

National Transportation Safety Board

Office of Aviation Safety

Washington, DC 20594



CEN22FA331

AIRWORTHINESS

Group Chair's Factual Report

August 7, 2023

A. ACCIDENT

Location: North Fork, Idaho
Date: July 21, 2022
Time: 1644 mountain daylight time
Helicopter: Columbia Helicopters CH-47D, registration N388RA

B. AIRWORTHINESS GROUP

Group Chair	Chihoon Shin National Transportation Safety Board Washington, District of Columbia
Group Member	Ian Hansen Federal Aviation Administration Boise, Idaho
Group Member	Robert Roedts Columbia Helicopters Aurora, Oregon
Group Member	Ely Woods ROTAK Helicopter Services Anchorage, Alaska
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C. SUMMARY

On July 21, 2022, about 1644 mountain daylight time, a Columbia Helicopters CH-47D, N388RA, was destroyed after it impacted the Salmon River and its riverbank near North Fork, Idaho. The pilot and copilot were the only occupants on board and were fatally injured. The helicopter was operated as a public use firefighting flight.

The operator, ROTAK Helicopter Services (ROTAK), was working under contract for the United States Forest Service (USFS) for the Moose Fire and had relocated the helicopter to the area on July 19, 2022; firefighting flights began on July 20, 2022. On the day of the accident, the pilots had completed about 1.5 flight hours and multiple bucket loads via a water bucket attached to the helicopter at the end of a 200-foot long line attached to the helicopter's cargo hook.

From July 23-29, 2022, members of the Airworthiness Group convened at the accident site to document the wreckage. The wreckage was recovered and subsequently transported to Inter-State Aviation in Pullman, Washington. From August 16-18, 2022, members of the Airworthiness Group convened at Columbia Helicopters' facilities in Aurora, Oregon to conduct functional testing and examination of the longitudinal cyclic trim (LCT) actuators; the upper boost actuators (UBA); and the integrated lower control actuators (ILCA). On September 20, 2022, the Airworthiness Group Chair and Honeywell Group Member convened at Triumph Engine Control Systems' facilities in West Hartford, Connecticut to recover data from the engine electronic control units (ECU). From October to November 2022, the yaw ILCA was scanned using computed tomography (CT) to document the internal condition of the actuator. On March 21, 2023, members of the Airworthiness Group convened at Columbia Helicopters' facilities in Aurora, Oregon to conduct a teardown examination of the yaw ILCA. From May 31-June 1, 2023, members of the Airworthiness Group convened at Inter-State Aviation facilities in Pullman, Washington to examine the cockpit flight controls and the yaw/thrust pallet. Subsequently, on June 1, 2023, the National Transportation Safety Board (NTSB) investigator-in-charge (IIC), the Airworthiness Group Chair, and representatives from ROTAK, the USFS, and the Federal Aviation Administration (FAA) examined the cockpit flight control system on an exemplar CH-47D at Caldwell Executive Airport in Caldwell, Idaho.

D. DETAILS OF THE INVESTIGATION

1.0 Helicopter Information

1.1 Helicopter Description

The Columbia Helicopters CH-47D is type certificated under FAA type certificate data sheet (TCDS) No. R00051SE. Originally manufactured by Boeing for the United States (US) Army, the Columbia Helicopters CH-47D is a surplus military helicopter that was type certificated under the restricted category. The CH-47D has two fully-articulated, three-bladed rotor systems, in a tandem (forward and aft) configuration that provides helicopter lift, thrust, and attitude control. The forward rotor system turns counterclockwise and the aft rotor system turns clockwise, both when viewed from above. The helicopter is equipped with two Honeywell T55-GA-714A turboshaft engines, one mounted on each side of the aft pylon. The helicopter

was equipped with four non-retractable wheeled landing gears mounted to the fuselage. The accident helicopter was not equipped with a cockpit voice recorder (CVR), flight data recorder (FDR), or a cockpit image recorder.

All left, right, up, and down orientations as well as clock positions referenced in this report are in the aft-looking-forward frame of reference unless otherwise specified.

1.2 Accident Helicopter History

The accident helicopter, N388RA, was serial number (S/N) 88-0097. The accident helicopter was originally manufactured as a CH-47C with S/N 71-20952 and delivered to the US Army in 1972. In 1988, the helicopter was remanufactured as a CH-47D and delivered to the US Army in 1989 as S/N 88-0097. After its military service, the helicopter was sold to Columbia Helicopters at a General Services Administration (GSA) Auction in 2014 and registered as N476CH. After completion of modifications and FAA certification under TCDS No. R0051SE, the helicopter was delivered to ROTAK on June 5, 2022, as N388RA with an aircraft total time (ATT) of 7,666.4 hours and a Hobbs time of 0 hours. The No.1 (left) engine was S/N 10GGA01436 and the No. 2 (right) engine was S/N 09GGA01377. According to the accident helicopter records, at the end of July 20, 2022, the helicopter accumulated an ATT of 7,735.9 hours and the Hobbs time was 69.5 hours.

1.3 Accident Flight Summary

A ground witness video had captured the accident flight. The video was analyzed by the NTSB Vehicle Performance Division.¹ At the start of the video, the accident helicopter was hovering about 200 feet above ground level (AGL) over the Salmon River with its water bucket, at the end of a 200-foot long line, swinging close to the surface of the river. After 2 seconds, the helicopter began to ascend up to 325 feet AGL over a period of 8-9 seconds; its heading remained generally the same throughout the ascent. Subsequently, the hovering helicopter began to yaw to the left. Once the helicopter had turned about 180°, the helicopter pitched down, continued to yaw left, and began to descend. The left yaw continued through the descent until the helicopter impacted the river and riverbank.

2.0 On-Scene and Post-Recovery Wreckage Examination

From July 23-29, 2022, members of the Airworthiness Group convened at the accident site to document the helicopter wreckage. The wreckage remained in the Salmon River until July 27, 2022, when the wreckage was removed from the river and onto the riverbank. The wreckage was examined in situ and subsequently transported

¹ For additional details of the analysis of the ground witness video, see the NTSB Video Study in the docket for this investigation.

to Inter-State Aviation in Pullman, Washington. From May 31-June 1, 2023, members of the Airworthiness Group convened at Inter-State Aviation facilities in Pullman, Washington to further examine the cockpit flight controls and the yaw/thrust pallet.

2.1 Structures

2.1.1 Airframe Overview

The CH-47D fuselage is of semi-monocoque construction and is divided into four sections: cockpit, cabin, aft fuselage, and aft pylon. The cockpit contains the forward pylon that contains the forward rotor system. Two main fuel tanks are attached on the left and right side of the cabin structure. The aft fuselage contains the cargo ramp and engines. The aft pylon contains the aft rotor system.

2.1.2 Wreckage Observations

The airframe came to rest upright in the Salmon River except for the aft fuselage and aft pylon (**Figure 1**). The aft pylon partially separated from the aft fuselage and came to rest on its right side and was partially submerged in the water (**Figure 2**). The lower portion of the airframe exhibited significant upward deformation and crushing due to ground impact. The cockpit floor and the ramp were submerged in the water while the cabin floor was deformed significantly upward. The two cockpit doors were already separated from the airframe by the time the investigation group examined the wreckage.



Figure 1. The accident helicopter in the Salmon River.

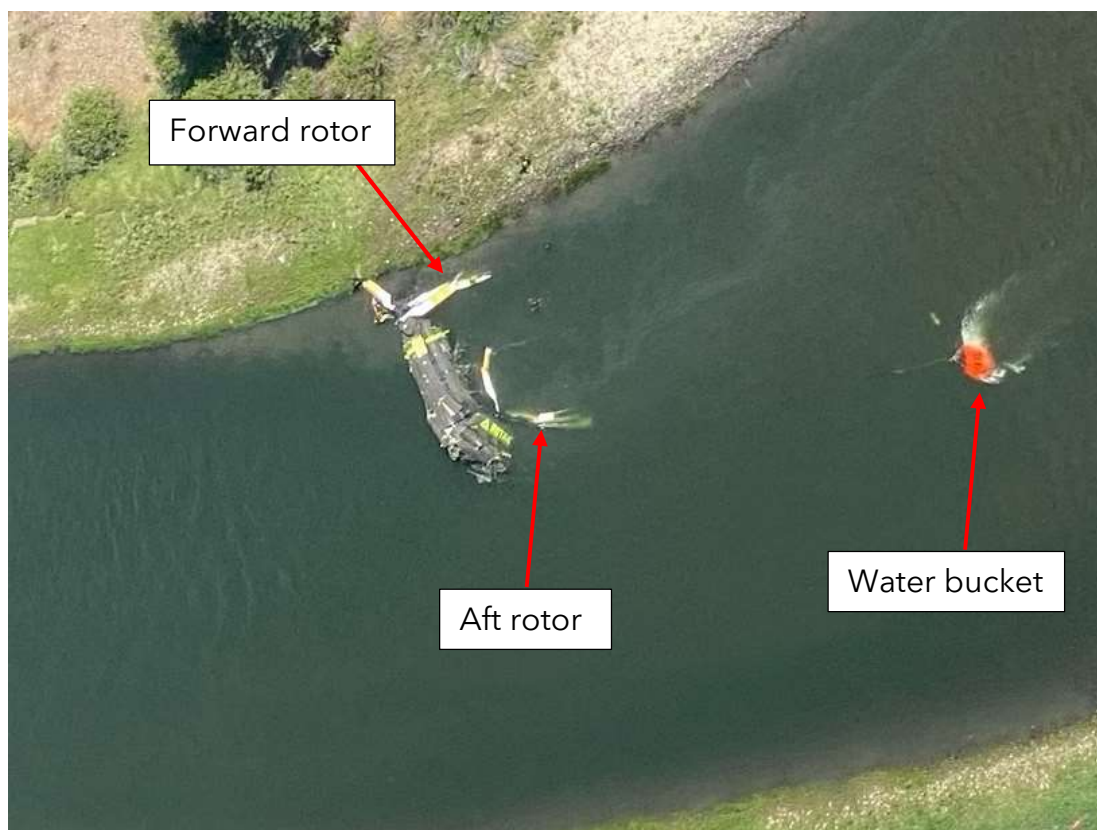


Figure 2. An aerial view of the accident helicopter. (Image courtesy of ROTAK)

Both left and right main fuel tanks were detached from the helicopter but remained with the helicopter. The forward and aft aux tanks remained attached and intact. There was no evidence of excessive fuel leakage from any of the tanks. The tanks were defueled during the recovery effort.

Both forward landing gears remained attached and upright. Both rear landing gears were present in the wreckage; the right-rear wheel was folded inward and the left-rear wheel was intact.

2.2 Rotor Systems

2.2.1 System Overview

An engine transmission is mounted at the front of each engine and contains a sprag clutch (freewheeling unit). The two engine transmissions are connected to, and power, a combining transmission. The combining transmission outputs its power to the forward and aft transmissions via synchronizing drive shafts ("sync shafts"). Additionally, three oil coolers on top of the combining transmission provides oil cooling for the Nos. 1 and 2 engine transmissions and the combining transmission.

The forward rotor system is driven by the forward transmission, the latter of which is bolted to structure directly above the cockpit. Additionally, the forward transmission powers the No. 1 hydraulic pump. The aft rotor system is driven by the aft transmission via the aft vertical shaft. The aft transmission, bolted to structure above the ramp area, also powers the Nos. 1 and 2 main generators, the No. 2 hydraulic pump, and the utility hydraulic pump.

