Multiple Engine, All Electric Drive, Magnetic Suspension Rotorcraft

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Abstract

Heavy lift rotorcraft will require multiple engines that are cross coupled via transmissions and connecting shafts that are sources of reliability and redundancy concerns. With today's electric alternator technology and magnetic materials, it is possible and feasible to design a heavy lift rotorcraft employing multiple engine-alternator systems and distributing the output among multiple large diameter electric motors for redundancy and increased reliability. Furthermore, the design of large diameter magnetic bearings in concert with the distributed electric motors effectively eliminates all mechanical components, mainly transmissions and cross shafts, while providing the potential for increased reliability and reduced maintenance costs.

The Sunlase Magnetic VTOL or MVTOL system concept employs electric drive and magnetic suspension bearings to eliminate conventional bearings, transmissions and cross shafts in a multi-engine heavy lift system. The MVTOL system can be designed to optimize the individual blade aerodynamic efficiency and take advantage of the ducted geometry to produce an efficient vertical lift system. This paper discusses the basic design of a MVTOL system in relation to technologies that are not commonly employed in vertical lift systems which enables non-rotorcraft industries to enter the vertical lift market.

Keywords: Magnetic bearing, distributed electric motor. multiple engine-alternator, redundancy and reliability

Introduction

The technology trend to all electric aircraft and magnetic levitation for high speed trains and flywheels [1,2] has produced a number of technologies that can be applied to rotorcraft. Specifically direct turboshaft drive, high frequency alternators at the multiple megawatt level and permanent magnetic materials for magnetic bearings. These technologies can be employed in a rotorcraft in the following manner.

Magnetic VTOL Configuration

The basic SunLase MVTOL[3] system for heavy lift applications is illustrated in Fig. 1. The objective of the MVTOL system is to increase lift by increasing the number of blades providing lift at the optimum velocity, optimizing the blade configuration, and eliminating tail rotor by configuring the blades in counter rotating annuli around the body of the rotorcraft. Note from Fig 1 that the top and bottom blade rings are supported by annular magnetic bearings. The aerodynamic lift is supported by the annular magnetic bearings around the body of the craft, the blades tips are confined and the blade pitch is controlled with passive, permanent magnet bearings.

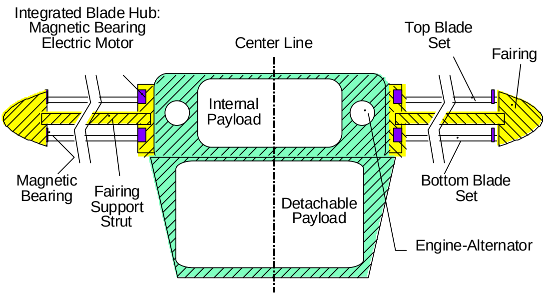

Figure 1. Basic MVTOL Configuration

Magnetic Bearing Technologies

Permanent magnet, Halbach array[4] bearing technologies developed for the flywheel energy storage[5] and the Inductrak[6,6,7] magnetically levitated train can be applied directly to rotorcraft applications.

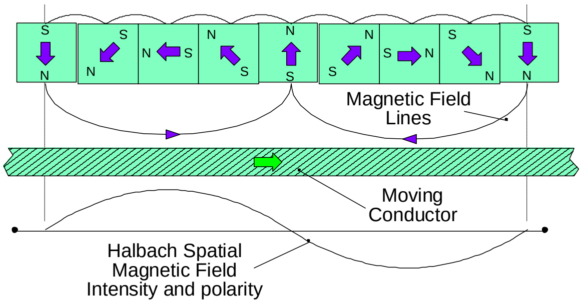

Figure 2. Halbach Array Magnetic Bearing

A Halbach array consist of multiple permanent magnetic sections arranged as in Fig. 2, such that the magnetic field adds in a sinusoidal fashion on one side and effectively cancel of the other side. When the sinusoidal magnetic field interacts with a moving conductor, the magnetic field resulting from current induced in the conductor interacts with the driving

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magnetic field to repel or suspend the conductor from the Halbach array face. The magnetic bearing technology used to support the rotorcraft body on the M-VTOL counter-rotating rotor blade hubs was developed and demonstrated for high speed trains, the Inductrak™ system[7], by the Lawrence Livermore National Laboratory (LLNL) of the Department of Energy (DOE). The magnetic bearings have demonstrated supporting force of 50 lbs/in^2 when the rotor is moving at 20 m/s. The magnetic bearings function independently of drive power which makes to the standard auto-rotation safety operation used in conventional rotorcraft possible with the M-VTOL. Also, note that the repulsive force increases with velocity while the magnetic drag drops after a critical velocity is reached. The confined rotor hub can be designed such that the mass of magnetic material in all magnetic bearings is about 2 percent of the lift that can be supported.

