AIAA in March of this year. The purpose of the Workshop was to establish an industry consensus on the potentials for significant fuel conservation, to define the more promising options, and to present a set of recommendations for an organized plan to implement the necessary short-and long-term programs. The Workshop summary is presented in Ref. 1 and covers four major areas: aircraft design, propulsion, fuels, and operational procedures. Some of the findings are quite pertinent to the subject matter of this paper and will be introduced as appropriate.

PROPULSION SYSTEMS

In general the gas turbine has been accepted as the preferred core engine for most large transport vehicles where compactness and low specific weight are vital to mission effectiveness. There are, however, some categories of the transportation spectrum, such as the small general aviation aircraft, for which the lower cost and better fuel consumption of the piston engine will continue to be attractive. In this category there is also the prospect that the new rotary combustion engine may eventually prove to be a good compromise between the piston and gas turbine engines. This will be discussed briefly, but, for the most part, this paper will concentrate on the matching of gas turbines to advanced vehicles.

Much work has been done in recent years, and is continuing, in an effort to upgrade gas turbine technology and to improve cycle efficiency. Some of the more promising areas are:

1. Higher bypass ratio/variable pitch fan
2. Higher overall pressure ratio
3. Higher turbine inlet temperature
4. Variable nozzle and stator vanes
5. Multi-cycle engines

These efforts have been quite fruitful and can best be exemplified by the trends of increasing overall pressure ratio and turbine inlet temperature depicted in Fig. 1. The resultant improvements in performance and fuel consumption have been significant and have been achieved at rather modest increases in complexity, weight and cost. Some further gains are anticipated from the projected advances, but their net benefits have yet to be assessed by detailed trade-off studies.

Another form of improvement currently receiving attention is the multi-cycle engine whereby the usual compromises in off-design performance can be minimized for the extreme flight conditions of such advanced vehicles as V/STOL and SST. Here, too, the gains must be examined relative to increased complexity and cost.

Other refinements such as inter-stage bleed to help achieve the higher compression ratios and the use of variable stators and nozzles to improve compressor and turbine performance are being developed in the propulsion industry.

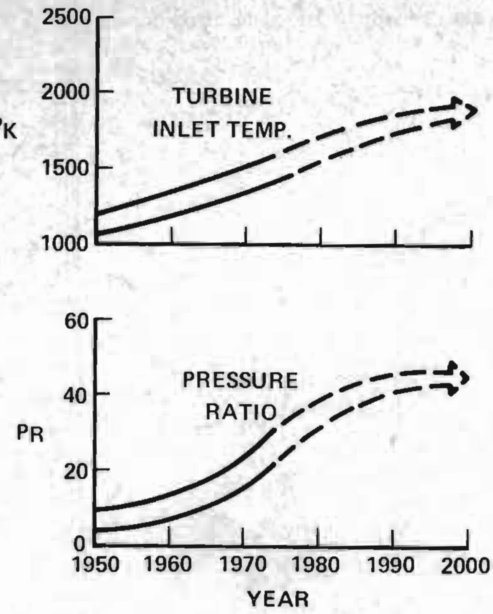

FIGURE 1. CORE ENGINE TECHNOLOGY

The attainment of this additional level of technology will not come easy. Some of the required keys are: improved materials for the hot end of the compressor; more efficient cooling techniques and improved materials for the turbine; more effective air seals; lower weight fan blades, discs and cases; integrated designs using advanced composites, improved burner design; etc. Active programs are continuing in each of these areas and have been sufficiently documented in the literature to not need further elaboration here. Suffice it to say that the sum total of the more probable refinements from this ongoing effort could lead to another 15-20% improvement in specific fuel consumption of the basic core engine.

VERY HIGH BYPASS/VARIABLE PITCH FANS(VHB/VPF)

Paralleling the increase in thermal efficiency of the core engine has been the trend toward higher bypass ratio from the 1:1 ratio of the early turbofan engines of the 60's to today's 5:1-6:1 bypass advanced transport engines. This has been most instrumental in the development of the economically viable jumbo jets. The attained improvements in low speed thrust and the ability to produce the higher thrust, without increase in noise level, have made it possible to operate these larger aircraft from the existing airports of the world.