The two rotor systems are each composed of a rotor head assembly, three rotor blades, and a swashplate assembly. The rotor blades are composed of a fiberglass D-shaped spar, a Nomex honeycomb core afterbody covered in a fiberglass skin, a titanium leading edge, and a nickel erosion tip cap. The three rotor blades are identified by color, presented in the order of advancing rotation: "green", "yellow", and "red". Hinges allow for the blade to lead-lag and flap, with dampers to limit the amount and rate of lead-lag movement. A pitch-varying shaft and housing assembly (a spindle and sleeve design) allows the blade to rotate around its pitch axis.

2.2.2 Rotor Transmission Systems

Both the forward and aft rotor transmissions and the combining gearbox remained installed on the airframe. The forward rotor transmission was above the surface of the water and its sight gauge showed a full oil fluid level. The aft rotor transmission came to rest on its right side, along with the aft pylon, and was submerged in the water until recovery. The oil filter bowl and element were not present on the aft transmission, but a portion of the filter bowl mount remained attached on the aft transmission. The forward rotor transmission mast and the aft rotor transmission vertical driveshaft remained attached and did not exhibit significant damage.

The Nos. 1 thru 7 sync shafts remained installed along top of the fuselage (within the tunnel). The No. 1 sync shaft remained connected to the forward transmission. The No. 7 sync shaft remained connected to the combining gearbox quill shaft, but this quill shaft was separated from the combining gearbox. The Nos. 8 and 9 sync shafts aft of the combining gearbox were present but exhibited rotational gouges due to contact with adjacent structure during ground impact.

The No. 2 engine-to-transmission driveshaft remained attached to No. 2 engine gearbox but was separated at its splined connection at the combining gearbox. The No. 2 engine gearbox fairing was present and not shattered, but the foreign object debris (FOD) screen was not present nor recovered. The No. 2 engine-to-transmission driveshaft exhibited rotational scoring on its exterior. This driveshaft rotated when the No. 2 engine power turbine was rotated.

The No. 1 engine-to-transmission driveshaft was present. Because the No. 1 engine power turbine could not be manually rotated, the No. 1 engine-to-transmission driveshaft was not rotated. No. 1 engine gearbox remained installed on the engine. The No. 1 engine gearbox fairing and FOD screen were both installed and did not exhibit significant damage.

2.2.3 Forward Rotor System

The three rotor blades remained attached to the forward rotor head but exhibited fragmentation on their outboard ends due to impact with the ground and water. All three dampers were present, but the 'green' and 'red' dampers were separated on the blade side. All three pitch links remained connected between their respective pitch horns and the rotating swashplate. The rotating drive arm remained installed between the rotor shaft and rotating swashplate. The swashplate and its spherical bearing (uniball) remained installed on the rotor shaft and exhibited no anomalous damage.

2.2.4 Aft Rotor System

The three rotor blades remained attached to the aft rotor head but exhibited fragmentation on their outboard ends due to impact with water. All three dampers were present, and each were impact separated on the blade side. All three pitch links remained connected between their respective pitch horns and the rotating swashplate. The rotating drive arm remained installed between the rotor shaft and rotating swashplate, but the rotating drive arm was jammed at the full upward position, contacting the rain shield due to travel of the uniball (along its slider) beyond its upper stop. The swashplate and uniball remained installed on the rotor shaft and exhibited no anomalous damage.

2.3 Flight Control System

2.3.1 System Overview

For each pilot, the cockpit flight control system contains a cyclic control, a thrust (collective) lever, and pedals. The left and right pilot seat controls are interconnected and are routed underneath the cockpit floor. The pedals in each pedal set can be individually adjusted fore and aft by pressing a lever mounted on the pedal support and moving the pedal to a new position. Each pedal is adjustable to five positions, with "1" as the aft-most position, "3" as the middle position, and "5" as the forward-most position.

Cockpit control inputs by the pilot are transmitted to the transfer bellcranks, which provide control inputs to two control pallets (pitch/roll pallet and yaw/thrust pallet) as well as the ILCAs, one each for pitch, roll, yaw, and thrust. Depending on the control axis, a pallet may contain balance and centering springs, viscous

dampers, and magnetic brakes. On the yaw/thrust pallet, the yaw controls contain a viscous damper, a magnetic brake, a centering spring, a balance spring, and a control position transducer. The pitch/roll pallet, yaw/thrust pallet, and the four ILCAs are located in the flight control closet located behind the left seat pilot (**Figure 3**)

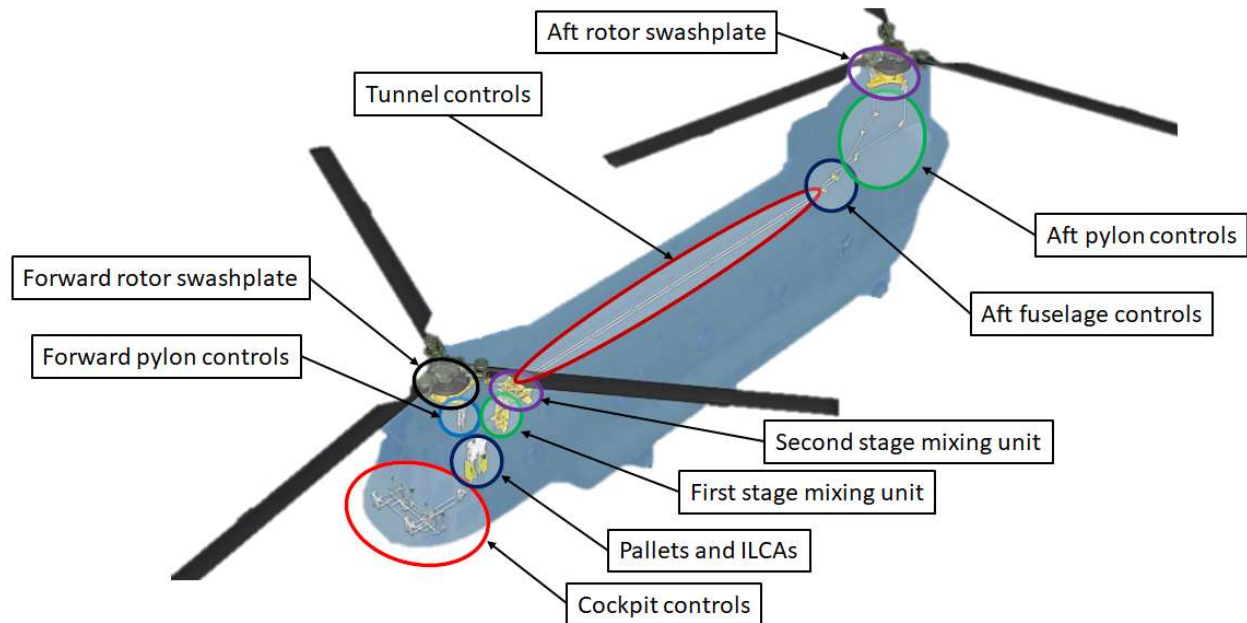


Figure 3. A diagram of the major areas of the flight control system in the helicopter.
(Image courtesy of Columbia Helicopters and edited by the NTSB)

The ILCAs provide hydraulic assistance to the flight controls, prevent control feedback to the cockpit controls, and have an integrated stability augmentation system (SAS) actuator called the extensible link. The ILCAs are designed to operate at a pressure of 1,500 pounds per square inch (psi). Generally, each ILCA is composed of two identical actuators that share a common output piston. The ILCAs, are mounted vertically, with the No. 1 hydraulic system powering the upper half of the ILCA and the No. 2 hydraulic system powering the lower half of the ILCA. On each ILCA, jam indicators are present for each side independently powered by a hydraulic system, with extension of the jam indicator occurring when a jam is detected in the actuator control valve.

The output from all four ILCAs is combined via the first stage mixing unit. The output from the first stage mixing unit provides control inputs to the second stage mixing unit. The output of the second stage mixing unit provides control inputs to the swiveling UBAs and pivoting UBAs of the forward and aft rotor systems. The UBAs are hydraulically powered, operating at 3,000 psi, and move the swashplate and slider assembly. Each UBA is composed of two hydraulically actuated pistons that share a common housing and a common connection point to the stationary swashplate. One piston is powered by the No. 1 hydraulic system and the other piston is powered by the No. 2 hydraulic system. On each UBA, jam indicators are present for each side

independently powered by a hydraulic system, with extension of the jam indicator occurring when a jam is detected in the actuator control valve.

Each rotor system contains a swiveling UBA and a pivoting UBA that controls the swashplate and slider assembly. On the forward rotor system, the swiveling UBA is on the left side of the swashplate and the pivoting UBA is on the right side of the swashplate. On the aft rotor system, the swiveling UBA is on the right side of the swashplate and the pivoting UBA is on the left side of the swashplate. Movement of the swashplate will change the rotor systems' cyclic pitch for helicopter roll control, via synchronized lateral tilt of the swashplates, and helicopter yaw control, via differential lateral tilt of the swashplates. Movement of the slider will change the rotor systems' collective pitch for helicopter pitch control, via differential thrust, as well as lift and propulsive force, via synchronized thrust.

The helicopter has an automatic flight control system (AFCS) that includes features such as rate damping in all axes and several autopilot modes (as airspeed hold, altitude hold, heading hold, and pitch and roll attitude hold). Each cyclic grip contains a thumb-actuated AFCS trim switch as well as a trim release button, also called a centering device release switch. A toggle-type trim release switch, located on the center console and protected with a guard, allows for continuous operation with the magnetic brakes released without the need to hold the trim release button on the cyclic grip. The LCT actuators, part of the AFCS, reduces fuselage nose-down attitude as forward airspeed is increased by applying longitudinal cyclic pitch input to the swashplate. Each rotor system has one LCT installed under, and connected to, their respective swashplate.

2.3.2 Cockpit Flight Controls

Both pilot's (left seat) and copilot's (right seat) cyclic controls remained attached and connected to their mounts. The copilot's cyclic control was partially fractured at its base. Manual movement of the pilot's cyclic control resulted in a corresponding movement of the copilot's cyclic control in both lateral and longitudinal axes. Additionally, manual movement of the pilot's cyclic control resulted in movement of the longitudinal control tubes that route to the transfer bellcranks, but the longitudinal control tubes were fractured near their aft end. However, the aft end of the longitudinal control tubes remained connected to the transfer bellcranks via their rod ends. Both the pilot's and copilot's cyclic control grips remained installed on their respective cyclic controls.

Both the pilot's and copilot's thrust levers were present in the cockpit structure. The pilot's thrust lever remained connected to its bellcranks but the bellcrank was impact separated from the airframe. The pilot's thrust lever grip was whole, but its buttons were damaged during recovery of the wreckage. Manual movement of the pilot's thrust lever resulted in a corresponding movement of the copilot's thrust lever

as well as movement of the longitudinal control rod going to the transfer bellcranks. However, the longitudinal control rod was fractured near its forward end as well as near its aft end, but the central portion of the longitudinal control rod was not present. The copilot's thrust lever grip and switches were crushed downward.

