Studies of Convertible Turboshaft/Turbofan Engines for High-Speed Rotorcraft

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Rotary wing aircraft require auxiliary thrust to fly at speeds higher than current helicopters. One approach is to use the turboshaft engine to drive both the vehicle rotor and a variable geometry fan which allows independent variation of shp and thrust. Various convertible engine configurations including variable pitch fans, variable inlet guide vane fans, and clutched fans are described and their suitability for two types of aircraft is examined. One is a 225 knot U.S. Army combat rotorcraft in which the rotor operates in high-speed flight. The variable inlet guide vane fan with or without a clutch is shown to be a viable approach. The second aircraft is a 400 knot X-wing commercial transport in which the rotor is stopped in flight. The variable inlet guide vane fan and prop/shaft systems are shown to be competitive.

Introduction

It is generally accepted that a rotary wing aircraft must employ direct thrust to achieve speeds significantly higher than current helicopters, approximately 200 knots being considered the dividing line. One logical approach is to use the same basic engine to supply power to the vehicle rotor and to an auxiliary propulsion device. This propulsive unit may be a propeller, a fan remote from the basic turboshaft engine, or a fan integrated with the turboshaft engine. The latter is called a convertible engine.

The primary function of a convertible engine is to provide shaft power for flight in the helicopter mode and direct thrust for high-speed flight. For rotorcraft where the vehicle rotor continues to run when thrust is required, independent variation of power output and thrust must be provided over a range that depends upon the vehicle. For rotorcraft in which the rotor is stopped at high speed, this feature may or may not be required for flight in the rotary wing mode. In the rotary wing mode, the output rpm will normally be set by vehicle requirements. If variation in thrust is required with output rpm specified, a fan driven by the same turbine that supplies power to the rotor must have variable geometry. The fan concept of the convertible engine is conventional, requiring an inlet to prepare the flow for entry to the fan and a jet nozzle to provide the proper back pressure on the fan that distinguishes it from the propeller or shrouded propeller concepts.

The convertible engine as defined above is not new. In the late 1960s, there was a flurry of activity stimulated by U.S. Army interest and several programs were conducted that analyzed various approaches to the convertible engine.[1-4] An experimental program to investigate the effects of variable inlet guide vanes (IGV) fans over a wide range of conditions was carried out in that time period and the results have proved useful in more recent programs.[5] Although there was little activity during the 1970s, there was still some interest among the U.S. Army helicopter technology people.[6] A program directed at supplying data on alternate approaches to convertible engines for evaluation in Army-type missions was carried out by the General Electric Co. in the 1981-1982 time period under the sponsorship of the U.S. Army. The current paper includes an evaluation of the merits of various convertible engines using data from this program.

NASA Lewis Research Center also became interested in convertible engines in the 1980 time period as part of their rotorcraft technology program and sponsored two studies of convertible engine concepts for a variety of rotorcraft.[7-9] The current paper includes a portion of the results from the General Electric study.[7] NASA Lewis Research Center in cooperation with DARPA also launched an experimental program for variable IGV-type convertible engine technology using a modification of the TF34 engine.[10]

Types of Convertible Engines

Variable IGV Fan

The variable IGV (VIGV) type of convertible engine can be considered for a range of fan pressure ratios. Figure 1 shows one approach to the VIGV fan. The fan incorporates a splitter between the bypass and primary streams starting ahead of the IGV, which has the advantage of isolating the flow entering the gas generator from the variable bypass flow. Thus, the supercharging of the gas generator and the entering flow conditions are retained as the outer fan IGVs are varied. A bleed valve may be required, however, in order to match the flow from the fan hub to the needs of the gas generator as the power setting is changed with the fan speed held constant. The outer fan stream is shown with a variable exit guide vane (VEGV) as well as a VIGV. This has been found to be desirable to improve fan efficiency at partially closed IGV conditions and to reduce the windage loss in the more closed conditions.

The performance characteristics of a VIGV convertible engine are illustrated in Fig. 2. At the rated turbine temperature, it is possible to trade thrust for shp by varying the fan IGVs, maximum thrust being obtained at the fully open setting (IGV = 0 deg) and maximum shp at the most closed setting (IGV = 85 deg, for example). Lower levels of thrust and shp are obtained by reducing the power setting (turbine temperature) of the basic engine. Note that the fan need not be sized to accept the full output of the basic engine, as there is usually a requirement for a certain level of shp at the same time that maximum thrust is required. Also, there is some residual thrust even with the IGVs fully closed. This is due primarily to the flow leaving the power turbine with a

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small contribution from the bypass flow as it is not possible to reduce this flow to zero.

A complete convertible engine involving a VIGV fan driven by a T700 turboshaft engine is shown in Fig. 3. The configuration shown involves a gearset between the power turbine and the fan. At higher fan pressure ratios, it is reasonable to consider a direct-drive fan. The layout incorporates an inertial-type separator in the duct between the fan hub and the gas generator to minimize the number of particles in the flow entering the gas generator, the particles being scavenged to the bypass duct. A separate flow exhaust is shown, but mixed flow is also an option that may be useful in certain situations.

