ASSESSMENT OF POWER SOURCES AND ELECTRIC MOTORS FOR HYBRID ELECTRIC TILTROTORS

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ABSTRACT

Tiltrotors operate in two distinctly different regimes: helicopter mode and rotor mode. In optimized designs, the rotors operate at continually varying RPMs and the cruise power can be as low as 50% of the hover power. This places unique demands on the power source and the drive system. It is necessary to understand and to match the best operating points of the rotor, drive system, and the power source to obtain an efficient vehicle. The influence of several powerplant and drive options, including electric batteries, fuel cells, gasoline and diesel powered piston engines, turboshaft engines, electric generators, and electric motors, are evaluated for a tiltrotor based on the University of Maryland's Excalibur (2011 AHS Student Design) as a baseline system. Results of parametric studies are presented to show that current batteries and fuel cells do not have the energy densities necessary to be useful for tiltrotors. It is shown that the diesel engine option can result in a fuel saving of over 50% compared with the baseline turboshaft version. A diesel hybrid electric option is shown to result in 34% lower fuel consumption and to be a viable lead-in for all electric tiltrotors. The parametric studies are used to identify areas of high payoff research for making hybrid/electric tiltrotors a reality.

NOMENCLATURE

battX	Energy density of battery/Energy density of current batteries
DL	Disc loading
PL	Power loading
PEMFC	Polymer Exchange Membrane Fuel Cell
RPM	Revolutions per minute
sfc	Specific fuel consumption
stackX	Stack power density of PEMFC/ power density of current PEMFC stacks
tankX	Hydrogen storage tank weight/ weight of current storage tanks
V_{BR}	Speed for best range
VDTR	Variable diameter tiltrotor
VSTR	Variable speed tiltrotor
η_P	Propulsive efficiency of rotor

1. INTRODUCTION

Currently, there is a great deal of interest in developing fuel efficient high speed aircraft with VTOL capabilities. Some of the configurations that are capable of high speed flight and also have VTOL capabilities are: the Sikorsky X-2 concept, the Airbus Helicopters X3 concept, and the tiltrotor concept. Out of these, the tiltrotor concept is more fuel efficient in forward flight than the other two concepts. The efficiency of a tiltrotor depends on the design of the rotor that can operate both as an efficient hovering rotor as well as an efficient propeller. Current tiltrotors are a compromise between a helicopter and a propeller airplane. It is possible to realize the full potential of tiltrotors by controlling the tip speed of the rotor by varying either its rotational speed (RPM) or its diameter. In the Variable Diameter Tiltrotor (VDTR) concept, the rotor RPM is kept constant but the rotor diameter is varied to change the tip speed [1]. In the Variable Speed Tiltrotor (VSTR) concept, a gear box is used to continuously change the rotor speed. The Optimum Speed Tiltrotor of Karem [2] is one type of VSTR concept. The VDTR requires a mechanically complex system to change the diameter of the rotor from helicopter mode to airplane mode and adds significant weight penalty to the rotor system. The VSTR concept is simpler and ideally requires that the rotor's

RPM is reduced by about 50% in the propeller mode. For efficient operation, it is also desirable to reduce the rotor RPM continuously to suit the flight condition of the vehicle. Current tiltrotors can reduce the rotor RPM by only about 10% because of the poor off-design performance of turboshaft engines, which are most efficient near a specific RPM and torque. Two possible methods of implementing the VSTR concept are either to use a Wide Speed Range Turboshaft engine or to use a continuously variable transmission (CVT). Both of these concepts appear beyond the capabilities of current technology because of the high torque levels at which rotors are required to operate. Therefore, it is necessary to examine if an alternate power plant or an alternate transmission choice can be used to implement the VSTR concept.

A recent study [3] examined the possibilities of using different power sources in electric powered helicopters. This study included a comprehensive survey and comparison of several power sources including IC engines, turboshaft engines, electric batteries, fuel cells, electric generators and electric motors. The influence of these power sources on two helicopters (an ultralight and a 1700 kg class helicopter) was evaluated and the results indicated that replacing the turboshaft engine with a diesel engine resulted in a 15% reduction in take-off weight and a 47% reduction in mission fuel weight. The results also showed that a hybrid electric helicopter powered by diesel engines could results in a 38% reduction in mission fuel and can be a replacement for current helicopters powered by piston or turboshaft engines. Because the diesel engines operate at lower RPMs than the turboshaft engines, implementation of the VSTR concept may be easier by using either the diesel engines directly or the diesel-electric hybrid engines for powering tiltrotor aircraft. The present paper is motivated by these results to examine if these benefits can be extended to tiltrotors that operate both as a helicopter and a propeller airplane.

For this study, it is necessary to examine the RPM requirements of the rotor, in hover and in forward flight, for minimum power because this determines the required performance of the power source and the drive system.

In the present paper, the following power sources and drives are investigated: gasoline engine, diesel engine, turboshaft engine, Li-ion battery, diesel generator, Polymer Exchange Membrane Fuel Cell (PEMFC), and electric motor. Combinations of these sources are also analyzed to determine combinations of powerplant choices that will lead to better fuel economy and weight reduction.

This paper is organized as follows. First, the performance characteristics of rotors are discussed. Next, a comparative evaluation is made of the various power plant options (gasoline and diesel piston engines, turboshaft engines, batteries, fuel cells, and range extenders). Finally, the influence of using different types of powerplants on the characteristics of the baseline tiltrotor is presented.

2. ROTOR POWER AND TORQUE

The rotors of tiltrotors operate over a much broader range of flight conditions than either helicopter rotors or propellers and are required to have high levels of aerodynamic performance both in hover and in forward flight. Because of the difficulty of designing a rotor that has good hover performance in a helicopter mode as well as good propulsive efficiency in an airplane mode, compromises are usually made in the design of rotors.