Efforts aimed at extending this favorable trend to even higher bypass ratios were initially not productive. It was concluded that the drag and weight penalties associated with the larger fans and shrouds would more than offset the improved performance and noise benefits.

Several innovations were needed to realize the full potential of higher bypass. First, it was necessary to recognize that the more lightly loaded fan could be designed to operate efficiently with much reduced blade solidity and with subsonic tip speed. Then it was found highly desireable to go to lower aspect ratio blades of advanced composite construction and without part-span shrouds in order to reduce blade weight. Finally it was the combination of the much reduced blade loads and the fewer blades that made it feasible to introduce variable pitch.

This radical change in fan design technique has resulted in more favorable trade-off trends with further increase in bypass ratio (decreased fan pressure ratio). The light weight blade construction tends to offset the adverse weight trend due to the larger fan size. The subsonic fan speed and fewer fan blades combine to produce a distinct change in the fan noise signature and levels. The resultant sizeable reductions in fan perceived noise at its source permits the attainment of low installed noise levels with less nacelle treatment. The variable pitch feature provides not only improved off-design performance but, more importantly, it affords a more effective means of aircraft braking than the present practice of using fan and primary flow reversers or air brakes. This not only offers better cost and weight trades for the basic hardware, but the combined effect of the higher reverse thrust, faster response and the ability to hold reverse thrust to zero air speed should result in much reduced wear on such high maintenance items as wheels, brakes and tires.

These all add up to a "new look" potential for very high bypass/variable pitch fans(VHB/VPF).

DEVELOPMENT STATUS

Active R & D programs on VHB/VPF have been pursued in the U.S. and the U.K. over the past five years and have produced a strong technological base in the required disciplines of aerodynamics, acoustics, blade structural analysis, mechanical design and advanced materials. This has permitted the initiation of two major powerplant development programs involving VHB/VPF: the NASA Quiet, Clean, Short Haul, Experimental Engine (QCSEE) program in the U.S. and the Rolls Royce M45SD-02 program in the U.K. The development testing of these 9:1 to 10:1 bypass experimental engines is scheduled for 1975-76.

Although both are classified as merely experimental engines, the planned test programs are quite extensive and will provide the required design criteria and complete data banks from which to proceed into derivative production VHB/VPF engines. Fully developed engines could be available for operational aircraft in the late 1970's.

Available core gas turbines can be modified to accommodate VHB/VPF with optimized fans to match a variety of these vehicle requirements. Figure 2 indicates the wide range of available cores and the broad spread of thrust ratings that could be achieved, in each case, by varying bypass ratio.

The prospect of marrying these cores to a range of VHB/VP fans affords the vehicle designer a new opportunity for exact matching of propulsion to vehicle requirements. For example, Fig. 3 illustrates the ability to cover the full spectrum of commercial airliners from 25 to 500 passenger size and from STOL to CTOL types with only 6 core sizes, five of which are currently available. Similar commonality of core matching to other