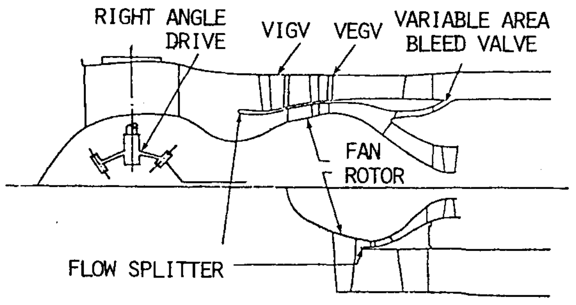

Fig. 1 Comparison of VIGV and conventional fan designs.

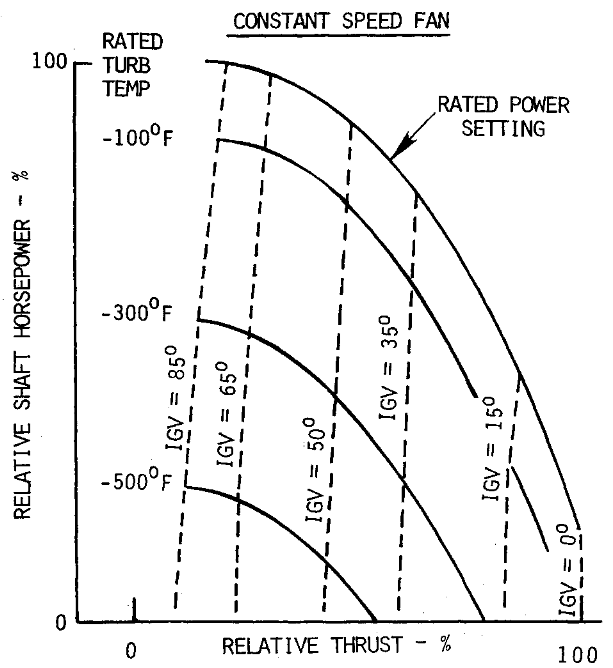

Fig. 2 Performance characteristics of a VIGV convertible engine.

Variable Pitch Fan

The variable pitch (VP) fan has also been considered as the basis for a convertible engine.[4] Although not directed at convertible engines, General Electric under the sponsorship of NASA conducted a program in the 1970s called the quiet clean short-haul experimental engine (QCSEE) that included the design and test of a variable pitch fan as shown in Fig. 4.[11] This program produced useful data that were used in more recent studies of convertible engines. The VP fan is limited to relatively low tip speeds to provide practical blade retention and actuation designs even if composite or other lightweight fan blade designs are employed. This restricts the VP fan to the lower range of fan pressure ratios.

The operating characteristics of the VP fan are similar to those of the VIGV fan except that the fan blade pitch is varied rather than the direction of the flow entering the blade. The variable pitch fan does have the capability for a limited amount of reverse thrust when varied through fine pitch.[12,13] This allows the residual thrust of the power turbine exhaust to be cancelled, but the net engine reverse thrust capability is quite low. A limitation of the VP fan is that the flow leaving the fan hub and entering the gas generator varies in pressure level and distortion as the blade pitch is varied. In the unloaded fine pitch condition, the supercharging of the gas generator is lost, which affects the maximum shp capability of the engine.

For both the VIGV and VP fans, there is a significant loss in maximum shp of the engine due to the windage loss of the fan in the unloaded condition, closed IGV or closed pitch. The loss for the IGV case is especially high, on the order of 15-20% of the normal full-open power consumption of the fan based on limited experimental data.[5]

Other Types

A means of eliminating the windage power loss is to incorporate a clutch in the engine to decouple the fan from the power turbine shaft when thrust is not needed. Supercharging of the gas generator is lost in the shaft mode of operation, but fuel consumption is significantly better than for configurations in which the fan continues to rotate. Variable fan geometry is still required if independent variation of thrust and shp is to be achieved in the thrust mode. A convertible engine involving a fixed geometry fan and a torque converter was studied by Allison in their NASA sponsored study.[8]

Convertible Engines for Combat Rotary Wing Aircraft

The primary purpose of the U.S. Army-sponsored convertible engine program was to provide data for evaluation of the convertible engine concept in higher-speed U.S. Army rotary

