Accident

Aircraft Type and Registration:	VA-1X, G-EVTL
No & Type of Engines:	8 Equipmake HTM-1900 electric motors
Year of Manufacture:	2022 (Serial no: 1)
Date & Time (UTC):	9 August 2023 at 0715 hrs
Location:	Cotswold Airport (Kemble), Gloucestershire
Type of Flight:	Experimental flight test
Persons on Board:	Crew - None Passengers - None
Injuries:	Crew - None Passengers - N/A
Nature of Damage:	Damage to right wing, fuselage, landing gear and engine pylon
Commander's Age:	60 years
Commander's Flying Experience:	More than 4,300 hours (of which 3 were on type) Last 90 days - 6 hours Last 28 days - 0 hours
Information Source:	AAIB Field Investigation

Synopsis

The aircraft was being flown by a remote pilot on a test flight at 30 ft agl when a propeller blade detached from the electric propulsion unit 3 forward motor due to a failure of the adhesive bond between the propeller blade sheath and spar. Large out-of-balance loads generated by the blade release caused structural failure of the right inboard pylon, resulting in damage to the aircraft's wiring harnesses. This caused a loss of thrust from motors 4 and 7. Whilst the aircraft's flight control system was able to maintain a level attitude, the high rate of descent caused by the loss of vertical thrust resulted in substantial damage to the aircraft when it struck the ground.

The aircraft manufacturer was, at the time of the accident, in the process of introducing a blade design that, amongst other things, eliminated the bonding failure mode that caused the blade release. The manufacturer's investigation identified 36 product and process improvements resulting from findings of the investigation.

History of the flight

G-EVTL was in the second phase of its test flying having completed the initial tethered phase. The accident flight was the twenty-second flight of the programme. The aim of the test was to look at one engine inoperative performance during out of ground effect hover. The aircraft was being flown remotely under the CAA Specific Category[1].

Footnote

[1] CAA Cap 722 Unmanned Aircraft System Operations in UK Airspace – Policy and Guidance http://publicapps.caa.co.uk/modalapplication.aspx?appid=11&mode=detail&id=415 [Accessed September 2023].

Routine checks were completed, and the aircraft set up according to the test card. At 0712:16 hrs aircraft flight mode was selected, and all the electric propulsion units (EPUs) began idling. At 0714:25 hrs G-EVTL completed a normal vertical takeoff with all EPUs operating. Once the aircraft was stable in ground effect, the remote pilot shutdown EPU1 in accordance with the test card. At 0714:40 hrs the remote pilot then began a gentle climb to 30 ft agl. The test card required the aircraft to be stable at this height for 10 seconds before proceeding with the flight. This was completed and the remote pilot began a gentle acceleration towards 7 kt ground speed (GS). At 0715:47 hrs, as the aircraft speed passed 2-4 kt GS, a loud 'pop' was heard, and a propeller blade was released from EPU3.

The resulting imbalance caused the structural failure of the right inboard pylon (pylon 3). Despite EPU1 restarting automatically the aircraft was unable to maintain height and at 0715:50 hrs it struck the ground on the left edge of the runway with a vertical descent rate of 19.45 ft/sec. During the impact the right wing failed outboard of pylon 3, the nose gear collapsed and there was other structural damage. There were no injuries and no damage to any third party.

Figure 1

Pylon 3 failure following the release of a propeller blade from EPU3
(courtesy of manufacturer)

Aircraft description

G-EVTL is an Electric Vertical Takeoff and Landing (eVTOL) prototype with a carbon fibre composite structure, fixed tricycle landing gear, V-tail and a high wing. In its configuration for this test the aircraft had a maximum takeoff mass of 3,737 kg and could be flown with a pilot onboard or remotely.

Flight control system (FCS)

The aircraft was fitted with three Flight Control Computers (FCCs). The FCCs communicate EPU speed commands and tilt position commands (as well as their associated monitoring), over Controller Area Network (CAN) data buses. There were six CAN buses in total (two for each EPU and two for each tilt system) with each CAN bus consisting of two wires each. Part of this monitoring included the position of each EPU tilt mechanism.

Propulsion system

The aircraft is fitted with eight EPUs, each driving a propeller, with four on the wing leading edge and four on the trailing edge. The forward EPUs are numbered 1 to 4, from left to right, and the rear EPUs are numbered 5 to 8, also from left to right. The leading edge EPUs drive five-bladed, fixed pitch 'Generation 1' carbon composite propellers and each has a tilt mechanism allowing a variation of propeller angle between 0° and 100°, where 0° is straight ahead and 90° is vertically upwards. The forward EPU propeller blades comprise an external sheath that is adhesively bonded, with an expanding adhesive film, to a carbon fibre spar fixed to the propeller hub.

The trailing edge EPUs are fixed vertically upwards and drive four-bladed, fixed pitch composite propellers.

Each EPU consists of a three-phase motor, an inverter and a thermal management system. Three-phase cables connect the motor to the inverter; the inverter is fed both high voltage (HV) power for drive and low voltage (LV) power for control. Each EPU is connected to two independent and redundant CAN buses, used for motor control and monitoring.

