DESIGN AND CONTROL STUDIES FOR THE VECTOROTOR HYBRID VTOL HEAVY LIFT VEHICLE

T. R. Quackenbush
Continuum Dynamics, Inc., Ewing, NJ
todd@continuum-dynamics.com

W.F. Putman, J.E. Risser*, and W.McE. Miller
Aereon Corporation, Princeton NJ
aereon@aereoncorp.com

Abstract

There has been a resurgence of interest in both lighter than air vehicles and hybrid designs that combine buoyant lift with powered or rotorborne propulsion. While the potential of such vehicles to undertake short range heavy lift functions has been long understood, many concepts have been found to lack the control capability necessary for precision vertical flight or easily controllable forward flight. This paper describes initial design work on a novel concept – denoted VectoRotor – that bypasses these problems; VectoRotor combines buoyant and dynamic lift in a hybrid, rotary-wing aircraft that employs a unique joined-rotor design. The resulting configuration provides vertical thrust and direct lateral force control for precision hovering in a structurally efficient manner. Preliminary analysis suggests this concept offers reduced fuel burn, lower noise, and lower operating costs than heavy lift helicopters conducting similar missions. This paper will outline the design history of the concept and results of preliminary scaling analyses on sizing for practical flight vehicles. It will also describe the application of a comprehensive rotorcraft model to define key performance issues for hover and forward flight, in particular engine power and flight control requirements and estimated limits on trimmed forward flight.

Introduction

Recent research and development activity has seen revived interest in both lighter than air vehicles and hybrid designs that combine elements of buoyant lift and powered or rotary wing propulsion ([1]-[5]; see also Figure 1). This activity is in response to widely recognized needs for energy-efficient heavy lift; while much interest has focused on vehicles with moderate to long range (e.g. the Lockheed Martin P791), the role of such vehicles in precision short range heavy lift missions has also been long studied (e.g., [6]-[9]). However, many such hybrid buoyant/VTOL concepts have been found, when tested, to suffer from a lack of control capability necessary for precision vertical flight.

Work at Aereon the 1990s entailed initial design of a novel concept to bypass these problems with a short range heavy lift capability at significantly lower cost than either large buoyant systems or conventional helicopters [10]. This concept, denoted VectoRotor, combines buoyant lift with dynamic lift in a novel hybrid, rotary-wing aircraft (Figure 2).

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* currently Battelle, Aberdeen, MD

The VectoRotor's unique joined-rotor design distinguishes it from other hybrid, rotary-wing designs. The joined-rotor concept consists of two rotors – an upper rotor with drooped blades and a lower rotor with blades that are coned upward. The resulting rotor configuration provides vertical thrust and direct lateral force control for precision hovering in a structurally efficient design. Each rotor operates with a large-span trailing edge flap which can be controlled cyclically (Figure 3), providing one per rev variations in blade loading thereby enabling generation of direct lateral forces for flight control and precision hover in winds.

Preliminary design studies conducted at Aereon in the late 1990s indicated that, when compared to conventional helicopters in civil vertical, heavy-lift applications, the VectoRotor potentially offers substantial advantages, including: lower fuel burn and emissions due to the use of buoyant lift and tip-driven rotors; reduced noise due to the low disc-loading and tip speeds; improved safety due to the use of buoyant lift and mitigation of engine-out emergencies; good hovering characteristics from direct force control; and potentially lower production and operating costs due to the use of standard general aviation construction technologies [10]. Full details of the fundamental VectoRotor concept are contained in existing

U.S. and international patents [11].

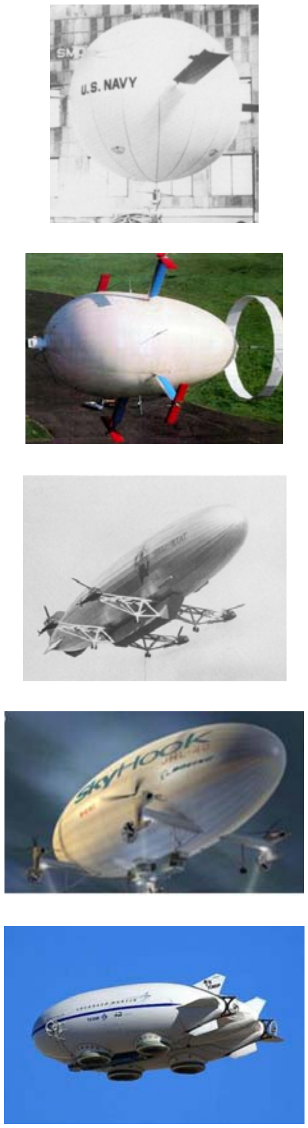


Figure 1: Legacy and current hybrid buoyant /rotorborne vehicles (top to bottom) Aerocrane, Cyclocrane, Piasecki Helistat; Boeing/Skyhook JHL-40, Lockheed P791.

