Investigating a Unique UAV

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Abstract: Phantom Eye is a unique "One-of-a-Kind" unmanned, liquid hydrogen-fueled, test bed air vehicle designed to operate at high-altitude and long-endurance for persistent intelligence, surveillance and reconnaissance and communications missions – an Eye in the Sky. The demonstrator aircraft is capable of maintaining its altitude for multiple days while carrying a 450-pound payload. Typical payloads include multiple sensor packages for monitoring, tracking and communications. A full size Phantom Eye variant is designed to stay aloft for over a week and carry a payload of 2,000 pounds. The inaugural flight of the demonstrator aircraft was marked a success across all the planned test points with the exception of the lakebed landing at Edwards Air Force Base CA. The resulting unplanned recovery event threatened the continuance of the flight test program. This paper presents the challenges of investigating an experimental unmanned demonstrator aircraft, lessons learned, and planning preparations to ensure for a successful investigation.

Description

The Boeing Company designed Phantom Eye is a High Altitude/Long Endurance (HALE) unmanned air vehicle (UAV). There are various operational needs to have a long endurance air vehicle in the stratosphere. Examples include: Battlefield and Border Observation, Port Security, or Telecommunications, to name a few. The Phantom Eye prototype air vehicle was designed to stay aloft for 5 days at an altitude of 65,000 feet without landing or refueling. Specifications of this prototype include:

- 150 foot wingspan

- 45 feet length
- Empty weight of approximately 6100 lbs.
- Takeoff gross weight of approximately 8265 lbs.
- Triplex (Vehicle Management System (VMS) for redundancy
- All composite structure
- Two 2.3L Ford Hydrogen engines
- 3-stage turbochargers, 1 stage gear box, variable pitch, 3-blade propellers
- Two 8 ft diameter Vacuum Dewar tanks
- Liquid Hydrogen to Gaseous Hydrogen Heat Exchanger

First Flight Timeline

At 0621, on June 1st, 2012, the first flight of Phantom Eye performed a 26 minute flight, up to 4000 feet. A high level overview of the time is as follows; 0621 – Takeoff from Lakebed Runway 15, with a transition to normal flight guidance, 0629 – All systems and performance normal, the pilot commanded aircraft to enter south lakebed holding pattern per plan, 0636 – As planned, the pilot manually commanded gear down, Gear extension observed by chase aircraft, Range Officer, Telemetry (TM) Pilot display all indicated down and locked gear, 0640 – Cleared to land, 0647 – Landing on Lakebed Runway 33, Vehicle dynamics were as predicted on final approach, with sink rate on target, the main skid touched down normally followed quickly by the Nose wheel separating upon contact with the runway, and the Nose strut bending back from drag force, with finally main skid collapse.

Recovery

After the landing gear collapsed, the air vehicle is now in an unknown state. The team must use utmost caution to approach and place the vehicle into a safe state. The telemetry showed no issues or anomalies with the fuel system, detected up until the vehicle shutdown. Tank active vent behavior and pressure rise rate following landing were as-expected, once again, up until power off from the vehicle shutdown. Test personnel approached with hydrogen detectors that indicated no Hydrogen leakage. An item to note, anything filled with liquid hydrogen should capture and keep your attention as long as it is fueled. Even while the engines are off and the vehicle has no power on, in what, appears to the uninformed observer in a calm state. It is quite dangerous. Pressure is constantly building as the liquid hydrogen warms and turns to gas, constantly increasing the pressure inside the tanks. If the valves stick or moisture freezes the valves, there could be the danger of an overpressure explosion. A tagline for this program was from the fuels subject matter expert had for any hydrogen fueled items – "The system is always actively trying to kill you!" A great reminder for test personnel approaching and monitoring the state of the air vehicle. The team needed to ensure there was no leaks of the highly volatile liquid (or gaseous hydrogen) before approaching the vehicle to start the incident investigation along with defueling and purging process to get into a safe condition. Normal fuel system pressure and expected quantities were verified by the pilot before the launch crew was cleared for approach. The recovery crew verified there was no fire or leakage using an Infra-Red (IR) camera, along with H2 detectors. Once confirmed safe for recovery, the Mishap Plan was initiated at the Ground Control Station (GCS) with notifications made, data preserved, and statements collected per the pre-mishap plan and recovered from the Edward's Air Force Base lake bed runway, to the hangar area for defueling and purging of the fuel system.

Investigation

The mishap occurred on Friday, 01 June 2012. The aircraft was rendered safe, secured and all evidence lie in sequester awaiting arrival of the investigation team to begin the accident investigation process on the afternoon 02 June. The process initiated with a team meeting to understand eye witness first accounts, read statements, discuss the investigative process to include general plan forward and conduct a site visit to capture lakebed witness mark evidence to include mapping and measuring indentures, skids, and overall footprint.

The on-site investigation spanned slightly over one week with many activities occurring in parallel. There were three key activities that contributed to the finding of root cause. In no particular order of priority, they were: Photogrammetry evidence compilation and analysis, design pedigree research, and Engineering Investigations (EIs). The on-site aspect of the latter consisted of identifying components and arranging logistics for follow-on detailed EIs in the St Louis metallurgical lab.

Photogrammetry

The fortunate aspect of conducting flight testing on a range is that you have the luxury of operating in a controlled environment and are afforded the opportunity to build contingency management and data acquisition into the plan. Data acquisition served the program and the investigation quite well. Telemetry data, capturing vehicle performance parameters, became instrumental in aligning witness marks with the vehicle environmental recovery data which corroborated the evidence captured through the lens of long range, onboard, and chase video. A trifecta of data that complimented and confirmed the events as they unfolded that Friday morning.