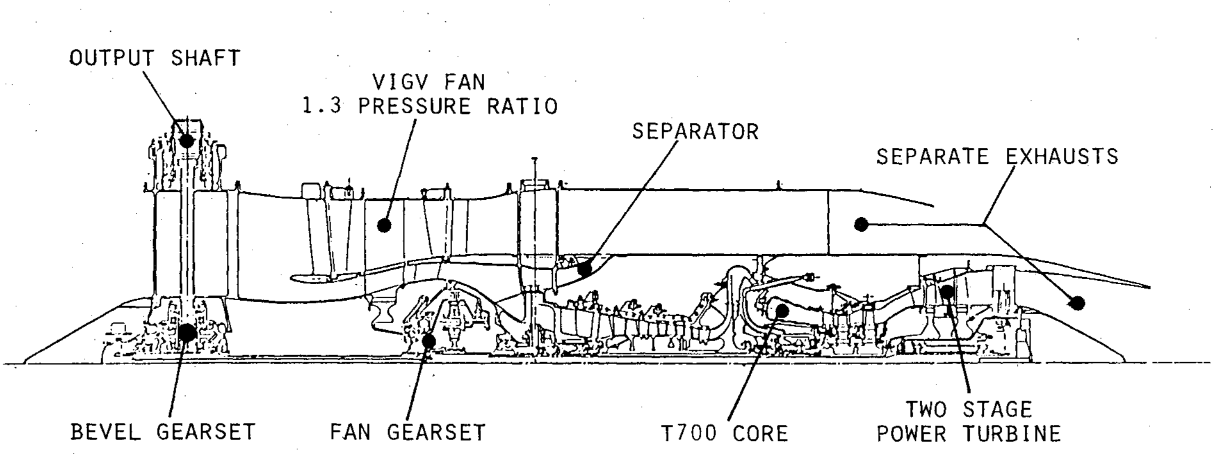

Fig. 3 Variable guide vane geared fan convertible engine.

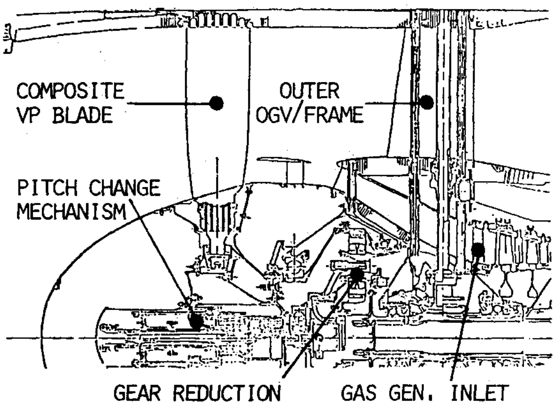

Fig. 4 QCSEE variable pitch fan.

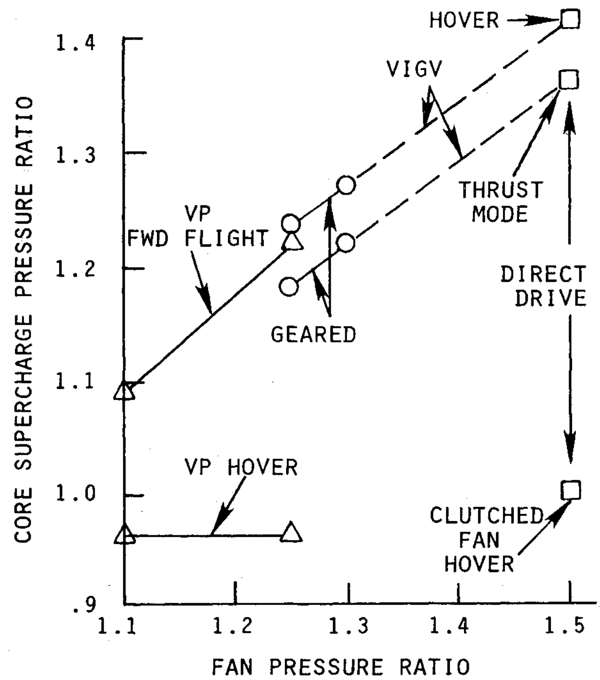

Fig. 5 T700 convertible engines (core supercharging).

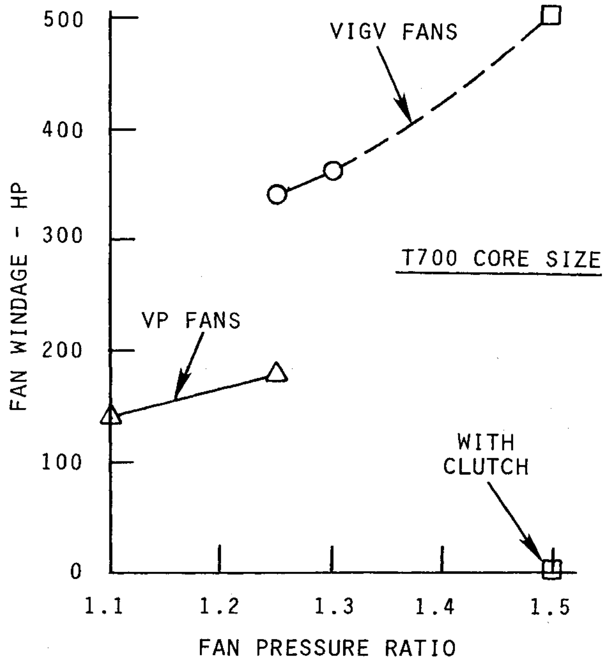

Fig. 6 Fan windage at hover, 4000 ft, 95°F, 100% rpm.

