

NATIONAL TRANSPORTATION SAFETY BOARD

Office of Aviation Safety

Washington, D.C. 20594

December 14, 2017

System's Group Chairman's Factual Report

NTSB ID No.: CEN16FA372

A. ACCIDENT:

Location: Alexandria, Minnesota
Date: September 17, 2017
Time: 0207 Central Daylight Time
Aircraft: Agusta S.p.A A109S helicopter, N91NM

B. GROUP MEMBERS:

Chairman: Mike Hauf
National Transportation Safety Board

Member: Jay Eller
Honeywell Aerospace

Member: Chris Lemieux
Leonardo

C. SUMMARY:

On September 17, 2016, at 0207 central daylight time, an Agusta S.p.A A109S helicopter, N91NM, impacted trees and terrain near Chandler Field Airport (AXN), Alexandria, Minnesota. The commercial rated pilot and two crew members sustained serious injuries and the helicopter was destroyed. The helicopter was registered to North Memorial Health Care, Brooklyn Center, Minnesota, and operated by North Memorial Medical Center under the provisions of 14 Code of Federal Regulations Part 135 as a positioning flight. Night instrument meteorological conditions prevailed at the accident site and an instrument flight rules (IFR) flight plan had been filed. The helicopter departed Brainerd Lakes Regional Airport (BRD), Brainerd, Minnesota about 0135 and was destined for the Douglas County Hospital helipad, Alexandria, Minnesota.

D. DETAILS OF THE INVESTIGATION:

D.1 Wreckage Examination:

During the period of April 24 and 25th 2017, the systems group convened at the Wentworth Aircraft hangar at Airlake Airport (LVN), Lakeville, MN, for the purpose of examining the helicopter's flight control and helipilot systems. As part of this activity, the components identified in Table 1 were recovered from the wreckage and retained for further examination. System and component examination results are detailed in their respective sections in this report.

The artificial feel & trim actuator, both roll and linear actuators and one pitch linear actuator were shipped to Varex Imaging Corporation, located in Chicago, Illinois, for radiographic studies to examine and document their internal configuration. Reference the NTSB Computed Tomography Specialist's Factual Report in the Safety Board's public docket for accident number CEN16FA372.

Table 1 Recovered System's Components

COMPONENT	PART NUMBER	SERIAL NUMBER
Pitch Linear Actuator (Left)	4012373-908	04066217
Pitch Linear Actuator (Right)	4012373-908	90078694
Roll Linear Actuator (Left)	4012373-909	05066993
Roll Linear Actuator (Right)	4012373-909	05056894
Yaw Linear Actuator	4012373-905	0506H036
Artificial Feel & Trim Actuator	L109BDM	11687
Helipilot Computer	109-0900-64-103 (1010063A03-00AD)	0668
Helipilot Computer	109-0900-64-103 (1010063A03-00AD)	0669
Flight Director Computer	109-0900-56-101 (1010067A01-00AA)	0020
Main Rotor Actuator (Blue Label)	306-28007-00	8011
Main Rotor Actuator (Red Label)	304-28007-00	4006
Main Rotor Actuator (Yellow Label)	305-28007-00	6021

D.2 Flight Control System:

D.2.1 Description:

The flight control system provides a means of controlling the main rotor blades and the tail rotor blades for horizontal, vertical, and directional flight. As shown in Figure 1, the helicopter was equipped with a conventional helicopter flight control system, which included collective and cyclic sticks and left and right pedals for each pilot.

The collective stick increases and decreases the total thrust produced by the main rotor by increasing or decreasing main rotor pitch blade angle equally and simultaneously. The cyclic stick controls helicopter movements in the pitch and roll axes. The cyclic stick is moved forward, aft, to the left, or to the right to vary the pitch of the main rotor blades at different points throughout each revolution of the main rotor and tilt the rotor disk in a particular direction, resulting in the helicopter moving in that direction.

The collective control inputs are mechanically transmitted through a torque tube and bellcrank, located beneath the cockpit floor, to a control mixing unit, located in a compartment above the cockpit, via one control tube routed up through the left side of the fuselage. Cyclic inputs (pitch and roll) are independently transmitted through a series of torque tubes and push-pull tubes located beneath the cockpit floor via two control tubes routed up through the right side of the fuselage, through their respective set of dual linear actuators to the control mixing unit.

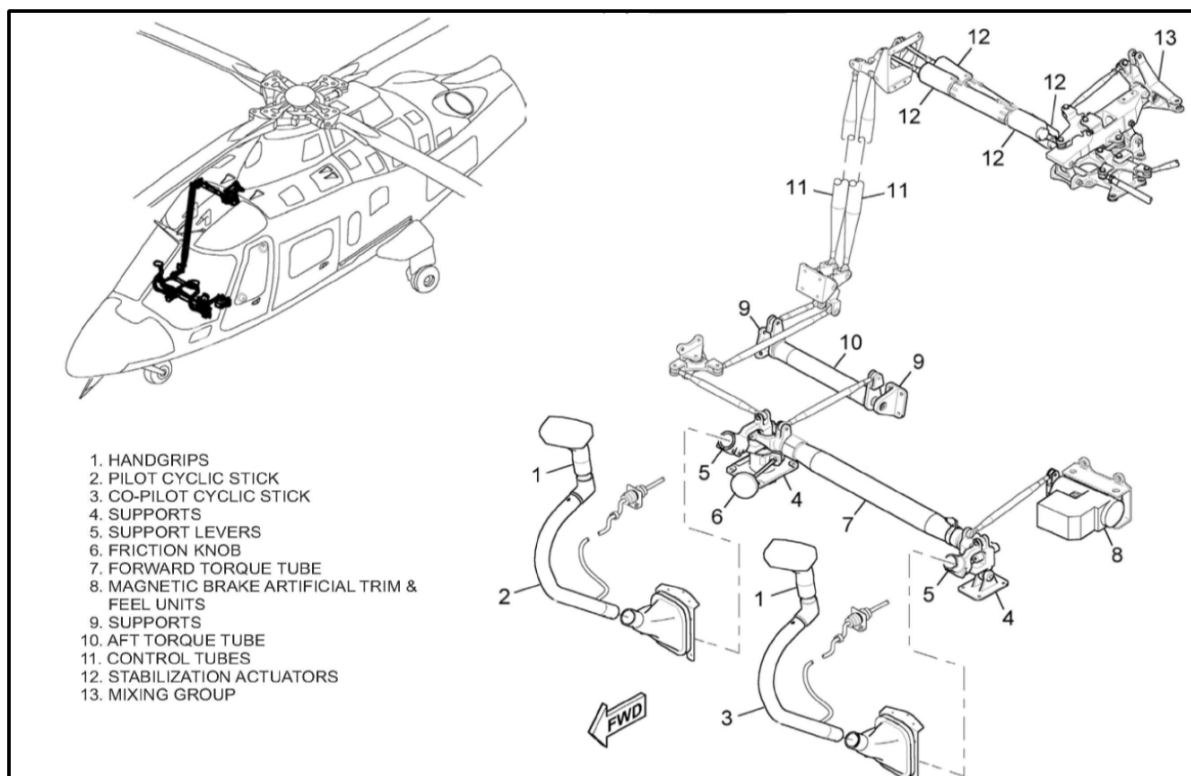
Control motion from the collective pitch lever and cyclic stick are combined in the mixing unit and are transmitted via pushrods to the three dual-cylinder main rotor servo actuators. The main rotor hydraulic actuators, which are mounted on the main gearbox, transfer control movements to the stationary swashplate. Movements of the stationary swashplate are transferred into movements of the rotating swashplate, which alters the pitch on the rotor blades.

The pedals (pilot and copilot set) increase and decrease the total thrust produced by the tail rotor by increasing or decreasing the pitch angle of both tail rotor blades equally and simultaneously. For example, as the main rotor torque increases, a corresponding left pedal control input is required to increase tail rotor thrust to maintain the helicopter's heading, thereby controlling the left right yaw imparted by the main rotor, which turns in a counter-clockwise direction.