The pilot's pedal set was present but both left and right pedals were not connected to their respective pedal position adjustment plates, therefore movement of the left and right pedals did not result in a corresponding movement of both pedal jackshafts (**Figure 4**). All pedal position adjustment plate stops were present on the pilot pedal set. The right pedal position lever had moved beyond its limit and was pointed to the aircraft left direction. The left pedal position lever had no anomalous damage. Both pedal return springs remained installed. Both left and right brake levers remained installed, and all brake lines remained attached. Movement of the pilot's pedal position adjustment plates resulted in a corresponding movement of the copilot's pedal set as well as the longitudinal control rod leading to the transfer bellcranks. The lateral interconnect control rod between the pilot's and copilot's pedals remained connected but was deformed upward about mid-length.

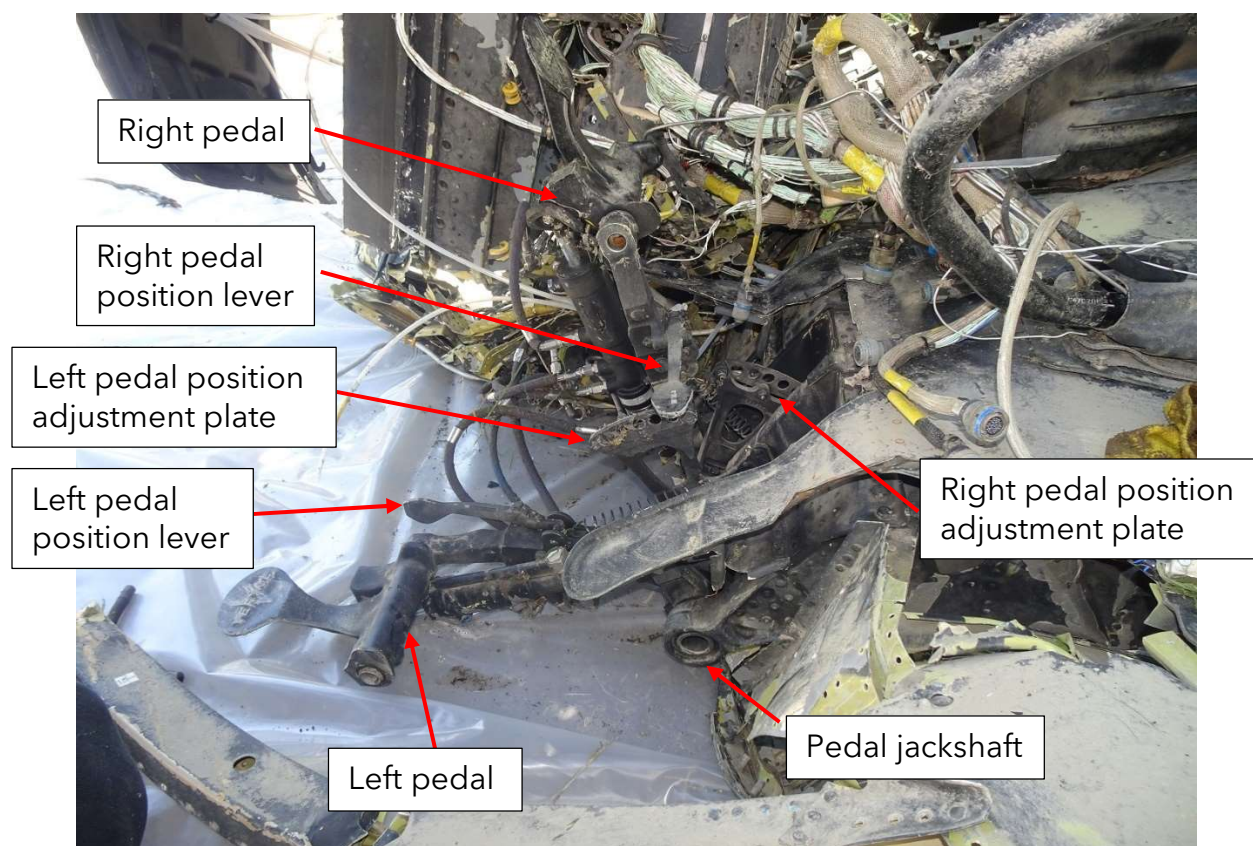


Figure 4. The pilot's pedal set.

The copilot's pedal set was present, and both remained connected to their respective pedal position adjustment plates (**Figure 5**). The left pedal was in the "5"

position and the right pedal was in the "3" position. The left pedal position lever was intact. The right pedal position lever was fractured near its base. Both left and right brake levers remained installed, and all brake lines remained attached. The right pedal shaft support, attaching to the airframe, had separated from the airframe but remained attached to the right pedal jackshaft with all rivet heads present on the support. The left pedal control rod, connecting to the left side of the left pedal jackshaft, had separated from its control tube, the latter of which remained installed.

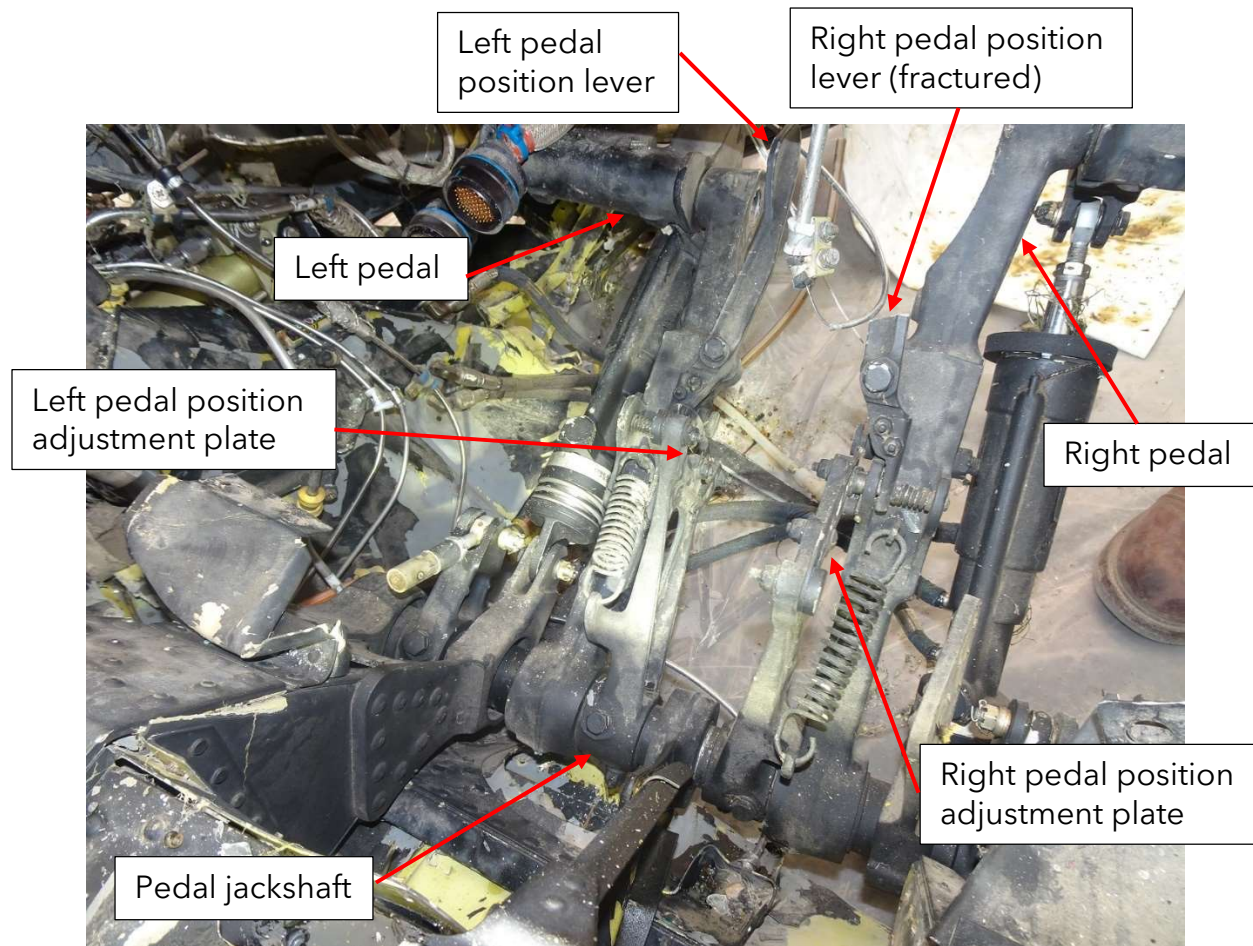


Figure 5. The copilot's pedal set.

The yaw control rod was continuous from the left-side bellcrank to its transfer bellcrank, below the ILCAs. The thrust control rod was fractured, and its mid-section was not present, but the two ends remained connected between the cockpit bellcrank and the thrust transfer bellcrank. All four transfer bellcranks moved freely and were not seized. On the yaw/thrust pallet, the yaw magnetic brake, yaw viscous damper, and yaw centering control spring remained installed. Manual movement of the yaw centering spring revealed no evidence of restriction in both directions of

travel. The yaw magnetic brake's clevis was in the up position, consistent with a cockpit left pedal forward position (**Figure 6**).²

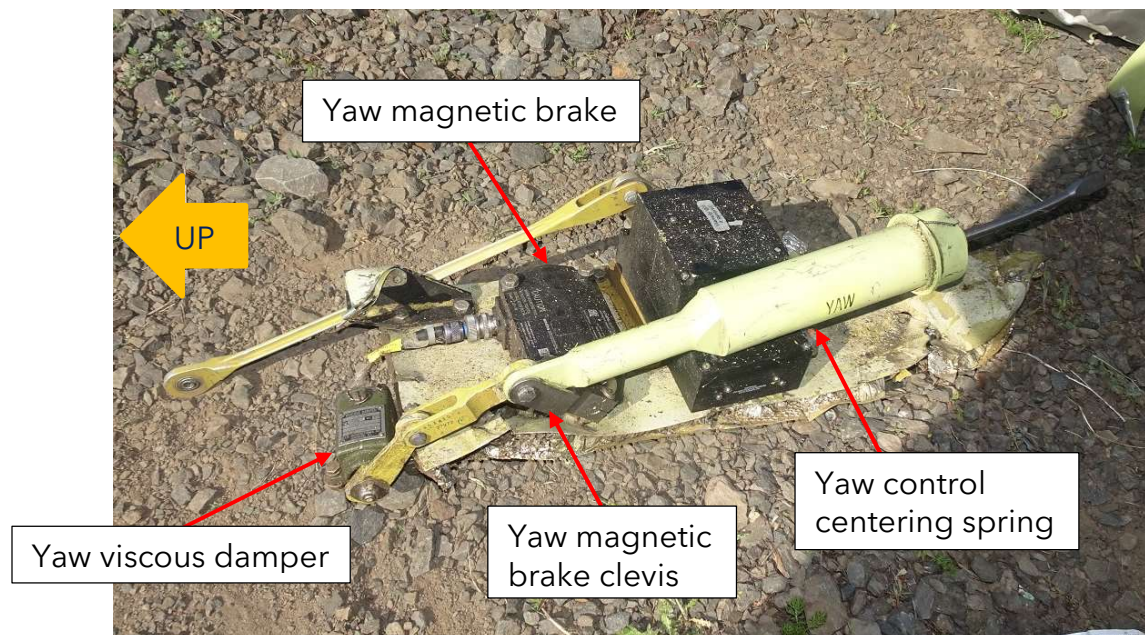


Figure 6. The thrust/yaw pallet removed from the wreckage.

2.3.3 ILCAs

The transfer bellcrank remained attached to remnant structure but was found separated in the airframe behind the cockpit. All rod ends remained connected to the transfer bellcrank, but their control tubes had fractured and separated. The pitch/roll and yaw/thrust pallets had separated from the airframe, but the pallet components were present in the wreckage behind the cockpit.