2.1 Variable Diameter Tiltrotor

One method of improving the aerodynamic efficiency of a rotor in both hover and in forward flight is to use a Variable Diameter Tiltrotor (VDTR). This was adapted for the University of Maryland's Excalibur VDTR (2011 AHS Student design) [4]. This rotor was optimized for both hover and cruise flight modes. It was designed in the extended condition to a diameter of 30 ft for hover efficiency and in the retracted condition to a diameter of 20 ft for cruise efficiency in airplane mode. The rotor RPM was not changed between the two modes.

Figure 1 shows a comparison of the propulsive efficiency as a function of the forward flight speed for both the extended and the retracted rotors. For the retracted rotor, it is necessary to change the RPM continuously to obtain the best performance from the rotor. The propulsive efficiency is almost constant at about 0.85 over most of the flight speeds with the retracted rotor of 20 ft. At a flight speed of 300 knots, it is increased from 0.61 with a 20 ft rotor to 0.85 with a 30 ft rotor, resulting in a 28% reduction in the power required for level forward flight. The VDTR does not need a speed reducing gear box but needs a complex system for varying the diameter of the rotor.

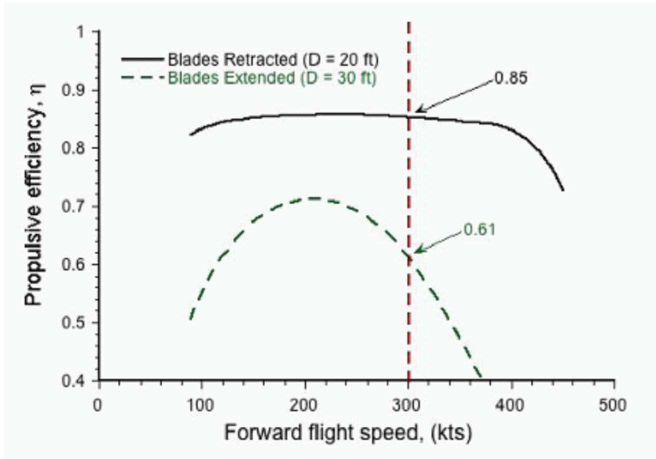

Figure 1. Excalibur. Improvement in propulsive efficient due to reduction in diameter [4].

The rotor of this tiltrotor was optimized for the cruise condition and had a hover figure of merit of 0.71. The power required for hover was 2431 kW and the power required for cruise at the best range airspeed (V_{BR}) was 1309 kW. If the VDTR concept had not been used and the rotor had the same diameter and RPM in cruise, the propulsive efficiency would have been about 0.70. In this case, the power required for cruise at V_{BR} would have been 1549 kW.

Because the RPM of the rotor is not changed, the ratio of the rotor torques is the same as the ratio of the corresponding powers:

$$(1) \quad \frac{\text{Torque at } V_{BR}}{\text{Torque at Take-off}} = 0.54 \text{ (VDTR)}$$

$$= 0.64 \text{ (Constant diameter rotor)}$$

For a tiltrotor equipped with a constant speed engine and constant reduction ratio transmission, the engine also operates at the same torque ratios of 0.64. For a turboshaft engine, this means that the sfc in cruise is much higher than that at take-off unless it is designed for efficient operation over a wide range of RPMs.

2.2 Variable Speed Tiltrotor

Another possible concept that can lead to an efficient rotor is the Variable Speed Tiltrotor that was used for the tiltrotor design of the Kestrel, designed by the University of Maryland (2014 AHS Student Design Competition) [5]. This was a 500 kg class tailsitter configuration designed to have a maximum forward speed of 350 knots. The rotor was designed to have a hover figure of merit of 0.8 and a propulsive efficiency of about 0.9. This was achieved by using a dual speed rotor. Figure 2 shows the variation of the figure of merit for this rotor as a function of the blade loading for different RPMs for this aircraft.

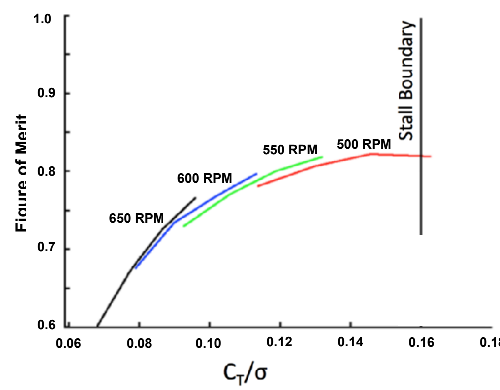

Figure 2. Variation of hover efficiency with the blade loading for various values of rotor RPM [5].

It is seen that the figure of merit increases with an increase in the blade loading and also with increases in the rotor RPM. For this rotor, a rotor speed of about 550 RPM in hover results in a hover efficiency of about 0.8 and also gives an adequate margin from the stall boundary

For the same rotor operating as a propeller, Figure 3 shows the variation of propulsive efficiency as a function of the helical tip Mach number for a number of values of the rotor RPM. Lower values of the rotor RPM lead to higher propulsive efficiencies. A two-speed gear box was designed that allowed the rotor to operated either at 555 RPM (hover and high speed flight) and at 269 RPM cruise at Best Range speed. This resulted in a hover efficiency of 0.80 and a propulsive efficiency of 0.89. If this design was used for the Excalibur, the power required for hover would have been reduced by 11% and the power at V_{BR} would have been reduced by 6%.

The ratio of cruise power to the power required to hover is 0.57 and the ratio of the rotor RPM at cruise to the hover RPM is 0.48. Therefore, even though the output power in cruise is 57% of the hover power, the engine is required to operate at 22% higher torque levels in cruise. This has important implications on the choice of powerplant and also on aircraft performance estimates of VSTR designs.