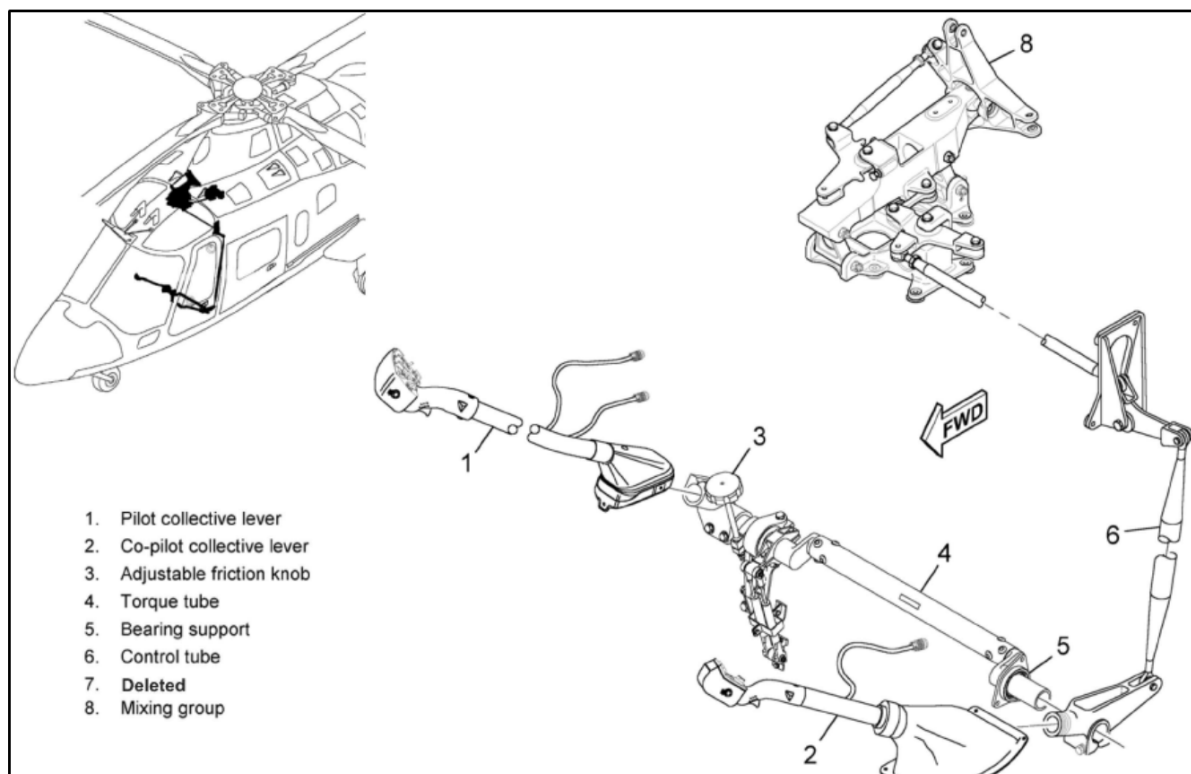
Pedal control inputs are transmitted to a single-cylinder tail rotor servo actuator through a series of control linkages, bellcranks, and a yaw stabilization actuator (linear actuator). The control inputs can also be directly transmitted to the blades' pitch change mechanism via a mechanical bypass in case of hydraulic pressure loss.

Figure 1 Flight Controls – Main Rotor

SCHEMATIC OF CYCLIC CONTROLS



SCHEMATIC OF COLLECTIVE CONTROLS



D.2.2 Flight Control Examination:

On April 24, 2017, the systems group visually inspected and documented the helicopter's main and tail rotor flight control systems during the wreckage examination at the Wentworth Aircraft hangar at Airlake Airport (LVN), Lakeville, MN.

The flight controls inspected included the collective and cyclic components located beneath the cockpit floor, the control tubes located on the left and right side of the fuselage, the components located in the compartment above the cockpit and the three main rotor actuators. The tail rotor flight controls inspected included the yaw stabilization actuator (linear actuator) and the tail rotor servo actuator.

Continuity for cyclic (pitch and roll) and collective control between the cockpit controls and the mixing unit, located in a compartment above the cockpit, could not be established. Several pushrods and control tubes within the system were found fractured.

As shown in Figure 2, the main and tail rotor flight control system components (pushrods, torque tubes, attachment hardware, etc.) located beneath the cockpit floor were found in place and remained properly connected via their attachment hardware. The artificial feel & trim actuator, P/N 109-0021-18-1, S/N 11687 was removed from the helicopter and retained for functional testing at Thales Italia Avionics. Reference section D.7.4 of this report.

As shown in Figure 3, both cyclic (pitch and roll) pushrods and control tubes were found fractured near their respective lower bellcrank assemblies. Inspection found that the rod ends for both pushrods and both control tubes remained properly connected via their attachment hardware to their respective bellcrank assembly. The upper end of the control tubes remained intact and properly connected to their respective bellcrank assembly with their attachment hardware.

The lower end of the collective control tube was found fractured just above its rod end; which remained intact and properly connected to the lower bellcrank with its attachment hardware. The upper end of the control tube remained intact and properly connected to the upper bellcrank with its attachment hardware.

As shown in Figure 4, the dual pitch and roll linear actuators, which were located in the compartment above the cockpit, remained mechanically connected to their respective attachment points (upper bellcrank assembly and the mixing unit); all attachment hardware remained intact and in place. Additionally, each of the four linear actuators remained electrically connected to its respective electrical connector. The pitch and roll linear actuators were removed from the helicopter and retained for functional testing at Honeywell. Reference section D.7.3 of this report.

Figure 4 also shows that the pushrod, connecting the collective control tubes upper bellcrank to the mixing unit, was found separated in the area near the upper bellcrank.

Continuity was established between the mixing unit and each of the three main rotor actuators. As shown in Figure 5, the controls (control tubes, bellcranks, etc.) from the mixing unit to the three-main rotor actuator input levers remained properly connected to their respective linkages and all attachment hardware remained intact and in place. Some structural deformation/damage was observed on the control tubes and bellcranks.