Table 1 Referee mission and aircraft: combat-type compound helicopter

U.S. Army close ground support
Max speed: 225 knots
Approximately 14,000 lb gross weight
Twin convertible turboshaft/turbofan engines based on scaled T700 core
Engine sizing: 3200 shp two-engine liftoff at 4000 ft, 95°F day; 2500 lb fan and 600 shp at 225 knots, 4000 ft, 95°F day
Rotor speed: 100% to 180 knots, 90% at 225 knots

wing aircraft. As an aid to defining these engines, the four American rotary wing aircraft manufacturers were surveyed for their input on mission and aircraft characteristics and the referee definition shown in Table 1 was selected. The key choice was to set the maximum flight speed at 225 knots with the engines sized to achieve this speed at a 4000 ft altitude on a 95°F day. The nominal aircraft gross weight was 14,000 lb, but this was varied as necessary to achieve design range and payload in the evaluation.

Engine Characteristics

Various convertible engines based on the T700 core were defined for analysis. These were scaled up as necessary to satisfy the engine sizing requirements at liftoff or maximum flight speed, whichever was limiting. The vehicle rotor speed was reduced 10% at the maximum flight speed condition to limit the blade Mach number level. The analysis covered a range of fan pressure ratio of 1.1-1.5 and included VIGV, VP, and clutched fan configurations. Figure 3 shows a layout of one of the configurations analyzed.

For the study of fan pressure ratio variations, the turbine temperature was set at approximately 2200°F, consistent with the capability of the T700 and taking into account the increased supercharging of the core that increases the blade coolant temperature. Cycle pressure ratio levels were set at 18-22 by limiting the core rpm as the core supercharging was varied. The bypass ratio was a dependent variable, the size of the fan being set by the capability of the core to drive a given fan pressure with the exhaust conditions from the turbine being established for a balance between the jet thrust and shp. The bypass ratios ranged from 3 for the 1.5 fan pressure ratio case to 24 for the 1.1 fan pressure ratio case.

The supercharging pressures at the hover and thrust mode conditions for the engines considered are shown in Fig. 5. In the thrust mode, the supercharging pressure ratio is closely related to the fan pressure ratio. In the hover mode, the supercharging of the VP and clutched fan engines is lost and replaced by a pressure loss. In the hover mode, however, the VIGV and VP fans involve a significant loss in power associated with the windage of the fan in the closed IGV or VP fan blade condition as shown in Fig. 6. Windage estimates for the VIGV fans were based on an extrapolation of data from an early experimental program and therefore involve considerable uncertainty.[5] The net shp output power level resulting for T700 size engines is shown in Fig. 7.

At the maximum flight speed condition, the fan is sized to utilize the equivalent maximum continuous rating of the T700 core, the resulting fan diameters being a function of the fan pressure ratio as shown in Fig. 8. The fan is designed

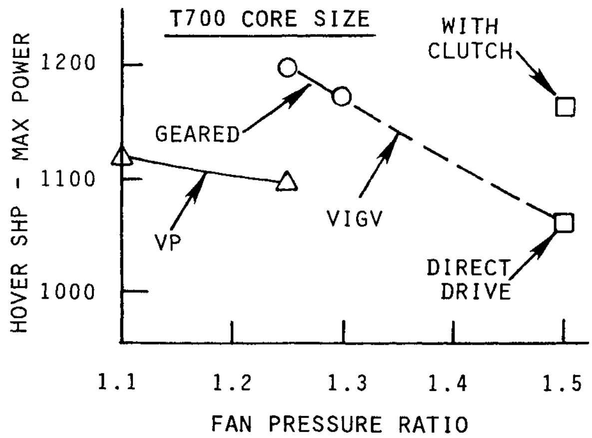

Fig. 7 T700 convertible engine power at hover, 4000 ft, 95°F.

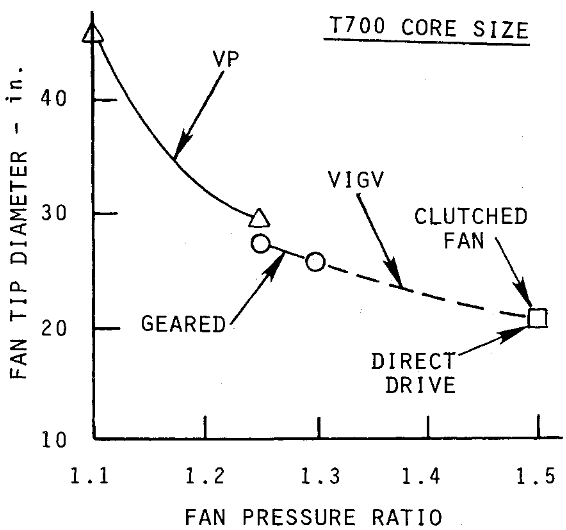

Fig. 8 Fan tip diameter of T700 convertible engines.

aerodynamically at this condition at an rpm that is 90% of the rpm which will be run at lower flight speeds. The resulting thrust levels at the maximum flight speed condition with shp extraction in relation to thrust as required by the aircraft are shown in Fig. 9.

