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A Multifunctional Rotor Concept for Quiet and Efficient VTOL Aircraft

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One promising solution in the search for a quiet, efficient VTOL aircraft configuration employs two-blade rotors which lock into a fixed position during horizontal flight, becoming lifting surfaces. The design of these blades and their integration onto an airframe pose many challenges, including performing this blade repositioning with a mechanism that is adequately simple, reliable, lightweight, and aerodynamic; determining a blade geometry that strikes the right compromise between performance as a rotor blade and as a wingtip; and providing sufficient pitch and yaw control in vertical and transitional flight without resorting to overly complex and heavy mechanisms, such as rotor cyclic. A spiral development model is employed in which a series of increasingly large and complex subscale prototypes are built and tested. Results from these tests demonstrate the strengths, weaknesses, and design tradeoffs of this configuration. Conceptual design is aided by an aerodynamic and structural mission analysis code. Detailed aerodynamic analysis of these designs is performed in CFD, which illuminates the unusual aerodynamics of this design in vertical and horizontal flight and the effects of these aerodynamics on overall performance. Compelling applications of this concept to the personal air vehicle and on-demand aviation markets are examined.

I. Introduction

Although vertical takeoff and landing (VTOL) aircraft have always been desired, compromises in the realization of these aircraft have limited their usefulness and adoption to certain niches. Notably, helicopters are relatively loud, slow, short-ranged, and expensive to operate. Joby Aviation is capitalizing on recent advances in electric motors, battery technology, and control systems to create revolutionary VTOL aircraft that are quiet, safe, and efficient.

One design that Joby Aviation is researching is based off of the configuration of the NASA Dos Samara design study.[1] This configuration employs a large outboard wing panel on each wingtip that spins to generate thrust to lift the vehicle in vertical flight. In horizontal flight, these outboard wing panels lock and a pusher propeller provides forward thrust. Although this design has the potential for relatively low cruise drag, by employing monoblade rotors it sacrifices rotor efficiency and introduces significant cyclic loading. Additionally, rotor and/or cruise efficiency are impaired by the monoblade counterweight, the shape of which must be a compromise aerodynamically because the local airflow arrives from one edge in vertical flight and the opposite edge in horizontal flight.

To addresses these compromises, a two-bladed variation has been designed in which both blades pivot to become two separate tandem wingtips in horizontal flight. Employing two blades improves rotor efficiency and reduces cyclic loading. This geometry results in the airflow arriving from the leading edges of the blades

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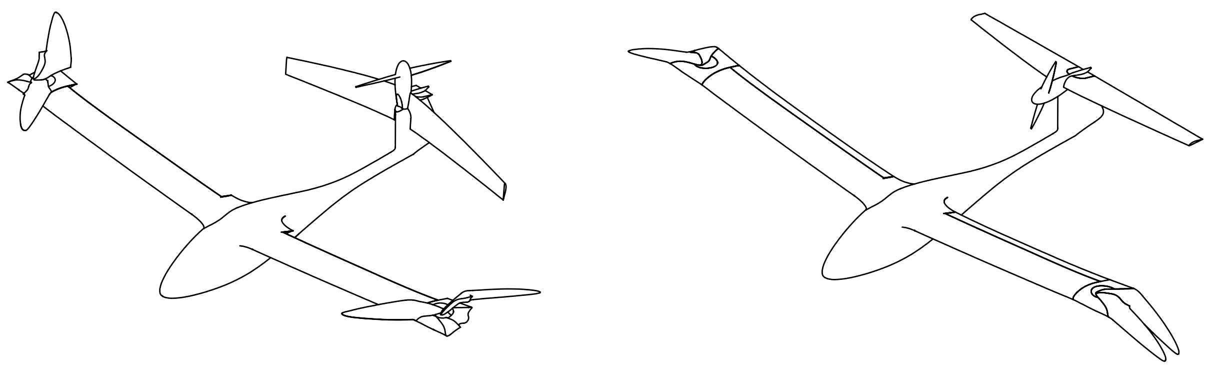
in both vertical and horizontal flight, requiring fewer design compromises. The two blades balance the propeller, precluding the need for a counterweight. An aircraft configuration employing these multifunctional rotor blades was designed, and to validate this concept, a spiral development model is employed in which prototypes of progressively larger scale and degree of complexity are tested; in parallel, extensive CFD analyses are being performed to ensure performance targets are within reach.