Figure 2 Photograph of flight controls located beneath cockpit floor

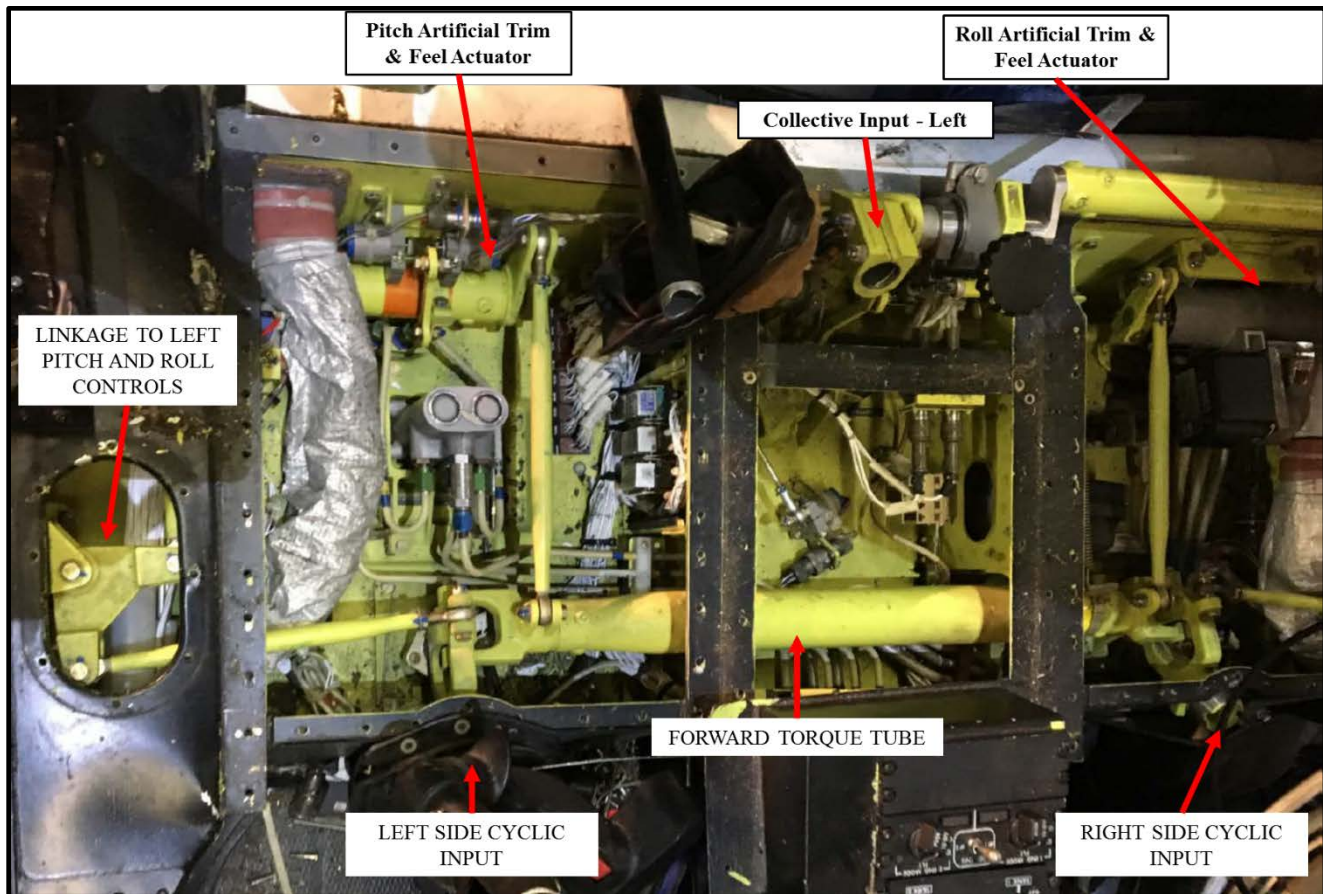
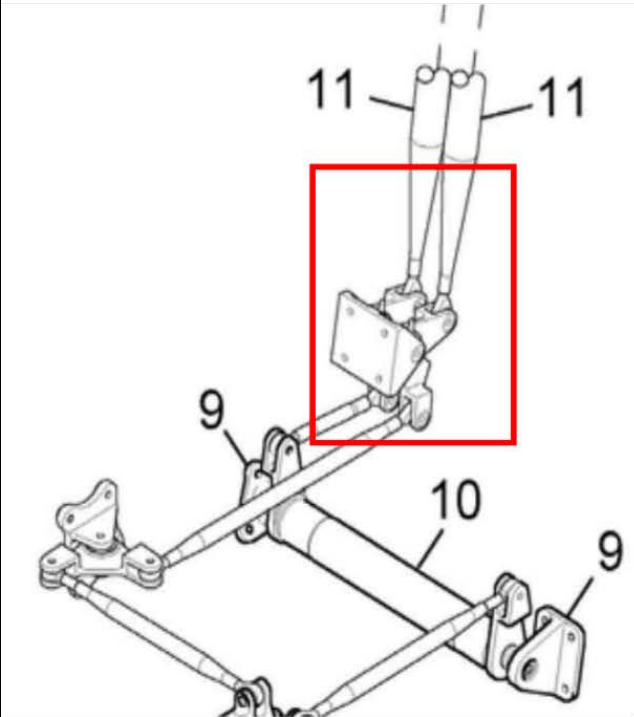
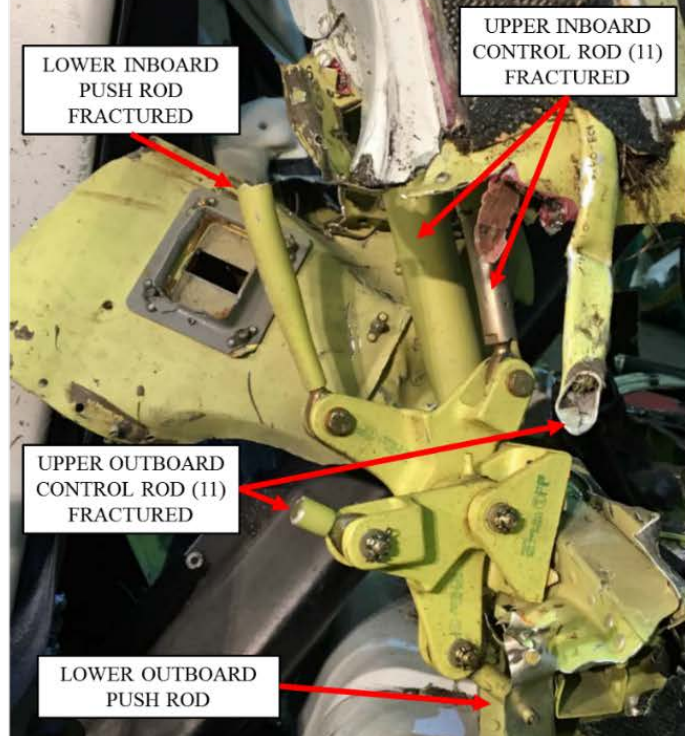


