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Electric Drive - Magnetic Suspension Rotorcraft Technologies

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ABSTRACT

The recent advances in electromagnetic technologies have made electric drive-magnetically suspended rotorcraft a feasible and practical approach to heavy vertical lift systems. This paper describes the Electric Drive -Magnetic Bearing Vertical Take Off and Landing (MVTOL) system concept that optimizes lift through multiple, optimum blade rotors driven by multiple engine-alternator systems and suspended with large diameter, permanent magnetic bearings. This embodiment of technologies is outside of conventional vertical lift technology and will enable non-rotorcraft industries to enter the market

INTRODUCTION

The availability of very powerful permanent magnets and the development of electrical components for the More Electric Aircraft (MEA) program and anticipated directed energy systems offer the opportunity to consider replacement of mechanical systems in aircraft and rotorcraft with electrical and magnetic systems. Passive, permanent magnet bearings that support at least 50 times the weight of the magnet have been demonstrated for levitating high speed levitated trains. High power alternators, driven by turbine engines at power levels of over 5 MW (~ 7000 hp) and linear electric motors have been demonstrated for powering advanced electric weapons on mobile platforms. SunLase has combined these technologies in a Magnetic Vertical Take Off and Landing (MVTOL) [1] concept that has a number of advantages in applications in which efficiency, redundancy, personnel safety, and maintainability are important.

PERMANENT MAGNET BEARINGS

The basic structure of the magnetic levitation in a high speed train is a Halbach array [2], [3] of permanent magnets arranged, as in Fig. 1, to produce a sinusoidal magnetic field along the front side of the structure and minimal magnetic field on the back side of the structure. A single sided Halbach array bearing, shown in Fig. 1, is formed when a moving conductor is subjected to the Halbach array magnetic field. In moving the conductor through the magnetic field, a reaction current is induced in the conductor to produce an opposing magnetic field that generates a repulsive force to move the conductor away from the array. Two Halbach arrays, one on top of the moving conductor and the second beneath the conductor, can be used to suspend or magnetically levitate the moving conductor.

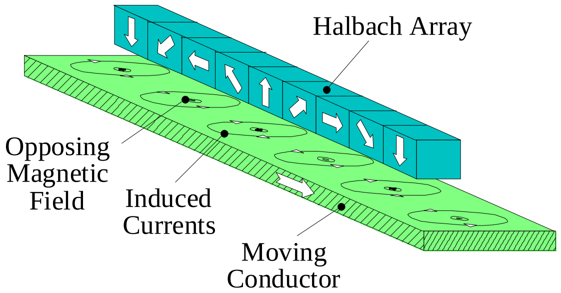

Figure 1. One Sided Halbach Array Magnetic Bearing

The Inductrak™ magnetically levitated train system [4] work has demonstrated a lift force of 85 lb/square inch of Halbach Array face when the conductor is moving at 20 m/s (~ 65 ft/s). Additional work has shown that the lift force increases as the conductor velocity increases and the eddy current loss in the conductor decreases at lift off to reduce the resistive losses in the conductor. In order to design a double sided magnetic bearing, the total effective lift of the bearing is at least 25 lb/sq. in. If the density of the permanent magnet is 7500 kG/m3 and the permanent magnet section is a cube, the weight supported per permanent magnet can be in excess of 150 pounds of lift for one pound of permanent magnet. Thus for a double sided magnetic bearing, the mass of the bearing would be less than 2 percent of the mass suspended.

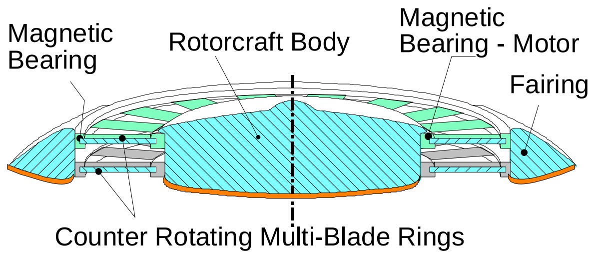

Figure 2. MVTOL Magnetic Bearings

A number of Halbach magnetic bearings can be used in the MVTOL system to support the body of a rotorcraft from the lifting blades system, to control the pitch

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of the rotating blades and to tie town the tips of the blades fin a ducted fan configuration, as illustrated in Fig. 2 and 3.

The main Halbach magnetic bearings, one on top of the blade hub and one below the blade hub, support the weight of the craft on the blade hubs that surround the aircraft and transfer the blade lift to the fuselage, illustrated in more detail in Fig. 3. The blade tip magnetic bearings suspend the moving conductor connected to the blade tip within the conducting channel attached to the fairing. The pitch control magnetic bearing supports the moving conductor connected to the bell crank within a conducting channel that is moved vertically to change the blade pitch. The Halbach bearing above the blade hub supports the weight of the rotorcraft while the bottom bearing confines the conducting hub within the drive structure. Note that the electric drive system is independent of the magnetic bearings such that auto-rotation can be used in the event of electric drive failure.