Matching to Aircraft

In order to power the referee aircraft at 14,000 lb gross weight, it was necessary to scale the T700-based convertible engines. The airflow scale factors are shown in Fig. 10. The engines were sized by liftoff or maximum flight speed, whichever was limiting. The lower fan pressure VP engines tended to be sized at liftoff and the remaining engines by maximum speed, but none of the engines were mismatched by a significant amount.

The estimated weights of propulsion systems including bevel gearset and nacelle in addition to the engine are shown in Fig. 11 when sized for a 14,000 lb gross weight vehicle. Composite or other lightweight blades were assumed for the VP engines and titanium for the remaining engines. The weights are high for the lower fan pressure simply because the engine airflow and fan diameter are large. The clutched fan engine assumed a mechanical clutch built into the engine based on an Allison program.[14]

The mission fuel breakdown for a VIGV engine is shown in Fig. 12 for the design mission (the portion of the fuel associated with providing thrust is shaded). At the 150 knot cruise condition, it was more efficient to use the vehicle rotor for thrust rather than the fan, in spite of the penalty of run-

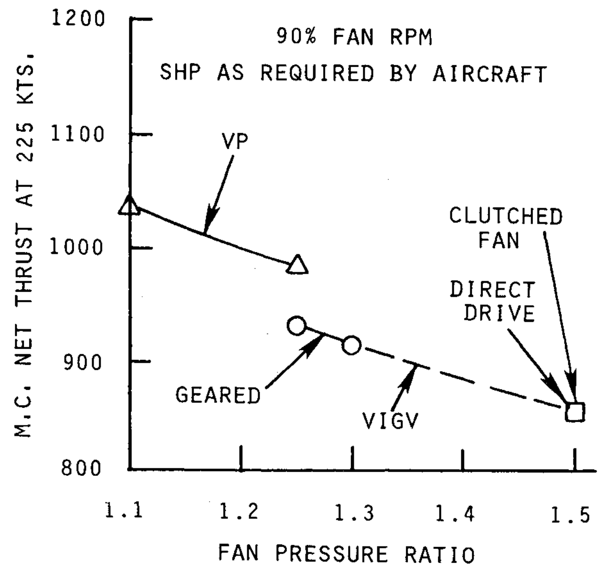

Fig. 9 T700 convertible engine thrust at 225 knots, 4000 ft, 95°F day.

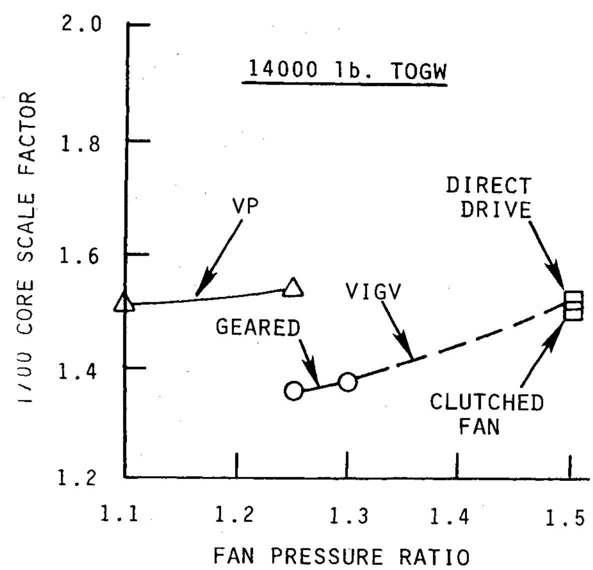

Fig. 10 T700 core scale factors.

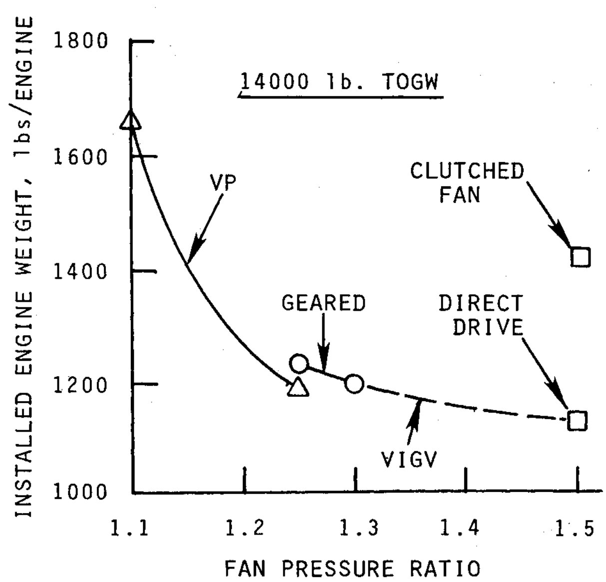

Fig. 11 Installed engine weight trends.