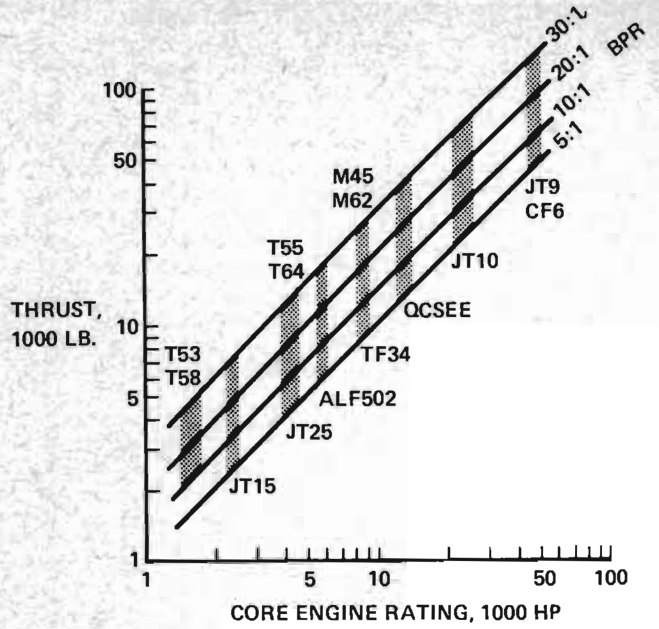

FIGURE 2. AVAILABLE CORE ENGINES

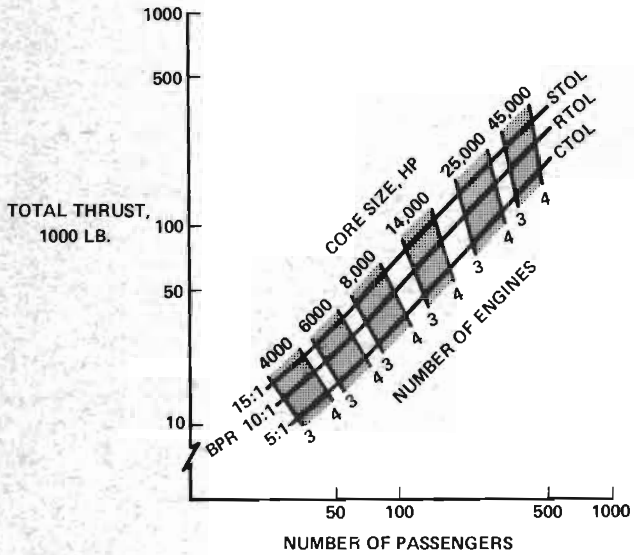

FIGURE 3. CORE COMMONALITY

classes of military and commercial vehicles can be shown to be equally attainable.

It should not be misconstrued, however, that this implies a mere replacement of an existing fan with a new fan. Any appreciable change in bypass ratio requires a complete rematching of the fan and core engine aero/thermodynamics. The extent of such modifications to the core engine would vary from case to case and would be dependent on the specific core engine design and the magnitude of the bypass ratio change.

In general, the change to VHB/VPF could involve some of the following core modifications: additional compressor supercharging, additional turbine stages, larger primary nozzle area, variable fan nozzle, etc. There is, of course, the compensating factor of significant nacelle simplification by virtue of the elimination of both fan and primary flow reversers. In any event, the cost and schedule of effecting such core modifications and its redevelopment with the new VHB/VPF would be much more attractive than that of developing a complete new turbofan engine. Fig. 4 is intended merely as a gross representation of the large potential savings in time and cost to develop this more effective form of refanning.

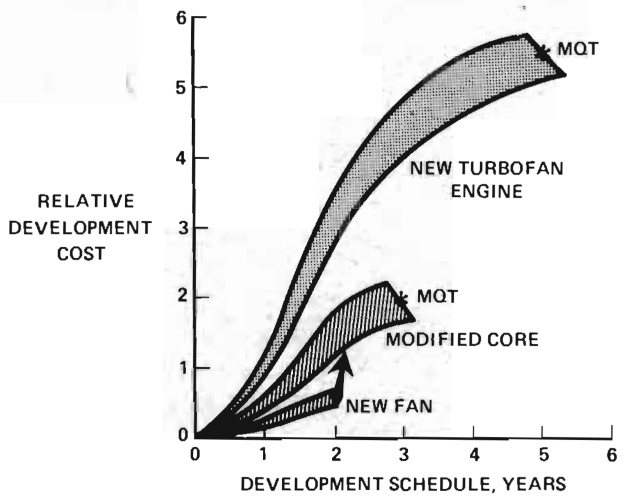

FIGURE 4. COMPARITIVE DEVELOPMENT PROGRAMS

MATCHING POTENTIALS

The gains from this closer match of powerplant to vehicle can be quite impressive and are achievable in a variety of forms: lower procurement costs, improved fuel productivity, reduced noise and emissions, better D.O.C., improved reliability, less maintenance, better ride quality and passenger appeal, longer endurance (military missions), less crew fatigue, and improved flight safety.

These have been well substantiated by preliminary design studies for a variety of vehicle types. It must be emphasized, however, that to assure equitable assessments in such studies, each vehicle/powerplant variant must be properly optimized for the particular mission being evaluated.