Figure 3 Left bellcrank assembly

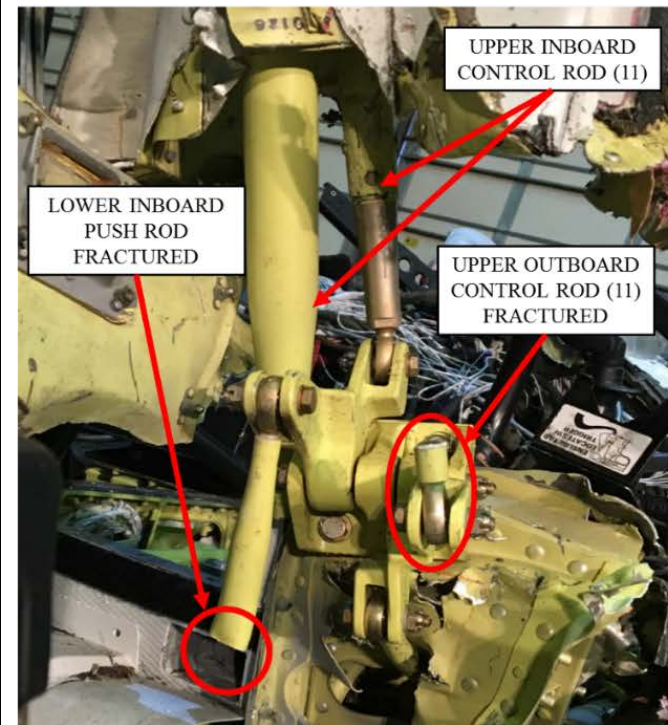
SCHEMATIC OF BELLCRANK ASSEMBLY



VIEW OF BELLCRANK ASSEMBLY LOOKING INBOARD



VIEW OF BELLCRANK ASSEMBLY LOOKING FORWARD



VIEW OF BELLCRANK ASSEMBLY LOOKING FORWARD & OUTBOARD

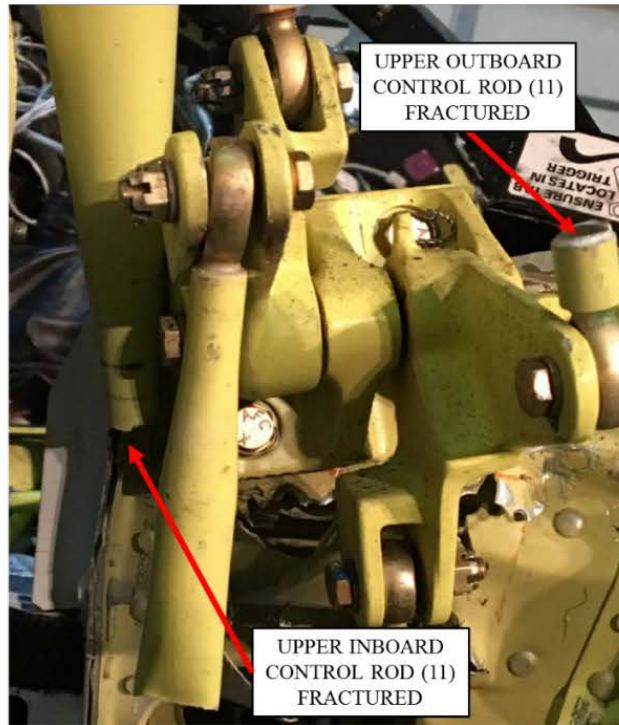


Figure 4 Flight Controls located in compartment above the cockpit

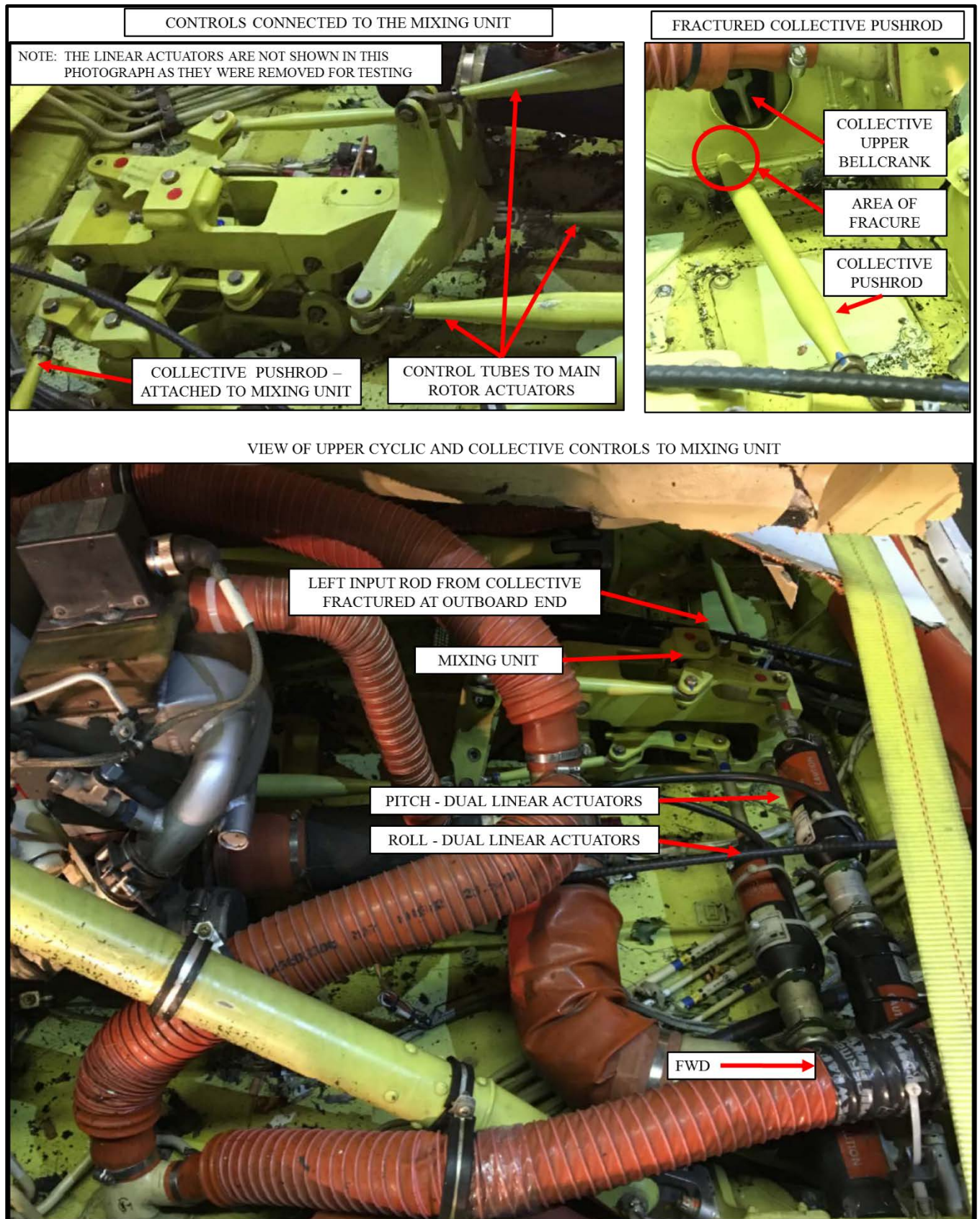
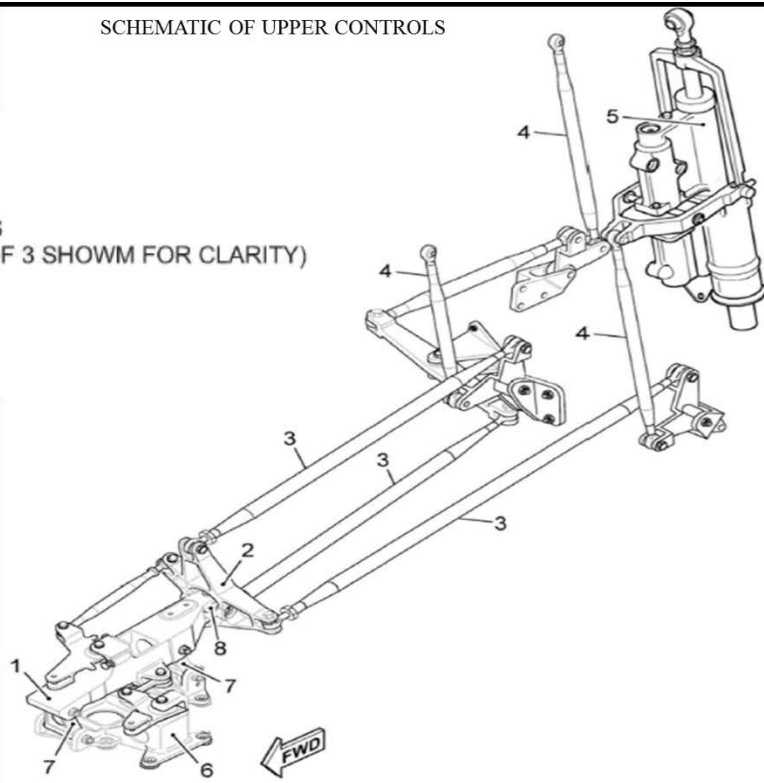