The present paper seeks to complement these prior activities by providing an overview of the VectoRotor (VR) concept and its development history, though the central focus in on reporting the application of the CHARM comprehensive rotorcraft model [12] to the VectoRotor concept to refine initial estimates of basic performance characteristics in hover and forward flight. As will be detailed below, CHARM has been used to develop a full-airframe multirotor computational model of a representative VR vehicle; Figure 4 shows an early representation, which was refined further for this study (see below). This modeling has been used define engine power requirements for hover and forward flight and to estimate limits on trimmed forward flight and hover in a crosswind. Sample results will be presented following an overview the VR development history.

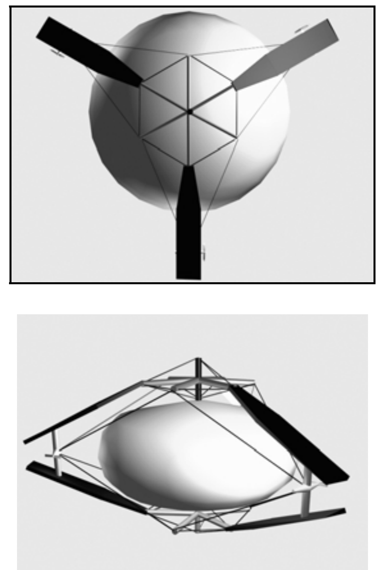


Figure 2: VectoRotor conceptual plan view (top) and side view (bottom).

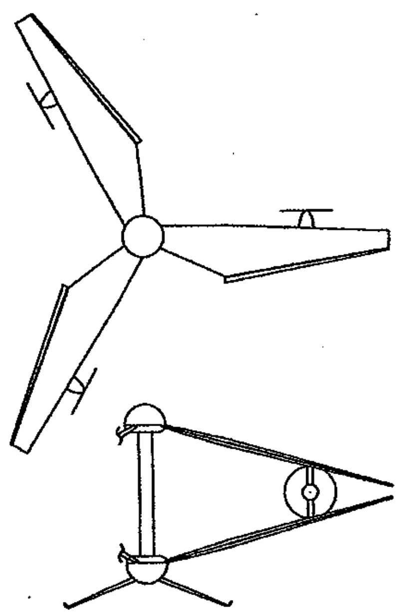
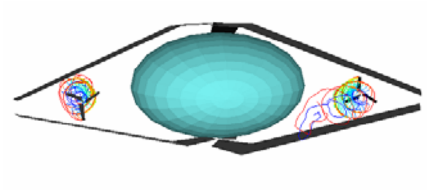
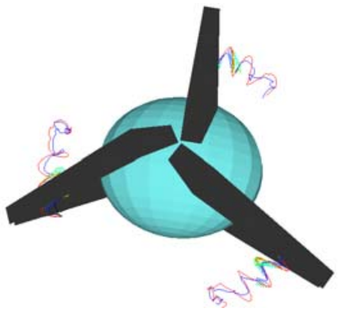


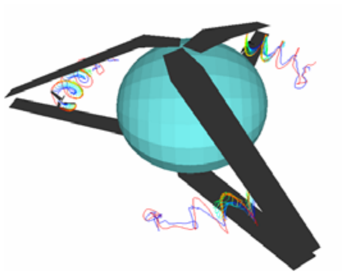
Figure 3: Top and side views of VectoRotor blades, showing tractor propellers and trailing edge flaps used for cyclic control.



Side View



Plan View



Oblique View

Figure 4: Three views of an early CHARM computational model of a VectoRotor vehicle showing all aerodynamically active elements (rotor blades, propellers, and buoyant centerbody). (Note: markers show the vortex wake of the propellers).

Overview of the VectoRotor Design Concept

As noted above, the VectoRotor combines the use of buoyant and dynamic lift. The oblate spheroid center-body, a large helium-filled cell, floats the unladen aircraft, thus conserving fuel for lifting cargo; a control cabin below the centerbody holds a cargo hoist for sling loads. While the aircraft can be scaled to many different sizes, conceptual design to date has focused on vehicles that range in payload from 12,000 to 24,000 lbs, a payload range that prospectively allows the aircraft to fill a niche in the heavy lift market. Specifically, it could serve as a “flying forklift”, providing short range lifting capability at lower operating costs than current helicopters while complementing the prospective capabilities of other, longer-range hybrid LTA/VTOL vehicles.