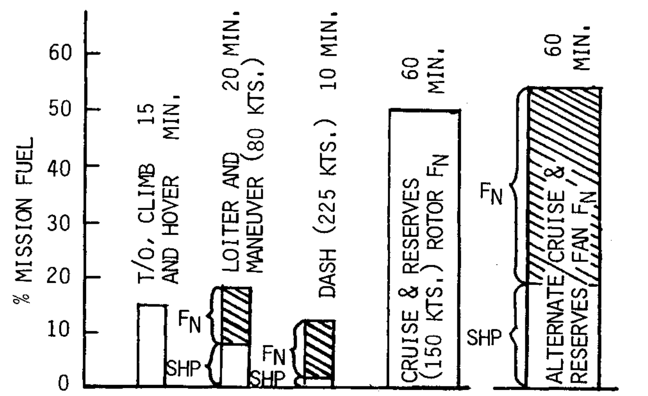

Fig. 12 Mission fuel distribution of close support mission with VIGV convertible engine.

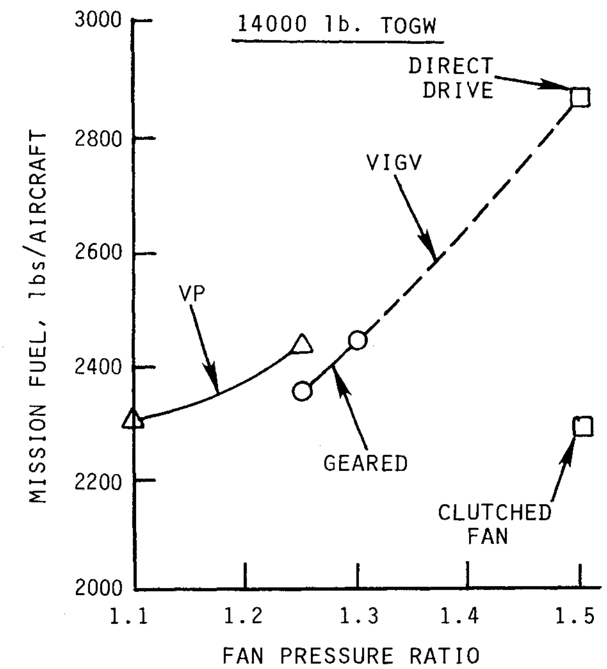

Fig. 13 Mission fuel trends.

ning with the fan variable geometry in the closed position. This is significant since most of the fuel is used in the shaft mode. The resulting mission fuel levels for the 14,000 lb gross weight vehicle are shown in Fig. 13. The VIGV engines with higher fan pressure ratios are a disadvantage primarily because of the fan windage loss.

Evaluation of Engines

In order to satisfy mission radius and payload, it was necessary to resize the aircraft for each of the engine types with results as shown in Fig. 14. The intermediate fan pressure ratio engine shows the minimum gross weight. The low fan pressure ratio engines suffer because of the high weight and the high fan pressure ratio engines because of high fuel consumption. The clutched design has an advantage because of its lower fuel consumption.

An evaluation of the life cycle cost (LCC) was also carried out with the results shown in Fig. 15. The change in LCC including aircraft cost changes associated with the gross weight is expressed as a percentage of engine related LCC (fuel, engine acquisition cost, engine maintenance cost). The trends are similar to those shown by the gross weight curves, with the clutched design showing somewhat less advantage because of the cost and maintenance penalties of the clutch.

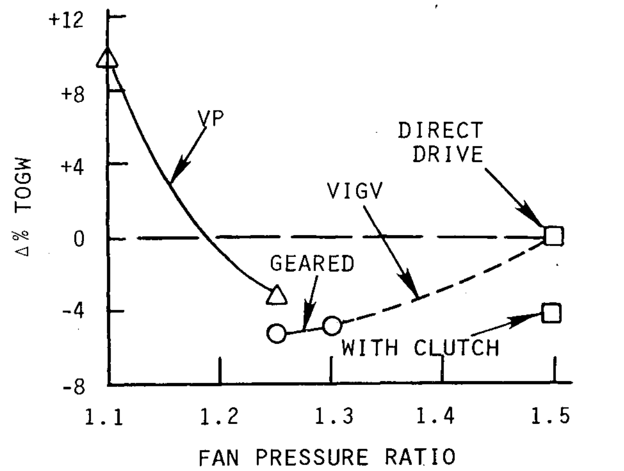

Fig. 14 Takeoff gross weight trends of aircraft sized for design mission.