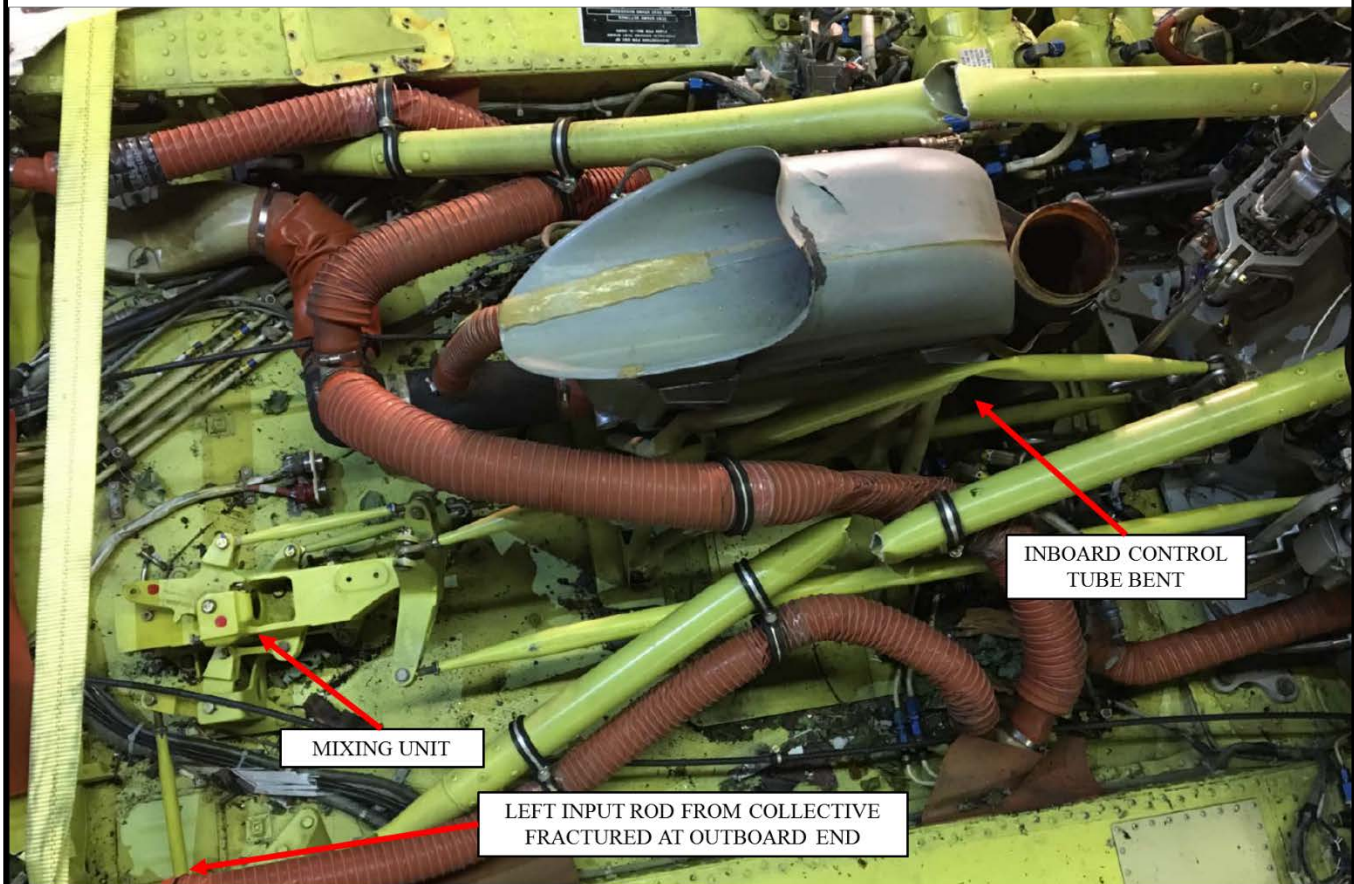
Figure 5 Controls to main rotor actuator

SCHEMATIC OF UPPER CONTROLS

1. CARRIAGE
2. MIXING LEVER
3. CONTROL TUBES
4. ADJUSTABLE CONTROL TUBES
5. SERVO ACTUATORS (ONLY 1 OF 3 SHOWN FOR CLARITY)
6. SUPPORT
7. LINKS
8. UNIVERSAL JOINT



VIEW OF UPPER PITCH AND ROLL CONTROLS AFTER LINEAR ACTUATORS WERE REMOVED



D.2.3 Main Rotor Hydraulic Actuators:

The aircraft was equipped with three dual redundant main rotor hydraulic actuators that received mechanical input commands from the mixing unit, of the flight control system, and provided output to the inner (fixed) swash plate through extension and retraction of the piston.

Examination of the three actuators found that the forward right actuator (blue) remained attached to the upper case of the transmission by its jointed support assembly. The left (red) and right (yellow) actuators were found not attached to the upper case of the transmission; their jointed support assemblies were found fractured.

All three actuators remained connected to the inner (fixed) swash plate and to their respective control linkage from the mixing unit.

The main rotor actuators identified in Table 2 were removed from the helicopter and shipped to their manufacturer, UTC Aerospace Systems, located in Brugherio, Italy for examination and functional testing. Reference section D.7. of this report.

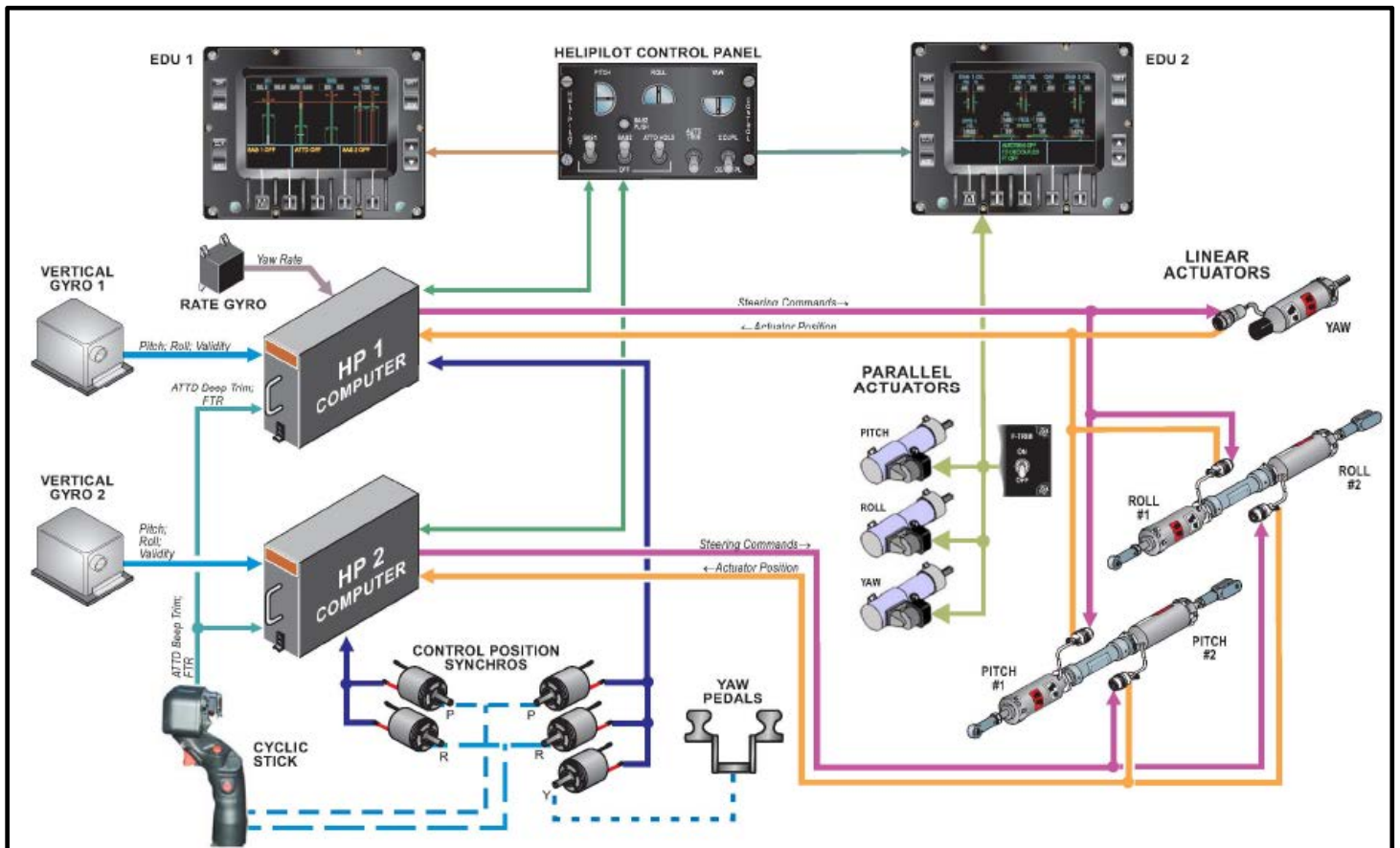
Table 2 Main rotor actuators

Actuator	Agusta Assembly P/N	Body Label Data		
		Microtecnica P/N	Microtecnica S/N	Agusta P/N
Forward Right (Blue)	109-0110-42-136	306-28007-00	8011	109-0110-42-131
Rear Right (Yellow)	109-0110-42-135	306-28007-00	6021	109-0110-42-131
Rear Left (Red)	N/A	306-28007-00	4006	109-0110-42-131

D.3 Integrated Flight Control System:

The helicopter was equipped with an integrated flight control system (IFCS) which provides three-axis (pitch, roll and yaw) helicopter attitude stabilization and path control. The IFCS is composed of a flight director (FD) system, Helipilot system and a means of coupling the two systems together to provide automatic flight path control. As shown in Figure 6, this system consists in part of a flight director (FD) computer, two Helipilot computers, a FD mode selector, pitch, roll, and yaw servo-actuators and pitch, roll, and yaw linear actuators, a Helipilot control panel, COMM/NAV GPS, and vertical and directional gyros, and an Electronic Flight Instrument System (EFIS) which includes an electronic attitude director indicator (EADI), and an electronic horizontal situation indicator (EHSI).

