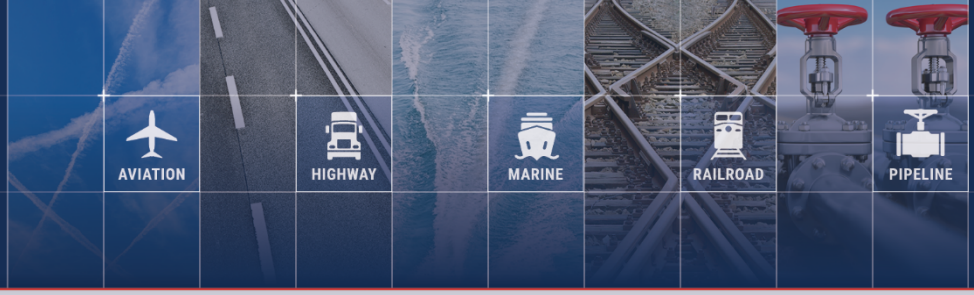

Aviation Investigation Final Report

Location:	Jolon, California	**Accident Number:**	DCA22FA082
Date & Time:	February 16, 2022, 09:58 Local	**Registration:**	N542AJ
Aircraft:	JOBY AERO INC JAS4-2	**Aircraft Damage:**	Substantial
Defining Event:	Part(s) separation from AC	**Injuries:**	1 None
Flight Conducted Under:	Part 91: General aviation - Flight test		

Analysis

On February 16, 2022, Joby Aero Inc. was conducting planned, remotely piloted, airspeed and altitude envelope expansion flight tests on aircraft JAS4-2, the first of their two second-generation, pre-production prototype flight test aircraft. The envelope expansion flight test conditions were beyond the expected operating conditions of the aircraft. During the second test flight, and after reaching a maximum dive speed of 181 knots indicated airspeed (KIAS) at an altitude of approximately 8,900 feet, a propeller blade on propulsion station 3 (located on the right wing inboard) experienced a bending failure near the root of the blade which culminated in the release of the propeller blade. The released blade impacted the propeller on propulsion station 4 (located on the right wing outboard), which subsequently resulted in a release of the impacted blade. Cascading effects resulted from the initial inflight blade failures including the separation of multiple propulsion motor/propeller assemblies and loss of remote pilot control of the aircraft. The aircraft departed controlled flight after the initial inflight blade failure and impacted the ground about 0.5 nautical miles (nm) south-southeast away.

Examination of the High-Resolution Recorder data for the accident time period revealed that the variable pitch actuator for station 3 was commanding a typical cruise pitch when the blade release occurred, whereas video evidence indicated a steeper pitch on some blades immediately before the initial blade release. Accelerometer data for station 3 showed a rapid growth in vibration after reaching the accident flights test condition before the initial blade release. Tilt actuator position values for station 3 also showed an oscillation at this time.

Examination of prior flight test data by Joby revealed consistent asymmetric behavior between station 2 and station 3, despite identical mirrored designs. In cruise mode, the tilt actuators on station 3 showed increased activity in all flight conditions compared to station 2. Tilt actuator linkage loads were also higher in station 3, which can be an indication of anomalous behavior in the tilt mechanism. The resonant response to this propeller mode crossing in station 3 was also

consistently stronger than in station 2, indicative of a coupled interaction with the anomalous tilt mechanism. While prior flights excited the propeller mode in transition flight, the strong excitation in cruise was not predicted; post-accident analysis revealed this strong excitation was due to aerodynamic interactions that only became significant when the airspeeds were beyond the expected operating conditions of the aircraft.

The dive speed of 181 KIAS reached during the speed and altitude envelope expansion flight test in conjunction with an anomalous propeller tilt system condition at propulsion station 3, likely resulted in unanticipated aerodynamic interactions that excited a propeller mode, leading to a non-uniform blade pitch increase beyond its design limitations. This likely caused a load exceedance which resulted in the initial blade failure. Aircraft control was lost as a result of cascading effects following the initial propeller blade separation.