The pitch, roll, yaw, and thrust ILCAs remained installed in their normal positions within the flight control closet (**Figure 7**). The output rod for the pitch ILCA was separated, but the remaining output rods remained connected. All hydraulic lines remained connected to the ILCA manifold. The yaw No. 2 jam indicator had extended. The thrust No. 1 jam indicator had extended. All other ILCA jam indicators were not extended. The connecting rods and levers between the ILCA output to the first stage mixing unit were continuous and intact.

² When the trim release is activated, electrical power releases the magnetic brake, allowing the pilots to reposition the flight controls; low forces are needed to move the cockpit flight controls. When the trim release is not activated, the magnetic brake is engaged, and the forces required to move the cockpit flight controls increase due to the need to overcome the centering control spring.

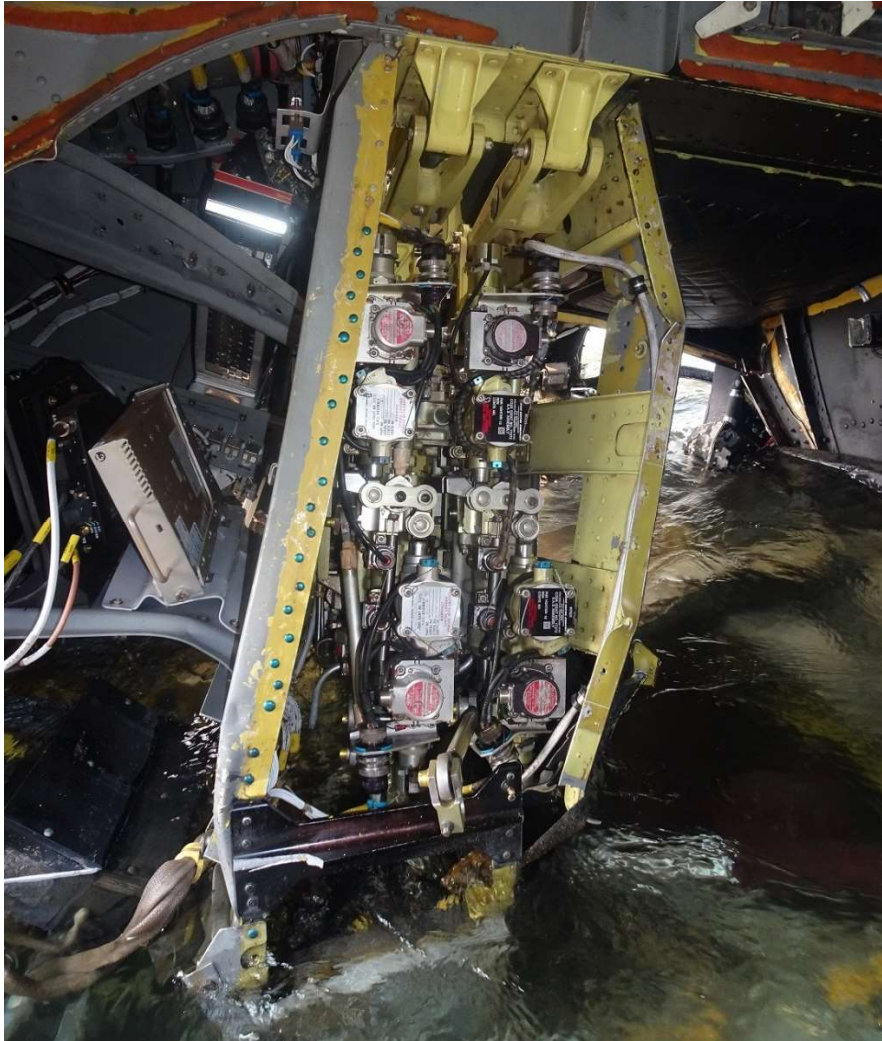


Figure 7. The pitch (right) and roll (left) ILCAs installed in the flight control closet. The yaw and thrust ILCAs are forward of the pitch and roll ILCAs.

2.3.4 Flight Control Linkages and Mixing Units

The two mixing units remained installed on the airframe (**Figure 8**). All linkages from the first stage mixing unit to the second stage mixing unit remained connected and intact except for the left yaw/right roll control rod. The left yaw/right roll control rod was fractured at its forward rod end, behind the rod end threads, but remained connected the aft rotor control bellcrank via its aft rod end; the forward rod end remained connected to the first stage mixing unit. The left yaw/right roll control rod exhibit signatures consistent with overload at its threads. The aft rotor control bellcrank was found swiveled aft beyond its aft control stop and the two aft rotor control rods (routed through the tunnel) had impacted its adjacent hydraulic lines. The aft stop was fractured and separated from the airframe and had pivoted upward from its normally installed location. The aft stop was pushed through its installation bore, resulting in the two forward jam nuts moving to the underside of the bolt head.

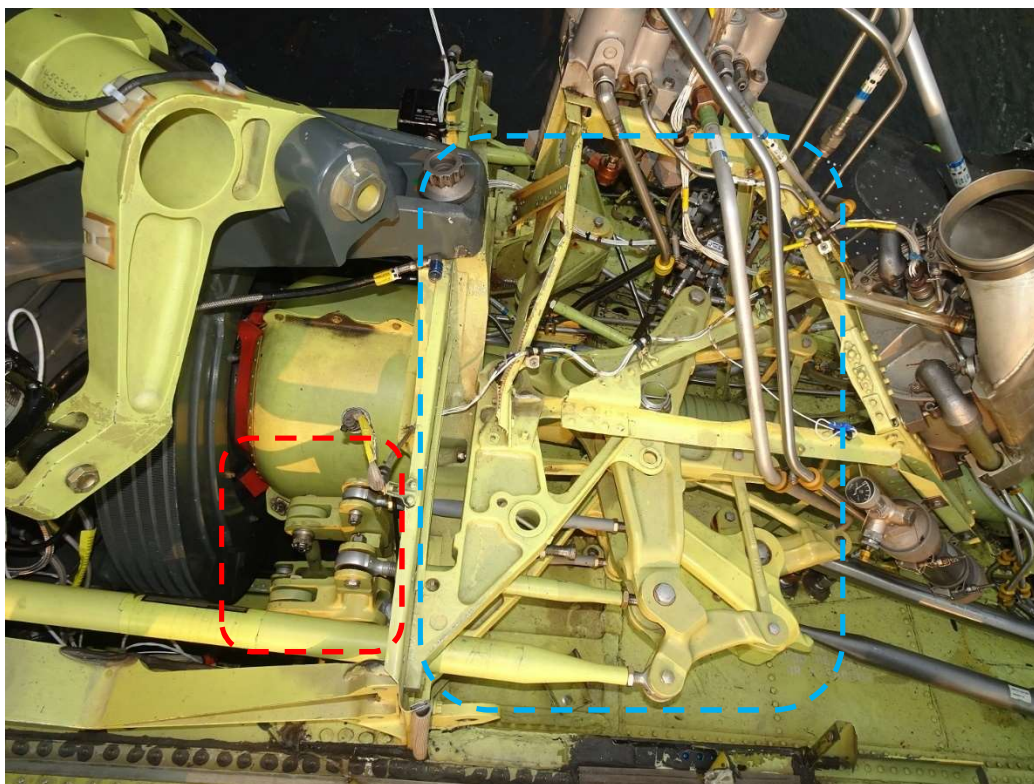


Figure 8. The upper portion of the first stage mixing unit (red dashed box) and the second stage mixing unit (blue dashed box).

All control linkages from the second stage mixing unit to the forward UBAs remained connected and intact. The two aft rotor control rods remained connected and intact from its forward-most attachment points to the aft fuselage idler bellcranks. All idlers and walking beams within the tunnel remained installed and intact. The aft fuselage bellcrank, leading to the aft swiveling UBA, was fractured at its large bore, but the control rod ends remained connected on both sides.

Once the two aft rotor control rods (routed through the tunnel) were disconnected at its forward-most connecting point, the aft rotor control bellcrank moved freely with no evidence of binding. All aft rotor controls remained connected from the aft fuselage bellcranks back to each UBA input valve. The lateral bellcrank for the aft swiveling UBA, near the combining gearbox was fractured in overload. The vertical bellcrank for the aft swiveling UBA, on the right side of the aft transmission, remained attached to a piece of airframe but this piece was separated from the airframe in overload. The aft rotor control bellcranks for the aft-left rotor UBA remained installed.

2.3.5 Forward Rotor Actuators

The forward rotor UBAs remained installed between the airframe and swashplate, and their exteriors appeared undamaged (**Figure 9**). For the pivoting UBA, both jam indicators were not extended. For the swiveling UBA, both jam indicators were extended. All hydraulic lines to the forward swiveling and pivoting UBAs remained installed.

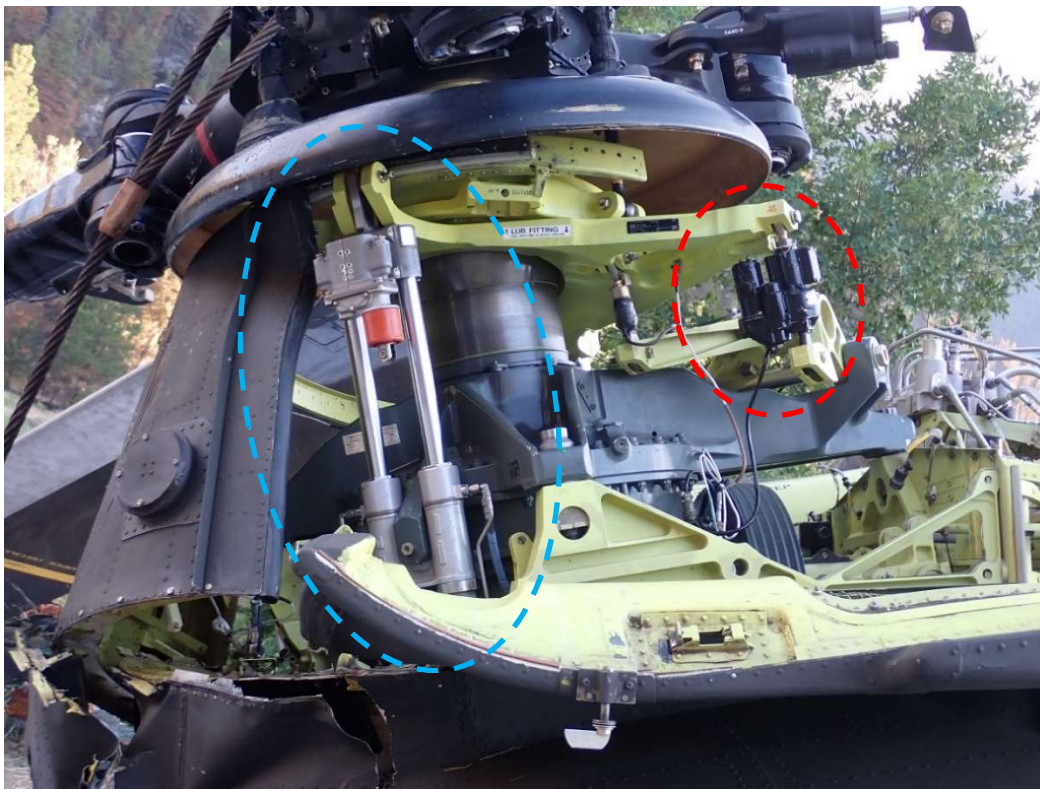


Figure 9. The forward rotor's swiveling UBA (blue dashed circle) and LCT (red dashed circle). The pivoting UBA is obscured in this view. (Image courtesy of Honeywell)

The input linkage for both of the forward UBA pilot valve were disconnected. On the pivoting UBA, the Nos. 1 and 2 pressure ports had no residual fluid when those fittings were removed. On the pivoting UBA, the Nos. 1 and 2 return ports contained residual fluid when those fittings were removed, with the fluid quantity was about the same for both. On the swiveling UBA, the No. 1 return port only contained a couple of drops of fluid when the fitting was removed while the No. 2 return port contained no residual fluid. On the swiveling UBA, both Nos. 1 and 2 pressure ports contained no residual fluid when those fittings were removed.

