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Joby Unveils EVTOL Design Details And Certification Plans

Guy Norris September 25, 2020

After more than six years of secret development, Joby Aviation lifts the lid on its innovative eVTOL air taxi program.
Credit: Joby Aviation

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A breathless hush descends on the secluded valley where the Joby Aviation team is preparing its gleaming white electric aircraft for a flight in the heat of a California afternoon.

Seldom seen and even more rarely heard, Joby's prototype electric vertical-site in central California, the company's first product—a pioneering air taxi design—is about to demonstrate that it will not only fly with ease and safety but do so extremely quietly.

Aviation Week has been invited to witness the flight and get a rare inside look at the aircraft and the steps underway to develop and certify what Joby believes will be a game-changing capability for advanced air mobility.

- Joby air taxi is on track for 2023 certification
- Aircraft includes power and controls redundancy for safer design
- Full-scale flight testing is underway

But first, the flight. Moments after the navigation lights show the vehicle is active, the propellers atop the aircraft's six upward-tilted electric propulsion units (EPU) whir into life. Almost instantly, the aircraft becomes airborne and, flown from a nearby ground-based remote cockpit, rises vertically to a relatively low altitude, where it begins a series of maneuvers and laps of the valley.

Designated the S4 for certification purposes, the yet-to-be-named air taxi is configured with four EPUs on the wing and two on the V-tail. Sized to carry four passengers and one pilot, it will be capable of operating day/night flights in instrument or visual flight rules up to 150 nm. Although only 21 ft. long overall, the aircraft has a wingspan of 38 ft., just 2 ft. less than that of an Embraer Phenom 100, giving a surprising impression of size as it moves in front of us.

Although not permitted to describe specifics about the maneuvers, speeds and altitudes flown, this Aviation Week editor was able to converse easily with Joby employees throughout the demonstration while standing within a few hundred feet of the takeoff-and-landing site. On start-up and liftoff for the demanding vertical-takeoff phase, the aircraft emitted a lower-intensity, lower-frequency sound quite unlike the urgent, high-pitched swarm-of-bees-like noise often associated with drones and large multicopters.

Joby is stepping up piloted flight tests of its air taxi eVTOL. Credit: Joby Aviation

In the hover, the overall noise level of the air taxi sounded significantly lower than any helicopter this editor has heard. The five-blade propellers on each EPU are carefully optimized for low acoustic signature, while the distributed electric propulsion system enables a lower overall loading with a resultant appears the design may also reduce blade vortex interaction, an impulsive noise source on rotorcraft that occurs in descent when blades pass through the vortices shed by previous blade passes.

There is no engine- or gearbox-generated noise, and the S4 also lacks the traditional sound wave pulse, or "thickness noise," that helicopters produce through the repetitive rotary motion of air being displaced by the blades. While maneuvering over the valley several hundred yards away, the aircraft made only a partially perceptible sound that, in this editor's view, would almost certainly be undetectable against the everyday noise background of an urban environment. These characteristics appear to be consistent with Joby's claim that the design is around 100 times quieter than a helicopter and virtually silent in wing-borne flight.

Low noise is key to eVTOL acceptance, but that is only part of the equation, says Joby founder, CEO and Chief Engineer JoeBen Bevirt. "The No. 1 priority is safety, and at a level you see in commercial aviation, which is the safest mode of transportation we have," he says. "Second, we need this to be incredibly accessible, in that people can easily get to takeoff-and-landing locations. It also has to be incredibly affordable and to become progressively more affordable over time."

- See also: **Catch An Air Taxi? Aviation Week Flies Joby's eVTOL Simulator**

To Bevirt, who set up Santa Cruz-based Joby Aviation in 2009, the S4 marks a key step toward realizing a boyhood dream of using aircraft for short-distance travel and "saving a billion people an hour a day." But even three years after the first flight of the initial "1.0" prototype and ongoing flights of the current "2.0" version, "We're just barely getting started," Bevirt says. "We are at the dawn of a transformational moment in aviation history, where we are moving from a society that moves on the surface to one that unleashes the third dimension. We believe it will be more transformative for society than the invention of the automobile."

Until now Joby was "a kind of show-don't-tell company, and now we're reaching a point where we have an opportunity to tell," says Executive Chairman Paul Sciarra. "We've purposely kept a relatively low profile—in part because this is a space where there's been a lot of smoke and very little fire for a while, and we've been doing the hard work of ensuring that we're able to hit the right commercial operating specifications for the vehicle."

Redundant propulsion and flight control systems are designed for extra safety. Credit: Joby Aviation

Sciarra, who was co-founder of social media company Pinterest and one of the first outside investors in the startup, says Joby is now shifting gears. "As a company, we are going from a project that was very much focused on development to now one that's far more focused on certification, initial manufacturing and, third, laying the groundwork for commercial operations," he says.