Two magnetic bearings are used in each of the counter rotating blade hubs as illustrated in Fig. 3. The top magnetic bearing supports the mass of the craft while the lower bearing contains the hub movement. The electric motor drive and the magnetic bearings are independent such that the magnetic bearing functions in the event of complete electrical failure.

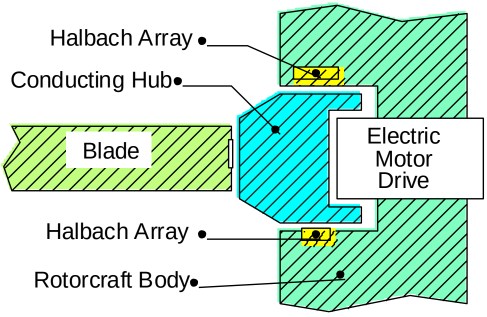

Figure 3. Blade Hub Magnetic Bearing Placement

Additional magnetic bearings, located in the fairing at the end of the blade as illustrated in Fig. 4, serve to restrict vertical movement of the rotating blade ends, but do not support thee lift forces. In this case, the blade tips contain small permanent magnet arrays (not Halbach arrays) that move along inside a conducting track.

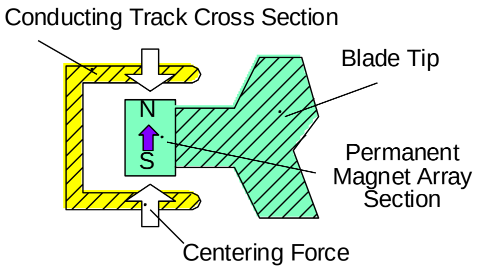

Figure 3. Blade Tip Magnetic Bearing

Finally the individual blade pitch is controlled with a magnetic bearing track that can be raised or lowered as illustrated in Fig. 5. Two tracks mounted on the rotorcraft body, one for the top blade set and the other for the lower blade set, can be moved vertically to control the pitch of the counter rotating blades. Note that the conducting track can be distorted as it extends around the fuselage to alter the blade pitch as a function of position around the fuselage.

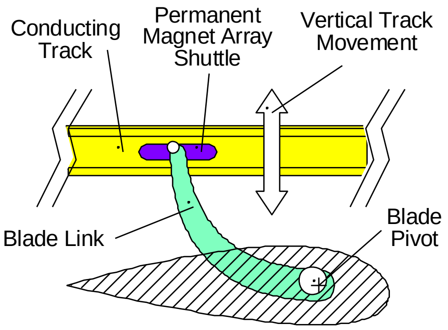

Figure 5. Magnetic Bearing Blade Pitch Control

Multiple Engine-Alternator Power System

The Sunlase MVTOL system design employs distributed electric motors around the body of the aircraft. The distributed electric motors require alternating current drive which is generated by multi-megawatt alternators driven directly by turboshaft engines. Presently available alternator technology can provide 1-5 MW of electrical energy at several hundred Hz without mechanical gearing which reduces system weight and increases efficiency. The specific weight of such alternators is approximately 3-5 KW/kG.
Multiple engine-alternator pairs are connected as illustrated in Fig. 6 to provide the drive necessary for a heavy lift rotorcraft. The electric motor circumference is divided into sections such that each engine-alternator pair drives a portion of the top electric motor and bladeset and the same portion of the lower electric motor and blade set. In the event of failure of one motor-alternator pair, the remaining engine-alternator pairs can provide drive to the system since the motor stators are connected via a common rotor. Note that in

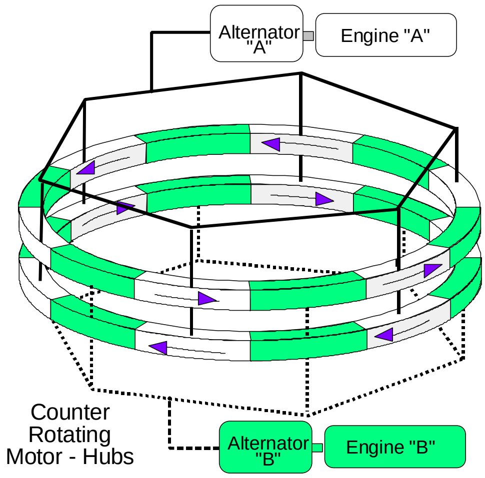

Figure 6. Multiple Engine Alternator Motor Drive

this approach, the alternating current from the alternator directly drives without gear down the large diameter induction motor.