These results show that for any type of tiltrotor (constant RPM, VDTR, VSTR), torque considerations are as important as power considerations.

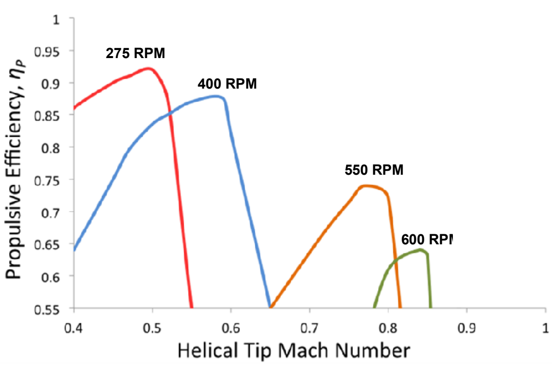

Figure 3. Variation of propulsive efficiency as a function of RPM and helical tip Mach number [5].

3. POWER, TORQUE AND SFC OF TURBOSHAFT ENGINES

Figure 4 shows the influence of power turbine speed (NPT) on the engine output power and the specific fuel consumption for different values of the gas generator speed (NG). The rotor is connected to the output shaft of the power turbine. For a given power turbine speed, changes in the output power are effected by changes in gas generator speed. Figure 4 also shows that for a given value of power turbine speed, reduction in output power results in an increase in sfc. Figure 5 shows the influence of power turbine speed on the engine output power and the specific fuel consumption for different values of the gas generator speed.

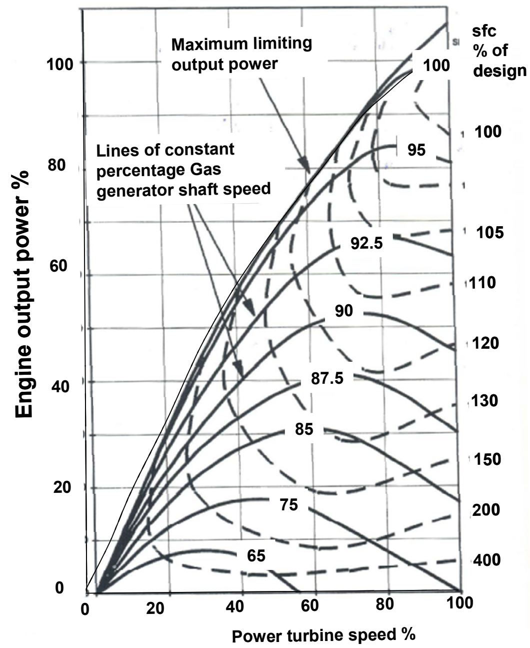

Figure 4. Influence of power turbine speed (NPT) on engine output power and specific fuel consumption for a turboshaft engine. Lines of constant sfc are also lines of constant efficiency. [6]

The power turbine can operate in the region bounded by the transmission torque limit, the maximum gas generator speed, and the maximum power turbine speed (NF). The power produced at a given gas generator speed can be absorbed by the power turbine in any combination of torque and power turbine speed. Therefore, in Figure 5, lines of constant power turbine speed are also lines of constant power. For a given value of the power turbine speed, the torque and the power increase with an increase in the speed of the gas generator [6].

For a tiltrotor, such as the Excalibur, the power required for cruise in airplane mode is typically of the order of 54% of the power required for hover in a helicopter mode. For a variable diameter rotor, it is possible to operate at 100% power turbine speed throughout the flight but for a variable speed rotor, it is necessary to operate at about 50% power turbine speed in the propeller mode. Both these options force the engine to operate at off-design conditions and at much higher values of sfc.

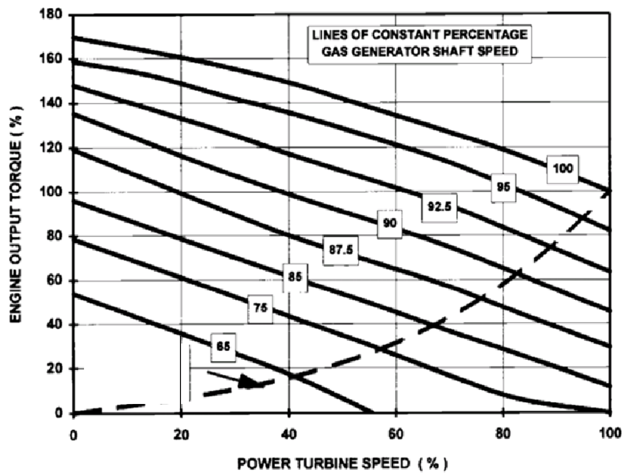

Figure 5. Output torque as a function of power turbine speed with constant gas generator speed as parameter. Lines of constant gas generator are also lines of constant power. [6]

4. PERFORMANCE OF GASOLINE AND DIESEL ENGINES

Figure 6 shows the engine map for a generic gasoline engine [6]. The contours of constant specific fuel consumption and the contours of torque for constant power (T(P)) are also shown. Both the full-load curve and the line of torque for minimum fuel consumption show that this engine produces maximum torque and maximum power at high RPMs. The lowest fuel consumption for this gasoline engine occurs at low values of power and moderate values of torque.