The VectoRotor concept emerged from an effort combining conceptual and hardware design with studies of past fabrication and testing of hybrid aerial crane concepts. The VR consists of a nonrotating ellipsoidal balloon around which rotate two large rigid rotors attached near their tips, each by a strut (Figure 5). Engines, mounted on the struts, propel the rotation of the rotor-lift system. The operating concept features buoyant support of the vehicle empty weight plus a part of the payload, with the balance of the payload supported by rotor thrust. When unloaded, the excess buoyancy is countered by downward rotor thrust thereby eliminating the requirement for ballast. The arrangement also provides for a low disc loading helicopter rotor to enhance lifting efficiency.

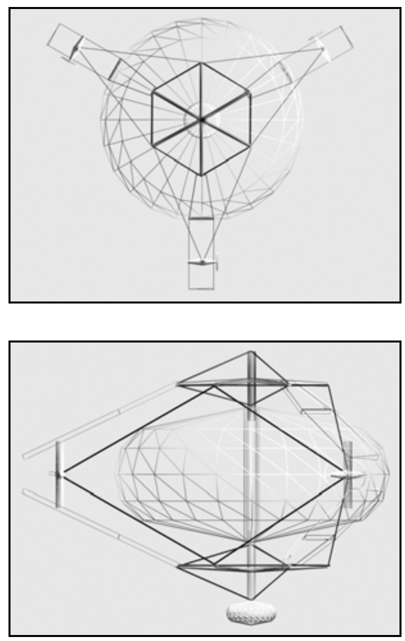


Figure 5: Structural schematic of the VectoRotor air vehicle (top view above; side view below).

Cyclic (1P) control of the loading on the rotor blades is required to allow controlled forward flight or a hover capability in a crosswind. While such a capability could be provided in principle by 1P control of the incidence of each wing, it is much more practical for large scale applications to apply this control through the use of moving trailing edge flaps, as suggested by Figure 3.

Prior Concepts

This approach to hybrid rotating wing technology embodied in VectorRotor is a departure from other prior or competing concepts. One of the earliest prototype hybrid aerial cranes was the Aerocrane vehicle that consisted of a rotating spherical buoyant centerbody with tip-driven blades providing addition lift and control [6], [8], [9]. Tests of this vehicle illustrated the general feasibility of achieving controllable flight in a hybrid vehicle; however, the aircraft had limited lateral force control. In addition, the rotating centerbody produced a Magnus force effect that made flight control more complex. Follow on derivatives of the original Aerocrane (Figure 6) and the Cyclocrane (Figure 1) were intended to enhance its directional force capability through the addition and/or reorientation of control surfaces on rotating blades. These design changes, however, introduced undesirable levels of addtional complexity.

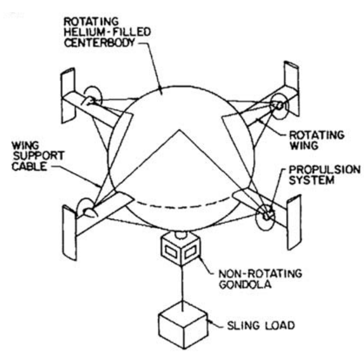


Figure 6: Follow-on variant of the original Aerocrane with additional tip-mounted lifting surfaces for direct lateral force control.

In this same period, the Piasecki Helistat [7] was tested; this vehicle was a hybrid buoyant quadrotor in which helicopter dynamic systems were attached to a blimp. Along with being structurally complex, this vehicle could not provide negative rotor thrust (so as to control excess buoyancy) and therefore was limited payload to the rotor's positive thrust. The failure of flight tests of the Helistat in 1986 led to a continuation of a search for a viable hybrid rotary wing/LTA concept. While further derivatives of the Aerocrane/Cyclocrane family were examined (e.g., Buoyant Copter, Figure 7), the need for more a more robust design led to examination of the joined-rotor VR concept. Initial studies indicated that it offered lighter weight and reduced aerodynamic drag; moreover, the more benign environment offered by inboard-mounted engines permitted higher rotational and flight speeds. In addition, the design makes the flight surfaces less vulnerable to structural accidents.

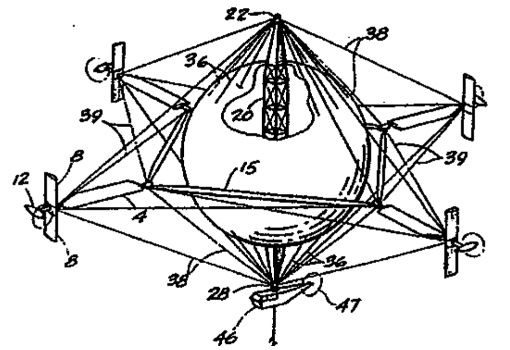


Figure 7: Notional Buoyant Copter hybrid aircraft design.