Probable Cause and Findings

The National Transportation Safety Board determines the probable cause(s) of this accident to be:

The separation of a propeller blade during expansion flight testing that resulted in cascading effects to include the separation of multiple propulsion motor/propeller assemblies and the loss of remote pilot control of the aircraft. Contributing to the accident was the tilt rotor actuator linkage for propulsion station 3 that allowed some propeller blades to be at a steeper angle than commanded.

Findings

Aircraft	Propeller blade section - Failure
Aircraft	Propeller controlling system - Malfunction

Factual Information

History of Flight

Maneuvering	Part(s) separation from AC (Defining event)
Maneuvering	Loss of control in flight
Maneuvering	Powerplant sys/comp malf/fail

On February 16, 2022, a Joby Aero Inc. JAS4-2 experimental aircraft, N542AJ, was engaged in a planned speed and altitude envelope expansion flight test, beyond expected operating conditions. The aircraft was remotely piloted from the ground and observed from a chase aircraft. The aircraft was performing a developmental flight test, operating under the provisions of 14 *Code of Federal Regulations* part 91, utilizing an experimental category special airworthiness certificate.

The flight began about 09:42 PST with a normal vertical takeoff, transition to wing-borne flight, and climb up to 11,000 feet mean sea level (MSL). After successfully completing one test condition, the remote pilot-in-command (PIC) began descending and increasing the speed of the aircraft in preparation for the next test condition. After reaching a maximum dive speed of 181 knots indicated airspeed (KIAS) at an altitude of approximately 8,900 feet, the propeller on propulsion station 3 (located on the right wing inboard) experienced oscillations in rpm and motor vibrations.

Based on a review of video evidence and recorded flight data, about 09:58, the station 3 propeller stabilized at a resonant condition with previously unidentified destructive effects which quickly culminated in a propeller blade release from propulsion station 3. The blade spar failed near the root outside the hub and the blade traveled outboard and impacted the propeller on propulsion station 4, resulting in the separation of a blade from this propeller and the separation of this station from the aircraft. The station 3 propeller continued to rotate with significant imbalance. Shortly thereafter station 6 (right tail propeller) experienced a single blade separation and the separation from the aircraft. Cascading effects (loss of other propeller stations from the aircraft) resulted in the aircraft subsequently breaking up in flight. The aircraft departed controlled flight, rapidly rolling to the left, entered an inverted dive, and crashed in an uninhabited area near Jolon, California. There were no injuries, and the aircraft was destroyed.

Pilot Information

Certificate:	Commercial	**Age:**	62,Male
Airplane Rating(s):	Single-engine land; Multi-engine land	**Seat Occupied:**	None
Other Aircraft Rating(s):	Glider; Helicopter	**Restraint Used:**	
Instrument Rating(s):	Airplane	**Second Pilot Present:**	No
Instructor Rating(s):	None	**Toxicology Performed:**	
Medical Certification:	Class 2 With waivers/limitations	**Last FAA Medical Exam:**	January 13, 2022
Occupational Pilot:	Yes	**Last Flight Review or Equivalent:**	October 17, 2021
Flight Time:	2965 hours (Total, all aircraft), 43 hours (Total, this make and model), 2641 hours (Pilot In Command, all aircraft), 80 hours (Last 90 days, all aircraft), 25 hours (Last 30 days, all aircraft), 2 hours (Last 24 hours, all aircraft)		

Aircraft and Owner/Operator Information

Aircraft Make:	JOBY AERO INC	**Registration:**	N542AJ
Model/Series:	JAS4-2	**Aircraft Category:**	Airplane
Year of Manufacture:	2019	**Amateur Built:**	
Airworthiness Certificate:	Experimental (Special); Special flight (Special)	**Serial Number:**	JAS4-201
Landing Gear Type:	Tricycle	**Seats:**	5
Date/Type of Last Inspection:	Condition	**Certified Max Gross Wt.:**	
Time Since Last Inspection:		**Engines:**	6 Electric
Airframe Total Time:	95.7 Hrs at time of accident	**Engine Manufacturer:**	AMA/EXPR
ELT:	Not installed	**Engine Model/Series:**	UNKNOWN ENG
Registered Owner:	JOBY AERO INC	**Rated Power:**	
Operator:	JOBY AERO INC	**Operating Certificate(s) Held:**	Certificate of authorization or waiver (COA)

The accident aircraft was the first of two second-generation, pre-production prototype flight test aircraft produced by Joby Aviation. The aircraft was all-electric, fly-by-wire, and capable of vertical takeoff and landing. Provisions for five occupants (a pilot and four passengers), were provided, though it could be piloted remotely. The design's maximum gross takeoff weight was 4,200 pounds.