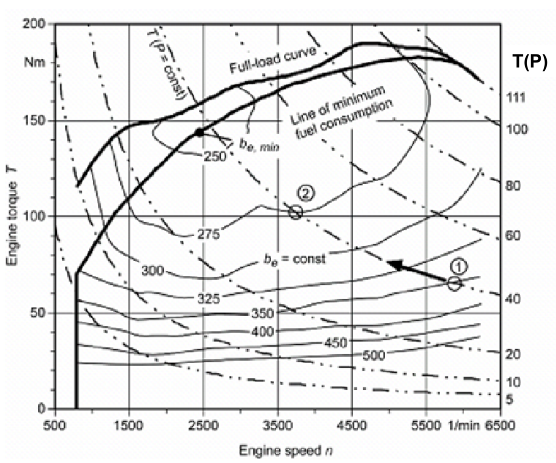

Figure 6. Engine map for a gasoline engine showing torque as a function of engine speed. Figure also shows the contours of torque for constant power and contours of constant fuel consumption. [7]

Figure 7 shows the engine map for a generic diesel engine [8]. The contours of constant specific fuel consumption are also shown. Unlike the gasoline engine, the diesel engine can produce high torques at low engine speeds. Also, unlike the gasoline engine, the diesel engine can output maximum torque over a wider range of low RPMs. This engine has low values of specific fuel consumption over a wide range of low RPMs.

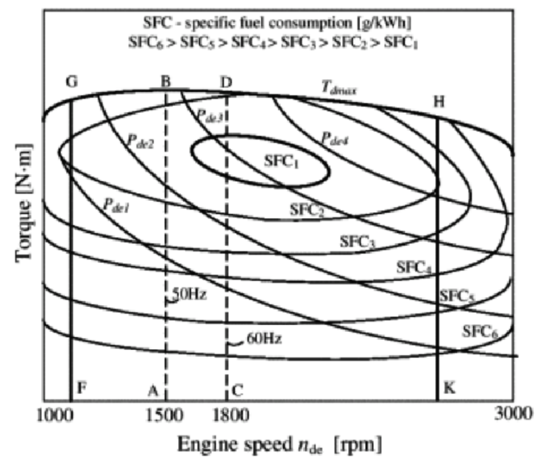

Figure 7. Engine map for a diesel engine showing torque as a function of engine speed. Figure also shows the contours of constant specific fuel consumption [8].

5. ELECTRIC MOTORS

Figure 8 shows the output torque and output power for an electric motor [9]. A typical electric motor has two operating zones: constant torque and constant power. At low RPMs, the torque has a high, constant value up to a base speed after which it reduces with increase in RPM. The output power increases almost linearly with increase in RPM up to the base speed beyond which it is constant for a small RPM range beyond which it decreases. Figure 9 shows the efficiency map of an electric motor. This motor has its highest efficiency for intermediate values of torque. The efficiency is low at both high torques and at low torques.

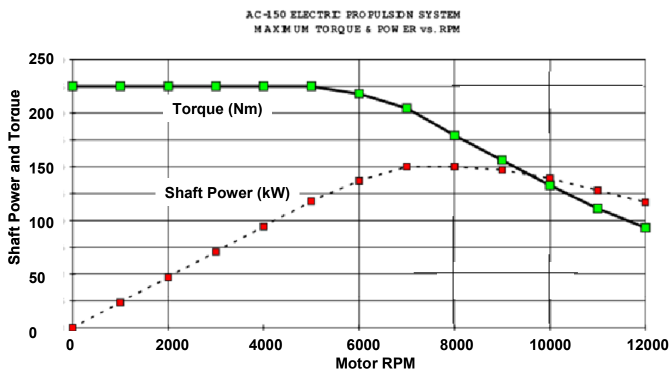

Figure 8. Torque and Power vs. RPM for the AC-150 electric motor [9].

A comparison of the variation of output torque with changes in the engine RPM for gasoline, diesel, and turboshaft engines and for an electric motor is shown in Figure 10. The diesel engine and electric motors can achieve high torques at low RPMs. For a given power, turboshaft engines can achieve high torques at low power turbine RPMs. However, the efficiencies of the engine are low at these RPMs. The gasoline engine has a broader torque curve and provides the maximum torque at a high RPM.

A comparison of the variation of output power with changes in the engine RPM for gasoline, diesel, and turboshaft engines and for an electric motor is shown in Figure 11. The power curves for the gasoline, turboshaft and the diesel engines are similar. The diesel engine can achieve high powers at relatively lower RPMs.

6. MATCHING THE ROTOR AND POWERPLANT

The aerodynamic performance of a rotor depends on the rotor RPM. If the rotor RPM is continuously variable to suit the flight conditions, the rotor can operate with maximum efficiency throughout the flight regime. The efficiencies of electric motors and power sources are also dependent on the power and RPM. It is therefore necessary to match the operating characteristics of the rotor, electric motor and the powerplant for optimum performance of the vehicle.

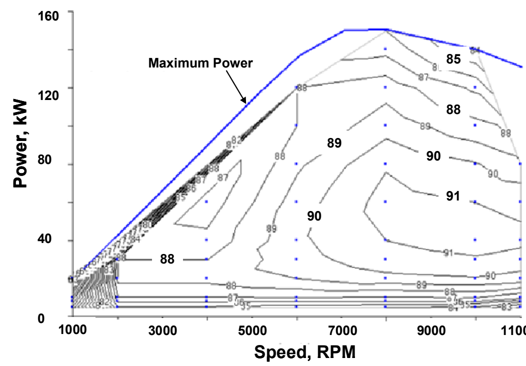

Figure 9. Efficiency map for the AC-150 electric motor [9]. Iso-efficiency lines are shown.