Figure 6 Helipilot system diagram



D.3.1 Flight Director - Description:

When engaged, the flight director computer computes pitch, roll and collective commands which are displayed on the pilot's Electronic Flight Instrument System (EFIS) and provided to the automatic stabilization system when in the coupled mode.

The pilot provides input to the flight director system through the mode selector panel located in the center of the forward instrument panel. As shown in Figure 7, the mode selector panel is equipped with ten push-on, push-off (buttons) that enable the pilot to select various flight director modes of operation (Table 3). All the FD modes are available for automatic (coupled) or manual (uncoupled) flight path operation by engaging the automatic stabilization system and selecting the desired mode of operation on the mode selector.

Figure 7 Mode selector panel

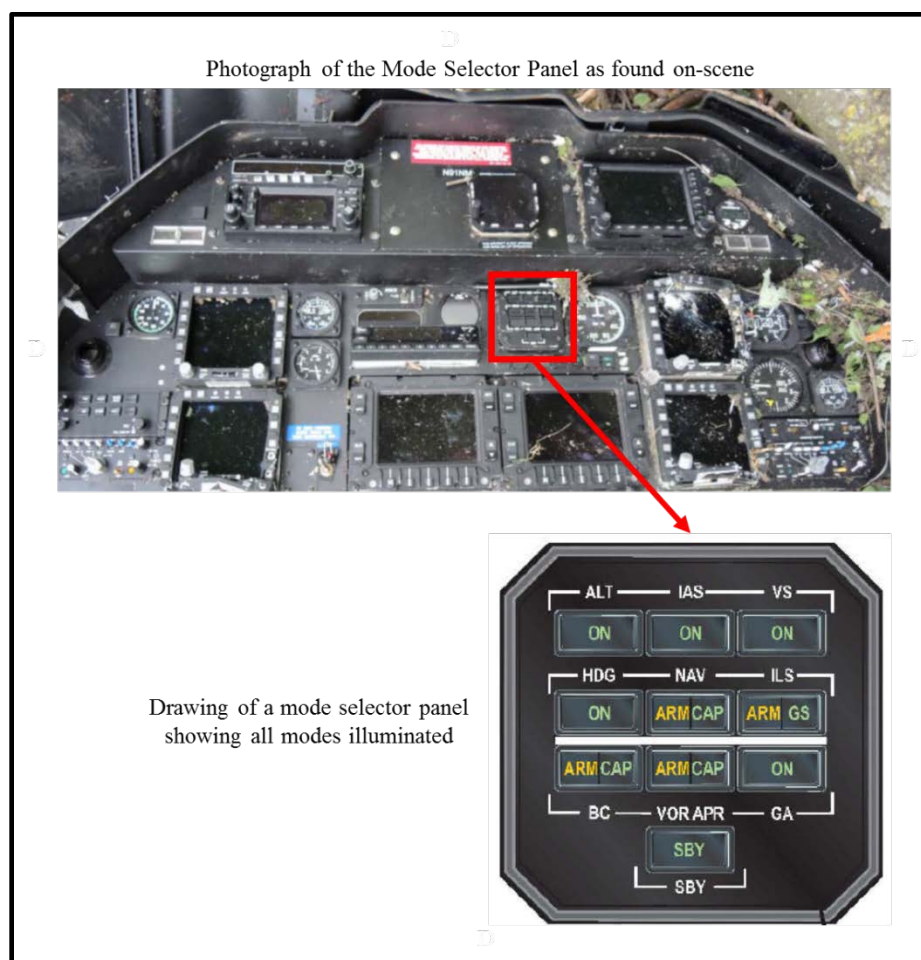


Table 3 Description of some of the mode selector modes

Mode	Description
ALT	The ALT mode commands the helicopter to maintain the altitude when selected.
IAS	In the IAS mode, the system responds to the signal from the air data sensor to maintain the helicopter speed existing at the moment of engagement.
VS	The VS mode maintains a selected vertical speed.
HDG (Heading Select)	When this mode is selected, the FD computer generates the necessary roll commands to bank the helicopter to intercept and maintain the heading selected on the EHSI. The bank angle limiter limits the commanded bank angle to +/- 20 degrees. In the event of a loss of valid data from the vertical or directional gyroscopes, the ADI vertical bar will be driven out of view and the automatic stabilization system roll channel will be driven to a level attitude condition.
NAV	The NAV mode provides intercept, capture and tracking of a selected VOR radial (or GPS track).
GA (Go-Around) (Back Course Localizer)	The GA mode is used to transit from a descent into a climb-out situation when a missed approach has occurred. When the GA mode is selected, the GA annunciator lights on the ADI and on the GA lighted pushbutton switch come on and the collective command cue comes into view. All other modes are cancelled. If the airspeed is less than 55 knots, the FD commands a level attitude and zero (0) fpm climb rate. At airspeeds between 55 and 65 knots, the FD commands a linear rate of climb between 0 and 750 fpm. Airspeeds above 65 knots produce a climb command of 750 fpm.

D.4 Autopilot - Description:

The Helipilot system provides stability and control through three types of operations: stability augmentation (SAS), attitude retention (ATT), and automatic flight path control (CPL) when in the coupled mode. The system comprises the following components in part: Dual Helipilot computers, Helipilot control panel, dual linear actuators¹ for pitch and roll axes, single linear actuator for the yaw axis and position synchros for pitch, roll and yaw. The Helipilot computers perform all the autopilot functions by processing altitude and rate of turn signals from the vertical and rate gyroscopes and position signals from the cyclic stick and pedal position transmitters to develop the appropriate control signals for the linear actuators (pitch, roll and yaw). Each Helipilot is capable of fully stabilizing the helicopter as it has its own attitude sensor, computer, and linear actuators. The only difference between the two systems is the capability to control the yaw axis; Helipilot number 1 controls this function.

The SAS mode provides for short term attitude and rate stabilization in order to stabilize the helicopter against external disturbances. It may be referred to as a damper system that is stabilizing the helicopter against outside disturbances and thereby is augmenting pilot workload. The SAS mode has been calibrated so that pilot control motions which cause helicopter attitude changes are not counteracted by the system. Only helicopter motions caused by outside disturbances are counteracted. This type of operation provides a stabilized mode wherein the basic helicopter handling qualities are not altered. When this mode is selected, the pilot must fly "hands on". The SAS mode is engaged by setting the Helipilot control panel SAS 1/OFF and/or SAS 2/OFF switches to SAS 1 and SAS 2 and setting the ATT switch to OFF. When helicopter motion is detected by the gyros (i.e. wind gust), a stabilizing control proportional to the amplitude and rate of the motion is computed in the Helipilot computers and applied to the appropriate linear actuators.

In Attitude retention mode (ATT), the Helipilot system's pitch, roll, and yaw channels are engaged (Helipilots engaged but not coupled to the flight director) to maintain indefinitely the attitude existing at the moment of engagement. If a change in attitude is desired, the pilot simply presses the beep trim switch on the cyclic control to obtain a small attitude change or the force trim release (FTR) switch on the cyclic control and then moves the cyclic to obtain the desired new attitude. When the pilot releases the selected switch, the system again resumes the attitude retention function.

