The Joby S2 VTOL Concept

Exploring the New Degrees of Design Freedom of Distributed Electric Propulsion

By Mark Moore

With 12 low-noise electric propellers, the Joby S2 is a completely new type of VTOL aircraft. (All graphics courtesy of Joby Aviation)

Despite more than 70 years of vertical flight development, there are only three operational types of vertical take-off and landing (VTOL) aircraft today: helicopters, the V-22 Osprey tiltrotor and the AV-8B Harrier jump jet. It could be argued that VTOL aircraft went through its period of rapid experimentation, and like commercial transports, settled on the configuration that offered the best approach. It could also be argued that the technologies that have developed over the past 40 years (composites, digital avionics, lightweight propulsion, etc.) have simply enabled the same approaches to be better. But a question that's quickly intriguing many VTOL aircraft design experts is whether the emerging electric propulsion technologies require us to fundamentally question which configuration approach offers the best value proposition for civil and military mission capabilities.

The New Technology Frontiers

Over the past decade, there's been amazing progress in autonomy and electric propulsion technologies. It's natural for us to see some of these proposed self-driving cars and think – if this can be done in very cluttered ground environments – how much easier it would be to implement in the air with small aircraft. We also see cars using electric propulsion technologies to achieve improvements in efficiency of ~50%, so naturally we should be asking if we can achieve similar improvements with aircraft. Hybrid electric technologies in particular make tremendous sense when there's a large mismatch in power required between a short-term power and cruise rating (i.e., rapid acceleration versus highway cruise for automobiles). VTOL aircraft experience this same power mismatch, which makes them prime candidates for this technology application. You may look at these technologies and say that they're not there yet, but one thing that's certain – they're improving very rapidly. In fact, they're progressing at a pace at which aerospace manufacturers aren't acclimated. And that's why companies such as Joby Aviation are stepping in to explore the opportunities these new technologies offer for new configuration approaches that better align with civil VTOL transportation needs.

Electric propulsion offers new characteristics that reciprocating and turbine engines don't provide: the opportunity to distribute the integration of propulsors across the airframe. This is a result of electric motors providing essentially the same power to weight and efficiency independent of the size of the motor, while maintaining highly compact and reliable motors that don't require the installation burdens of air-breathing engines. These motors are essentially insensitive to altitude and temperature changes, offer the same power at high altitude cruise as at takeoff, and have the ability to provide instant full torque without warm-up, as well as the ability to provide full power across a wide rpm range. None of these characteristics exist for reciprocating or turbine engines.

Propulsion technology has in many ways dictated the feasible configuration approach paths for VTOL aircraft. With such a fundamentally different propulsion technology, some fundamental questions deserve to be asked. Why would we merely attempt to utilize electric propulsion in legacy installations? Helicopters look the way they are precisely because centralized propulsion solutions were the only solutions available with the sufficient power to weight, efficiency and reliability. Even with the available propulsion of the 1960s, VTOL aircraft desired to have distributed propulsion, with aircraft such as the Bell X-22A paying tremendous penalties for cross-shafting and gearbox weight and complexity to distribute the thrust around the airframe to achieve improved performance and control. The question is, now that a new propulsion technology with dramatically different features is becoming available, how should VTOL aircraft configurations look to leverage the capabilities electric propulsion offers?

The Joby Aviation S2 Design Approach

Joby Aviation has been working to fundamentally question how to achieve the best civil transport VTOL aircraft with the newly available electric propulsion technologies. This questioning has led to a new concept type called the S2. The concept takes everything learned from two years of collaborative study with NASA that resulted in the NASA GL-10, Joby Lotus, and joint NASA/Joby LEAPTech concepts. The S2 offers the first high speed cruise efficient VTOL aircraft with complete propulsion system redundancy. Instead of requiring the wing to tilt with a single point of failure, the S2 permits each fixed pitch propeller to rotate at the laterally and longitudinally distributed nacelles. The concept uses the least number of propulsors that permits any propulsor to fail while maintaining reasonable power sizing and full roll, pitch and yaw trimming: 12 total, with eight along with wing and four along the tail. The concept was derived from the experimentation of the Lotus concept, which uses two multi-functional wingtip-rotors and a third propulsor that rotates at the junction of a T-tail (essentially providing a tri-copter arrangement specifically derived for UAV missions where flight safety and redundancy aren't valued as highly). As the Lotus concept was prototyped at small-scale, a rotation mechanism was developed after several iterations that worked incredibly well. It was this testing that convinced Joby engineers that a compact, reliable, lightweight rotation mechanism for a distributed VTOL system was feasible. It is this combination of sub-scale rapid prototyping flight testing experience along with full-scale component tests that CEO JoeBen Bevirt most values as the design now progresses to a full-scale flight vehicle.

A key attribute of the S2 design is the decision to stow and fold all the lift propellers at cruise flight, except for those at the wingtips. The reason for this is the huge difference in thrust required during hover flight (enough to provide a Thrust/Weight >1.3) versus cruise flight (when the aircraft is achieving a Lift/Drag ratio of ~20). If all propellers continued to be operating at cruise, the propellers would be operating at a far lower efficiency than ideal, with essentially too much blade area for the required thrust. Instead by folding the propellers at cruise, they can be designed for the hover/low speed flight condition, without needing variable pitch. This permits each propeller to be fixed pitch, and optimized to achieve the lowest possible community noise through low tip speed, high solidity blades. The blade folding hinge also permits flapping during the 90 degree rotation during transition from hover to cruise flight to alleviate the asymmetric blade loading that could result in cyclic fatigue. Certainly this is not a VTOL configuration approach that would have made sense with reciprocating or turbine engines – the complexity would simply be too great to permit reliable operation. But one thing Joby designer Alex Stoll points out is that the entire number of moving parts in the Joby S2 is less than in a single reciprocating motor – and the main moving parts in the drivetrain are bearings.