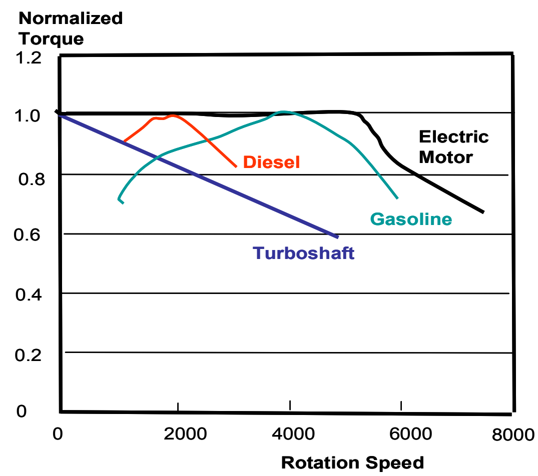

Figure 10. Comparison of torque as a function of RPM for gasoline, diesel, and turboshaft engines and for an electric motor

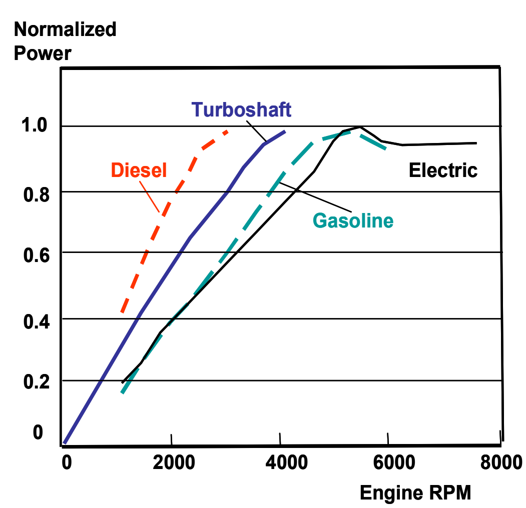

Figure 11. Comparison of shaft power as a function of RPM for gasoline, diesel, and turboshaft engines and for an electric motor.

Table 1. Comparison of Range Extenders

Property	IC Engine Otto Cycle	IC Engine Wankel	Free Piston Linear Generator	Micro Gas Turbine	PEFC Fuel Cell
Efficiency (%)	20-30	19-27	33-34	25-35	60
Specific Power (kW/kg)	0.43-0.6	0.89	0.35	3.75	0.65
Volumetric Power Density (kW/L)	0.315	0.64	0.28	0.95	0.825

6.1 Electric Power Sources

A comprehensive survey of electric power sources was presented in [3]. Among the available batteries, Lithium Polymer batteries encompass the high specific energy range (of the order of 150 Wh/kg), which is not sufficient for helicopter or tiltrotor applications. Fuel cells such as Direct Methanol fuel cell, Alkaline fuel cell, Phosphoric acid fuel cell, Molten Carbonate fuel cell, Solid Oxide fuel cell, and Polymer Exchange Membrane fuel cell (PEMFC), have certain advantages and disadvantages for helicopter and tiltrotor applications. PEMFCs have a proven track record in the automotive industry and are possible candidates for electric tiltrotor applications in about 10 to 15 years. Improvements in stack specific energy and reductions in weight of the storage system will make Hydrogen a very attractive fuel for electric tiltrotors with the added advantage of producing the lowest environmental pollution. As will be shown later, electric generators powered by diesel engines can provide an attractive first step toward electrically powered tiltrotors.

6.2 Electric Motors And Generators

A key component of an electrically powered tiltrotor is the electric motor. In the recent past, there have been a number of important developments in electric motor technology so that the designer has a choice of a number of technologies from which to choose a motor.

An interesting development in the automobile field has been the use of “range extenders”. In automobile usage, a range extender is an electric generator that is run by a small internal combustion engine to supply energy for electric propulsion. In earlier range extenders the generator was simply attached to the output shaft of an internal combustion engine. Several types of range extenders have been developed for the automobile market. These can be classified based on the prime power source: piston engine, rotary engine, free piston linear generator, and micro gas turbine

A comparison of some range extenders and a Polymer Exchange Membrane Fuel cell is given in Table 1. For producing electric power, the fuel cell is the best option because it is highly efficient and has the best gravimetric and volumetric power densities. Among the other systems, the Wankel engine comes closest to the fuel cell in power density. With improved packaging, the Otto cycle IC engine can also be a close contender. The free piston linear generator is an interesting option that has the potential of having a flat profile and using multiple fuels even though it is heavy and bulky in its present stage of development. The micro gas turbine range extender does not appear attractive from power density considerations.

For efficient operation, rotors of Variable Speed Tiltrotors should operate between about 200 and about 500 rpm. For all tiltrotors, it is desirable for the RPM to be continuously variable and that the motor should operate at high efficiencies. Because electric motors achieve their best efficiencies at high RPMs, it is necessary to use a reduction gear box to achieve the lower RPMs demanded by the rotors.

6.3 State of Art in Power sources and motors

The characteristics of currently available powerplant choices are summarized below [3]

1. Gasoline (Spark-ignition) engine: Specific power = 1.15 kW/kg, sfc = 0.255 kg/kW/hour.

2. Diesel (Compression-ignition) engine: Specific power = 1.8 kW/kg, sfc= 0.23 kg/kW/hour.

3. Turboshaft engine: Specific power=4.25 kW/kg, sfc at Take-off power = 0.35 kg/kW/hour.

4. Li-ion Battery and Electric motor: Specific Energy of 0.12 kWh/ kg, Specific Power of 2.5 kW/kg.

5. Diesel Range Extender (Diesel+electric generator): Specific power of 1.46 kW/ kg, (Electric motor+

Controller + Reduction gear box) of 2.76 kW/ kg.

6. Microturbine Range Extender: Specific power of turbogenerator = 3.75 kW/ kg, sfc = 0.45 kg/ kWh.

7. Independent Diesel engine, generator and motor: Engine: Specific power of 1.8 kW/ kg, Electric generator: Specific power of 8 kW/ kg.

8. Hydrogen PEMFC engine (Current Technology): Gaseous Hydrogen sfc = 0.055 kg/ kWh, Power density of Stack = 0.65 kW/ kg, Weight of Fuel tank = 18.4 times the Weight of Hydrogen fuel.