The forward LCT remained installed between the forward stationary swashplate and its bellcrank and its exterior exhibited no damage. The forward LCT yoke and its fixed link remained installed with no evidence of anomalous damage.

2.3.6 Aft Rotor Actuators

The aft rotor UBAs remained installed between the airframe and swashplate (**Figure 10**). The pivoting UBA was underwater but was visible and appeared to be fully extended. The swiveling UBA was not visible while the helicopter remained in the water. After the wreckage was recovered, the aft rotor UBAs' piston extension was measured. The pivoting UBA piston had a 11.75-inch extension with silt present on 10.5 inches of the extended piston. The swiveling UBA piston had a 9-inch extension with silt present on about 7.75 inches of the extended piston. All jam indicators on the two aft UBAs were extended. The pivoting UBA pressure line for the No. 1 hydraulic side was removed and there was no residual fluid; the No. 2 hydraulic pressure side was removed and there was some residual fluid. The pivoting UBA No.1 hydraulic return line was removed and there was water and hydraulic fluid that came out of it; the No. 2 hydraulic return line was removed and only hydraulic fluid came out.



Figure 10. The aft rotor's swiveling UBA (blue dashed circle) and the upper portion of the pivoting UBA (red dashed circle). (Image courtesy of Honeywell)

The input linkage to the pivoting UBA pilot valve was disconnected. The pivoting UBA was compressed to facilitate its removal from the wreckage. During piston compression, residual hydraulic fluid came out of the Nos. 1 and 2 return ports, with more fluid coming out of the No. 2 side than the No. 1 side.

The pressure-side lee plugs on the swiveling UBA were not present. The swiveling UBA hydraulic lines were removed. The No. 1 pressure line was removed and had no residual fluid. The No. 2 pressure line was removed and had a little residual fluid within its cap. The No. 1 return line was removed and there was no residual fluid. The No. 2 return line was removed and residual fluid came out. When the swiveling UBA piston was compressed, residual hydraulic fluid came out of both the Nos. 1 and 2 return ports, with qualitatively more fluid coming out of the No. 2 port.

The aft LCT was submerged in the water due to the aft pylon resting on its right side. The aft LCT remained connected on both ends to the aft stationary swashplate and its yoke, but the lower portion of the LCT housing was fractured. The fixed link remained installed. A small gear and bearing were found on the transmission upper deck below the aft LCT. An internal wire bundle was present and holding the two halves of the aft LCT together.

2.4 Hydraulic Systems

2.4.1 System Description

The CH-47D is equipped with three independent hydraulic systems. The Nos. 1 and 2 systems provide hydraulic boost to the flight control system. The Nos. 1 and 2 hydraulic systems are identical in design and operate in parallel at 3,000 psi.³ Each system contains a power control module (PCM) that is composed of pressure-operated valves, an accumulator, and filters for both the pressure-line and return-line. The No. 1 hydraulic pump, driven by the forward transmission, provides hydraulic pressure to the No. 1 hydraulic system. The No. 2 hydraulic pump, driven by the aft transmission, provides hydraulic pressure to the No. 2 hydraulic system.

The utility system provides hydraulic boost to additional helicopter systems, including the wheel brakes, power steering actuator, ramp actuating cylinders, and cargo hook actuator. The utility system's PCM contains multiple solenoid and pressure-operated valves and provides filtration of the hydraulic pressurized hydraulic fluid. When the auxiliary power unit (APU) is running, the utility hydraulic system is pressurized by an APU-driven hydraulic pump. When the APU is not running and the rotor systems are turning, the utility hydraulic system is pressurized by a hydraulic pump driven by the aft transmission.

2.4.2 No. 1 Hydraulic System

The PCM remained installed on the airframe. The No. 1 hydraulic system accumulator gauge showed a charge of 1,400 psi. The pressure from this accumulator was relieved to accommodate removal of the pressure and return filters

³ The hydraulic pressure is reduced to 1,500 psi for the ILCAs.

for the No. 1 hydraulic system. Both pressure and return filters were removed and no evidence of clogs were observed within the filter elements. The two filter bypass indicators and the pump impending bypass indicator were not extended. Both filter bowls contained residual hydraulic fluid that had a clean, reddish-colored appearance, and no significant debris was observed within the filter bowls. The reservoir/cooler's fluid level indicator was extended about 1.5 inches.

The power transfer unit (PTU) remained installed on the airframe and its hydraulic lines remained connected. The No. 1 hydraulic pump was removed from the forward transmission and its splined connection exhibited no anomalous damage.

2.4.3 No. 2 Hydraulic System

The PCM remained installed on the airframe. The No. 2 hydraulic system accumulator gauge showed a charge of 1400 psi. The two filter bypass indicators and the pump impending bypass indicator were not extended. Removal of both the pressure and return filters showed no evidence of clogs or significant debris. Both pressure and return filter bowls contained residual hydraulic fluid that had a clean, reddish-color appearance. The reservoir/cooler's fluid level indicator was extended about 5 inches.

The PTU remained installed on the airframe and its hydraulic lines remained connected. The No. 2 hydraulic pump was removed from the aft transmission and its splined connection exhibited no anomalous damage.

2.4.4 Utility Hydraulic System

None of the jam indicators on the PCM were extended. The utility accumulator was at 1,200 psi. The start accumulator and start module pressure gauges showed about 3,000 psi. Both were discharged by the investigation team. The reservoir's fluid level indicator was extended about 5 inches. The cargo hook pressure gauge showed about 1,000 psi. The utility pump jam indicator housing was fractured. The APU utility pump was removed to facilitate removal of the APU and the pump splines exhibited no anomalous damage.

2.5 Powerplants

2.5.1 Engine Overview

The Honeywell T55-GA-714A is composed of an air intake, a 7-stage axial compressor, a single-stage centrifugal compressor (impeller), a reverse-flow annular combustor, a 2-stage gas producer turbine, and a 2-stage power (free) turbine. The power turbine shaft drives the power output shaft that is connected to the engine transmission via a quill shaft. A tail cone exhaust is mounted to the rear of the engine.

Each engine is equipped with an ECU, part of a full authority digital engine control (FADEC) system, which has a primary channel and a reversionary backup channel.

2.5.2 No. 1 Engine

The left engine remained installed in the airframe. The left engine was not submerged in the water. No damage was noted on the exterior of the engine. The FOD screen was removed to access the compressor. The first compressor was intact and appeared undamaged (**Figure 11**). The gas producer section rotated without resistance.



Figure 11. A view of the first stage compressor blades from the No. 1 engine. (Image courtesy of Honeywell)

Looking through the exhaust, the second stage power turbine blades appeared intact and undamaged. Metal spray was observed on the second stage power turbine nozzle. The power turbine was unable to be manually rotated. The exhaust exhibited impact damage primarily on its underside and was bent upward and to the left. The oil filter bypass indicator was not able to be visually accessed. The oil quantity indicator showed empty.⁴ The No. 1 engine ECU was removed and retained for further examination.

⁴ The accuracy of the oil quantity indicator float is dependent on the orientation of the engine.

2.5.3 No. 2 Engine

The right engine remained installed in the airframe. The right engine was submerged in the water due to the aft pylon resting on its right side. The engine exterior was intact and appeared undamaged except one starter bolt was sheared. The FOD screen was not present on the right engine. The exhaust was bent upward and to the left. Corrosion was present on several bolt heads on the exterior of the engine. Multiple first stage compressor blades were bent in the direction opposite of normal rotation, with one blade separated at its root (**Figure 12**). The first stage stators were not present. The second stage compressor blades were bent in the direction opposite of normal rotation. The second stage compressor blades exhibited leading edge and tip damage whereas the first stage compressor blades had primarily tip damage. The second stage stator exhibited leading edge damage. The gas producer section was unable to be rotated by hand.



Figure 12. A view of the first stage compressor blades from the No. 2 engine. (Image courtesy of Honeywell)

The airframe exhaust was removed to facilitate inspection of the second stage power turbine. The second stage power turbine blades were intact and earthen debris was present. A borescope was used to examine the first stage power turbine rotor and no damage was noted. Metal spray was observed on the second stage power turbine nozzle and rotor. The power turbine was able to be manually rotated with a corresponding rotation of the No. 2 engine-to-transmission drive shaft. The main chip detector was removed with no metallic debris observed. The right engine oil quantity indicator showed about $\frac{1}{4}$ full, but the float accuracy depends on the

orientation of the engine. The oil bypass indicator was extended. The oil filter housing was removed and the filter housing gasket was present. The oil filter element was removed and there was no evidence of metallic debris or clogs. Residual oil within the oil filter housing had a medium-tan color. The No. 2 engine ECU was removed and retained for further examination.

2.6 Cockpit Flight Instruments and Indicators

The instrument panel had separated from its mounts but remained partially attached to the structure. The Hobbs meter showed about 71.4 hours. On the AFCS control panel, the dial was in the "BOTH" position. The LCT select switch position could not be determined but the switch was bent to the left. The FADEC panel showed the switch for No. 1 was in the reversionary and the No. 2 was in the primary. The rotor speed (NR) dial was set at 100%. The backup power (B/U PWR) switch was in the "ON" position. Both LCT gauges remained in the cockpit and their dials were to the left of the retract box. However, the LCT gauges will rest to the left when power is removed. The cargo hook select rotary switch was in the "FWD" position and the arming switch (with "OFF", "ARM", and "MASTER RESET") was in the "ARM" position.

The flight hydraulic system selector switch was bent slightly upward but the lower portion of the switch remained in the "BOTH" position. The switch was able to be manually actuated to select the No. 1 and No. 2 hydraulic system and the switch stayed in its selected place. Both PTU switches were in the "OFF" position. (With the PTUs in the "OFF" position, the utility hydraulic system would not be providing hydraulic pressure to the Nos. 1 and 2 hydraulic system and the flight control system hydraulic components.) The caution annunciator panel, AFCS control panel, maintenance panel (located adjacent to the cargo ramp at the aft of the helicopter), left and right master caution warning lights, and the left and right command select panels were retained for bulb filament analysis. (See Section 4.0 of this report.)

3.0 Engine ECU Download

On September 20, 2022, the Airworthiness Group Chair and Honeywell Group Member convened at Triumph Engine Control Systems' facilities in West Hartford, Connecticut to recover data from the engine ECUs.

The No. 1 engine ECU data plate showed P/N 2-170-700-21 and S/N 10ANV1611. The No. 2 engine ECU data plate showed P/N 2-170-700-21 and S/N 11ANV1719.