Test and development work is spread across the company's three main sites at Santa Cruz, nearby San Carlos in the San Francisco Bay Area and Joby's growing new production facility at Marina, California. Learning lessons from automaker Toyota, which is also a significant investor, Joby is "preparing for large-scale production," says Bevirt. Receiving advice from the Japanese automaker on attention to detail, reliability and manufacturing efficiency is like "we won the lottery."

With certification becoming the key focus, Joby has less to say for the moment about its plans to also be the operator of the air taxi. Although it has partnered with Uber to provide and operate the aircraft for the ride-share company's forthcoming urban air mobility demonstrations, Joby also has "the opportunity to work with other partners," says Sciarra. The decision to be an operator as well as the manufacturer forms a key element of the company's safety strategy.

Joby's path to the S4 began with the Monarch personal air vehicle, an electric-powered VTOL motorglider concept unveiled in 2011. But Joby soon redirected efforts toward an S2 two-place air taxi eVTOL configured with a wing and 12 tilting and folding propellers. The S2 incorporated distributed-electric-propulsion system technology that was also developed and tested in parallel for NASA's Leading Edge Asynchronous Propeller Technology (LEAPTech) project starting in 2014. LEAPTech paved the way for NASA's ongoing X-57 Maxwell electric aircraft program, for which Joby provides the 60-kW JM-X57 cruise motors.

The S2, while "super compelling," was too small to make the market impact Joby wanted, says Sciarra. "We really wanted to reconfigure this vehicle for everyone. So a number of changes were made to go to a higher-capacity, faster vehicle with longer range to deliver a wider set of missions, and that's the vehicle that we built."

Subscale S4 prototypes were flown more than 700 times starting in 2015, and in 2017 the company began remotely piloted tests of the first-generation, full-scale "1.0" version. Building on this high-wing, six-propeller configuration, Joby started flight tests in 2019 of the second-generation "2.0" version. Changes included increased gross weight—up to 4,800 lb.—and a revised swept-forward V-tail.

Joby says "several hundred" flights have been completed to date, including some with a pilot onboard. Although some testing can be flown remotely, the certified S4 will be piloted to enable integration into the existing national airspace.

Development has included construction of a full-scale static test airframe. Credit: Joby Aviation

Driven by the goals of safety, noise abatement and affordability, Sciarra says the six-EPU configuration provides adequate redundancy in the event of a motor failure. “We also tried to take that same thinking in terms of the redundancy into the design of the subsystems,” he says.

The EPUs are arranged in an oval pattern to distribute the lift forces equally around the aircraft. If one fails, the control system will automatically reduce thrust on the opposing prop while compensating with extra torque on the other four. The tail-mounted and wingtip EPUs are mounted on simple pivots to transition from vertical to horizontal flight, while only the motor and propeller of the two inboard wing-mounted units tilt to avoid complexity.

Multiple redundancy is equally evident in the control surfaces, which are made up of dual-section ailerons outboard and six individual ruddervators on the V-tails. Two sections of simple slotted flaps are also fitted inboard of the ailerons. Control surfaces are moved by small but powerful linear electric actuators mounted at the inboard edge of each surface. “The surfaces and actuators are independent for redundancy, so if one breaks, we still have another, as well as all the props,” says Chief Test Pilot Justin Paines.

The five-blade propellers are driven by highly integrated, lightweight motors that, like virtually everything on the S4, are designed and built in-house. Joby is vertically integrated “by necessity,” says Sciarra. There were often no suppliers that could make the specific components needed. “And although it took longer and was more expensive to do that initial design and manufacturing work, we feel good about it because it allows for just the right component at just the right specifications for the vehicle,” he adds.

Each EPU includes the inverter as well as motors for electric propulsion, variable propeller pitch, nacelle tilting and cooling. The cooling unit pumps fluid through an integrated radiator as well as driving a fan that pulls air past the motor and ejects it through a nozzle at the base of each nacelle. The entire unit is so closely packaged that the propulsion motor looks not much larger than a party-size cookie tin.

Representative of the multilayered safety philosophy behind the entire S4 design, the motors are configured with dual windings and dual-redundant inverters that take power from four separate lithium-ion battery packs. Two of the packs are housed spanwise in the inboard sections of the gulled wing, and two are aligned fore-and-aft in the fixed horizontal nacelles of the inboard wing-mounted motors.

vent to dump gas overboard in a thermal runaway.

Joby's vertically integrated production system includes assembly of the electric-propulsion motors. Credit: Joby Aviation

The battery technology within the packs has driven both the fundamental design of the aircraft and the intrinsic approach to safe and reliable operations. "Lithium-ion battery technology is pretty well understood. We're not relying on some new breakthrough or some secret technology that no one else has access to," says Jon Wagner, powertrain and electronics lead for Joby. "From the beginning, we understood what we could purchase as far as battery cells, and then we put it on ourselves to design the balance of the system to work." The cells are a high-volume design already in production for an automotive application.