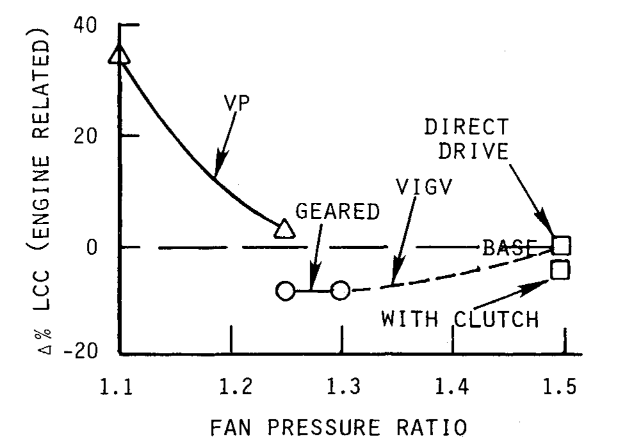

Fig. 15 Life cycle cost trends of aircraft sized for design mission.

There are factors other than vehicle gross weight and LCC that would influence the type of convertible engine that might be selected for an Army-type mission. In the analysis, no penalty for the larger diameter engines other than nacelle weight and drag was applied and it is likely that the smaller diameter, higher fan pressure ratio engines will be easier to install. The VP fans will have an advantage in that residual thrust can be eliminated and a small amount of reverse thrust achieved. Sand and foreign object ingestion are important for the U.S. Army application and will require that the core engine incorporate a separator. Lower tip speed metal fan blades are favored from the fan erosion standpoint.

Convertible Engines for Transport X-Wing Rotorcraft

Variable IGV Engine

In the NASA sponsored convertible engine study carried out by General Electric, convertible engines for commercial transport rotorcraft were studied.[7] Of those studied, the use of the VIGV-type convertible engine for a 400 knot X-wing rotorcraft will be discussed since it represents quite a different situation than the 225 knot compound helicopter application covered earlier. The mission and aircraft application used are shown in Table 2. Boeing Vertol provided the aircraft design, data on portions of propulsion and lift system other than the engine, and mission analysis for this study under subcontract to General Electric. The key choice was the selection of the 400 knot cruise speed at a 30,000 ft altitude.

A schematic of the propulsion system and drive train is shown in Fig. 16. In the rotary wing mode, the aircraft

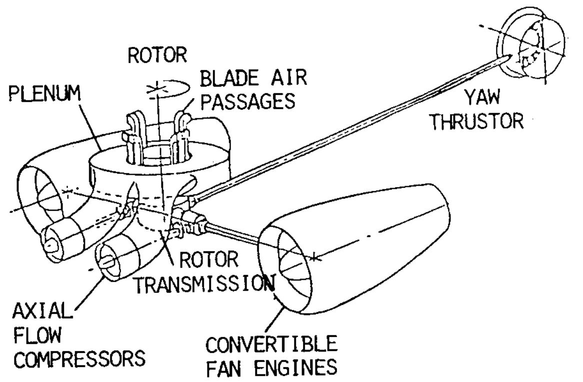

Fig. 16 X-wing convertible VIGV drive system.

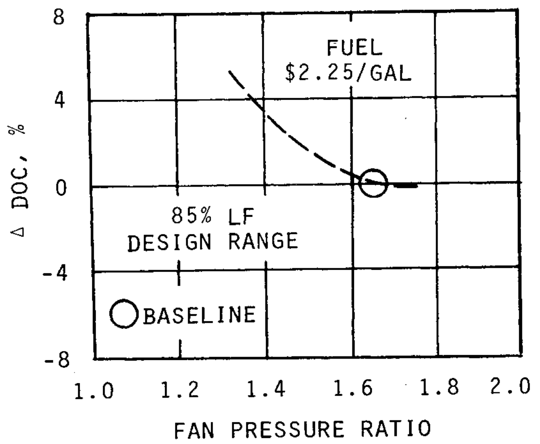

Fig. 17 DOC trends of X-wing transport.