It is not within the scope of this paper to attempt to present complete evaluations of all possible classes of vehicle applications. However, a few representative cases should serve to illustrate the effectiveness of the improved propulsion matching flexibility afforded by the VHB/VPF.

Fuel Productivity

The recent traumatic experiences resulting from curtailed fuel allocations and sharply escalating fuel prices has forced a reassessment of past criteria for the design and operation of both commercial and military aircraft. Even though the fuel supply situation has eased considerably, the era of cheap fuel is a thing of the past (Fig. 5) and fuel cost will continue to represent a much larger factor in the economics of aircraft operation. Accordingly the subject of improved fuel productivity (Payload-range/Fuel) is receiving increasing attention.

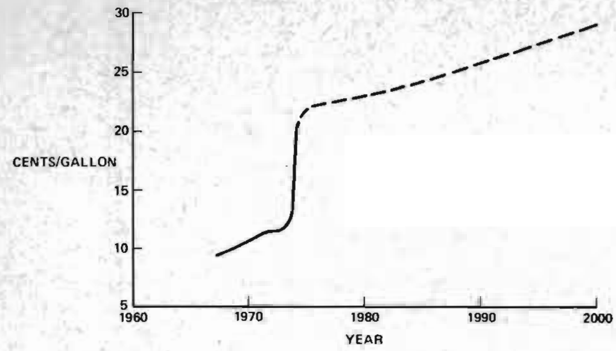

FIGURE 5. AIRLINE FUEL COST (U.S. TRUNK LINES)

There are many trade-offs that must be considered in evaluating the potential improvements in fuel productivity by increase in bypass ratio. The improved take-off thrust permits higher gross weight with a given core size, thus resulting in a better ratio of useful load to fuel load. This could further facilitate the current practice of stretched aircraft. Since cruise thrust will not increase as much with bypass ratio as does the take-off thrust, the larger aircraft will be somewhat slower. However, the specific fuel consumption will be better and, when combined with the higher load-carrying capacity of the stretched aircraft, should result in significant improvement in fuel productivity.

Figure 6 illustrates an approximation of the trade-offs between fuel productivity and cruise speed which might be attainable on three representative types of transport aircraft. As a generality, high cruise speed is more vital to the economics of the longer range aircraft. Thus they cannot afford as large an increase in bypass as can the short and medium haul aircraft. Yet, even there, it appears that modest increases in bypass could result in something on the order of 5-10% improvement in fuel productivity for relatively small reductions in cruise speed (on the order of 20-25 knots).

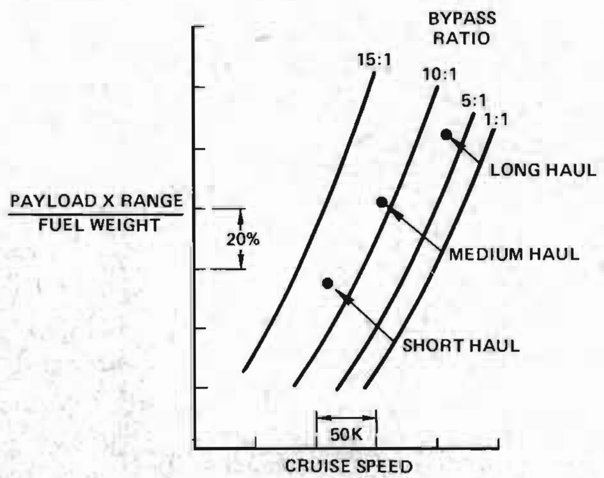

FIGURE 6. FUEL PRODUCTIVITY

Direct Operating Cost

Better fuel productivity cannot, however, be the sole criterion for propulsion matching, even with today's sharp focus on fuel conservation. The effect on operating costs and the resultant impact on fares and payload factors must be fully assessed. With specific regard to DOC evaluations, it should be noted that some of the standard ATA formulae, particularly those related to maintenance costs, need to be modified to account for the new trade-offs introduced by VHB/VPF. Some of the points to be considered are: the trade between variable pitch on the fan and the elimination of primary and fan flow reversers; use of variable pitch fan in lieu of other devices to control approach flight path; elimination of noise suppressor rings in the nacelles; less wear and maintenance of wheels, brakes and tires due to more effective, faster response in reversing with the variable pitch fan.