The transfer of vertical lift power from the engine-alternator to some form of thrust can be accomplished as illustrated in Fig. 7. The output power of the alternator is controlled by adjusting the alternator field current while the thrust power required is controlled by the adjusting the thrust fan pitch.

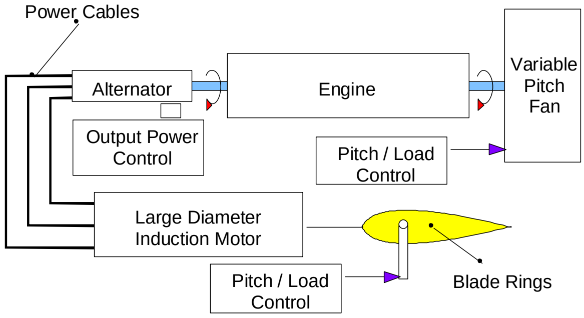

Figure 7. Power Transfer Block Diagram

Magnetic Bearing Point Design

The main magnetic bearings supporting the weight to be lifted can be scaled to a particular application. The design of a magnetic bearing system is presented in TABLE 1 for a total system mass of

TABLE 1: Halback Array Design

Parameter	Value	Unit
Inductrak (Train) Data		
Mass supported / per unit area	160	Mtons/m2
	160000	kG/m2
	16	kG/cm2
	89.63	lb/in2
Conductor Velocity	20	m/s
Magnetic Face Area to support 1 ton	22.31	in2
Magnetic bearing thickness	1	in
Magnetic bearing volume	22.31	in3
Mass supported / volume	89.63	lb/in3
Permanent magnet density	7.5	gm/cm3
	7500	kG/m3
	0.27	lb/in3
Mass of magnet supporting 1 ton	22.31	lb
Ratio: Support mass / magnet mass	89.63	
Total Mass of Rotorcraft + load	80	Tons
	160000	lbs
Permanent Magnet Mass	1785	lbs

The total magnet mass is small compared to the mass supported or levitated which points out the potential of this technology in this application. Note that the large diameter of the magnetic bearings is an advantage. Obviously the associated hardware will reduce the weight to mass advantage, but the structure which is symmetric has some advantages in system design.

First Order Aerodynamic Point Design

The technologies discussed above are employed in a first order point design of a heavy lift system. The lift provided by the blades is transferred to the hub of each rotor and to the fuselage via the magnetic bearings. The lift aerodynamics are estimated via first order calculations that are presented in TABLE 2 and compared with the same calculations for commercial tilt rotor craft.

TABLE 2: MVTOL vs Commercial Tilt rotor Design Comparison

Parameter	Tilt Rotor	MVTOL	Unit
Blade outside radius	44	52	ft
Blade Inside radius	0	26	ft
Number of blades	8	24	
Blade tip speed	650	385	ft/s
Rotor Angular Velocity	14.77	7.4	rps
Air Density	6.86E-02	6.86E-02	lbm/ft3
Pitch Angle	0.174	0.174	rad
Inflow Angle	0.035	0.035	rad
Attack Angle	0.14	0.14	rad
Lift Coefficient	0.8	0.8	
Drag Coefficient	0.12	0.12	
Blade Chord	3	3	ft
Thrust	4.06E+06	4.42E+06	lbs
Drag	7.54E+05	8.21E+05	lbs
Non hover Power Required	1.52E+04	1.05E+04	hp
Induced Power Requirments			
Actuator Disk Area	1.21E+04	6.37E+03	ft2
Duct Exit Area	1.21E+04	6.37E+03	ft2
Required Thrust	4.06E+06	4.42E+06	lbs
Induced Velocity Hover Downstream	98.7	100.5	ft/s
Induced Ducted Fan Power	8.30E+03	9.20E+03	hp
Total Hover Power Requirements	2.35E+04	1.97E+04	hp
	1.76E+04		kW
	17.60		MW
Alternator Power Density	1.50		kW/lb
Alternator Mass	1.17E+04		lb

The zero order calculations indicate that the large number of blades moving at larger average velocity result in increased lift efficiency with only slightly higher downdraft velocity. In addition, the shaft horsepower required corresponds to an electrial power of over 17 MW which is possible with four, presently available 5 MW alternators.. A very large amount of aerodynamic analysis and engineering remains, but the MVTOL approach appears to have some advantages in power distribution which can translate into increased reliability and reduced maintenance..