Power for the propulsion system is provided by multiple battery subpacks located within the fuselage. Each battery subpack consists of lithium-ion cells connected together to provide HV DC power. An HV power distribution unit (PDU) then transfers this power to the EPUs.

The aircraft has a dualLV systems to power all onboard systems.. Power can be supplied to the system from the main aircraft LV battery, an external power socket or from DC-DC converters connected to the propulsion battery subpacks.

The landing gear is designed to accommodate sink rates of up to 10 feet per second without damage.

If the aircraft is being piloted remotely the pilot stands behind a remote cockpit with a wraparound screen, electronically displayed cockpit instruments and a control unit. The flight tests included a second pilot who maintained visual contact with the aircraft while the commander was in the remote cockpit. A Telemetry station and engineering team were live monitoring the aircraft status, in close proximity to, and in communication with the pilot remote cockpit.

Accident site

The aircraft hit the southern edge of Runway 26 in a level attitude with the right mainwheel on the paved runway surface and the left mainwheel and nosewheel on the grass. The right wing had broken at the inboard pylon but remained attached to the aircraft by wiring harnesses. Two propeller blades had detached from EPU3, with the blade sheath that separated in flight coming to rest 50 m from the aircraft, at its seven o'clock position. A section of blade spar that had also released came to rest close to where the sheath had landed. A second blade had detached during the ground impact as EPU3's propeller was still rotating when the aircraft touched down.

Figure 2
G-EVTL after the accident

Operator's accident response

Following the accident the operator carried out its pre-prepared emergency response plan, led by the lead flight test engineer. This plan had been practiced as a 'desk exercise' prior to commencement of the flight test programme. The initial actions involved ensuring the airfield RFFS was responding to the accident, quarantining the aircraft and associated data recordings and informing the AAIB and the operator's incident command group.

The RFFS arrived promptly and as no fire had occurred and no occupants were present, monitored the aircraft with a thermal camera in order to detect any overheating of the aircraft's batteries.

The aircraft's high voltage insulation monitoring system had detected a short circuit between the high voltage system and the airframe structure, but it was not apparent where the fault was located. The second remote pilot, dressed in appropriate personal protective equipment and accompanied by a high voltage-trained 'hook man' approached the aircraft to shut down the electrical systems. This included turning the high voltage system to OFF, to which the system responded as expected by opening the battery contactors to disconnect the high voltage system from the propulsion batteries. An ethernet cable was connected to the aircraft to allow direct laptop connection for system troubleshooting.

The left fuselage access panel was removed and the HV insulation fault was isolated by removal of a connector on the PDU. The battery pack voltages and temperatures were monitored over an immediate three-hour period and no abnormal behaviour was observed, allowing aircraft recovery to proceed. The damaged section of the right wing was cut free and the aircraft was recovered to the operator's hangar for further examination.

Aerodrome information

Aircraft testing was being conducted at Cotswold Airfield (Kemble) where special arrangements had been made to safeguard the area as well as G-EVTL. Untethered test flights were planned for outside the airfield's operating hours, but with both air traffic and airport fire services available. The risk assessment and CAA approval for the test had required a sterile area around the runway which included a significant safety margin. This area was reserved for G-EVTL operations at the time of the tests. The aircraft, including released propeller blade, remained well inside this area throughout the flight and subsequent accident.

Aircraft examination

Pylon 3 had failed in overload due to high out-of-balance loads caused when the EPU3 propeller blade released, allowing the forward section of the pylon to initially rotate vertically upwards under residual propeller thrust. This movement damaged the wiring harnesses where pylon 3 was attached to the wing front spar, severing the CAN bus C1 and C2 wiring. Low voltage wires providing power and return feeds to the EPU3 inverter were open circuit within a connector, due to cable strain. Damage to the high voltage wiring consisted of phases U and W pulling out of their connectors at the EPU3 motor and phase V pulling out of its connector to the inverter, with electrical arcing damage between the cable and the connector body.

The nose landing gear had collapsed and the left main landing gear oleo remained fully compressed. A number of skin-to-frame fasteners had pulled through the fuselage skin around the right main landing gear upper fitting. The right wing had failed in downward bending overload at the inboard pylon station.

The blade sheath that released during flight showed evidence of poor bonding between the sheath and the blade spar (Figure 3). Most of the adhesive remained attached to the internal sheath surface with very little present on the blade spar.

Figure 3

Released propeller blade including failed spar-to-sheath adhesive bond (lower three images, viewed in direction 'A')
(courtesy of manufacturer)

In the days following the incident, routine system monitoring identified one battery subpack exhibiting a greater than expected self-discharge rate. All the battery subpacks were purposely deep discharged as a precaution, rendering them inert, allowing safe removal from the airframe and for detailed inspections to occur.

Recorded information

The aircraft was fitted with a comprehensive data recording system, designed for the flight test campaign. This included an on-board recording system, and lower-rate telemetry data which was recorded off-aircraft. Data was recovered from both locations and allowed the manufacturer to perform a detailed post-flight analysis.

The recording system included video cameras which captured the propeller blade release and subsequent aircraft damage and descent. Post-flight review of the data confirmed that there were no data indicators that could pre-empt the propeller blade release.