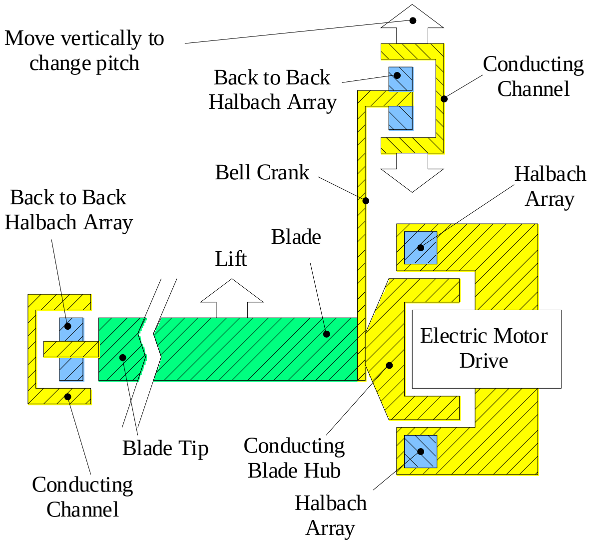

Figure 3. MVTOL Halbach Bearing Applications

The MVTOL application of Halbach bearings eliminates mechanical bearings in a geometry that reduces the local mechanical stress which should increase the reliability and reduce the maintenance required in critical vertical lift components.

REDUNDANT ELECTRIC HUB DRIVE

The recent developments in compact, high power electric power systems can be employed in concert with innovative SunLase electric rotorcraft blade drive system to provide additional redundancy and safety in multiple engine drive systems. The compact sources include turbine driven alternators at power levels up to 5 MW. Multiple sources can easily provide the equivalent power of over 10,000 hp.

In multiple engine systems, such as the V-22, transmissions cross shafts and shaft bearings are used to insure that the failure of one engine does not render the drive of both sets of lift blades inoperative. The fail safe operation can more easily be controlled using the MVTOL electric drive system, illustrated in Fig. 4 which powers two counter rotating blade hubs. The counter rotating Blade hubs used in the MVTOL system employs a large number of optimum blades at lower velocities to provide a more efficient aerodynamic lift when embodied in a ducted fan configuration. Therefore, the drive windings of the electric motors powering the blade hubs are subdivided into multiple sections. In the case illustrated in Fig. 4, each hub drive is divided into twelve sections. Engine-Alternator A drives six sections (white) of the top hub drive windings and six sections of the bottom hub drive windings. Engine-Alternator B drives the green sections of both the top and bottom hub drive windings. Thus, the SunLase segmented drive configuration enables the drive to be continued in the event that one of the engine-alternator systems fails. Furthermore, more than two sets of engine-alternator systems can be used to power the dual hub drive systems.

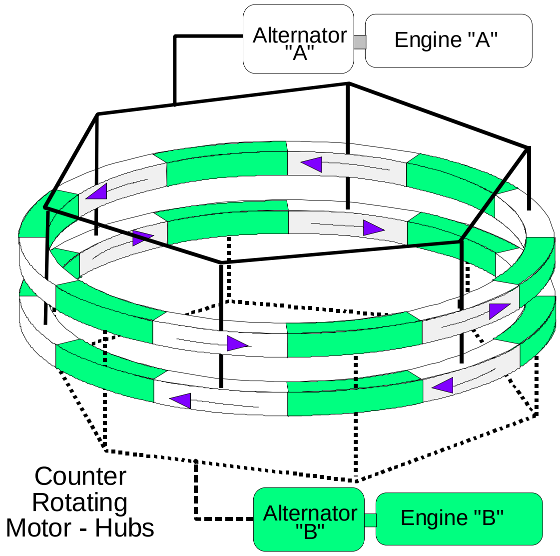

Figure 4. Multi-Engine Rotorcraft Drive System

ELECTRIC CONTROL SYSTEM

Forward thrust for the MVTOL configuration is provided by variable pitch fans driven by the same engines turning the electric alternators. The transfer of engine-alternator power from the lifting fan electric motors to the thrust fans for forward thrust can be accomplished as illustrated in Fig. 5. 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.

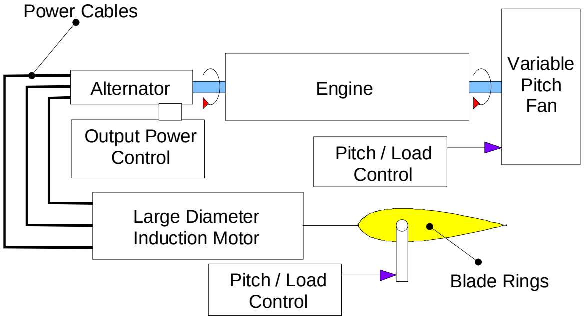

Figure 5. Power Transfer Block Diagram

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, presented in TABLE 1, requires a magnet mass of 1800 lbs to support a total system mass of 80 tons.

TABLE 1: Halbach 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.

Finally, these permanent magnet bearings have been shown to be stable and low loss. [5], [6]

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 lower 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 has 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 bearing technology in an aerodynamic design that facilitates the transition from vertical lift to horizontal, high speed transport. The power system defined in Fig. 5 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.

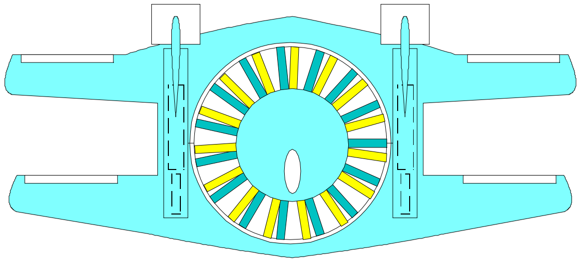

Figure 6. MVTOL Transport Configuration

One possible configuration, illustrated in Fig. 6, pictures auxiliary lifting surfaces, outside the center lift section, that provides lift during forward motion.

OPERATIONAL CONCERNS

This departure from the normal vertical flight technology approach generates concerns related to electrical failure of the bearings, maintenance requirements, and 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 nature of the permanent magnet bearings eliminates concerns about electrical bearing failures and the distributed nature 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 hundred 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 is 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 feasible and advanced 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 technologies 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 blades to be optimized and 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 3-5 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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