For each ECU, the top and bottom covers were removed to examine the condition of the circuit boards. There was no evidence of damage or water ingress within the ECUs. As a precautionary measure, the ECUs were baked in an oven at 100°C (212°F) for about 1 hour to remove residual moisture within the ECUs.

Subsequently, the ECUs were removed from the oven and allowed to cool to room temperature for about 30 minutes.

Each ECU was connected to an engineering bench to download its nonvolatile memory (NVM), which included engine history data, the last engine run, the engine information, the ECU information, and cumulative faults.

For the No. 1 engine ECU, a collective pitch rate fault was detected by both the primary and reversionary channels. There was also a cross-channel fault in the ECU.⁵

For the No. 2 engine ECU, there was an inlet temperature (T1) fault that triggered an "E2 hex fault". The "E2 hex fault" was not present within the faults for the last engine run and was possibly associated with a previous flight. The remaining faults were associated with a collective pitch rate fault that was detected only by the reversionary channel.

4.0 Bulb Filament Analysis

Various panels and lights were submitted to the NTSB Materials Laboratory in Washington, District of Columbia for bulb filament analysis. Each panel was visually examined and found to be intact with limited impact-related damage. The individual annunciator lights were removed from each panel and X-rayed to determine the status of the filament inside each bulb. **Table 1** shows a list of each panel and light and the associated number of bulbs.

Table 1. The number of annunciators and their bulb quantity for the panels and lights retained for filament analysis.

Caution Annunciator Panel	64 two-bulb annunciators
AFCS Control Panel	3 four-bulb annunciators
Left Master Caution Warning Light	1 two-bulb annunciator
Right Master Caution Warning Light	1 two-bulb annunciator
Left Command Select Panel	5 four-bulb and 3 two-bulb annunciators
Right Command Select Panel	5 four-bulb and 3 two-bulb annunciators
Maintenance Panel	1 six-bulb and 4 one-bulb annunciators

No evidence of hot filament stretching was found on any of the filaments analyzed. All bulbs were intact. In the caution annunciator panel, the "L FUEL PRESS", "RECT 2", and "AFCS 2" each had one bulb (out of two bulbs per annunciator) with a broken filament. In the left command select panel, the "VOR SEL" had one bulb (out of four bulbs for this annunciator) with a broken filament. In the right command select panel, the "CMD SEL" had one bulb (out of four bulbs for this annunciator) with a broken filament. The left master caution light contained no bulbs.

⁵ A loss of power to the ECU can result in a cross-channel fault to be recorded by the ECU.

5.0 Video Study and Boeing Simulation Study

The NTSB video study of the ground witness video estimated helicopter parameters for the accident flight, including attitudes and rates as well as height above the ground. Based on these estimations, the Airworthiness Group Chair requested Boeing conduct a study using a CH-47 mathematical model (simulation) to estimate the cockpit flight control inputs that would best match the helicopter attitudes and rates estimated by the NTSB video study for the portion of the flight that included the initial left yaw (about 12-13 seconds after the start of the ground witness video). To simplify this approach, the simulation only modeled the helicopter motions and did not include the motion of the long line and water bucket. **Table 2** shows the environmental conditions used for the simulation whose values remained fixed for the duration of the simulation.

Table 2. The conditions used for the Boeing simulation study.

Pressure altitude	3,800 feet
Outside air temperature	99.0° Fahrenheit
Density altitude	7,137.5 feet
Wind magnitude	6.1 knots
Wind direction	238.0°
Gross weight	27,500 pounds
Initial altitude (AGL)	331.037 ft

Assumptions made for the simulation included no failure modes of the flight control system, both AFCS computers activated and functioning normally, the trim release remaining unactivated throughout the simulation, and cockpit controls trimmed perfectly to the positions required for the initial hover as well as centered extensible link actuator commands. The simulation's helicopter motions generally matched that of the estimated helicopter motions from the NTSB video study.

Appendix A shows the estimated cockpit flight control inputs from the simulation study.

6.0 Actuator Examinations

From August 16-18, 2022, members of the Airworthiness Group convened at Columbia Helicopters' facilities in Aurora, Oregon to examine the two LCT actuators, four ILCAs, and four UBAs that were recovered from the wreckage.

6.1 LCT Actuators

6.1.1 Forward LCT Actuator

The forward LCT actuator data plate showed P/N 541604-8-1 and S/N 33-197. The forward LCT actuator position appeared to be in the fully retracted position

(**Figure 13**). The lower rod end bearing was stiff and could not be easily moved by hand. The upper rod end bearing was able to be easily moved by hand. Prior to installation on the test bench, the limit switch resistance was measured, using an ohmmeter, to be 0.7 ohms, below the requirement of 20 ohms for when the limit switch is in the retract position and consistent with the retract limit switch being activated. The switch cover was removed and the pin and the two switch nuts [that ride longitudinally along the pin] were present. The switch nut appeared to be on the retract limit switch. Adjacent to the pin, cables coming from the braided cable assembly had a blue-colored conduit. It could not be determined if this blue-colored conduit was a cable sleeve or a splice.



Figure 13. The forward LCT actuator. (Image courtesy of Honeywell)

The forward LCT actuator was tested using the acceptance test procedures (ATP) from the Model 234 component maintenance manual with the same P/N. 28 volt (V) power was applied and when the test bench's extend and retract switch was manipulated, the actuator piston responded in the commanded direction. The results of the ATP can be found in **Attachment 1** of this report. During the Rated Load Operation test, the bench voltage was increased up to 32.2V and the voltage was read at the actuator to be about 26V. This voltage decrease was due to losses of voltage through the test bench.

6.1.2 Aft LCT Actuator

The aft LCT actuator data plate showed P/N 541604-9-1 and S/N 69-2616. The aft LCT actuator position appeared to be in the fully retracted position (**Figure 14**). The switch cover was removed and the pin and the two switch nuts were present. The switch nut appeared to be on the retract limit stop. When power from the test bench was applied to the motor, the motor began to smoke, so power was removed. The remnant wiring within the actuator was cut to facilitate partial disassembly of the

actuator to remove the fractured rod end fitting. The fracture on the acme screw side was cleaned using acetone and dried using compressed air.



Figure 14. The aft LCT actuator. (Image courtesy of Honeywell)

The partially disassembled LCT was shipped to Honeywell facilities in Phoenix, Arizona to further clean and examine the piston fracture surfaces at the Honeywell materials laboratory. Post-cleaning examination of the piston fracture surfaces under a scanning electron microscope (SEM) showed signatures consistent with overload failure. Post-cleaning examination of the gear shaft revealed no evidence of cracks or other anomalous damage.

6.2 ILCAs

6.2.1 Pitch ILCA

The pitch ILCA data plate showed P/N 145H7300-21 and S/N 0022LV (**Figure 15**). The input rod stop for actuator extension, on the center housing of the ILCA, was fractured due to impact with the control rod and lever. The crank was also fractured at its splined connection to the input rod lever, but the remnant crank remained retained within the lever. The range of motion for the output piston was limited due to the piston being bent. The actuator was installed on the test bench and the output piston was manually actuated in the retract direction to collect residual fluid from the two systems in separate jars. The fluid had a clear appearance and color consistent with military performance specification MIL-PRF-83282 hydraulic fluid. The motion of the output piston [in the retract direction] exhibited no binding or restrictions. The piston friction was measured to be 12 pounds (lbs) in the extend direction and 17 lbs

in the retract direction. The limit for piston friction was 20 lbs. An ATP of the stability augmentation system (SAS) side of the ILCA was performed, the results of which can be found in **Attachment 1** of this report. An ATP of the stick boost actuator portion of the ILCA was not able to be performed due to the bend in the output piston and the fractured crank (to which the input arm connects).



Figure 15. The pitch ILCA.

6.2.2 Roll ILCA

The roll ILCA data plate showed P/N 145H7300-25 and S/N YW3390LV (**Figure 16**). The input rod stop for actuator extension, on the center housing of the ILCA, was fractured due to impact with the control rod and lever. The control rod and lever were jammed onto this extension stop, so the lever was removed. The crank could not be manually moved to recenter it. The actuator was subsequently installed on the test bench and the output piston was manually actuated to collect residual fluid from the two systems in separate jars. The fluid had a clear appearance and color consistent with MIL-PRF-83282 hydraulic fluid. The piston friction was measured to be 16 lbs in the extend direction and 10-11 lbs in the retract direction. The limit for piston friction was 20 lbs. An ATP of the SAS side of the ILCA was performed, the results of which can be found in **Attachment 1** of this report. An ATP of the stick boost actuator portion of the ILCA could not be performed due to the shifted crank. However, with hydraulic pressure applied to the stick boost actuator, manipulation of the input lever and crank resulted in movement of the output piston that was smooth with no judder or binding.



Figure 16. The roll ILCA.

6.2.3 Yaw ILCA

The yaw ILCA data plate showed P/N 145H7300-31 and S/N 0029LV (**Figure 17**). The input rod stop for actuator extension, on the center housing of the ILCA, was fractured due to impact with the control rod and lever. The control rod and lever were jammed onto this extension stop, so the lever was removed. The crank could not be manually moved to recenter it. The actuator was subsequently installed on the test bench and the output piston was manually actuated to collect residual fluid from the two systems in separate jars. The fluid had a clear appearance and color consistent with MIL-PRF-83282 hydraulic fluid. The piston friction was measured to be 15 lbs in the extend direction and 14 lbs in the retract direction. The limit for piston friction was 20 lbs.



Figure 17. The yaw ILCA.

An ATP of the SAS side of the ILCA was performed, the results of which can be found in **Attachment 1** of this report. The return hose on the test bench had a high fluid flow rate that could indicate excessive internal leakage of the actuator. A valve jam indicator test was performed on the stick boost actuator portion of the ILCA. The No. 1 system jam indicator, which was not extended at the wreckage examination at the accident site, had extended during this test. The No. 2 system jam indicator, which was extended at the wreckage examination at the accident site, functioned normally.

6.2.4 Thrust ILCA

The thrust ILCA data plate showed P/N 145H7300-26 and S/N A0058982 (**Figure 18**). The input rod stop for actuator extension, on the center housing of the ILCA, was fractured due to impact with the control rod and lever. The actuator was installed on the test bench and the output piston was manually actuated to collect residual fluid from the two systems in separate jars. The fluid had a clear appearance and color consistent with MIL-PRF-83282 hydraulic fluid. The piston friction was measured to be 12 lbs in the extend direction and 15 lbs in the retract direction. The limit for piston friction was 20 lbs. An ATP was performed, the results of which can be found in **Attachment 1** of this report. The output piston exhibited no evidence of binding or judder with commanded actuations. During the proof pressure test, the pressure relief valve on the No. 1 system made a “pop” noise at a bench supply pressure of 1,000 psi, but the source of this sound could not be identified and there was no noticeable leakage from this relief valve.



Figure 18. The thrust ILCA.

6.3 UBAs

6.3.1 Forward Pivoting UBA

The forward pivoting UBA data plate showed P/N 145H6600-19 and S/N UR1265BAN. The UBA input cover was removed and its input screws remained installed and were found to be non-magnetic, consistent with the installation of the required stainless steel screws. The UBA was installed onto the test bench. The test bench fluid temperature gauge read about 125°F. Residual fluid from the two systems' drain ports was collected in separate jars by manually actuating the output piston. The fluid contained several black-colored flecks, with the sample from the No. 2 system containing more flecks than the sample from the No. 1 system. Both fluid samples had a clear appearance and a color typical of MIL-PRF-83282 hydraulic fluid. Select steps for the ATP of the actuator were completed, the results of which can be found in **Attachment 1** of this report. The proof pressure test was performed last in the ATP for this examination. Generally, the actuator exhibited smooth actuation with no evidence of binding, juddering, or other anomalous movement or noises.