VectoRotor Conceptual Design

Conceptual design of the VR to date has focused on four main areas: primary structure; aerostat system; powerplant and propulsion; and fight control systems. The first two areas have been relatively thoroughly explored, since they entail extrapolations of known technology derived from prior LTA vehicles, though there are certain features unique to the VectoRotor concept. While initial feasibility studies have been conducted, obtaining full design closure on the second two elements requires the application of advanced models, and one goal of this paper is to assess the suitability of comprehensive tools such as the CHARM model for filling this need.

The primary structure includes the center column, upper and lower support strut assemblies, blade spars, blade aerodynamic surfaces, engine strut and all cabling and end fittings (Figure 5). The center column is the most critical member of the primary structure. It is large and highly loaded. It also substantially is enclosed in the aerostat assembly, making inspection, maintenance and repair particularly challenging. Development of this subsystem is necessarily intimately coupled and integrated with the aerostat/ballonet system.

Although completely different in structure and function from the center column, the aerostat system shares many important attributes with that assembly. It is large, highly loaded and much of its primary load path structure is hidden from ready view. In fact many of its most heavily loaded elements are immersed in lifting gas. However, comparable design challenges have been met in the construction and operation of existing aerostat systems (e.g., Figure 8), and design expertise is available in industry to support these aspects of possible future developments.

Figure 8: Current-generation aerostat - Tethered Aerostat Radar System (TARS) from ITT Systems Division.

Loads for the combined structural /aerostat system are determined by the vehicle's aerodynamic design; determination of these loads is intimately connected with propulsion system design. The latter consists of the prime mover engines (notionally, three propeller engines mounted on struts, as depicted in Figures 3 and 4; also included are fuel delivery and control system, throttle control system and propeller pitch control system. Full practical design of this system would include demonstration of the ability to operate the engine-propeller system continuously, safely and with acceptable loads in a high-G, rotating environment (e.g., propeller loads induced by gyroscopic precession and yaw rate); fuel control and delivery from rotating and non-rotating sources; and one-per-rev propeller pitch and throttle modulation for forward flight. Prior Aerocrane/Cyclocrane concepts have demonstrated this capability, though the ability of VR to mount engines farther inboard should provide an improved operating environment.

The projected flight control system consists in general of all-moving trailing edge aerodynamic surfaces; supporting hardware includes actuators, motors, pumps, driver electronics and instrumentation associated with the control of movable surfaces on both the upper and lower blades. One goal of the analyses below is to provide an initial estimate of the deflection of active control surfaces in hover and low speed forward flight, along with total power VectoRotor, unlike conventional aircraft or helicopters, exhibits a preferred control arrangement wherein all actuation is located in the rotating system, as opposed to operating a control by swashplate in the non rotating-system. As a consequence, for any cyclic control input the actuator must cycle continuously at one-per revolution (1P). This represents a potential challenge in terms of component life to the selection of actuation hardware. Final determination of system needs will require detailed aerodynamic flight control studies building on the initial analyses described below. The critical parameters are actuator power, bandwidth, rigidity and reliability in the presence of loaded and deformed structure and actuation assemblies.

As a final note, owing to the large size of the aircraft it is impractical mechanically to connect the pilot to the control surfaces. Hence the VectoRotor is assumed to be a "fly-by-wire (or light)" aircraft. This approach has been successfully employed on two prior hybrid aerial crane concepts.

While full scale testing of the VR concept has not been possible to date, initial model scale testing has been successfully carried out on a 4 ft. diameter scale model (Figure 9). Static and (indoor) free flight testing under radio control provided a substantial body of data indicating the fundamental feasibility of the concept. Larger scale flight tests would be a logical follow-on; however, since meaningful tests of the concept would require an vehicle of at least roughly 80-100 ft. diameter, developing computational models for this configuration prior to investing in construction and test is highly desirable.

Figure 9: 4 ft. diameter scale model of the VectoRotor used for static and indoor free flight tests.

Aerodynamic Modeling

Computational modeling of representative VR vehicles was undertaken using the Comprehensive Hierarchical Aeromechanics Rotorcraft Model, (CHARM), is a well-validated comprehensive rotorcraft analysis with unique capabilities in the area of multiple rotor/wake/airframe modeling of rotorcraft aerodynamics and dynamics [12-17]. CHARM couples a full-span, free vortex wake model with a fast lifting surface panel analysis to provide a capability for modeling a wide array of current and future VTOL and UAV configurations largely from first principles (Figures 10 and 11).