II. Configuration Description

Illustrations of the aircraft concept in vertical and horizontal flight configurations are shown in figure 1. A brushless electric motor is located in each wingtip; the stator is fixed to the wing, and the blades are rigidly attached to the rotor, without flapping, lead/lag, or feathering hinges. In vertical flight, figure 1(a), the blades are locked 180 degrees away from each other to form a conventional two-bladed rotor, and in horizontal flight, figure 1(b), the blades are repositioned to act as two discrete tandem wingtips. Dihedral in the wing provides adequate clearance between the wing and the blades in vertical flight. Roll control in vertical flight is provided by differential RPM control of the two wingtip motors.



(a) Vertical flight

(b) Horizontal flight

Figure 1. 55-pound prototype configurations

Several actuators are employed to provide adequate control in vertical flight without requiring complex and heavy mechanisms such as rotor cyclic. Both wingtip motors are articulated about the pitch axis to provide yaw control; additionally, the motors can be tilted together, pitching the thrust vector to improve maneuverability in vertical flight and to provide some amount of forward thrust during transitional (vertical to horizontal and horizontal to vertical) flight.

A tractor propeller that tilts about the pitch axis is mounted on the top of the vertical stabilizer. The aircraft's center of gravity is located between the wing and the tail, so when tilted upwards, this propeller provides adequate pitch control in both directions in vertical flight via differential RPM control of the tail propeller and the wingtip rotors. This propeller tilts forward during transition and is the sole propulsion source in horizontal flight. The horizontal tail, placed in a T-tail configuration, tilts with the propeller to reduce download on the surface and provide additional control by always locating the elevator in the propwash. Placing this propeller on the tail instead of on the nose provides the benefit of reduced scrubbing drag in horizontal flight. The vertical tail is swept such that the leading edge is vertical to maximize propeller clearance.

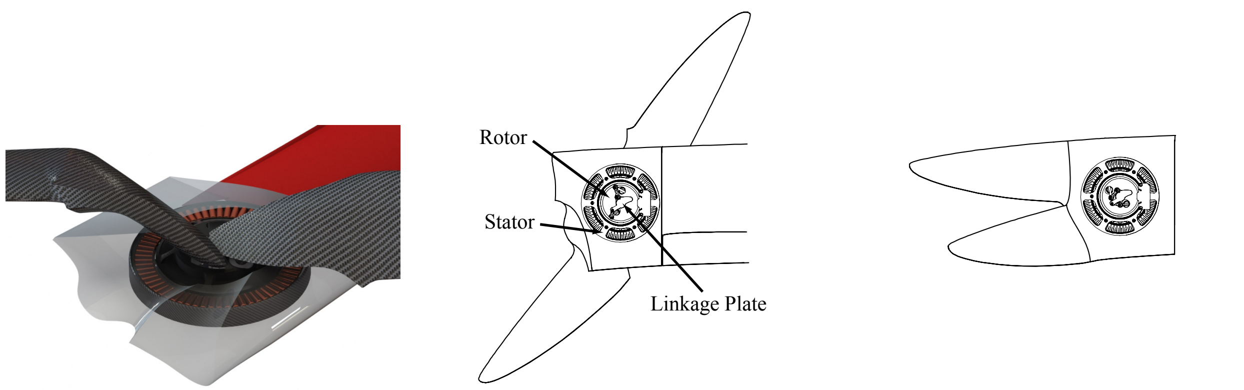
In steady vertical flight, the three rotors are nominally run at a low tip speed of 350 feet per second to significantly reduce noise during takeoff and landing. Custom electric motor designs eliminate the need for gearboxes, reducing weight and noise and improving reliability.

An active control system stabilizes the aircraft in vertical and transitional flight, reducing pilot workload and simplifying control. Conventional takeoffs and landings are possible in the horizontal flight configuration.

A. Blade Reconfiguration Mechanism

Figure 2 illustrates the blade reconfiguration mechanism. The blades are repositioned from the vertical flight (rotor) configuration, figures 2(a) and 2(b), to the horizontal flight (wingtip) configuration, figure 2(c), using the same motor that spins the blades in vertical flight configuration. When the linkage plate inside the rotor of the electric motor is fixed to the wing with a solenoid, rotation of the rotor causes the blades to reposition between vertical and horizontal flight configurations. Transition from the horizontal flight configuration to the vertical flight configuration proceeds in the following sequence:

1. A solenoid releases, unlocking the blades. This solenoid holds the blades in position during cruise.
2. The rotor rotates 80 degrees; during this rotation, linkages rotate the blades away from each other into diametrically-opposed positions.
3. A second solenoid releases the linkage plate inside the rotor, and the blades are now held in position fixed relative to each other by a spring. In this configuration, rotation of the rotor causes both blades to rotate in the same direction.