6.3.2 Forward Swiveling UBA

The forward swiveling UBA data plate showed P/N 145H6700-19 and S/N UR1808A. The UBA input cover was removed and its input screws remained installed and were found to be non-magnetic, consistent with the installation of the required stainless steel screws. The test bench fluid temperature gauge read about 110°F. Residual fluid from the two systems' drain ports was collected in separate jars by manually actuating the output piston. The fluid from both systems contained a few black-colored flecks, but otherwise had a clear appearance and a color typical of MIL-PRF-83282 hydraulic fluid. Select steps for the ATP of the actuator were completed, the results of which can be found in **Attachment 1** of this report. The proof pressure test was performed last in the ATP for this examination. Generally, the actuator exhibited smooth actuation with no evidence of binding, juddering, or other anomalous movement or noises.

6.3.3 Aft Pivoting UBA

The aft pivoting UBA data plate showed P/N 145H6600-20 and S/N UR1908AS. The UBA input cover was removed and its input screws remained installed and were found to be non-magnetic, consistent with the installation of the required stainless steel screws. The UBA was installed onto the test bench. The test bench fluid temperature gauge read about 120°F. Residual fluid from the two systems' drain ports was collected in separate jars by manually actuating the output piston. The fluid had a clear appearance and a color typical of MIL-PRF-83282 hydraulic fluid. Select steps for the ATP of the actuator were completed and the results can be found in **Attachment 1** of this report. The proof pressure test was performed last in the ATP

for this examination. Generally, the actuator exhibited smooth actuation with no evidence of binding, juddering, or other anomalous movement or noises.

6.3.4 Aft Swiveling UBA

The aft swiveling UBA data plate showed P/N 145H6700-18 and S/N UR1805SA. The UBA input cover was removed and its input screws remained installed and were found to be non-magnetic, consistent with the installation of the required stainless steel screws. The UBA was installed onto the test bench. The test bench fluid temperature gauge read about 120°F. When manually actuating the piston, residual fluid composed of a mix of hydraulic fluid and water came out from the pressure-side lee plugs⁶ bores from both Nos. 1 and 2 systems; the pressure-side lee plugs were not present. For both the Nos. 1 and 2 lee plug bores, a 0.219-inch diameter gauge pin could be inserted into them, but a 0.220-inch diameter gauge pin could not, which met the drawing requirement and was consistent with a non-oversized lee plug bore.

Replacement lee plugs, P/N 2180010A, were installed and the piston was manually actuated again to collect the remaining fluid from the drain ports. The remaining fluid was a mixture of hydraulic fluid and water. Subsequently, an ATP of the actuator was completed, the results of which can be found in **Attachment 1** of this report. The proof pressure test was performed last in the ATP for this examination. Generally, the actuator exhibited smooth actuation with no evidence of binding, juddering, or other anomalous movement or noises.

7.0 Detailed Examination of the Yaw ILCA

7.1 CT Scan

From October to November 2022, the yaw ILCA was scanned using CT to document the internal condition of the actuator prior to disassembly. The CT imaging showed a crack on the outer sleeve near the No. 1 side of the ILCA. Additional details of the CT imaging can be found in the Computed Tomography Specialist Report in the docket for this investigation.

7.2 Teardown Examination

On March 21, 2023, members of the Airworthiness Group convened at Columbia Helicopters' facilities in Aurora, Oregon to conduct a teardown examination of the yaw ILCA.

⁶ The lee plug normally installed should be a 218-series short PLGA Class 2 plug, P/N 2180010A. Proof pressure for this plug is 9,000 psi.

The safety wiring was removed throughout the actuator for the purposes of disassembly. The torque of the fasteners securing the authority covers to their respective housings were checked and all four fasteners on each authority cover moved below the required 25 inch-pounds (in-lbs). The torque for the fasteners securing the extensible links to the body were checked and the No. 1 lower-inboard and the No. 2 lower-outboard bolts moved slightly (about 1/8 turn) below the required 45-55 in-lbs, but the remainder met the required torque of 45-55 in-lbs. The fasteners connecting the extensible link pistons to the center crank did not exhibit looseness.

The Nos. 1 and 2 extensible links were removed from the yaw ILCA. The pressure and return ports had evidence of residual hydraulic fluid but no anomalous damage or clogs were present.

The control rod and lever remained installed. The torque for the nuts for the piston clevis ends were checked and met the required torque. The splines for the piston clevis ends did not exhibit anomalous damage. The tie rod was removed from the piston and its splines did not exhibit anomalous damage aside from the clevis ends which exhibited a circumferential witness mark about where the tie rod splines mate to the clevis end splines.

On the No. 2 side, the forward-inboard and forward-outboard castellated nuts had no torque (the required torque is 15-20 in-lbs). On the No. 2 side, the aft-inboard and aft-outboard nut torque were checked and met the required torque. For the forward fasteners between the center housing and the Nos. 1 and 2 housings, the forward-upper fastener exhibited about a 1/8 turn and forward-lower fastener exhibited about a 1/4 turn. The torque for the three bolts for the cam cover all turned below the required torque value (20-25 in-lbs), about a 1/8 turn loose.

The cam cover was removed and residual hydraulic fluid was present; the fluid was collected. The pin on the center housing that contacts the No. 1 sleeve was present and contacting the sleeve. The outer sleeve exhibited a crack near the No. 1 side, which was consistent with the anomaly found in the CT scan (**Figures 19 and 20**). The cam was removed and exhibited an impact mark on the cam arm in a location that would contact the crack on the outer sleeve (**Figure 21**). An overtravel of the cam in the direction of the actuator extension stop (where the stop was fractured) could result in the impact mark between the cam arm and the outer sleeve. The cam bearing was manually rotated and exhibited ratcheting and did not exhibit smooth rotation; however, the bearing could be rotated and was not seized. The bearing on the cam cover plate was manually rotated and its rotation had a slight ratcheting feel but did not exhibit restriction or seizure.



Figure 19. The crack (red arrow) as seen on the outer sleeve after removal of the cam cover.

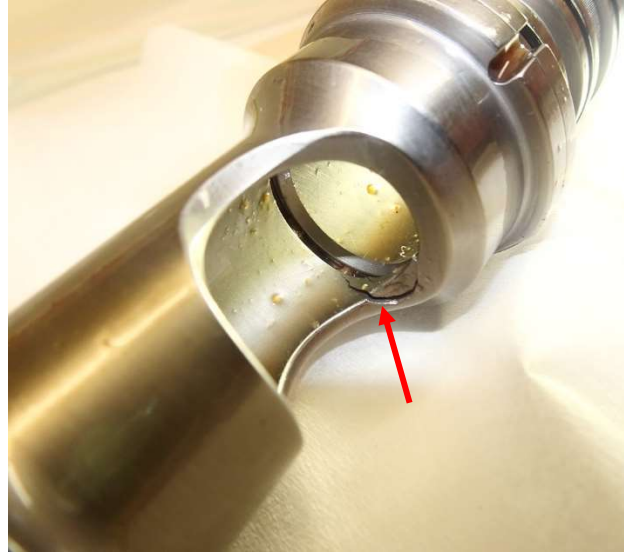


Figure 20. The crack (red arrow) on the outer sleeve of the yaw ILCA.



Figure 21. The red arrow points to the impact mark on the cam of the yaw ILCA.

The end gland bolts on both sides of the piston were torque checked. The lower-outboard-aft bolt met the required torque, but the remaining bolts did not meet torque. In order to remove the tapered pin, installed between the Nos. 1 and 2 housings and the center housing, heat was applied to the housing and the pin was tapped out. The pin was whole and exhibited no evidence of camming or other anomalous damage.

The No. 2 housing was removed, revealing the No. 2 side of the outer sleeve. All O-rings were present, and they did not exhibit anomalous damage. No anomalous damage was present on the outer sleeve and the No. 2 housing's outer sleeve bore. The center housing was removed and the pin, adjacent to the spanner nut on the No.

1 side, was present and did not have anomalous damage. The spanner nut for the No. 1 sleeve-to-housing was checked and met the required torque of 180 in-lbs. The outer sleeve was removed from the No. 1 housing, revealing the No. 1 side of the outer sleeve. All O-rings on the No. 1 side of the outer sleeve were present and did not exhibit anomalous damage. The alignment pin for the outer sleeve was located at the 12 o'clock position of the sleeve bore.

The Nos. 1 and 2 inner sleeves and spools were removed from the outer sleeve. The inner sleeves and their spools did not exhibit anomalous damage (**Figure 22**). White-colored material was observed within the inner diameter of the No. 1 side of the outer sleeve as well as the center housing (**Figure 23**). The white-colored material was collected for further evaluation.

The Nos. 1 and 2 inner sleeves were examined and exhibited no anomalous damage. The electrical discharge machined (EDM) slots on both Nos. 1 and 2 inner sleeves were examined and had no evidence of clogs or obstructions. The Nos. 1 and 2 spools showed no evidence of anomalous damage.

The Nos. 1 and 2 output pistons were removed from their respective housings. No anomalous damage was observed on the two pistons shafts and the piston heads. There was no evidence of anomalous damage on the inner and outer glands from both the Nos. 1 and 2 housings.



Figure 22. The spools and sleeves from the two systems of the yaw ILCA.



Figure 23. The white-colored material (red circle) observed within the No. 1 side of the outer sleeve of the yaw ILCA.

The inner diameter of the outer sleeve, with both inner sleeves and the spool removed, was rinsed with alcohol and the liquid was collected to filter the debris present within the outer sleeve. The inner surfaces of the center housing were also rinsed with alcohol and the liquid was collected to filter the debris within the center housing. The debris was collected and retained for further analysis.⁷

The No. 1 extensible link was disassembled. No evidence of white-colored material was present, and no anomalous damage was found within the No. 1 extensible link assembly. The No. 1 extensible link filter was removed and there was no evidence of debris on the filter. The electrohydraulic valve (EHV) filter was removed and also exhibited no evidence of debris.

The No. 2 extensible link was disassembled. No evidence of white-colored material was present, and no anomalous damage was found within the No. 2 extensible link assembly. The No. 2 extensible link filter was removed and there was no evidence of debris on the filter. The No. 2 EHV filter was removed and the filter had potential debris on the upstream side of the filter; this filter was retained for further evaluation of the potential debris.

8.0 Maintenance

Aircraft records showed that the accident helicopter was maintained in reference to, and in accordance with, the programs recommended by the manufacturer (Columbia Helicopters) in their instructions for continued airworthiness (see TCDS No. R00051SE). The helicopter had accumulated an ATT of 7,735.9 hours

⁷ At the time of this report, analysis of the debris was in progress at the NTSB Materials Laboratory.

and a Hobbs time of 69.5 hours at the end of the day before the accident. On July 14, 2022, at an ATT of 7,715.2 hours and a Hobbs time of 48.8 hours, the Nos. 1 and 2 hydraulic PCM pressure and return filters were removed and replaced. On July 8, 2022, at an ATT of 7,697.3 hours and a Hobbs time of 30.9 hours, the No. 1 hydraulic PCM pressure switch packing was replaced. On July 3, 2022, at an ATT of 7,697.3 hours and a Hobbs time of 30.9 hours, the No. 1 hydraulic PCM pressure switch and the No. 2 hydraulic cooling blower were replaced. On June 6, 2022, at an ATT of 7,667.3 hours and a Hobbs time of 0.9 hours, the aft rotor LCT actuator was removed and replaced. **Attachment 2** of this report contains the maintenance logbook entries for the day before the accident and the maintenance conducted on July 14, 2022.