The aircraft was operated with a civil Optionally Piloted UAS Experimental Airworthiness Certificate. The Certificate of Authorization (COA) assigned to the aircraft dated May 5, 2021, was not applicable for the accident flight which occurred in special use airspace.

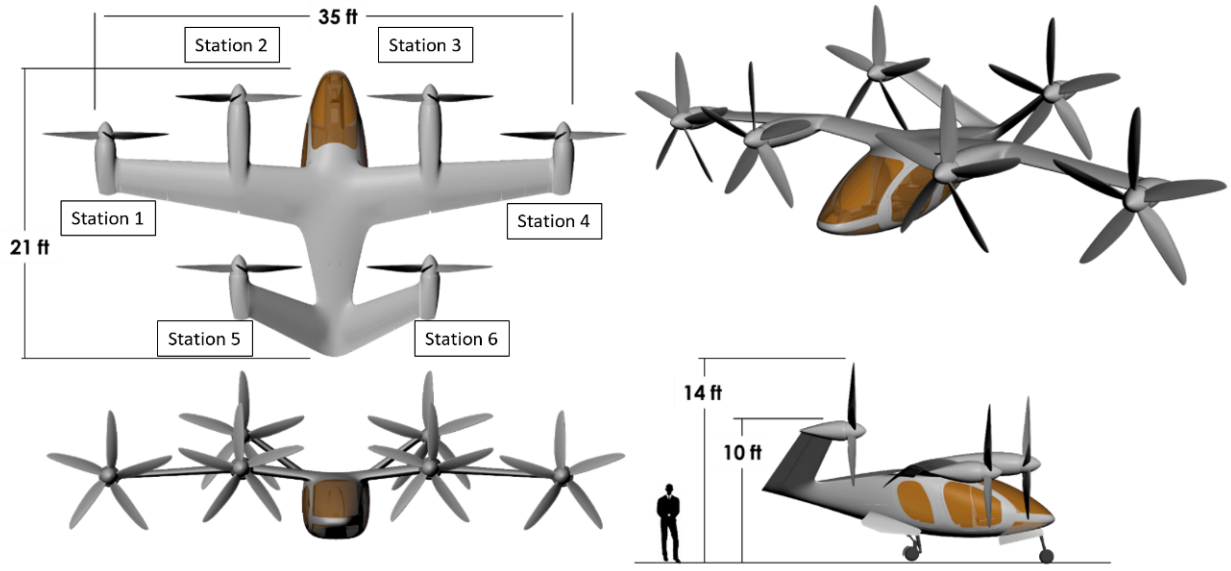

Figure 1. Depiction of a JAS4-2 aircraft (Source: Joby Aviation)

The aircraft was configured with six tilting propellers directly driven by six dual-powered electric motors supplied by power from four battery packs. The six electric propulsion unit (EPU) stations are identified numerically based on location as station 1-outboard left wing, station 2-inboard left wing, station 3-inboard right wing, station 4- outboard right wing, station 5-left tail, and station 6-right tail. Each of the six variable pitch propeller assemblies were equipped with five blades and actuated by a single variable pitch actuator driving a mechanical pitch change mechanism.