(a) Vertical flight, top view (b) Vertical flight, bottom view (c) Horizontal flight, bottom view

Figure 2. Illustrations of the wingtip blades in both configurations, showing the internal motor configuration

Custom motor controllers, along with rotary encoders, allow the exact positioning of the blades and facilitate simultaneous reconfiguration of the blades to reduce asymmetrical effects during transitional flight.

III. Development Process

A. Design Process

Initial configuration design is performed using a purpose-written configuration analysis code. This code allows the parametric definition of a configuration and mission; using this definition, the component masses and moments of inertia are estimated, and AVL, a vortex-lattice tool that was developed at the Massachusetts Institute of Technology, is run to estimate drag and stability of the wings and tails. Statistical methods are employed to estimate the effects on drag and static longitudinal stability of the fuselage, as well as other parasitic drag sources not properly captured by vortex-lattice analysis (interference drag and leakage and protuberance drag). The code begins with a provided takeoff weight and computes the available payload mass, allowing range to be computed if a portion of this payload mass is used for fuel or batteries. Although this configuration ties the disk loading and planform geometry together in unusual and unfamiliar ways, use of this code aids in the identification of important trends and tradeoffs. For example, if the wingtip blade radius is too high for a given total wing area and aspect ratio, the wing taper ratio becomes too high to be structurally efficient, resulting in a tradeoff in power requirements between cruise (through wing size and aspect ratio) and vertical flight (through disk loading).

Initial aerodynamic and acoustic design of the rotor blades is performed using a blade-element momentum design and analysis code suite employing the 2D viscous panel code XFOIL to estimate section aerodynamics, Goldstein's vortex theory to predict induced velocities, and the Ffowcs Williams-Hawkings equation to estimate acoustics.[2] Due to increasing dynamic pressure with radius when the blades are operated as rotor blades, rotor performance is more sensitive to the design of the outer portion of the blades; conversely, due to the larger chord near the root, performance in horizontal flight, when the blades are positioned as wingtips, is more sensitive to the root design. Therefore, twist and chord in the inboard portion of the blades were chosen to improve aerodynamics in horizontal flight by imposing constraints in the rotor design code. Airfoils were chosen by 2D viscous panel code analysis of many airfoil designs, including custom designs, at the conditions encountered in both the vertical flight configuration, when the blades act as rotor blades, and the forward flight configuration, when the blades act as wingtips. Blade thickness was conservatively chosen to preclude the possibility of adverse aeroelastic effects.

Extensive CFD analyses have been performed to further guide design of both the airframe configuration and wingtip blades. STAR-CCM+, a commercial CFD code, was used for both mesh generation and CFD solutions. Unstructured meshes were employed, and Navier-Stokes simulations were run using the SST k-ω turbulence model and the γ-Re_θ transition model. These simulations were used to tune the spanwise lift distribution of the aircraft in forward flight for maximum efficiency, check stability predictions of lower-fidelity analyses, and estimate rotor efficiency and download caused by the wing. A CFD result for a 55-pound prototype at 43 knot cruise at standard sea level conditions is shown in figure 3, showing the complex tip vortex system that develops. Results of this configuration show a L/D in excess of 20 at this flight condition, although this is expected to be somewhat reduced in the flight vehicle due to control surface gaps, antennas, motor cooling, etc.

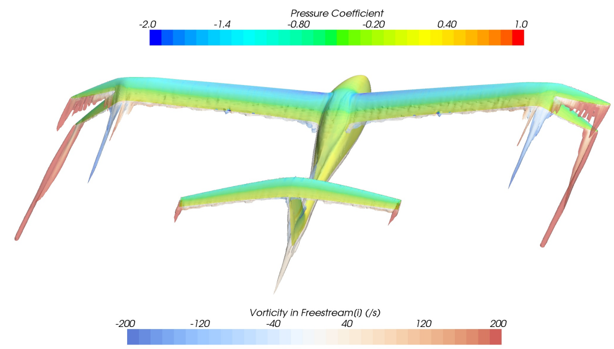
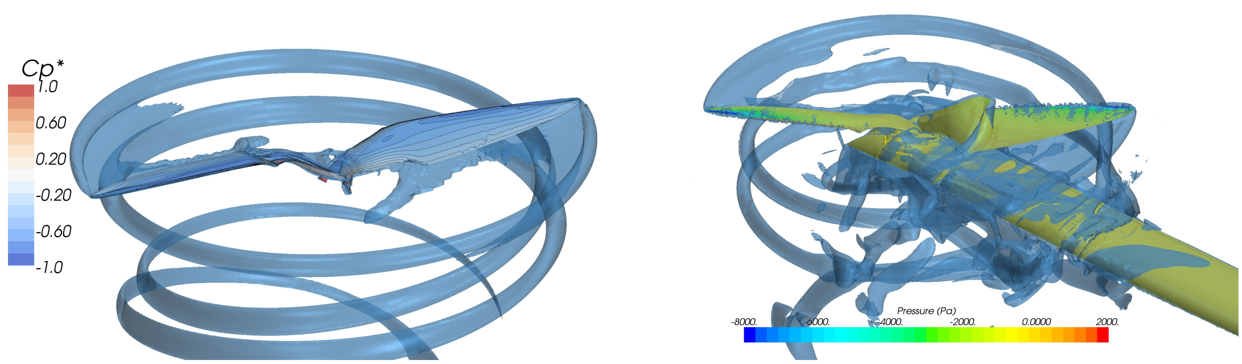