CHARM incorporates a vortex lattice lifting surface model of the rotor blade and a source/doublet singularity (panel) method for modeling lifting and non-lifting surfaces (e.g., the vehicle airframe, in this case the VectoRotor centerbody) with the full-span wake model [13], [15]. Hierarchical Fast Vortex and Fast Panel techniques allow CHARM to perform these calculations at computation times reduced from $O(N^2)$ to $O(N \log N)$ where N is the number of vortices or panels. Recently CHARM algorithms were extended and further accelerated to allow real-time free-wake/fast panel modeling of general maneuvering flight [16]. CHARM uses a linear finite element structural analysis for determining rotor blade mode shapes. Blade dynamic response is determined using either a harmonic analysis solution when studying steady (periodic) flight or a predictor-corrector method when analyzing maneuvering (aperiodic) flight. In addition, CHARM has a demonstrated record of success in modeling rotor blades with trailing edge flaps [17]. While the model has chiefly been applied to conventional rotorcraft configurations (Figure 10), its demonstrated suitability for complex coaxial configurations (Figure 11, see also [15]) makes it well suited for the design studies envisioned here.

Regarding setup for modeling of the VR with CHARM, Figure 12 shows the general configuration adopted for these studies, focusing on the principal aerodynamic surfaces and the buoyant centerbody. An ellipsoidal centerbody geometry with a 2:1 diameter to height ratio is used, along with constant-chord blades with symmetric anhedral/dihedral of 25 deg. As shown in the initial modeling presented in Figure 4, the propellers can also be included, but these were bypassed in these studies as being judged to have little influence on overall vehicle aerodynamics.

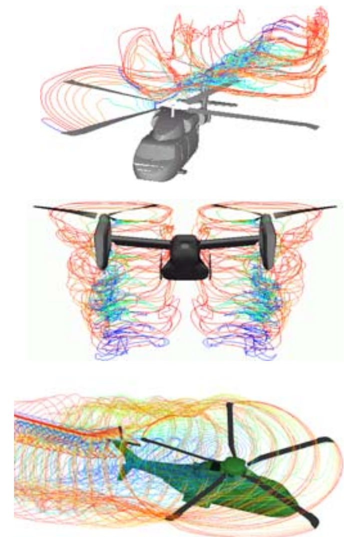


Fig. 10: Configurations modeled with CHARM, showing near-wake evolution. From top to bottom: UH-60A Blackhawk helicopter, V-22 Osprey tiltrotor, EH101 helicopter.

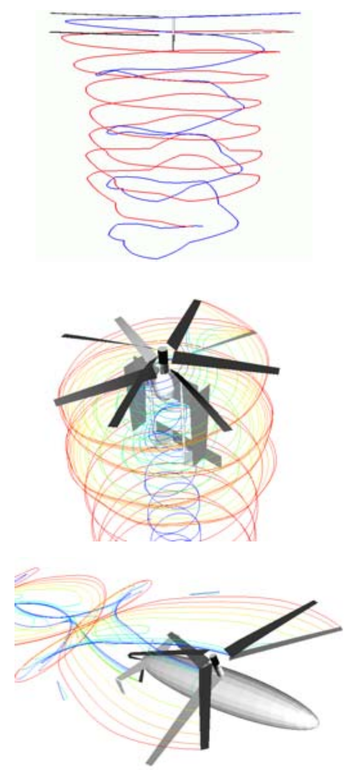


Figure 11: General rotary wing systems modeled with CHARM: generic coaxial rotor and wake (top); notional MonoTiltrotor (center) and coaxial compound (bottom) aircraft.

In addition, while the drag of supporting structure (e.g., struts for the joined-rotor system) will clearly be important for the aerodynamics of the actual aircraft, they cannot be directly included in the CHARM potential flow model; drag properties are therefore included in terms of empirical loss coefficients based on the cross-section area of the struts. Also, in terms of modeling of the blades, a standard feature of CHARM is the use of 2D airfoil data tables to provide drag and maximum lift characteristics. Finally, while not evident in Figure 12, an aerodynamic model that captures trailing edge flap effects on sectional aerodynamics is included in the model of each wing.

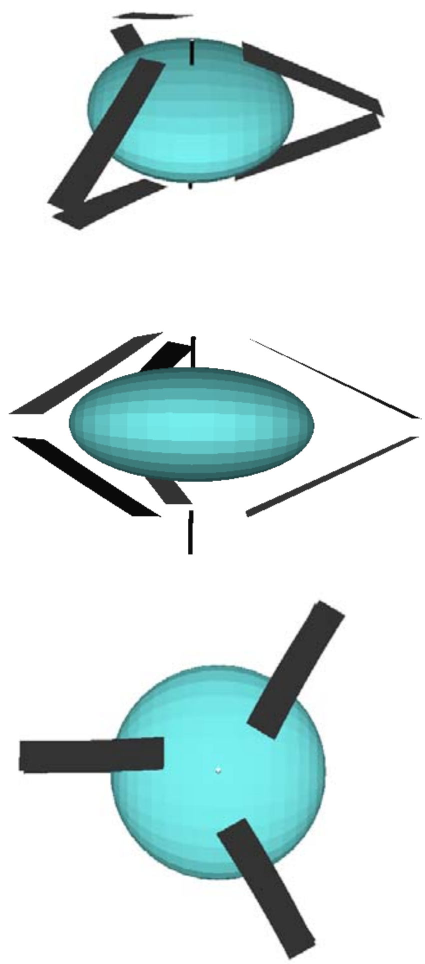


Figure 12: Oblique (top), side (middle) and overhead (bottom) views of the CHARM model of the major aerodynamic surfaces of a representative VectoRotor aircraft (propellers not included in this model).