Meteorological Information and Flight Plan

Conditions at Accident Site:	Visual (VMC)	**Condition of Light:**	Day
Observation Facility, Elevation:		**Distance from Accident Site:**	
Observation Time:		**Direction from Accident Site:**	
Lowest Cloud Condition:	Clear	**Visibility**	
Lowest Ceiling:	None	**Visibility (RVR):**	
Wind Speed/Gusts:	/	**Turbulence Type Forecast/Actual:**	None /
Wind Direction:		**Turbulence Severity Forecast/Actual:**	/
Altimeter Setting:	28.9 inches Hg	**Temperature/Dew Point:**	11°C / 3°C
Precipitation and Obscuration:			
Departure Point:	Jolon, CA	**Type of Flight Plan Filed:**	
Destination:	Jolon, CA	**Type of Clearance:**	Unknown
Departure Time:		**Type of Airspace:**	

Wreckage and Impact Information

Crew Injuries:	1 None	**Aircraft Damage:**	Substantial
Passenger Injuries:	N/A	**Aircraft Fire:**	On-ground
Ground Injuries:		**Aircraft Explosion:**	None
Total Injuries:	1 None	**Latitude, Longitude:**	35.97087,-121.17582(est)

The aircraft's main wreckage consisted of the main body of the aircraft, wings, station 3 motor, and most of the tail. The main fuselage of the aircraft impacted the ground about 0.5 nautical miles (nm) south-southeast of the initial in-flight failure event. The separated stations 1, 4, and 5 EPUs (including attached propellers), separated propeller blades and fragments from stations 2, 3, and 6, various nacelle cowlings, skin sections from the right tail, and other lightweight debris were scattered in a debris field up to 4 nm south-southeast of the main wreckage. The station 6 EPU separated from the aircraft with no propeller blades attached and impacted the ground about 0.8 nm southeast of the main wreckage. The station 2 EPU and separated propeller blades were located between the main wreckage and an area about 0.1 nm northeast.

Flight recorders

Several devices onboard the aircraft were capable of recording data or video. The following items were recovered from the wreckage with recoverable information.

- 3x High-Resolution Recorders (HRRs) data.
  - Only one of these included a full data set for the accident.
- GoPro 360 video from the onboard pilot eyepoint.
- Right door-mounted GoPro video looking out the right wing and slightly aft.

Information was unable to be recovered from the data acquisition system (DAQ) and GoPro forward-pointing nose camera.

Additionally, the following data and video were captured off aircraft:
- Ground control station recordings of the nose and tail First Person Video (FPV) cameras
- Ground control station antenna video
- Chase aircraft video
- Ground control station video

The majority of the recorded parametric data came from the Joby Aero Inc. high-resolution recorder (HRR), a custom unit that captured various on-vehicle information, including control system messages. There were multiple HRRs on the aircraft to ensure consistent recording of data between redundant aircraft systems. One HRR, which recorded the data relevant to this incident, was the source for all data used in this report.

Joby also employed a commercial off-the-shelf data acquisition system (DAQ) to record additional flight test data. This dataset would have included vibration and strain gauge information. This unit was not designed to be crash-resistant and did not survive the accident. No data was recovered from this device.

Valuable information was recorded by a cockpit-mounted GoPro 360-degree video camera. This unit was not crash-resistant. The unit's files were corrupted in the accident but were recovered by the NTSB flight recorders laboratory. Much of the analysis of the accident sequence – specifically, the behavior of the blades and subsequent blade pitch angles on station 3 – was constructed from this recording. Additional video sources on the aircraft include a camera looking outboard in the right door and a forward looking "stinger" camera mounted on a shaft extending behind the tail and looking forward.

Fire

Debris at the main wreckage site was largely located in an area about 100 feet in diameter. Battery pack structures failed during the impact and battery cells were found spread in the wreckage. Two main fires occurred at the primary impact site and were largely confined to battery cells that were damaged during the impact. Both fires affected an area about 10 feet in diameter and were contained with handheld fire extinguishers.

Additional Information

Flight Test Video Review

Joby performed a detailed frame-by-frame analysis of the cockpit-mounted GoPro 360 view camera to document the station 3 propeller condition prior to and during the accident sequence. The blade pitch angles were estimated by comparison to the station 2 blade pitch angles and a CAD model of the blades at various pitch angles. Joby indicated that, seconds before the first propeller blade separated from station 3, it appeared normal and was operating with blade pitch angles within their normal range.