Aerodynamic Configuration of MVTOL

One of the many remaining questions is how to employ the magnetic levitation kernel in an aerodynamic design that facilitates the transition from vertical lift to horizontal, high speed transport. The power system defined in Fig. 7 illustrates a method of transferring power from vertical lift to horizontal thrust. This paper is an electrical engineering description of a power and magnetic levitation system and not an aerodynamic description of the rotorcraft. One possible configuration, illustrated in Fig. 8, pictures auxillary lifting surfaces outside the center lift section. A second possible configuration would use the body for lift and locate the thrust fans outside the main body as illustrated in Fig. 9.

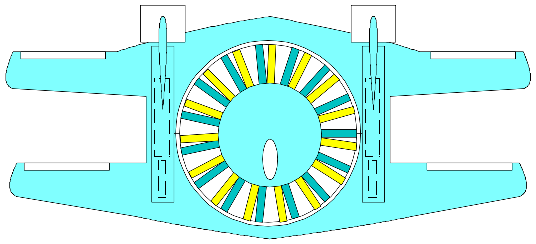

Figure 8. MVTOL Transport Configuration

Figure 9. MVTOL Transport Configuration 2

Operational Concerns

This departure from the normal vertical flight technology approach generates concerns related to electrical failure at the bearings, maintenance requirements, electro-magnetic effects on avionics and navigation systems.

The distribution of the motor windings and the large number of parallel windings tend to minimize the effect of failure in an individual winding and thus the potential for increased reliability and redundancy. Note that the drive windings for the top and bottom rotors are in series and the loss of one winding affects the drive for both in a similar manner.

The passive natue of the permanent magnet bearings eliminates concerns about electrical bearing failures and the distributed natuue of the bearings results in low local stress loadings that provide potential for reduced mechanical maintenance. The bearings function in the event of loss of electrical power as long as the rotors are turning which enables conventional auto-rotation procedures.

The effect of the stray electromagnetic fields on avionics related to the frequency of operation. The drive frequency for the electric motors is several huncred Hertz which does not radiate efficiently and the design of the motors require efficient and thus tight coupling of the electromagnetic energy. Furthermore, the electronic alternators and drive windings do not require electronic switching which would generate electromagnetic energies at higher frequencies. Therefore, the electrical drive interference on avionics and navigation electronics should be very minimal.

Maintenance costs are also a concern, especially in a vertical flight system. In conventional helicopter systems, the reliance on mechanical components that are highly stressed are a constant maintenance check and service point. In the MVTOL system, the mechanical loads are distributed over large areas such that the local mechanical stress is reduced which should also reduce maintenance. The MVTOL system relies on non contact magnetic bearings for all transfer of power and control system which should further reduce maintenance.

Conclusions

The first order analysis of the electric drive, magnetic bearing VTOL or MVTOL, approach is a possible and feasible technology for heavy vertical lift applications. Presently available permanent magnets and magnetic levitation / bearing systems have been demonstrated that can provide the parameters necessary for a heavy lift rotorcraft. Currently available engines and alternators can provide the electrical power required for heavy lift rotorcraft applications. Magnetic bearing technologies for supporting the mass of a heavy lift platform with minimal permanent magnet mass were presented. In addition, magnetic bearing technogies for pinning the ends of the numerous lifting blades and for controlling the blade pitch were identified in this paper.

First order aerodynamic lift analysis also indicates that the MVTOL system can provide the lift required at comparable power requirements. The large number of blades enable the lift to be generated at lower blade velocities, but the downdraft velocity is similar to a commercial tilt rotor system.

The power analysis indicates that a 80 ton heavy lift, MVTOL rotorcraft would be powered by 4-5 turbine engine – alternator pairs that distribute the power via electrical conductors rather than transmissions and connecting shafts.

Finally, this paper is focused on an electrical engineering analysis and large amount of additional aerodynamic analysis and mechanical design are required to define the configuration most appropriate for an MVTOL high speed transport.

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