A first step in general aerodynamic modeling was execution of initial hovering wake calculations for isolated rotor blades (no centerbody). Figure 12 shows the intermeshing wake of the two rotor systems for the case of a simple kinematic (rigid) wake in hover; since many operating conditions for the VectoRotor involve relatively light rotor loading, such a model – involving minimal wake-on-wake interaction – is a reasonable approximation for first order estimates of performance, though free wake rotor/rotor and rotor/rotor body interaction is important in many flight conditions.

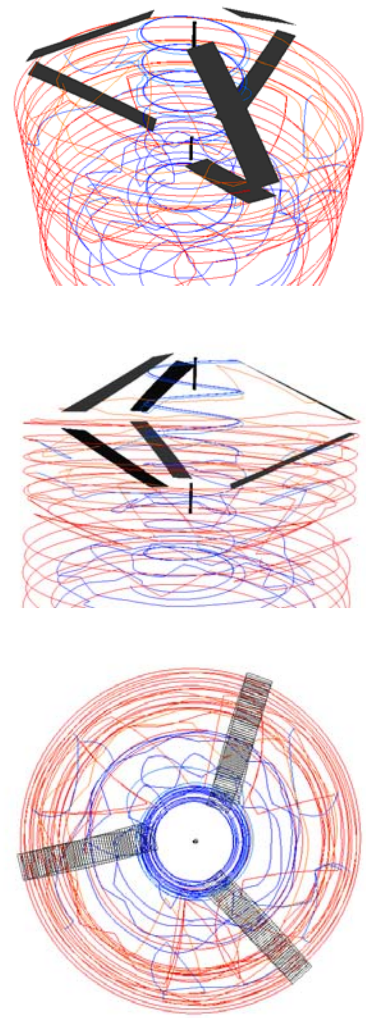


Figure 13: Oblique (top), side (middle) and overhead (bottom) views of the hovering wake of a kinematic wake model of the dual rotor system for the case of light rotor loading (C_T=.0020 for each rotor).

In terms of particular dimensions to be applied to this model, these are selected using preliminary design estimates for 6-ton ("VR-6") and 12-ton ("VR-12") variants of the aircraft. The table shows the assumed values of major parameters for each design and the target value of rotor thrust. As is evident, the design principle is to have the buoyancy roughly match the dry weight+fuel of the aircraft, with the rotor thrust lifting the payload. The table also shows the thrust coefficient (per rotor) for the target payload. The design studies discussed below will focus on the VR-6 configuration.

Table 1: Target design parameters for the VR-6 and VR-12 variants of the VectoRotor

	VR-6	VR-12
Rotor Dia. (ft)	124	160
RPM	35	27
Tip Speed (fps)	216 fps	228 fps
Buoyancy	6500 lbs	15,000 lbs
Dry Weight	4800 lbs.	11,000 lbs.
Net Buoyancy	1700 lbs.	4,000 lbs.
Fuel	1400 lbs.	3,000 lbs.
Target payload	12,000 lbs.	24,000 lbs.
Net rotor thrust	11,700 lbs.	23,000 lbs.
C_T per rotor (SL)	0.0039	0.0046

For these studies, the following parameters are assumed: a constant blade chord of 10 ft.; 20% chord full-span trailing edge flaps; a NACA 23012 airfoil cross-section; a -6 deg. linear twist on each blade; and a 25% root cutout. These design parameters are consistent with prior preliminary studies as well as with the scale model tests discussed above.

Hover Power Required

A key initial design parameter is the hover power required for a relevant range of thrust levels. (Note: all results below are corrected for an assumed download of 10% of total thrust on the aerostat body; this is based on an approximate vertical drag coefficient of 0.42 for the ellipsoidal body and assumes the mean momentum theory downwash impinges on the aerostat). For these calculations, rotor pitch is assumed fixed and trailing edge flap deflection is used to control thrust on the rotors.