As an illustration of the sensitivity of DOC to such considerations, Figure 7 is reproduced from Ref. 3, representing an advanced short haul transport aircraft. This shows a worsening of DOC with decrease in fan pressure ratio (increasing bypass) when attempted with a fixed pitch fan. However, the combined weight, performance and maintenance benefits associated with variable pitch completely offset the adverse effect on DOC at fan pressure ratios above 1.2.

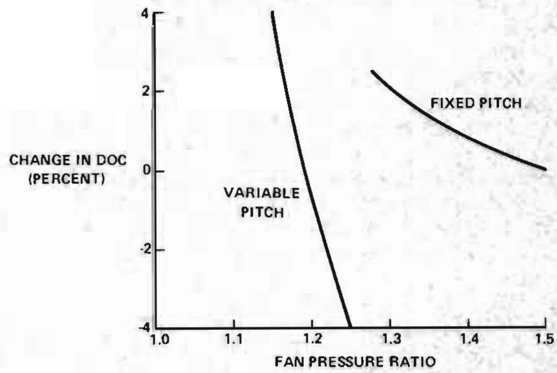

FIGURE 7. EFFECT OF FAN PRESSURE RATIO ON DIRECT OPERATING COST

MILITARY LONG DURATION APPLICATIONS

A vital element of the future inventory of military aircraft will be a class of long duration vehicles. These will be of medium to large size and each designed for very specific missions. Some will be more advanced replacements of current ASW and AEW aircraft. Others will provide new mission capabilities such as airborne missile launching platforms and airborne command posts. However, they will have one requirement in common, the ability to remain airborne for long periods of time.

The VHB/VPF propulsion systems offers an attractive new mission potential for this class of vehicles. The better take-off and climb thrust with higher bypass results in reduced time and fuel to reach cruise altitude. Improved

TSFC at normal cruise reduces the cruise-out and cruise-back fuel consumption. However, it is the large portion of the mission devoted to very low throttle loiter which provides the maximum gain. Loiter operation may occur at throttling settings as low as 50% where the improvement in TSFC afforded by VHB/VPF could be as much as 20-40%. When this is added to the other fuel savings the net effect on mission effectiveness can be quite large, as indicated in Figure 8.

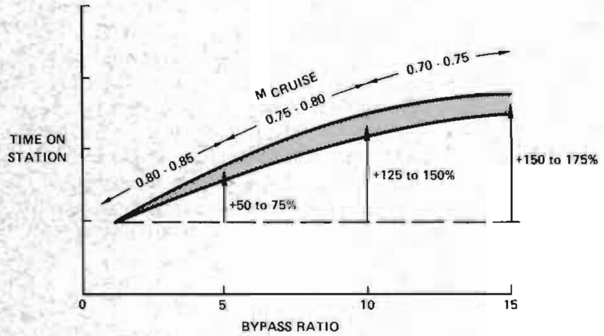

FIGURE 8. LONG DURATION AIRCRAFT

The level of bypass ratio which would be selected for a specific application would be limited by the magnitude of cruise or dash speed desired for the particular mission. Those with short radius of action would not need the high speed capacity and would thus tend to optimize at the higher bypass ratios.

Another attribute of the VHB/VPF system which would contribute further to the mission effectiveness of these long duration aircraft is its low noise generation. Crew fatigue obviously becomes a point of major concern when considering the feasibility of appreciable increases in their work period. Cabin noise levels on current long duration aircraft are already exceeding fatigue criteria. Thus the 15-20 dB reduction potential which has been indicated for the VHB/VPF system is quite complementary to its potential for increased time-on-station.

The magnitude of these improvements in mission effectivity are quite large and could result in greatly reduced fleet inventories to perform their required tasks. This could reflect itself in reductions of 30-40% in life cycle costs and comparable savings in fuel utilization.