In the coupled mode, the Helipilot system's pitch and roll channels are coupled to the flight director by setting the COUPLING/DECOUPLING switch on the console to COUPLING, engaging the Helipilots in the ATT mode, and then selecting any flight director mode on the mode selector panel. The Helipilot system will respond automatically to follow any lateral or vertical path guidance commands generated by the FD computer. When operating in the coupled mode, retrimming the cyclic control can be accomplished either manually or automatically. With the autotrim system engaged, cyclic control retrimming is accomplished automatically. When both systems are engaged, trimming starts when both linear actuators reach 30 percent of their travel from center for a period of three seconds, provided both actuators are commanding the same direction. Trimming stops when the linear actuators are essentially re-centered.

¹ The linear actuators are mounted in series in the flight control linkage and therefore operate without operating the cyclic stick and the pedal positions.

D.5 Heading/GPS Steer Switch:

The helicopter was equipped with an STC installed HEADING/GPS STEER switch which allows the pilot to manually select the heading (HDG) reference source (heading selected on the EHSI or roll steering commands from the GPS). When the switch is selected to HEADING, the FD computer calculates the necessary roll commands to bank the helicopter to intercept and maintain the heading selected on the EHSI. With the switch selected to GPS STEER, the FD computer will receive the Heading error signal as computed by a dedicated STC box which compares the requested GPS heading (generated by GNS530W) and the actual heading. The FD transmits the calculated roll commands to the Helipilot computers, which drive the pitch and roll “linear” actuators to achieve the target attitude and rate.

In case of malfunctioning or erroneous setting of the system, the A109S AFCS has at least two different limiters in place to prevent excessive roll commands: one in the Flight Director computer (which imposes a max roll command in HDG mode of $\pm 20^\circ$, when coupled to the AFCS for hands-off flying) and one in the Helipilot computer(s), which has a target maximum roll attitude of $\pm 24^\circ$ and a maximum commanded roll rate of $\pm 8.2^\circ/\text{second}$ for short term stabilization purposes.

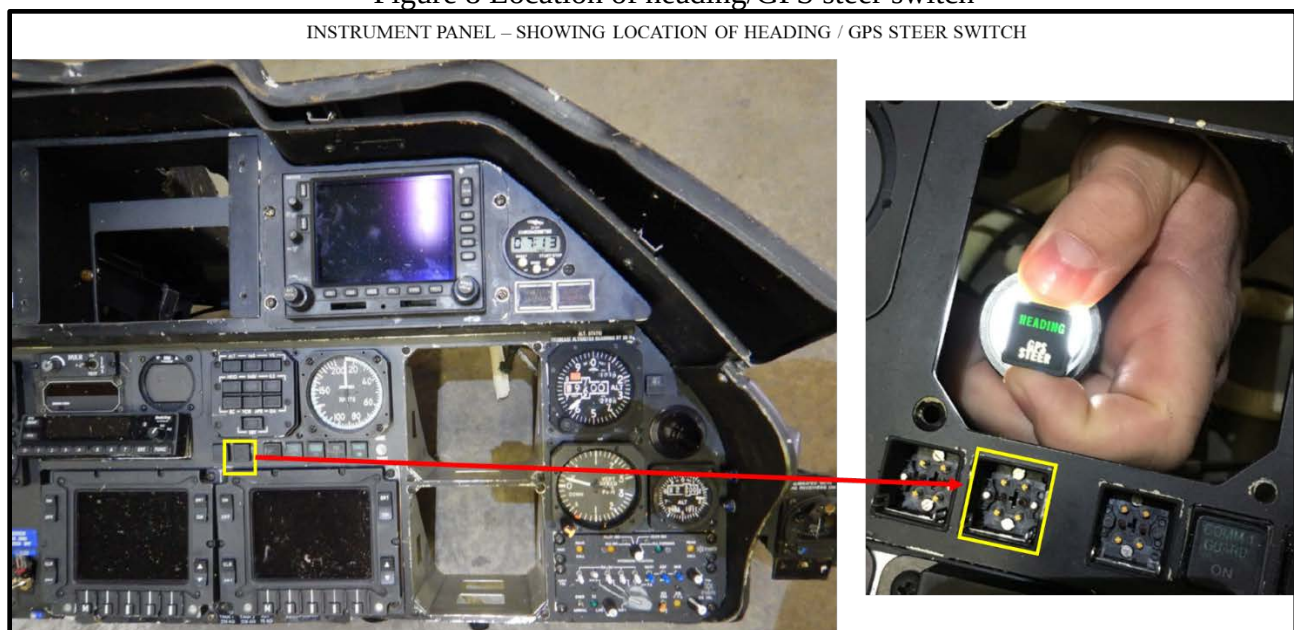
On April 24, 2017, the systems group examined and tested the HDG/GPS STEER Switch at the Wentworth Aircraft hangar at Airlake Airport (LVN), Lakeville, MN. A visual inspection of the switch found that its pushbutton remained in an extended “HEADING” position. According to the MSP Aero roll steering modification drawing, when continuity exists between pins A3 and A2, the HDG/GPS STEER Switch is positioned to “HEADING” and when continuity exists between pins A3 and A1, the HDG/GPS STEER Switch is positioned to “GPS STEER”. Using a multimeter, a check of the “as found” switch position was conducted and the following results were measured²:

- A2 to A3 – Continuity
- A1 to A3 – No Continuity

The switch button was depressed (GPS STEER) and a continuity check was again performed. The following results were measured:

- A2 to A3 – No Continuity
- A1 to A3 – Continuity

Figure 8 Location of heading/GPS steer switch



² The switch assembly remained within the instrument panel during continuity testing.

D.6 Go-Around Mode:

D.6.1 Description:

Go-around mode is used to transition from a descent into a climb-out situation when a missed approach has occurred. The pilot can select the go-around mode by pushing the Go-around (GA) button located on the collective or by pushing the GA button on the mode selector. When this mode is selected, the GA annunciators on the EADI and on the mode selector will illuminate, the collective command cue on the EADI will come into view, and any pitch (vertical) or roll (lateral) modes that were engaged. GA mode will also disable all other flight director modes and extinguish their mode annunciators.

In GA mode, if the helicopter's speed is greater than 65 knots, the flight director will command the helicopter's attitude to a wings level position (intention for straight and level flight on existing course) and provides the pilot with the collective cue, displayed on the EADI, to establish a 750 fpm climb.

The pilot can setup and engage another flight director mode once comfortable to navigate to a new course using the Flight Director System, or he could take manual control of the helicopter, including pitch and roll, through activation of force trim release (FTR³) switch or by disabling the Flight Director entirely, including ATTD hold mode. The pilot can also override with manual force on the cyclic stick but will have some resistance on the stick from force gradient spring load if not also engaging the FTR switch. The FTR switch releases the cyclic and tail rotor magnetic brakes on the trim actuators, essentially disconnecting any actuation of the controls by the flight director system. As soon as FTR is released the AP system inputs would be active again on cyclic and yaw. If ATTD Hold mode is still engaged, it will keep the controls at the same position the pilot had them upon release of the switch.