9. Hydrogen PEMFC engine (Long term projections): Gaseous Hydrogen sfc of 0.041 kg/ kWh, Power density of Stack= 3.0 kW/ kg, Weight of Fuel tank = 6.7 times the Weight of Hydrogen fuel.

7. INFLUENCE OF POWERPLANT CHOICES ON SIZING AND PERFORMANCE OF TILTROTOR

7.1 Analysis Methodology

The sizing analysis is based on Tishchenko's methodology [10], modified at the University of Maryland to analyze various rotorcraft configurations such as single main rotor, co-axial, tandem, compound helicopter, and tiltrotors. The method requires the specification of the main performance targets (for example, payload, range, cruise speed, mission profile, or the use of a specified powerplant). The method has been organized in a modular fashion so that the performance estimates, rotor and wing sizing, weight estimation, mission performance etc. can be estimated properly. Some of the outputs of the sizing methodology are the component weights, power required, empty weight, take-off weight, fuel required, and rotor dimensions.

7.2 Baseline Tiltrotor

The baseline aircraft is a Variable Diameter Tiltrotor (Figure 12) based on the Excalibur aircraft designed at the University of Maryland [4]. This aircraft is powered by a "rubber" turboshaft engine and has a maximum take-off weight of about 8700 kg. The sizing mission (Figure 13) requires the aircraft to have an HOGE capability at 6K95 conditions while carrying a payload of 1360 kg. In this mission, it is also required to have a radius of action of 250 nm (460 km) and a cruise speed of 220 knots (405 km/hour). All the results presented in this paper are for this specific mission.

All the aircraft are designed to operate at the same disc loading of 12.5 lb/ft^2 and have the same hover figure of merit of 0.71 and a propulsive efficiency of 0.84.

Figure 12 University of Maryland's "Excalibur", Variable Diameter Tiltrotor aircraft.

7.3 Comparison of Turboshaft, Gasoline and Diesel Engines

7.3.1 Case I: Constant Payload

The first comparisons are for aircraft powered respectively by turboshaft, gasoline and diesel engines. All three aircraft are sized to carry the same payload and to perform the same mission. Table 2 provides a comparison of some key system weights and power required for the three configurations.

In spite of having a higher empty weight, the diesel version has a 7.3% lower take-off weight and consumes about 51% lesser fuel than the baseline turboshaft version. The gasoline engine version is 15.6% heavier and also consumes about 34% lesser fuel. Of the three options, the diesel version has the lowest empty weight and lowest fuel consumption

Because of its low take-off weight, the diesel version also needs the lowest take-off power (6.7% lower than the baseline version). Diesel engines operate at lower RPMs than turboshaft engines. This leads to a lower weight of the transmission for this version. In addition, diesel engines are less expensive than turboshaft engines. These considerations make the diesel engine option a more economical than the baseline turboshaft option.

Table 2. Comparison of baseline turboshaft, gasoline, and diesel powered aircraft for fixed payload.

	Turboshaft	Gasoline	Diesel
Engine system weight (kg)	1072.0	1991.1	1418.9
Drive system weight (kg)	655.6	700.1	636.2
Empty weight (kg)	5635.2	7362.9	5838.4
Fuel weight (kg)	1652.7	1089.1	812.5
Gross take-off weight (kg)	8715.2	10080.1	8080.0
Take-off power (kW)	2430.8	2827.7	2267.3
Cruise power (kW)	1309.4	1483.4	1232.2

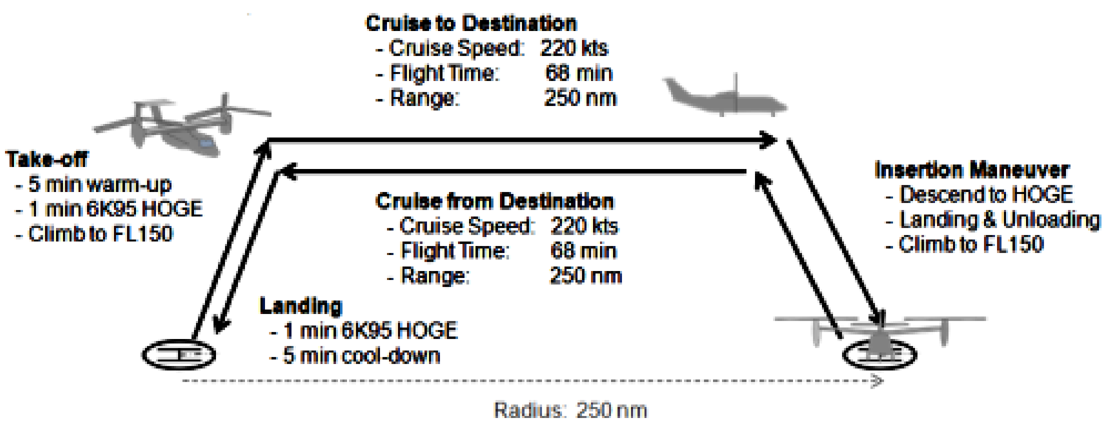

Figure 13. Sizing mission for Excalibur.

7.3.2 Case II: Constant Takeoff Weight

The next comparison is for the aircraft designed to have the same take-off weight but with different payloads. Table 3 shows a comparison of the baseline turboshaft, gasoline and diesel powered options. All the versions have the same take-off weight (8715.2 kg).

Table 3. Comparison of baseline turboshaft, gasoline, and diesel powered aircraft for the same take-off weight (8715.2 kg).

	Turboshaft	Gasoline	Diesel
Engine system weight (kg)	1072.0	2118.1	1529.0
Drive system weight (kg)	655.6	657.2	657.1
Empty weight (kg)	5635.2	6983.8	6225.8
Fuel weight (kg)	1652.7	866.8	866.5
Payload weight (kg)	1360.8	780.2	1542.2

The weight of the drive system for all the versions is of the same order (656 kg). The gasoline version requires 52% of the fuel and can carry 57% of the payload of the baseline turboshaft version. The diesel version also needs about 52% of the fuel but can carry 13.3% more payload than the turboshaft version. This comparison also shows the diesel version is more attractive than the baseline turboshaft version.