Alignment and agreement of the data was comforting in the final analysis but, the investigation was accelerated in the initial days with the benefit of long range video recorded in high fidelity. The video evidence permitted review to be slowed to a frame by frame basis without introducing the negative pixelating that often hampers video quality. This clarity allowed photogrammetry measurements and assessment to be performed narrowing the window of speculation as to the mishap's root cause. The significant events that occurred during the lakebed recovery were easily identified and quickly steered the investigation focus to further delve into the nose landing gear structure unveiling further evidence leading to root cause identification. A pictorial summary of this product is presented in the PowerPoint presentation accompanying this paper.

Design Pedigree

Research into the history of the nose landing gear structure became a primary focus. The examination centered on reviewing the evolution of the design and in particular, the latest or current design version compared to the installed version. The drawing revealed an engineering change order initiated circa 1985 stipulating removal of a counter bore. This counter bore proved to be in the origin of the gear failure location.

Engineering Investigation (EI)

The EIs consisted of visual and magnified fracture surface inspection and material pedigree review. All visual inspections revealed classic ductile overload fracture. The fracture origin was determined to be on the forward side or zero degree position of the outer fillet radius between the lower cylinder and the larger diameter upper cylinder. The piston microstructure was normal with no internal defects. No other anomalies were noted at the fracture origin or other elements of the fracture zone. The overload fracture propagated upward through the thickness and outward circumferentially in both directions around the cylinder. Aft bending load from landing drag forces tore the piston lower cylinder with the attached wheel assembly out of the upper piston cylinder. This action resulted in the remaining landing gear stub ultimately collapsing under the balance of remaining frictional forces.

Investigation Summary

The program responded to the first flight anomaly by initiating an accident investigation team and a Root Cause Corrective Action (RCCA) team. Both were formed to investigate the incident, determine proximate cause, and recommend corrective actions. The Nose Landing Gear (NLG) experienced a greater than expected vertical load, but much lower than the maximum specified load that resulted in a piston shaft failure. The greater than expected load was caused by a combination of unexpected bearing friction, piston shaft bending and increased drag on the Main Landing Gear (MLG) skid. These unexpected behaviors of the piston where primarily due to two factors. First, the lack of dynamic load modeling and testing. Interesting to note that the dynamic load modeling and testing performed post anomaly predicted these failure modes. Second, the piston "as-built" configuration did not conform to the "as-designed" version which was due to a failure in the Non-Conformance Review (NCR) process.

Recommended Actions

There were three recommended actions that came as a product of the mishap investigation and RCCA. The first two being engineering design and the third being engineering process. First, the NLG was recommended to be redesigned and its performance to be verified using dynamic load modeling and testing. Second, The MLG was further scrutinized via analysis, testing to ensure adequate landing safety margins existed. Third, successfully conduct a Preliminary and Critical Design Review on the redesigned NLG and MLG to include independent Subject Matter Experts.

Lesson Learned

Test only that which you intend to test. In other words, independently verify that each item of the configuration build has the demonstrated credentials to safely support the future test objectives. Trust your baseline engineering data BUT verify the data to be accurate, current and representative of the configuration to be tested.

Challenges

Vehicle Peculiarities

Investigating a mishap of "one of a kind" aircraft has a unique set of challenges. Although, this air vehicle had basis on a previous air vehicle, multiple baseline contributors were designed and documented in the 1980s. Attributable to the engineering hiatus, there was a lack of data for reference due in part to record retention policies. The potential to review past test reports for similar landing gear events or issues was non-existent. Unlike investigating a production aircraft mishap where a trove of previous mishap data exist, a one off air vehicle will have limited or no production data or history to reference.

Fuel Instability

The instable nature of the hydrogen fuel introduced an additional investigation challenge. The challenge comes in the form of evidence preservation. The instability of liquid hydrogen, required the team to defuel the aircraft and purge the lines. As it turned out in this case, it was not a factor, however variables such as fuel contamination or exact weight at landing could have been lost critical data in the pursuit of getting to root cause. No Pilot 1st account – Even with onboard cameras, chase and long range cameras, there is no "in the seat" or "feel" that an onboard pilot may have during an event. Especially with no on board "Voice Recorder", sounds from the event cannot be detailed as with a pilot or Cockpit Voice Recorder (CVR). The team is limited to onboard TM and camera's being functional through the event.

TM limitations

In addition to no CVR, the vehicle configuration did not include an onboard crash survivable Data Recorder. The team did have live streamed TM data which was limited to certain parameters, although the team had accurate indications of the fuel state along with gear position (down and locked). Had the TM stream been disrupted, those indications/confirmations would have been unknown adding to the complexity of the investigation.

Key preparation ingredients for a successful investigation

- Controlled Test Range
- Chase Aircraft
- Video (Long Range, Short Range, Airborne, Stills, Onboard, Ground Chase and GoPro™)
- TM
- Lakebed (optional – can conveniently capture witness marks)
- Flight test venue limited exposure to competing Users/traffic

Summary

In recognition, the test team successfully navigated a high stress, off-nominal first flight event where the vehicle was recovered safely. The vehicle was repaired and updated with a redesign of the landing gear and flown 8 more times, achieving greater altitudes and endurance times with each subsequent flight. Lessons learned were archived for a follow on version along with passing on additional best practices to future UAS test teams. Accolades include, The Society of Flight Test Engineers (SFTE) 2012 James S. McDonnell Team Award for Outstanding Achievement in Flight Test Engineering and the Boeing Flight Test Safety Award in 2014.