Starting with battery capability, "you set up a vehicle design and start making budgets for weight and targets for performance," says Wagner. "One of the key things is the battery mass fraction, which is how much of the plane is made out of batteries and how much is everything else. So to achieve all those mass targets and the performance metrics, it starts to drive everything else."

Battery energy density therefore became a key parameter along with vehicle size, motors and other variables that fed the custom design optimization and mission analysis tools developed by Joby aeronautical engineer Alex Stoll.

"There are people who are saying that these types of aircraft are not viable with the lithium-ion we have today, and that we need some major improvement in [watt hours per kilogram] before this is viable," Wagner says. "But we've realized that we can achieve this, and it has to do with the aircraft design. It's a glider with batteries that can take off vertically."

Beyond energy density, other key challenges include battery charging time. "We will make our revenue when we're flying people in the air," he continues. "Turning the airplane around between flights is a really critical aspect. Quite a bit of our battery development does go into fast charge and developing a system that's capable of turning around a 25-mi. flight in 6 min., so that's a key number that we focus on."

The S4 is designed to fly efficiently on routes ranging from innercity short hops and intra-suburban flights to intercity missions. "On a longer flight, you can have a longer turn time. But the 25-mi. flight is the most difficult one from the battery-charging perspective because you've got to put all that energy back in that took 25 mi. to expend. We want to accomplish the charge in the same amount of time it takes to get people out of the plane and put the new

Battery safety, like that of the rest of the powertrain, is addressed using a layered approach. “That first layer is about taking something that’s already mass manufactured for automotive customers and bringing that high level of quality and refinement into our program,” says Wagner. “At the next level, we’re doing very advanced battery electronics and software to monitor and control every cell in the airplane. That way we can control the way that they’re being treated and their behavior.”

Beyond this, additional measures include containment between individual cells within each liquid-cooled battery pack. “These ensure that if we did have a failure in a subsystem, it would be contained and would not spread,” Wagner notes. “And then . . . we run physical testing for the worst-case scenario where maybe we have even more than one failure. And even in that scenario, we hold the standard, where we continue to allow safe flight and landing.”

The highest power requirement during flight will be during the short periods of vertical flight, but the bulk of the S4 flight time will be spent in wing-borne operation when the vehicle’s high lift-to-drag capability creates a “very low power requirement,” adds Wagner. The ability to easily maintain level flight, even with a failed or degraded battery pack, is a key element of Joby’s safety case and its drive to certify the S4 under the revamped Amendment 64 of the FAA’s Part 23 airworthiness standards as a normal category aircraft that is also capable of vertical takeoff and landing.

Like most of the eVTOL concepts, the S4 fits somewhere in between the standard Part 23 rules for general-aviation aircraft and light helicopters that are certified under Part 27 regulations. Adding more complexity, aircraft certified under Part 23 or 27 must also comply with Part 33 and Part 35 certification requirements for engines and propellers, respectively.

Joby submitted its type certificate application for the S4 in 2018 and considers itself to be blazing a trail for eVTOL airworthiness qualification, says Garrett Homan, certification and systems engineering lead for the company. “We have a certification basis locked down with the FAA. The majority of the regulations —around 85%—reflect a normal category airplane, and they’re relatively straightforward and traditional. Then the remaining 15% is comprised of special conditions to handle the novel aspects of the project including areas such as fly-by-wire, the batteries, electric propulsion and vertical-takeoff-and-landing capabilities,” he says.

Joby’s progress toward certification under the amended Part 23 shows the value of the effort going back almost 15 years to revise the regulations, says Peter Bunce, president of the General Aviation Manufacturers Association (GAMA). Introduced in 2017 to allow more flexibility for bringing new technology to aircraft, Amendment 64 is already being exercised to the full as other developers engage with the FAA over certification of the upcoming generation of other advanced air mobility designs.

“More than a decade ago, when companies like Joby didn’t even exist, everybody got the idea that if we had a regulation that could be used for the new types of electric-powered aircraft that were on the horizon, then that could be very useful,” says Bunce. “So it was written in such a way that Part 23 could be used, because none of these vehicles that we’re seeing out there are like traditional rotorcraft.” The rewrite also has big implications for where Joby will find pilots for the S4, at least initially, because Part 23 certification will open the door to recruiting fixed-wing pilots.

The details of the proposed S4 certification basis have been gathered into a document known as a G1 issue paper—a process by which the FAA documents technical issues related to a certification project. “The G1 is really the very first maintenance vice president for GAMA. The G1 also includes any special conditions. "Some of the requirements might be an exemption or an equivalent level of safety," he adds.