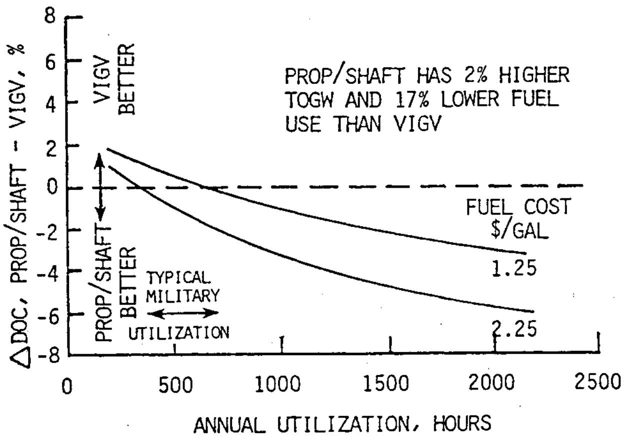

Fig. 18 DOC comparison of prop/shaft and VIGV systems.

operates much like a helicopter with the engine supplying shp to the main rotor, the yaw thrustor, and the compressors that supply air to the vehicle rotor for circulation control. In the fixed wing mode, the engine supplies thrust and a small amount of shp to the compressors, the main rotor and yaw thrustor being decoupled from the engine. Most of the fuel is used at high speed in the thrust mode, which differs from the situation on the compound helicopter in the U.S. Army combat mission. Also, the fan speed can be set lower in the shaft mode than in the thrust mode since the vehicle rotor in decoupled from the fan in the latter. This is opposite to the situation for the compound helicopter and reduces the impact of the closed IGV fan windage losses at the hover condition.

As part of the NASA study, the effects of fan pressure ratio for VIGV-type convertible engines were evaluated on a mission basis. The engine configuration is essentially the same as that shown in Fig. 3 except that an advanced technology core is used and the engine sized and matched to the X-wing mission. The turbine inlet temperature was set at 2350°F and the cycle pressure ratio at 25 for this study. The bypass ratio was again a dependent variable being set by matching the fan and primary exhaust pressure levels in a mixed-flow exhaust system. Figure 17 shows direct operating cost (DOC) trends resulting from this study. It was concluded that a moderately high fan pressure was desirable for the high-speed X-wing mission and the 1.65 level shown as base was used in comparisons with other concepts.

Table 2 Referee mission and aircraft: X-wing transport

Commercial-oil rig transport
Number of passengers: 48
Max speed: 400 knots at 30,000 ft
Design range: 450 n.mi.
Approximately 44,000 lb takeoff gross weight
Twin convertible turboshaft/turbofan engines based on advanced core
Engine sizing: Hover out of ground effect (OGV) with one engine inoperative
Fan sizing: Cruise at 30,000 ft
Rotor: Stopped at high speed

Comparison with Alternate Engines

The use of completely separate engines for shp and thrust was also evaluated and was clearly shown to be inferior to the convertible engine approach. The VP convertible engines were not competitive since they are restricted to relatively low fan pressure ratios and are therefore heavy. The clutched fan approach did not show an advantage since there was no significant reduction in fuel consumption to offset the clutch weight, as was the case for the lower-speed combat mission. However, the use of a propeller in place of the fan was competitive and a more in-depth comparison at the two approaches was made.

The propeller used was the advanced technology prop/fan with characteristics defined by Hamilton Standard.[15] They were mounted remote from the engine at the rear of the aircraft to avoid interference with the vehicle rotor. The results of this evaluation were a 2% gross weight penalty for the prop/shaft system relative to the VIGV fan system but a 17% saving in fuel. The latter result is not surprising since it is consistent with most recent studies for conventional transport aircraft in the 0.7-0.8 Mach number range. The relative DOC is dependent upon the utilization and fuel cost as illustrated in Fig. 18, the prop/shaft system showing and advantage for the 2000 h utilization typical of a commercial transport, but no advantage for the lower utilizations typical of military aircraft.

A factor that might affect the suitability of the VIGV system is the potentially high noise of the VIGV fan operating in the fully closed mode at liftoff and landing. Although both propulsion systems are complex, the prop/shaft system with its remote propellers involves additional shafting, bearings, and gears.

Conclusions

Observations based on the analysis of convertible engines for U.S. Army combat aircraft are as follows:

1) The VIGV fan type engine with a fan pressure ratio in the 1.25-1.3 range is a viable approach. Although lower fan pressure ratios have better propulsive efficiency, only about

20% of the fuel is burned in the thrust mode and the heavier weight of the large airflow fan engines predominates. Windage losses of the fan operating in the far-closed mode are a problem area since they are uncertain and detract from engine performance in the shaft mode.

2) A clutched fan engine with VIGV avoids the high fan windage loss in the shaft mode and therefore provides an advantage for missions in which much of the fuel is burned in the shaft mode.

3) The VP fan engine with lightweight fan blades was not as good in mission performance as the VIGV engine, but has an advantage in that any residual thrust can be eliminated in the shaft mode.

Observations based on the study of convertible engines for the X-wing transport are as follows:

1) The VIGV fan type engine with a fan pressure ratio in the 1.65-1.7 range is a promising approach for the X-wing application. The windage losses of the fan in the shaft mode will be relatively lower than for the compound helicopter because of greater freedom to set fan rpm and their impact will be less since most of the fuel is burned in the thrust mode.

2) The prop/shaft combination is a competitive approach. Although more complex than the VIGV convertible engine system for the X-wing aircraft, the higher propulsive efficiency of the propeller leads to an advantage in fuel consumption.

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