GENERAL AVIATION APPLICATIONS

At the other end of the spectrum are the small general aviation aircraft which also indicate possible benefits by this improved flexibility of propulsion matching. There has been a modest trend in general aviation to larger and faster jet powered business and commuter transports but the growth has been inhibited by high procurement and operating costs. Recent studies (Ref. 8 & 9) have generated an interest in the application of VHB/VPF propulsion to the general aviation field. These studies have examined the feasibility of VHB/VPF not only on gas turbines but also on piston and rotary combustion engines. The latter looks quite promising for the smaller general aviation aircraft but VHB/VPF gas turbine propulsion could provide the means to a new generation of more cost effective, very quite business jets and commuter transports.

OTHER APPLICATIONS

The above three aircraft categories were selected for illustration of the VHB/VPF propulsion matching technique because of their recognized importance and because some preliminary assessment studies were available. There are, obviously, other vehicle categories where similar benefits may accrue and such applications are not necessarily restricted to aircraft. Several classes of advanced surface vehicles have been looked at and have indicated promising capabilities. In particular the prospect for compact, low noise air propulsion on tracked levitated vehicles (TLV) and advanced hovercraft or air cushion vehicles (ACV) are very encouraging.

In addition to the propulsion needs for TLV and ACV craft it appears that the VHB/VPF technology can be applied equally effectively to improved lift fan systems to better meet their levitation requirements. This is particularly applicable to the large, ocean-going surface effect ship programs currently being initiated, where fast-acting modulating fans have been shown to provide a most effective means of achieving adequate heave alleviation in high sea states[10].

Figure 9 presents a graphical representation of the new propulsion matching capability afforded by the VHB/VPF system. The chart illustrates the prospects of filling a large gap in the propulsion spectrum between relatively low speed propeller vehicles and very high speed turbofan vehicles. It should be noted that the VHB/VPF category covers a very wide range of bypass ratios (19:1 to 30:1). In general the higher the vehicle cruise speed the lower will be the best bypass match. It is also interesting to observe that the indicated match points for VHB/VPF in each vehicle category fall much closer in cruise speed to the turbofans than to the turboprops. In other words, the compromise in cruise speed required to achieve the benefits of VHB/VPF propulsion matching are quite modest.

The number of vehicle classifications shown on Fig. 9 are limited in order to keep the chart from getting too cluttered. Other vehicle types which might be considered, particularly in the

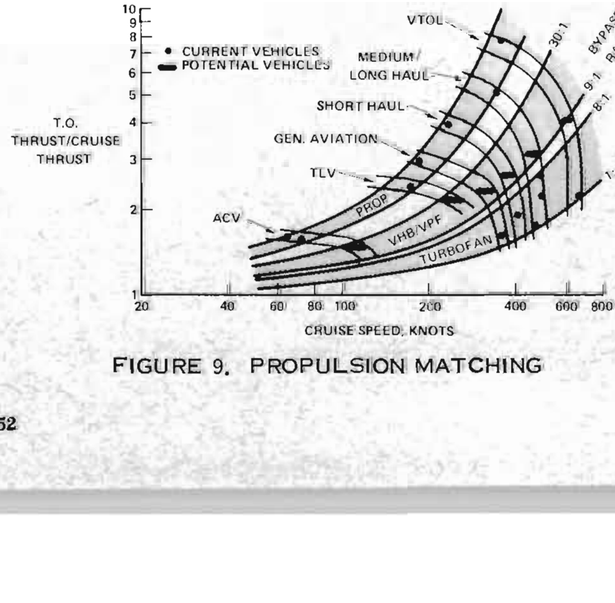

FIGURE 9. PROPULSION MATCHING

military categories, are close support, forward area reconnaisance, compound helicopter, COD, V/STOL, AMST, etc. In each of these there could be the potential for improved mission effectiveness with better matched propulsion of the VHB/VPF type.

SUMMARY

It has been the intention of this paper to provide an overview of the prospects for more exact matching of propulsion capability to vehicle requirement now offered by the very high bypass, variable pitch fan propulsion system. The detailed trade-off assessments for selecting the optimum bypass ratio are quite complex and specific to a particular mission, thus limiting the ability to present accurate generalizations of the benefits. However, preliminary studies, to date, have indicated such large potential gains that further detailed studies appear warranted.