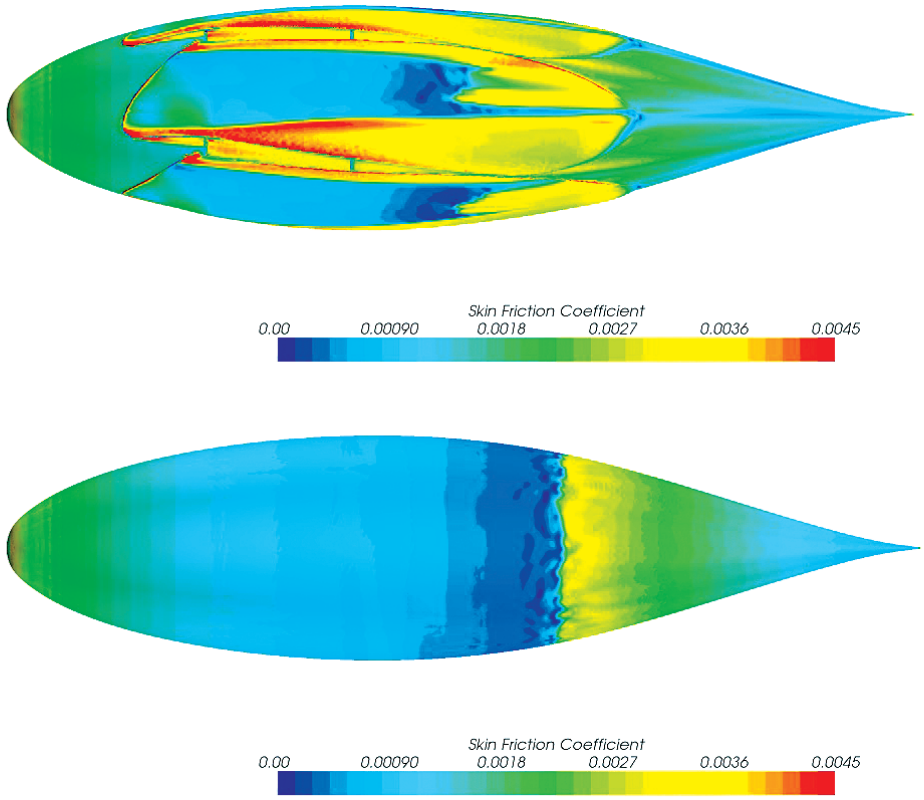
With the VTOL propellers folded back, the S2 cruises on its aerodynamically efficient wing, with thrust provided by four cruise propellers.

The Joby S2 Value Proposition

So why go to the trouble of developing an entirely new VTOL configuration approach? What value does it offer compared to current rotorcraft VTOL solutions? A comparison of the S2 to the Robinson R22 was made.

One of the key differences between the S2 and R22 is the disc loading, at 16.3 lb/ft^2 (80 kg/m^2) for the S2 and 2.6 lb/ft^2 (13 kg/m^2) for the R22, and the resulting cruise speed of 200 mph (320 km/hr) for the S2 and 110 mph for the R22 (177 km/hr). While the S2 requires more power for the one to two minutes of hover/transition time, it cruises at essentially the same power as the R22 but at nearly twice the speed. This is a result of the Lift/Drag ratio of the S2 being approximately five times better. Both achieve about 200 mile (320 km) ranges at the same payload weight of about 400 lb (180 kg), but the S2 weighs around 2000 lb (900 kg) with currently available lithium batteries of 200 W-hr/kg versus only 1370 lb (620 kg) for the R22. (The S2 relies on using only batteries for the current configuration being investigated, but Joby is also looking at hybrid-electric versions that can offer greater range.)

The really amazing aspect of this new breed of cruise-efficient electric



Extensive CFD simulations have been performed in the design of the S2, such as this analysis of the benefits in nacelle drag with folding propellers and gaps (top) versus a fully streamlined nacelle.

VTOLs is the cost of energy, due to the combination of ~5x increase in aerodynamic efficiency (big benefit), ~3x increase in propulsive efficiency (big benefit), a 30% reduction in structural efficiency (small penalty), and ~2x reduction in energy cost. The result is a ~10x reduction in energy cost per mile, from the baseline R22 cost of $0.53. With energy cost being ~40% of the total operating cost, electric propulsion for short-range trips provides the opportunity to eliminate about a third of the total operating costs. While there's too much uncertainty to predict the difference in aircraft cost or maintenance cost, this huge differential in operating costs is potentially a game changer for missions where significant range isn't required. But the most exciting aspect of designs like the Joby S2 is not that they offer a single capability improvement. It's that the configuration design approach is well balanced across achieving higher efficiency and lower costs, while also accomplishing a VTOL aircraft that has the potential to achieve far lower community noise. With the lift propellers utilizing tip speeds that are 50% lower than existing helicopters, and noise varying to the fifth power of tip speed, the S2 has the clear possibility of achieving at least a 10 dB lower signature.

The S2 is such a radically different VTOL solution that it is difficult to estimate the probability of success for this concept. There are issues such as the propeller downwash during transition fighting the wing leading edge upwash, which could result in transition control challenges. But the big picture advantages over helicopters have the real potential of being achievable – particularly for shorter range, limited hover endurance VTOL missions.

About the Author

Mark Moore is the LEAPTech Flight Demonstrator Principle Investigator and On-Demand Mobility Portfolio Manager at NASA Langley Research Center. A recent conference paper describing the Joby S2 design and CFD analysis in more depth is available at **www.jobyaviation.com/S2.**