Among many novel aspects of the Joby approach—and one likely to become more commonplace with other eVTOL projects—is that the company plans to certify the electric propulsion units as engines and propellers under one type certificate. This means that the airplane, engines and propellers will all be covered by a single type certificate rather than in the traditional process where the airframe-maker incorporates the existing type certificate already held by the engine-maker. "We're doing it all as one," says Homan.

"Because electric propulsion isn't fully addressed by Part 33/35, the FAA Engine and Propeller Division has worked for the last five years to create special conditions to assure the design details are appropriately addressed," Homan explains. "Joby will not receive independent type certificates for the engine and propeller, but just one for the airframe, propeller and motor designs."

Joby now is also formulating a certification plan that will include the ways it will demonstrate compliance to each of the requirements. Some areas will be covered by engineering and analysis, while others will involve tests. "We're focused on finalizing the means of compliance that will serve as the specific airworthiness criteria or airworthiness standards for our designs," says Homan. "In parallel, we're working on developing externally our methods of compliance that we'll be proposing to show compliance with those performance-based regulations. So there's a few steps that we're working through that are different with this Amendment 64 project."

Joby is "somewhere between 70% and 80% complete" with defining the means of compliance and is working with various FAA departments to organize the program around a series of more detailed certification plans. "There's one for the overall project, and then we're breaking up the project into a number of more specific areas," Homan explains. "Structures, mechanical systems or flight controls are all separate areas. And within those, we are probably halfway through our detailed methods of compliance definition," he adds.

"When those are finalized, they'll be submitted to the FAA for acceptance," he continues. "We're working toward a program plan that has us achieving type certification by the end of 2023. We are currently working in order to finalize these planning details and get test plans submitted so we can start certification testing for credit in the near future."

Simultaneously, Joby is also investing in its own separate certification team of subject matter experts including current and former FAA designated engineering representatives (DER). "We've been very strategic and are building a world-class certification team comprised of individuals from major airframe-makers and Tier 1 suppliers," Homan says. Collectively, the group has more than 250 cumulative years of certification project experience across 24 new aircraft type certificates.

Much effort is focused on the special conditions, primarily high-voltage power electronics and energy storage, flight envelope protection and aspects involved with vertical-takeoff-and-landing performance. "Thermal safety is something that we're taking very seriously," says Homan.

Electrically powered aircraft are "still extremely new to the FAA," he adds. "How we're doing it with distributed propulsion and with our level of redundancy and safety is quite different than the other applications, as far as we can tell, so high-voltage electric propulsion, motor design and motor

Although the FAA is familiar with fly-by-wire flight envelope protection, mostly in airliners, the Joby approach of integrating flight control computers with control surfaces and six tilting propellers is novel, particularly in a Part 23 aircraft. “How we are implementing our design to provide envelope protection is different, which is really leveraging the strengths of the flight control system,” he adds.

Describing the flight control system as the “critical enabler” for the S4 along with battery maturity and certification, Sciarra says: “That’s one of the other pieces that has come together at the right time to make this happen.” Pivotal to Joby’s plan to make it simple and safe to operate, the S4 will be the first Part 23 aircraft to be certified with a version of the unified flight control law originally developed to make it easier to land the Lockheed Martin F-35B vertically.

The system splits velocity control over two inceptors. The left-hand inceptor controls fore/aft acceleration, while the right hand controls the vertical axis (up/down), as well as bank angle and roll rate. For hovering, the system automatically engages translational rate command, in which the pilot can make small corrections easily and which brings the aircraft to a standstill if the controls are released.

In hover mode, the triplex fly-by-wire system limits “how fast you can go sideways and aft, so we protect the airplane that way,” says Buddy Denham, a former U.S. Navy test pilot who helped develop the F-35 control system and is the father of the related Magic Carpet “Delta path mode” carrier landing system for the F/A-18 Super Hornet. At higher speeds, in wing-borne flight, “there’s envelope protection where we’re not allowing the airplane to go faster than its design speed,” he says. “We are putting in normal acceleration command and g-limiters, and then as we slow down, we also have alpha [angle of attack] protection in there as well.

“As a part of flight test, we are exploring what our control authority and control margins are, and then we’re overlaying protection on those margins. We have sensing redundancy for angle of attack, sideslip and normal acceleration, so that keeps us in a protected envelope,” he adds.

With flight-testing and plans for certification well advanced, it seems Joby is poised for success in the emerging eVTOL market. “People have been talking about electric vehicles for a while, and we finally have the building blocks in place to allow that to happen for the first time,” Sciarra says.

Guy Norris

Guy is a Senior Editor for Aviation Week, based in Los Angeles. Before joining Aviation Week in 2007, Guy was with Flight International, first as technical editor based in the U.K. and most recently as U.S. West Coast editor. Before joining Flight, he was London correspondent for Interavia, part of Jane's Information Group.

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