Figure 3. CFD result of 55 lb prototype in flight, showing isosurfaces of constant vorticity magnitude

Figure 4 shows results of CFD analyses of the blade performance of a 55-pound prototype in axial climb at standard sea level conditions. Uninstalled figure of merit (computed as the ratio of ideal climb power required from momentum theory to computed power) is 72%, and the thrust lost to the download on the wing is 13%.

As the design process progresses, future CFD analyses are planned to include unsteady simulations of transitional flight, as well as an aero-propulsive analysis of the aircraft with a rotating propeller in cruise to determine propeller installation effects on aircraft performance and propulsive efficiency.



(a) Steady simulation of uninstalled blades with isosurfaces of constant vorticity magnitude and with blades contoured by C_p^* (the pressure coefficient nondimensionalized by the local rotational velocity)

(b) Unsteady simulation of the blades and the wing, with 25% chord flaps deflected to 55 degrees, showing pressure contours and isosurfaces of constant vorticity magnitude

Figure 4. CFD results of wingtip blades of the 55-pound prototype in 100 ft/min axial climb

B. Subscale Prototypes

A spiral development model is utilized in which several prototypes of increasing scale and complexity are designed, built, and tested. The first prototype aircraft, weighing about 5.3 pounds, utilized a modified hobby airframe with a foam wing and a plastic molded fuselage. Forward thrust was provided by a fixed pusher propeller, and a fixed propeller oriented facing upwards was installed on the tail boom to provide pitch control in hover. Hobby propellers and motors were used, so forward flight was performed with the wingtip rotors freewheeling instead of reconfiguring into wingtips. This aircraft validated the general configuration and paved the way for the second prototype, a 12-pound aircraft of similar configuration built utilizing the airframe of a Joby Energy wind turbine prototype. The third prototype, shown in figure 5, is of similar dimensions to the second, but was purpose-built, resulting in a mass of only about 9 pounds. This prototype is functioning as a control systems testbed while the fourth prototype is built.

The first three prototypes all feature tilting wingtip propellers, a third upward-facing propeller on the tail boom, and a separate forward flight propeller. These vehicles have validated the controllability of this configuration and have proven robust and maneuverable in vertical flight. However, the complexity of this design is evident during vertical and transitional flight, when the pilot must juggle two throttles (one for the three vertical propellers and one for the horizontal propeller) and the neutral pitch angle of the tip propellers, as well as roll, pitch, and yaw inputs. The fourth prototype will be similar to the third, except the separate forward thrust propeller and boom-mounted pitch control propeller will be replaced by a single tilting propeller that will tilt along with its motor and the horizontal tail. This aircraft will be even more complex to pilot through transition, and for this reason, a greater degree of control automation is being explored to simplify transition control.

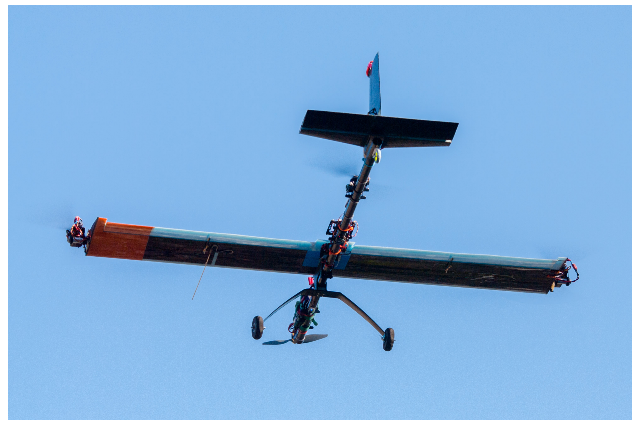


Figure 5. The third prototype in vertical flight

The fifth prototype will weight 55 pounds and be fully representative of the concept; it will be the first design to fly with the wingtip blade reconfiguration mechanism, although the blades and mechanism will be extensively ground-tested before they are flown. It will also employ custom motors and motor controllers, in contrast to the hobby components used in the four smaller prototypes. The structure will be fabricated in high-quality preimpregnated carbon fiber to reduce weight and improve part quality, using a rapid-prototyping high temperature molding process in which the molds are cut directly on a CNC router, simplifying the process by sidestepping the production of plugs.