E. LIST OF ATTACHMENTS

Attachment 1 - ATP results for the forward LCT; the pitch, roll, yaw, and thrust ILCAs; and the forward and aft pivoting and swiveling UBAs.

Attachment 2 - Recent maintenance accomplished on N388RA.

Submitted by:

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APPENDIX A

Boeing Simulation Study Results

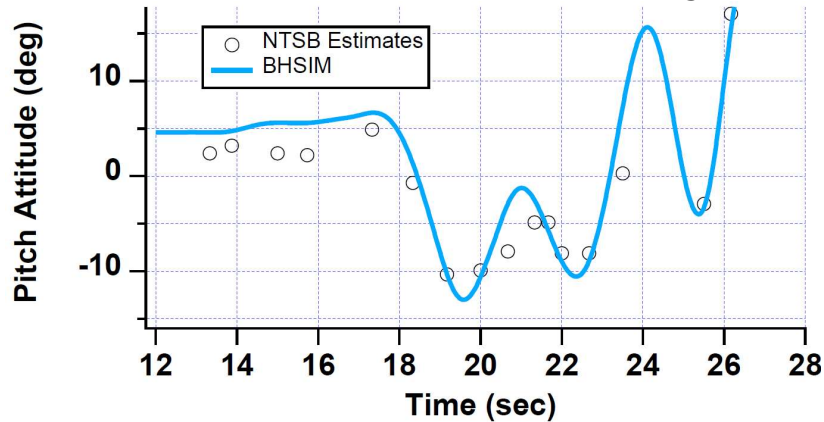


Figure A-1. The estimated pitch attitude from the Boeing simulation study and the NTSB video study.

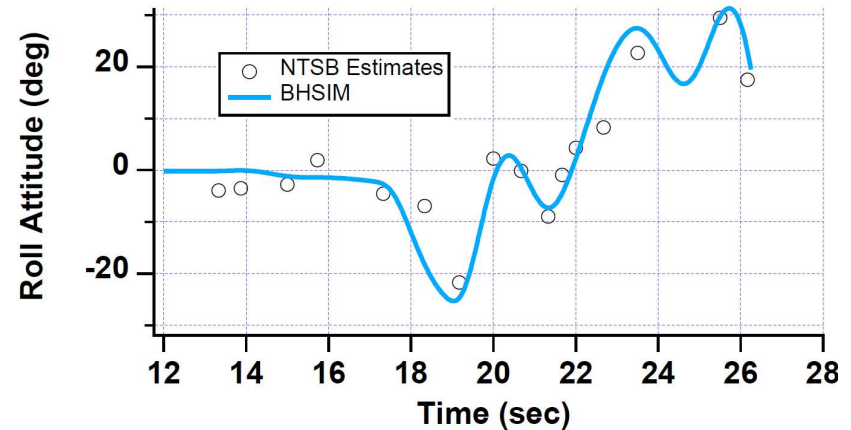


Figure A-2. The estimated roll attitude from the Boeing simulation study and the NTSB video study.

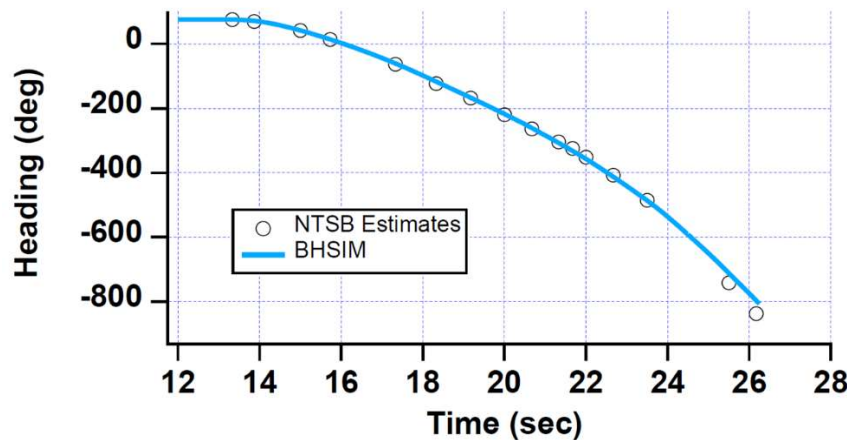


Figure A-3. The estimated heading from the Boeing simulation study and the NTSB video study.

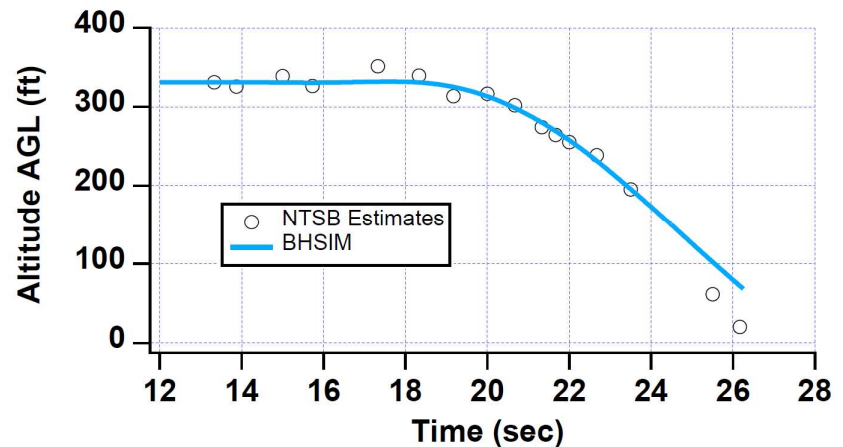


Figure A-4. The estimated altitude from the Boeing simulation study and the NTSB video study.

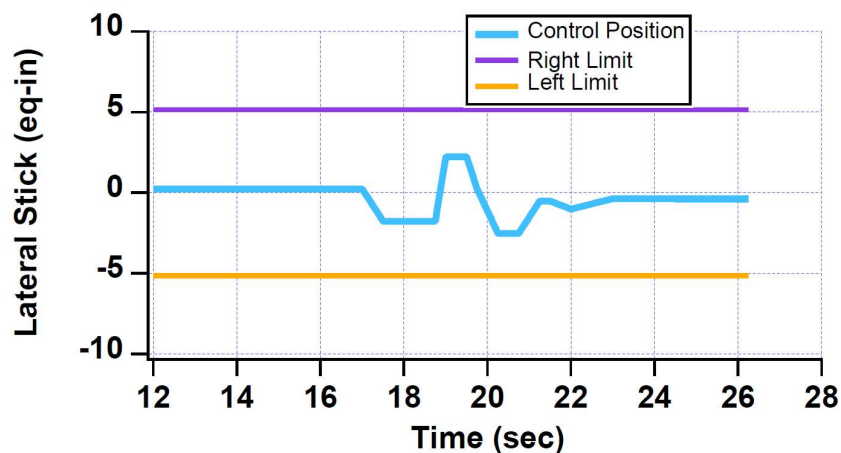


Figure A-5. The estimated lateral cyclic position from the Boeing simulation study.

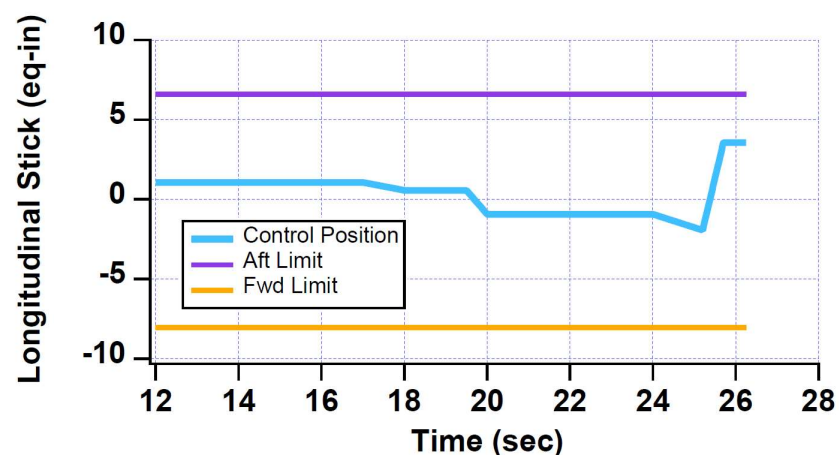


Figure A-6. The estimated longitudinal cyclic position from the Boeing simulation study.

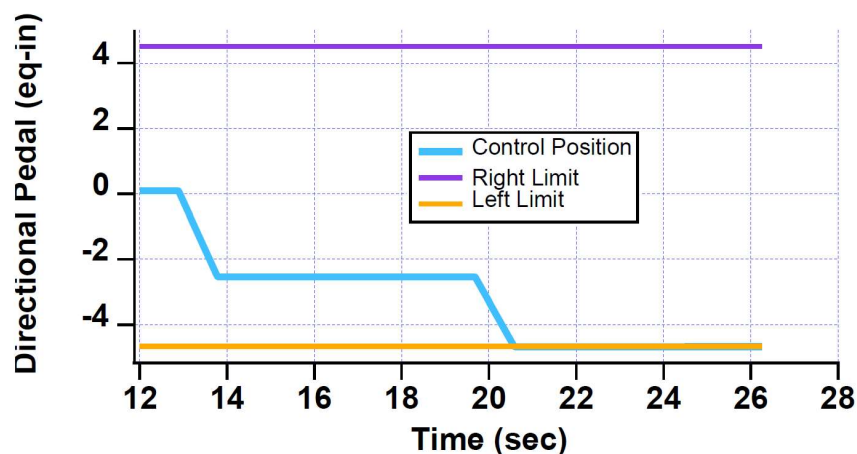


Figure A-7. The estimated pedal position from the Boeing simulation study.

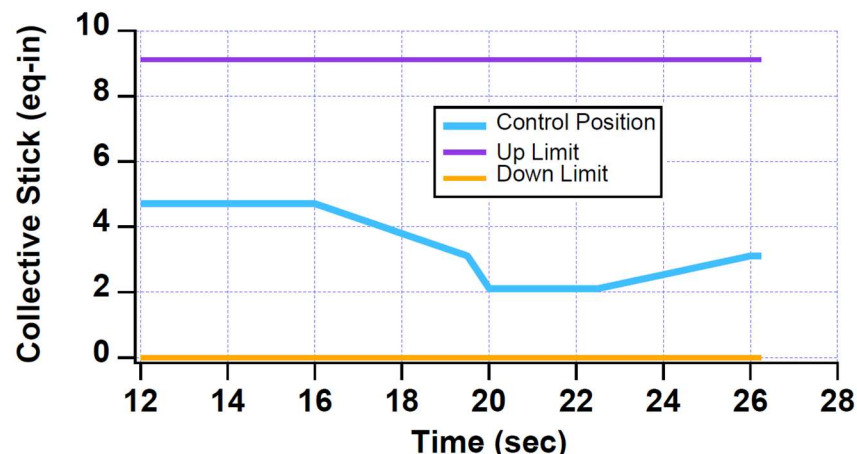


Figure A-8. The estimated thrust lever (collective) position from the Boeing simulation study.