7.4 Battery Powered Tiltrotor

The battery powered version was powered by generic battery with a specific energy of 0.12 kWh/kg and equipped with an electric motor resulted in a very heavy vehicle. Figure 14 shows the influence of increasing the specific energy of the battery on the gross take-off weight of the tiltrotor. The take-off weight of the baseline turboshaft version is also marked in the figure. The battX denotes the ratio of the energy density of the installed battery to the baseline energy density. It is seen that it requires nearly an 11-fold increase in the energy density to match the take-off weight of the baseline version. This does not appear feasible even in the distant future, and an electric version of the tiltrotor using only batteries may not be possible without a major breakthrough in the energy density of batteries.

7.5 Polymer Exchange Membrane Fuel Cell (PEMFC) Powered Tiltrotor

Using current stack densities and tank weights, a PEMFC powered tiltrotor does not appear to be practicable at this time. The main contributor to the empty weight of a PEMFC powered tiltrotor was the weight of hydrogen storage tank. Figure 15 shows the variation of the take-off weight as a function of stack power density for a tank density of tankX of 3.0. In Figure 15, the following notation has been used:

$$\text{tankX} = \frac{\text{Hydrogen storage tank weight}}{\text{Weight of current storage tank}}$$

$$\text{stackX} = \frac{\text{Stack power density}}{\text{Current stack power density}}$$

It is seen that in order to match the take-off weight of the baseline turboshaft tiltrotor, it is necessary to reduce the tank weight by one-third and also to increase the stack power density by a factor of 3.2.

For a value of tankX = 3, Figure 16 shows the variation of the hydrogen fuel weight and the tank weight as a function of stackX. It is possible to match the take-off weight of the baseline tiltrotor for tankX of 3.0 and stackX of 3.2. The weight of the hydrogen fuel is 219.1 kg and the weight of the tank is 1198.7 kg. The weight of the hydrogen fuel is only 13% of the fuel weight required for the baseline turboshaft powered tiltrotor.

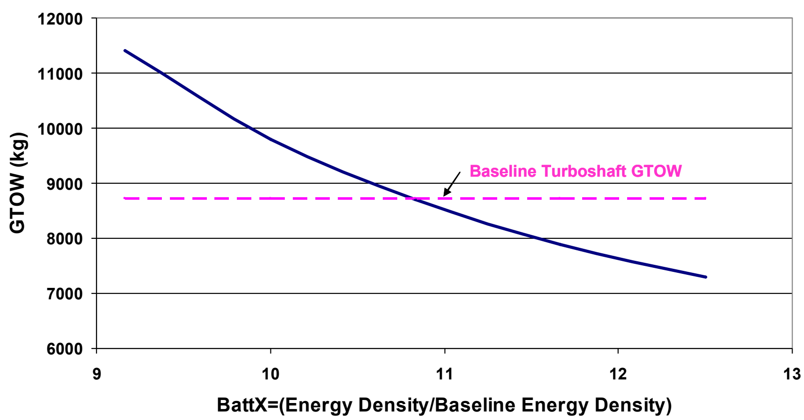

Figure 14. Influence of energy density of battery on the gross take-off weight of the vehicle.

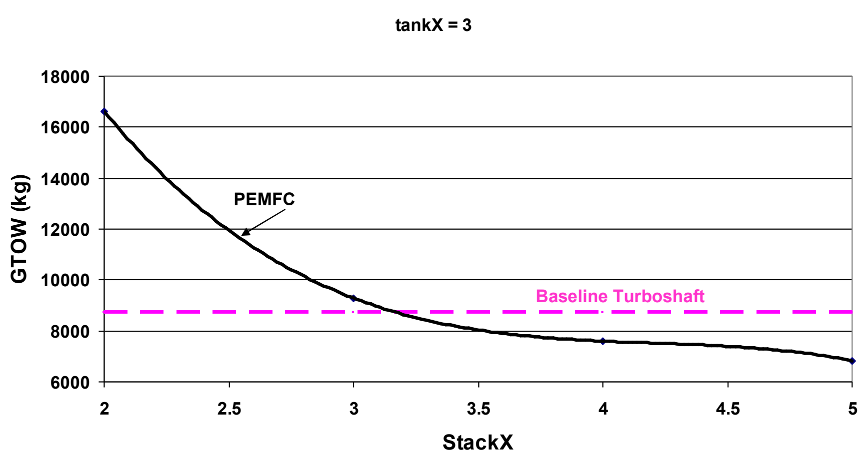

Figure 15. Influence of stack power density of PEMFC on gross take-off weight.

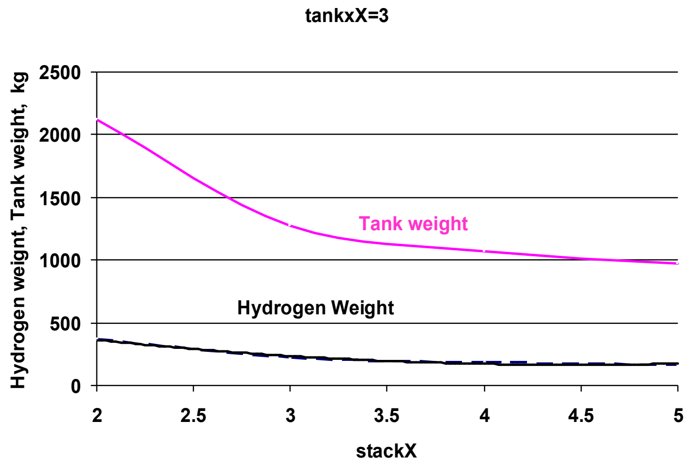

Figure 16. Influence of stack power density of PEMFC on weight of hydrogen fuel required for the mission and corresponding storage tank weight.