The aircraft was established in a descent, then accelerated to a commanded 181 KIAS test point prior to the accident condition. About 0.07 seconds prior to the first propeller blade separating from propulsion station 3, the failure blade (blade 4) was located near the 2 o'clock position (as viewed from behind looking forward, rotation direction counter-clockwise). Joby indicated that the blade's pitch angle appeared greater than the other blades. When the blade was near the 10 o'clock position, its pitch angle was estimated to have exceeded the commanded pitch angle and appeared to be near or beyond the physical pitch stop. The outer one-third of the trailing edge of the blade appeared to be disbonded. The following propeller blade (blade 5) also exhibited evidence of a core disbond.

Blade 4 failed near the root when it was near the 7 o'clock position; its trailing edge root skins appeared to be ruptured and the blade pitched and deflected in a way consistent with a failure of the blade spar near the root.

At this time, blade 5 was near the 10 o'clock position and its pitch angle was estimated to have exceeded the commanded pitch angle and appeared to be near or beyond its physical pitch stop.

Shortly after blade 4 separated, the video showed it approaching the station 4 propeller; subsequently, the station 4 EPU began to separate from the aircraft.

Following the separation of blade 4 from station 3, three additional propeller blades separated from the station 3 propeller within a couple of seconds, and the fifth blade separated during the aircraft's descent to the ground.

Flight Test Data Review

Examination of the HRR data for the accident time period revealed that the variable pitch actuator for station 3 was commanding a typical cruise pitch when the blade release occurred, whereas video evidence indicated a steeper pitch on some blades immediately before the initial blade release. All propellers were at different operating speeds at the time of the incident – an intended behavior of the control system – and the station 3 propeller speed was recorded near a predicted propeller natural frequency (resonance) crossing mode. Accelerometer data for station 3 showed a rapid growth in vibration after reaching the accident flight condition before the initial blade release. Tilt actuator position values for station 3 also showed an oscillation at this time.

Further examination of prior flight test data by Joby revealed that there was consistent asymmetric behavior between station 2 and station 3, despite identical mirrored designs. In cruise mode, the tilt actuators on station 3 showed increased activity in all flight conditions compared to station 2, which experienced steady loading after achieving zero tilt angle. Tilt linkage loads were also higher in station 3, which analysis by Joby determined could be an indication of anomalous behavior in the tilt mechanism. The resonant response to this propeller mode crossing in station 3 was also consistently stronger than in station 2, indicative of a coupled interaction with the anomalous tilt mechanism. While prior flights excited the propeller mode in transition flight, the strong excitation in cruise was not predicted; post-accident analysis revealed this strong excitation was due to aerodynamic interactions that only become significant above the design never-exceed airspeed.

Aircraft Component Examination

The recovered station 3 propeller blade segments were examined. Each of the blades was conclusively identified using distinct markings from the video. The initial failure blade spar was separated from the blade skins and was fractured about 50 mm outboard of the end of the titanium root fitting. This location corresponded to two closely spaced spar ply drops which created a stress concentration. The unidirectional fibers at the fracture location had a splayed, broomstraw appearance consistent with a bending failure. The top and bottom blade skins remained connected together at the tip, but the leading edge and trailing edge joints were disbonded. Only the 50 mm of spar stub remained attached to the hub. The fractured root areas of the initial separation blade skins were recovered separately, with some sections not identified. The separated leading edge "taco" had a kink consistent with impact with the station 4 propeller blade. There were abrasion marks on the inside of the blade skins at the leading edge consistent

with the spar being pulled out during the separation. There were irregularities noted in portions of the adhesive bond area on the upper skin that were consistent with amine blush. There were impact marks near the trailing edge of the root rib consistent with contact between the root rib and the motor resulting from chordwise blade flexure with the blades at a steep pitch. The tip of the station 3 initial failure blade was not identified.