Figure 14 shows the total power required as a function of net rotor thrust for the VR-6. For the target design point of 11,700 lbs, roughly 750 HP is required, or about 250 HP from each of the three engines assumed to be operating. (Note: the scaling factor to go to the VR-12 configuration is approximately 2.1, suggesting that approximately 1550 HP is required for the larger configuration). Given that the lower rotor operates in the downwash of the upper rotor, it is not surprising that a larger flap deflection is needed on the lower rotor (as seen in Figure 15); the increment in deflection grows from about 1 deg at low thrust levels to 3 deg. at higher thrusts. As is evident, the trend of thrust level with flap deflection is roughly linear for each rotor.

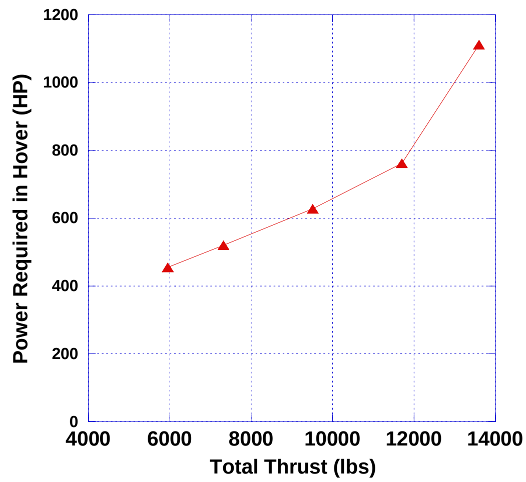


Figure 14: Total power required for the VR-6 variant as a function of rotor thrust.

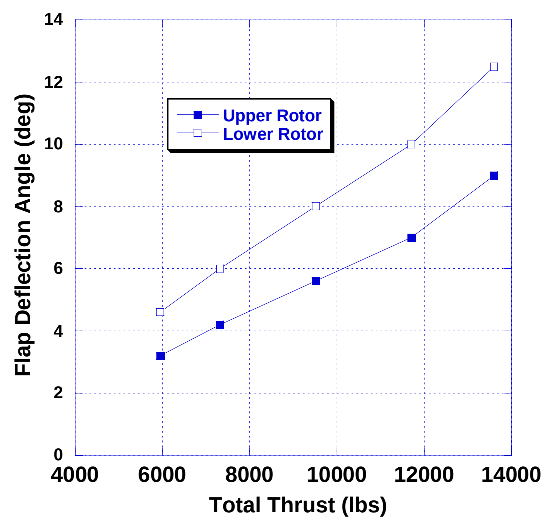


Figure 15: Full span flap angle settings for the hover performance points in Figure 14.

Forward Flight Power Required

The next stage in performance assessment was to assess the trend of power required with forward speed. The limiting factor with speed is the power required to overcome the parasite drag of the large centerbody. The data on page 3-12 of {18} presents the drag characteristics of ellipsoidal bodies; the general formula is

$$C_{d0} = 0.44(d/\ell) + 4\,C_f\,(\ell/d) + 4C_f\,(d/\ell)^{1/2}$$

Here, the diameter to length ratio is 0.5 and a representative skin friction coefficient C_f is 0.004. This yields an overall drag coefficient C_{d0} of 0.26 for this centerbody; also, the elliptical cross-section presents an area of 2060 ft^2 to the flow. The parasite drag the aircraft must then overcome is shown in Figure 16; as is evident, the drag becomes a large fraction of the overall aerodynamic thrust for speeds approaching 50 kts, suggesting that reaching speeds in this range will be challenging.

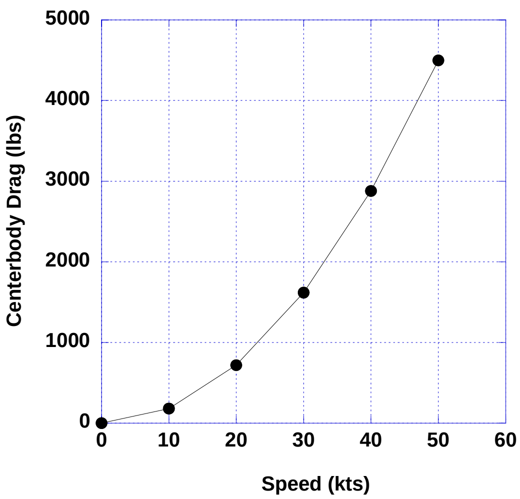


Figure 16: Centerbody drag as a function of forward speed for the VR-6 configuration.

As noted above, the use of the joined wing permits the VR configuration to generate the side force necessary to overcome this parasite drag. Figure 17 shows the force vectors associated with the joined wing, suggesting how the resultant of the upper (F_U) and lower (F_L) wing lift distributions can, with proper phasing, yield the desired resultant side force (compare to Figure 3 to see to correspondence with the joined wing structures). Here, time-varying flap deflection is required to produce the appropriately phased side force; phasing formulas derived from the subscale model flight tests outlined above can be used to select the appropriate flap deflection histories.