7.6 Diesel Generator Powered Tiltrotor

A performance comparison of an electric version of the tiltrotor using diesel generator and electric motor with the basic turboshaft version is presented in Table 4.

For the current diesel generator, the specific power was assumed to be 1.46 kW/kg. The power density of the (electric motor + controller + gearbox) was assumed to be 2.7 kW/kg. This configuration has a 39% higher take-off weight and a 69% higher empty weight. In spite of this penalty, the fuel consumption is 34% lower than that of the baseline. The take-off weights and the empty weights of the baseline and the electric version can be matched if the power density of the (electric motor + controller + gearbox) is increased by 87% to a value of 5.17 kW/ kg. In this case, the fuel consumption of the electric version is reduced by 51%.

It is possible to increase the power density of the motor to the required 5.17 kW/kg. If the motor can be made to work at 90% efficiency instead of the 70% assumed in these calculations, the power density is effectively increased to 4.05 kW/ kg. In addition, by using of split torque path gear train, new materials and composite housing, it is possible to achieve lower weights for the gear box. This will make the diesel generator option more attractive.

8. SUMMARY AND CONCLUSIONS

For optimum performance of tiltrotors, it is necessary to select the powerplant and drive system to match the requirements of the rotor. Rotors operate in two distinct regimes, hovering rotor and propeller, and the power required during the various stages of flight can be optimized by a continuous variation of the rotor RPM. For optimized rotors, the cruise power can be as low as 54% of take-off power, but the cruise torque can be either 120% of the take-off torque or about 50% of take-off torque depending on the rotor design. The power and torque characteristics of turboshaft, gasoline, diesel engines and electric motors depend on their output RPM. It is therefore necessary to match the operating characteristics of the rotor, electric motor and the powerplant for optimum performance of the vehicle.

The influence of the choice of powerplants was examined with reference to a turboshaft powered Variable Diameter Tiltrotor with a take-off weight of about 8700 kg. The sizing mission for this aircraft required it to take-off at 6K95 and to have a radius of action of 250 nm at a cruise speed of 220 kts.

(i) Comparison of Baseline Turboshaft, Gasoline and Diesel Powered Aircraft

It was found that the gasoline engine version was 15.6% heavier but consumed about 34% less fuel than the baseline turboshaft version. The diesel version had a 7.3% lower take-off weight and consumed about 51% less fuel than the baseline turboshaft version. Because of its low take-off weight, the diesel version also needed the lowest take-off power (6.7% lower than the baseline version). Because diesel engines operate at lower RPMs than turboshaft engines, the weight of the transmission can be further reduced for this version. In addition, diesel engines are less expensive than turboshaft engines. These considerations make the diesel engine option more economical than the baseline turboshaft option. When sized to the same take-off weight as the baseline tiltrotor, the diesel version needed about 52% of the baseline fuel and could carry 13.3% more payload than the turboshaft version.

(ii) Li-ion Batteries and Polymer Exchange Membrane Fuel Cell

The improvements required for Li-ion batteries and PEMFC to match the performance of the baseline turboshaft tiltrotor were found to be:

(a) Batteries: nearly 11 times increase in energy density

(b) PEMFC: 320% increase in stack power density

(c) Hydrogen storage tank: Reduction of 33% in weight

(d) Electric motor, controller and reduction gearbox: 187% increase in power density.

(iii) Hybrid diesel generator and electric motor

For the current generation diesel generator, the specific power was assumed to be 1.46 kW/ kg. The power density of the electric motor, controller and gearbox combination was assumed to be 2.7 kW/ kg. This configuration has a 39% higher take-off weight and a 69% higher empty weight. In spite of this, the fuel consumption is 34% lower than that of the baseline. If the power density of the electric motor, controller and gearbox is increased by 187%, the take-off weights and the empty weights of the hybrid version and the baseline are the same and the fuel consumption of the hybrid electric version is reduced by 51%.

Table 4. Comparison of baseline turboshaft with diesel generator option.

	Turboshaft	Diesel Generator (current)	Diesel Generator (future)
Motor Power density (kW/kg)	-	2.76	5.17
Engine system weight (kg)	1072.0	2630.6	1886.9
Drive system Weight (kg)	655.6	1391.6	532.9
Empty Weight (kg)	5635.2	9526.2	6412.9
Fuel Weight (kg)	1652.7	1089.1	812.5
Gross take-0ff Weight (kg)	8715.2	12149.7	8715.0
Take-off Power (kW)	2430.8	3409.2	2445.4
Cruise Power (kW)	1309.4	1738.2	1312.8

8.4 Suggested Areas of High Payoff Research

The results of the parametric studies suggest that areas of research that will result in high payoffs for tiltrotor applications can be:

(a) Batteries: Increase in power density with a target of 11 times increase over current levels; possible candidates are Lithium-air batteries.
(b) PEMFC: Increase in stack power density by at least 300% over current levels.
(c) *Hydrogen storage tank:* A reduction of at least 300% in weight over current levels. This will make the tank more compact and reduce the empty weight of the aircraft.
(d) Electric motor, controller and reduction gearbox: Increase in efficiency and a187% increase in power density.
(e) Controllers: to match the requirements of the rotor with the characteristics of the powerplant, generator, electric motor, and reduction gear box so that the electric system operates at a minimum of 90% efficiency throughout the flight. This is a very important area if the benefits of electric tiltrotors are to be realized.

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ACKNOWLEDGEMENTS

Authors acknowledge the help of Bharath Govindarajan and Elizabeth Weiner in the preparation of this paper.