Examination of the other station 3 propeller blade fragments revealed that all had impact marks near the trailing edge of the root rib consistent with contact between the root rib and propulsion motor elements at steep pitch. The second blade to depart fractured from the hub near the outboard end of the titanium fitting and was fractured near the 2/3 span location. The video showed this blade impacted the right wingtip after departure. The skins of the third and fourth blades to depart were separated from their spars, and the spars were fractured near the outboard end of the titanium fittings. The fifth blade to depart fractured from the hub near the outboard end of the titanium fitting and was mostly intact.
Station 4 (located on the right wing outboard) was found separate from the aircraft with the propeller intact except for a single propeller blade, which was not attached. Examination of the non-attached blade found that it exhibited significant mid-span leading edge damage consistent with the impact of another blade. The spar was intact in this blade and was broken similar to other failed blades.

A propeller blade from station 6 separated from the propeller before the station separated from the aircraft. The initial separation blade has not been identified. Two blades have significant damage but are not believed to be the initial separation blades based on video evidence. The three remaining blades have no obvious impact marks that would be consistent with collision with flying debris, unlike the damage seen on the separated Station 4 blade.

Stations 1 and 5 were found with intact propellers and cowlings near station 4. Stations 1 and 5 had no identified propulsion unit or propeller damage that could be attributed to impact with the terrain. Station 2 suffered a propeller rupture just prior to impact. The propulsion unit and tilt mechanism separated from the main aircraft immediately prior to impact and was located near the main crash site. The tilt mechanism was in nominal condition and was found in the cruise configuration.

Joby Aviation reported that computed tomography non-destructive testing scans from most of the propeller blades on the aircraft had been conducted prior to the accident. Ultrasonic testing (UT) inspections had also been conducted on all propeller blades on the day prior to the accident flight. The station 3 initial failure blade was found to be a typical blade prior to the accident in comparison to past inspections. Previous CT scans showed a small anomaly on the inner surfaces of the spar likely affecting a single ply, but scan comparisons of this anomaly over time revealed that this feature would not have met the criteria to remove the blade from service and was not likely a factor in the accident. There was no evidence of a skin-to-spar disbond on the initial failure blade.

The recovered station 3 propulsion unit – including the propulsion motor, propeller pitching

system, and propeller hub – were disassembled and examined on February 24, 2022, by Joby and observed by NTSB and FAA representatives.

The unit sustained significant mechanical damage to its propeller pitch system components and was fire-damaged. Elements of the blade pitching system were forced into the propeller hub by the impact; the portion of the system responsible for maintaining uniform blade pitch was crushed, with elements sheared off, and all components of the system were damaged. Although all five propeller blades had separated prior to impact, all five stub spars and their associated fittings remained installed in the hub. All blade retention hardware was intact. The blade pitch linkage was all present and similarly damaged by the impact. Two of the propeller hub-to-rotor fasteners were broken consistent with the inverted nose-low impact attitude. Some damage was found to the station 3 blade pitch stops. Damage to the stops was most observable on blade 1. Evidence of mechanical interference on Station 3 between blade 2 and 3 linkage prior to post-crash fire could represent abnormal propeller operation prior to impact. The interference was between the pitch arm on the blade root and the fastener connecting the pitch link to the pitch arm on the adjacent blade.

The propeller variable pitch actuator was found damaged and compressed consistent with impact. The corners of the hexagon-shaped thread locking washer under the retaining nut for the bearing between the rotating propeller and fixed actuator were mostly bent forward, away from the bearing and opposite of the direction expected from impact. The outer bearing grease seal showed signs of wear, heat, and deformation.

Joby indicated that these two observations were consistent with damage that could occur if the bearing and associated pitching system components were operating at or beyond the designed operational angular travel.

Administrative Information

Investigator In Charge (IIC):	Hauf, Michael
Additional Participating Persons:	Jill Wilson; Joby Aviation; Santa Cruz, CA David A. Gerlach; Federal Aviation Administration
Original Publish Date:	February 7, 2024
Last Revision Date:	December 13, 2024
Investigation Class:	Class 3
Note:	
Investigation Docket:	https://data.ntsb.gov/Docket?ProjectID=104654