Aircraft performance

The aircraft manufacturer spent a significant amount of its investigation on the aircraft performance after the rotor propeller blade release. The aircraft was designed to be able to continue to operate with one EPU inoperative, so the investigation focussed on the root cause of the propeller blade failure as well as the aircraft response following the failure of the propeller blade.

Once the blade released, there was a short delay before the aircraft systems detected a problem with EPU3. The rpm demand was then reduced to zero and the propeller rpm gradually reduced. After loss of EPU3, for the first second, the flight control laws assumed a higher than actual rpm for EPU3 as the EPU shutdown was instigated by the EPU, not the FCS. With this assumed higher rpm, to maintain control, the system reduced rpm on EPUs 4 and 8 for one second.

Detection of EPU3 failure led to the successful re-activation of EPU1. However, the subsequent movement of pylon 3 caused significant damage to the aircraft wiring and impacted the aircraft system response.

Two of the six CAN buses were severed completely and video footage showed a spark from around EPU3 caused by the high voltage power cables being damaged. Another CAN bus exhibited an intermittent connection, causing loss of the tilt position of EPU4 to the FCCs. With loss of tilt position, EPU4 rpm command was reduced to zero as designed.

In addition, the FCC lost CAN bus contact with EPU7, probably due to an inverter reset. As the FCC had lost contact with EPU7, it assumed zero rpm for this EPU as per design.

Despite the re-activation of EPU1, the damage to the aircraft wiring meant the system did not command sufficient thrust to the remaining EPUs to allow the aircraft to continue to hover, although it was successful in maintaining the aircraft in an approximately level attitude during the descent.

Meteorology

Conditions were described as ideal for this test flight with light winds from the south-west (240° 2-4 kt). Some early low cloud had lifted by the time the aircraft was prepared for the flight.

Analysis

Failure sequence

The failure of the adhesive bond between the EPU3 propeller blade sheath and spar allowed the sheath to translate radially outwards, increasing the bending load on the blade spar which caused the outer section of the spar to fracture and separate. The loss of the blade whilst the propeller was spinning at 1,200 rpm generated large out-of-balance forces, causing the structural failure of the forward section of pylon 3.

The upward rotation of the broken section of pylon 3, due to the remaining thrust from EPU3 whilst its propeller continued to rotate, damaged the aircraft's wiring harnesses. This resulted in the loss of thrust from EPU4 and EPU7. With the remaining vertical thrust insufficient to sustain the aircraft in a hover, it descended vertically whilst the flight control system retained a level pitch and roll attitude. The aircraft struck the ground at a rate of descent approximately twice the limit descent velocity that it was designed to withstand, leading to structural damage to the right wing, landing gear and fuselage.

Cause of the blade release

The released propeller blade was operating within its normal rpm and loading levels when it detached, without any increased vibration or foreign object impact prior to release. The blade sheath detached due to failure of the adhesive bond between the blade sheath and spar. Stress analysis performed by the manufacturer showed that only 5% of the spar-to-sheath bond area was required to retain the sheath at the centrifugal loading condition when the bond failed. It is therefore likely that progressive degradation of the bond occurred during operation prior to the blade release.

The manufacturer inspected two other similar propeller blades from its spares pool using CT scanning. Voids were widespread in the bond line in both blades, as were variations in the shape of the blade spar cross section. A review by the manufacturer determined that the blade structural design, and the relevant manufacturing control, quality assurance processes and verification programme were contributory factors to the blade release.

Safety action

As a result of this accident, the manufacturer has taken the following safety actions:

- The remaining 'Generation 1' propeller blades were withdrawn from use and, subject to a satisfactory inspection, will only be used for ground testing.
- The manufacturer was in the process of introducing a new 'Generation 2' propeller blade when the accident occurred that, amongst other things, eliminated the bonding failure mode that caused the blade release.
- Having completed its internal accident investigation, the manufacturer identified 36 product and process improvements. These include improvements in quality control, supplier qualification, design and verification processes, flight control laws, CAN bus architecture and the routing of wiring harnesses.

Conclusion

The blade released from EPU3 was caused by a failure of the adhesive bond between the propeller blade sheath and spar. It is likely that defects introduced in the bond when the blade was manufactured grew progressively larger during the blade's operational service to the point that the remaining bond area was insufficient to retain the blade under normal operating loads.

Large out-of-balance loads generated by the blade release caused structural failure of the right inboard pylon, resulting in damage to the aircraft's wiring harnesses. This caused a loss of thrust from motors 4 and 7. Whilst the aircraft's flight control system was able to maintain a level attitude, the high rate of descent caused by the loss of vertical thrust resulted in substantial damage to the aircraft when it struck the ground.

The manufacturer identified the propeller blade's structural design, the manufacturing controls, quality assurance processes and verification programme as contributory factors to the blade failure. It was, at the time of the accident, in the process of introducing a revised propeller blade design that, amongst other things, eliminated the bonding failure mode which caused the blade release.

The manufacturer's investigation identified 36 product and process improvements resulting from findings of the investigation.

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