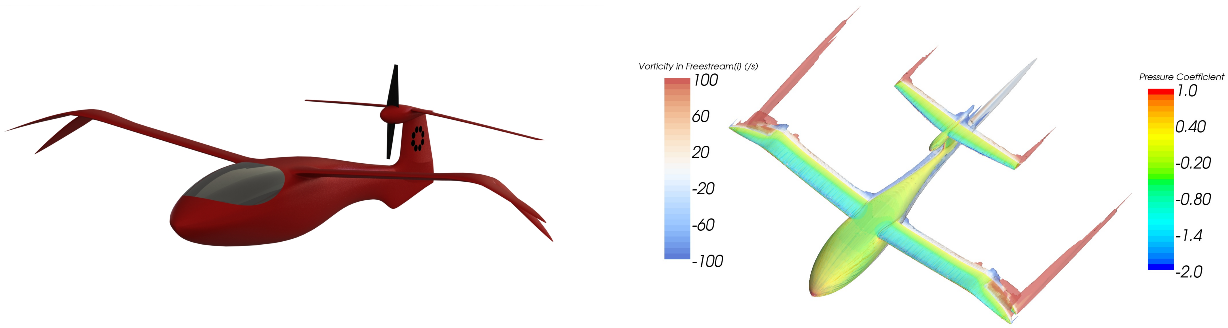
Table 1 summarizes the scales of the various subscale prototypes. The wing area for the fifth prototype includes the area of the tip blades.

Prototype	1	2	3	4	5
Approximate mass	5.3 lb	12 lb	9.5 lb	9.5 lb	55 lb
Wing area	1.7 ft^2	3.9 ft^2	4.2 ft^2	4.2 ft^2	8.1 ft^2
Wing loading	3.1 lb/ft^2	3.1 lb/ft^2	2.2 lb/ft^2	2.2 lb/ft^2	6.8 lb/ft^2
Number of motors	4	4	4	3	3

Table 1. Subscale Prototypes

IV. Potential Future Developments

This configuration is compelling for emerging markets such as personal air vehicles and on-demand aviation, due to its efficiency, low noise, and relative simplicity. Two 1650-lb two-place designs using the same airframe were studied: a hybrid-electric 200-knot design and a fully-electric 120-knot design. The designs are summarized in table 2 and illustrated in figure 6. The reference mission is vertical takeoff at 7000 ft at 100 ft/min for two minutes, climb to 12,000 ft for cruise, descent to 7000 ft, and vertical landing at 200 ft/min descent rate for one minute with a 90 second hover reserve. The hybrid utilizes a 94 hp turbocharged Wankel Supertec KKM 352 rotary engine promising 0.44 lb/hp-hr and directly driving the tail rotor, as well as a generator; batteries provide the additional power needed for takeoff and landing and can be recharged during flight. Efficiency assumptions are 90% for motors and generators, 95% for motor controllers, 85% for the (variable-pitch) tail propeller in cruise, and 60% figure of merit for rotors in vertical flight (including download effects).



(a) Aircraft geometry

(b) CFD result at 120 knots with pressure coefficient contours and isosurfaces of constant vorticity magnitude

Figure 6. 1650-lb personal air vehicle concept

These configurations have been designed using the lower-fidelity tools described on the previous page (although with a simpler weight model), and initial CFD results of cruise flight suggest the performance detailed in table 2. Induced drag was estimated from AVL, and the remaining drag from CFD results was incremented by 5% to estimate drag contributions not captured by CFD (e.g., leakage and protuberance drag). Future work will include developing a more thorough weight model for this scale and performing further CFD analyses to fine-tune the aerodynamics.

Design	Full electric	Hybrid electric
Cruise speed	120 knots	200 knots
Range including reserve	140 nm	700 nm
Cruise L/D	23.5	12.0
Fuel capacity	N/A	22 gal
Battery mass	490 lb	170 lb
Maximum battery discharge rate	6C	20C
Battery specific energy	180 Wh/kg	100 Wh/kg
Wing area	71.5 ft^2	
Wing aspect ratio	14	
Wingspan including tip blades	31.6 ft	
Disk loading	10 lb/ft^2	

Table 2. PAV Configurations

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