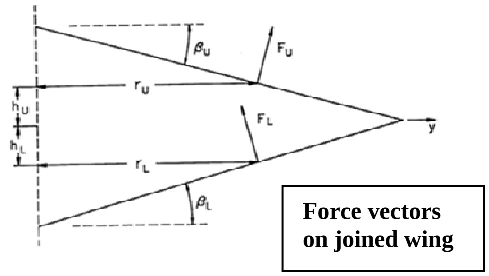


Figure 17: Schematic of force vectors on the joined wing in forward flight [11].

It is anticipated that trends in power with forward airspeed at constant thrust would be broadly similar for the VectoRotor as for a conventional helicopter, at least in the immediate vicinity of hover. As suggested by Figure 18, the change in wake structure for low forward speeds is very similar to that observed for helicopter rotors leaving hover. Thus, a drop in induced power can be expected at low forward speeds. As seen in Figure 19, such a drop does occur, though as speed increases the power required to overcome the parasite drag begins to rise rapidly, driving the power above the hover level at 40 kts forward speed. Also, in this speed range the flap variation amplitude to maintain propulsive force becomes large and may become the limiting factor in forward speed capability.

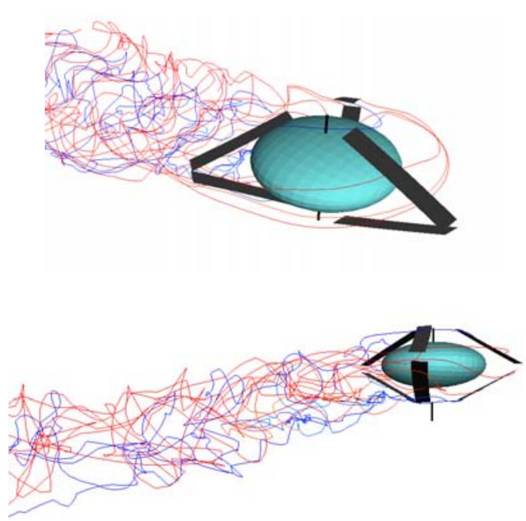


Figure 18: Oblique (above) and side (below) views of the free wake of the VR-6 in forward flight at 20 kts. (advance ratio 0.16) at a rotor thrust of 11,700 lbs.

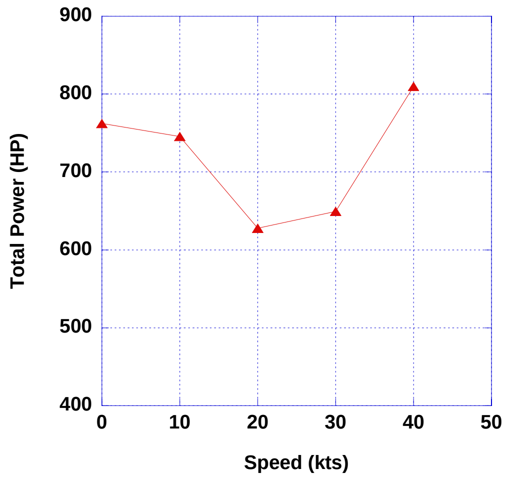


Figure 19: Total power required for the VR-6 variant as a function of rotor forward speed for a constant rotor thrust of 11,700 lbs.

Summary and Future Work

This paper has summarized initial design work on a novel hybrid LTA/rotorcraft concept – VectoRotor – that combines buoyant and dynamic lift in a unique joined-rotor design. Prior analysis suggested that this concept would be attractive for short range heavy lift functions, and the work outlined here took the first step in applying a current-generation comprehensive rotorcraft model to the analysis of representative VR configurations. In addition to outlining the design history of the concept and results of preliminary scaling analyses, calculations of power required in hover and forward flight were generated, along with predictions of expected deflection requirements for trailing edge flap control surfaces. Given the comprehensive nature of the aerodynamic model applied, a wide range of additional results regarding rotor blade loading, interactional aerodynamic effects, and local flow fields can be generated.

Desirable extensions to the design studies conducted to date would include:

Optimization of rotor blade chord, twist, and flap deflection strategy for improved performance; the selections made here are representative choices but alternate design parameters may allow considerable reductions in power required in hover and forward flight.

Tradeoffs in active flap design; full span flap actuation may not be necessary in all flight conditions, and the use of partial span flap elements may considerably simplify implementation of flight control actuation.

Direct inclusion of propeller modeling; while the direct effect of propeller flow on overall air vehicle aerodynamics would be small, the effect of 1P variations in flow field on propeller performance and in the generation of unsteady forces may be significant, and the CHARM model applied here provides the capability for such follow-on studies.

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