Essentially, the introduction of the VHB/VPF to the propulsion inventory has provided the aircraft designer with a new dimension for optimizing his vehicle to the more stringent demands of his customer. It offers the opportunity to more exactly fit his propulsion needs with a relatively few number of core engines by merely matching with the optimum bypass fan. Such propulsion packages can be developed in much shorter time spans and at much less cost than would be involved in the development of a complete, new powerplant to meet the same requirement.

Although a wide variety of vehicle types were listed for possible consideration of VHB/VPF propulsion, two aircraft categories stand out as attractive, early solutions to important mission requirements. One is a medium sized transport for the short haul civil market with adaptability to the military long duration ASW/AEW mission. The other is a much larger aircraft suitable for the burgeoning civil air freight market and which, in a military version, could better meet the needs for large, long-duration airborne missile platforms, command posts, etc. The gains in fuel productivity or time on station appear to be sufficient to warrant consideration of each of these for development as operational aircraft for the late '70's/early '80's. Their effectivity should also benefit from the lower external and cabin noise levels and improved maintainability afforded by the VHB/VPF propulsion system.

It is this opportunity to reap early and significant gains from such improved propulsion matching that provides the incentive to initiate the development of the VHB/VPF propulsion systems. When coupled with the substantial improvements in performance and fuel consumption projected for the next generation of core engines, the availability of adequate propulsion to meet the more stringent demands of future advanced transportation systems looks quite promising.

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DISCUSSION

G. Winterfeld (DFVLR, Porz-Wahn, Germany): Could the author briefly comment on the effects of flow distortion on the gas generator when the variable-pitch fan operates in the reverse mode.

E. Liban (Engine Branch, Bedek Aviation, Israel Aircraft Industries, Ben-Gurion Airport, Israel): Could you please comment on the fan reversal sequence contribution to the good engine response from full forward to full-back power.

G. Schairer (The Boeing Company, Seattle, Washington, U.S.A.): Besides its use for reversed thrust, what are the requirements for variable fan pitch?

G.M. Lilley (University of Southampton, U.K.): The use of the fuselage integrated fan for the helicopter in place of the conventional tail rotor is an interesting development. Could Mr. Rosen please give us some details of the noise reductions and the gains in weight with such an installation. Also what kind of performance advantages have been achieved with this arrangement.

G. Rosen: The questions raised by Mr. Winterfeld and Mr. Liban on reverse thrust transients with a variable pitch fan have been investigated thoroughly in full-scale testing and reported in AIAA paper No. 73-1215, "The Q-Fan™ Demonstrator Engine" by R.M. Levintan. It was demonstrated that fast reverse thrust transients (1 second from full positive to full reverse thrust) was achieved with no adverse distortion of inlet flow to the core engine.

In response to Mr. Schairer's question, the other major benefit of the variable pitch feature is its fast thrust response from idle to maximum thrust during critical landing and takeoff operations. For example, conventional turbofan engines with fixed pitch fans typically require about 5 seconds to accelerate from approach thrust to maximum thrust, whereas the variable pitch fan can do this in less than 1 second. This provides more flexibility in controlling the approach flight path for reduced noise footprint.

Further benefits can accrue from :

- Improved off-design tsfc
- Improved ground handling
- Zero-thrust fan setting for APU ground operation
- Fast thrust compensation for engine-out on multi-engined aircraft

Professor Lilley's question relates to an interesting fan application illustrated in the verbal presentation but not discussed in the written paper. The primary objective of the integrated fan-in-fin is to enclose it for protection against rotor damage in near-ground operations and reduced hazard to ground personnel. However, other significant improvements were indicated by the initial proof-of-concept installation on the Sikorsky S-67:

- More compactness
- Better tail rotor performance due to shielding from tail rotor downwash, and thrust augmentation by the duct.
- Improved agility in hover and low speed flight
- Reduced noise level

The full potential of this more compact, integrated fan concept will require further design study to establish optimum vehicle configurations and thus it is not yet possible to quantify these benefits. The fact that substantial gains were achieved, even when installed on a vehicle designed for the conventional exposed tail rotor, is most encouraging.