D.6.2 Operation:

1. Pilot pushes the "Go-Around" (GA) button either on the Collective or the FD mode selector panel.
2. GA annunciator on the ADI is illuminated.
3. Pitch (vertical) and Roll (lateral) channels are set to GA mode and all other flight director modes are cancelled. Yaw channel remains on stabilization duties, Collective is always manually controlled (it is a 3-axis system).
4. The Heading (HDG) error input (From HSI or GPS) is immediately zeroed within the FD computer resulting in the FD providing a signal to the Helipilots to bring the helicopter to a wings level condition.
5. The FD commands the pitch channel to achieve a pre-determined rate of climb based on the airspeed and accelerating the A/C (if needed) to reach approximately 65kts and 750 fpm climb.
6. The ADI displays a collective cue for the Pilot to follow.
 - If, by example, the collective cue is exceeded voluntarily by the pilot, the A/C slightly pitches down and accelerates to compensate for the excess of rate of climb.
7. The pitch and roll axis remain in GA mode until other vertical and/or lateral modes are selected.
 - As an example, the pilot can manually select a new Heading on the EHSI and activate the HDG mode on the lateral channel, while still climbing with GA active on the vertical channel. Note, the source of the heading information is dependent on the position of the HEADING/GPS STEER switch. If the switch had been previously selected to HEADING, the FD computer calculates the necessary roll commands to bank the helicopter to intercept and maintain the heading that is selected on the EHSI. If the switch had been previously

³The Force Trim Release Switch is mounted on the cyclic stick. When pressed, It releases the cyclic electromagnetic brake so the pilot can manually retrim the flight controls.

selected to GPS STEER (and not changed), the FD computer will receive roll steering information from the Garmin 530W. The FD transmits the calculated roll commands to the Helipilot computers, which drive the pitch and roll “linear” actuators to achieve the target attitude and rate.

D.7 Component Examinations:

Table 4 Component Examinations

COMPONENT	S/N	EXAMINATION INFORMATION
Helipilot Control Panel	N/A	Examined on-scene, reference section D.7.1 of this report.
Flight Director Mode Selector	N/A	Examined at the Wentworth Aircraft hangar, reference section D.7.2 of this report.
Pitch Linear Actuator (Left)	04066217	The actuators were examined at the Honeywell facility located in Boyne City, MI on August 16 and 17th 2017. Reference section D.7.3 of this report.
Pitch Linear Actuator (Right)	90078694	
Roll Linear Actuator (Left)	05066993	
Roll Linear Actuator (Right)	05056894	
Yaw Linear Actuator	0506H036	
Artificial Feel & Trim Actuator	11687	The roll artificial feel & trim actuator was examined at Thales Italia Spa Avionics BD Vergiate (VA), Italy on July 14, 2017. Reference report section D.7.4 of this report
Helipilot computer-668	0668	The two Helipilot and one flight director computers were examined at Leonardo Airborne and Space Systems located in Nerviano (MI), Italy on July 18, 2017. Reference report sections D.7.5 and D.7.6 of this report.
Helipilot computer-669	0669	
Flight Director Computer (1)	0020	
Main Rotor Servo (Blue Label)	8011	The main rotor actuators were examined at UTC Aerospace Systems Via San Maurizio al Lambro Brugherio (MB) – Italy on July 19, 2017. Reference report sections D.7.7 of this report.
Main Rotor Servo (Red Label)	4006	
Main Rotor Servo (Yellow Label)	6021	

D.7.1 Helipilot Control Panel:

During the on-scene activities, a photograph of the Helipilot control panel was taken (Reference Figure 9). A review of the photograph shows that its switches were found positioned as indicated in Table 5.

Figure 9 Helipilot control panel

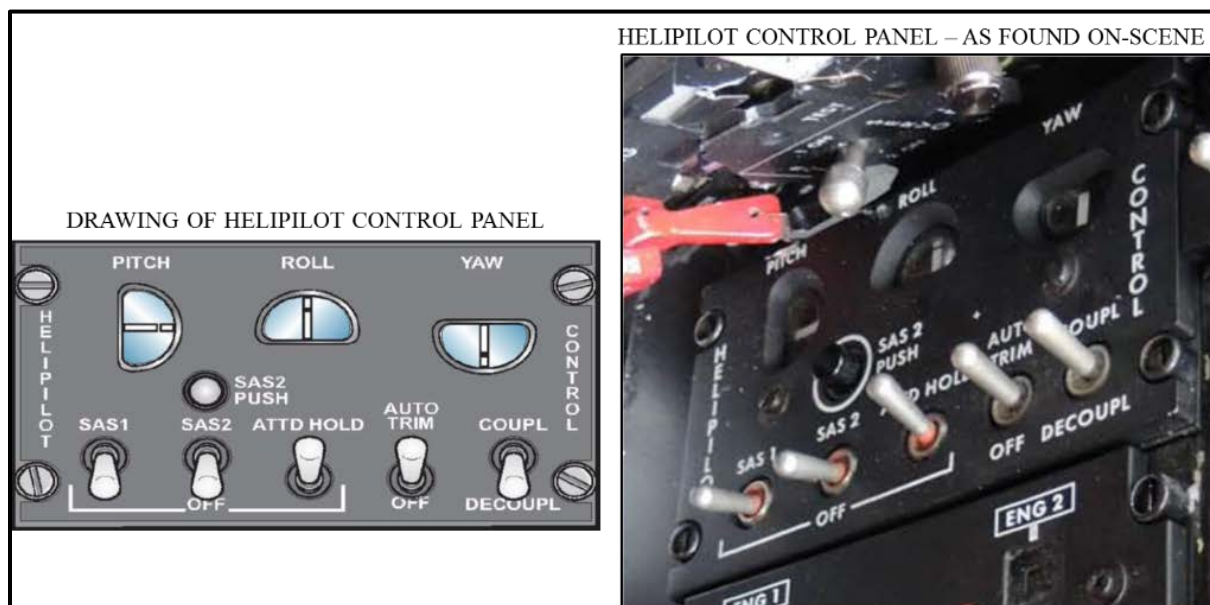


Table 5 Switch positions on Helipilot control panel

Switch	Position	Description
SAS1	OFF	No. 1 Helipilot is De-energized (See Note 1)
SAS2	OFF	No. 2 Helipilot is De-energized (See Note 1)
ATTD HOLD	ATTD HOLD	See Note 1
AUTO TRIM	ON	Auto trim enabled
COUPL/DECOUPL	COUPL	Allows coupling of the Helipilot to the FD

Note 1: The SAS1 and SAS2 switch toggles will automatically move to OFF (down) as soon as power is removed from the switch, while the ATT HOLD switch has its de-energized position on ATT HOLD (up).

D.7.2 Flight Director Mode Selector:

On April 24, 2017, the systems group examined and tested the mode select panel at the Wentworth Aircraft hangar at Airlake Airport (LVN), Lakeville, MN. The unit, P/N 7000605-901, S/N 05103020 was removed from the instrument panel so it could be partially tested per the Integrated Test Specification IT7000605-901, revision P, test 4.1 through 4.11. The results of the continuity testing are provided in Table 6.

Table 6 Results of continuity testing of the mode selector push-buttons

Push Button	Pin to Pin Tested	Results with button held in the pressed position	Results with button not pressed
HDG	J1-F to J1-Q	Open	Continuity
NAV	J1-F to J1-M	Open	Continuity
ILS	J1-F to J1-F	Open	Continuity
BC	J1-F to J1-I	Open	Continuity
VOR/APR	J1-F to J1-G	Open	Continuity
ALT	J1-F to J1-A	Open	Continuity
VS	J1-F to J1-Y	Open	Continuity
IAS	J1-F to J1-W	Open	Continuity
GA	J1-F to J1-V	Open	Continuity
SBY	J1-F to J1-L	Continuity	Open

D.7.3 Helipilot Linear Actuators:

The helicopter was equipped with a total of five linear actuators (Figure 10); two for the pitch system, two for the roll system and one for the tail rotor. As shown in Figure 11, the pitch and roll system linear actuators are connected in a series arrangement between the cyclic inputs and the control mixing unit.

Electrical commands from the Helipilot computers drive the motors of the actuators to extend or retract the control linkages which position the helicopter's controls to command the desired maneuver. Position feedback to the Helipilot servo loop is provided by a linear variable differential transformer (LVDT). An electrical brake releases the motor for operation when power is applied during Helipilot engagement. The actuators have stroke lengths assigned by a part number; the stroke length for the pitch (-908), roll (-909) and yaw (-905) actuators are 0.200 +/- 0.010, 0.236 +/- 0.010, 0.394 +/- 0.010 inches respectively.

Figure 10 Schematic of linear actuator

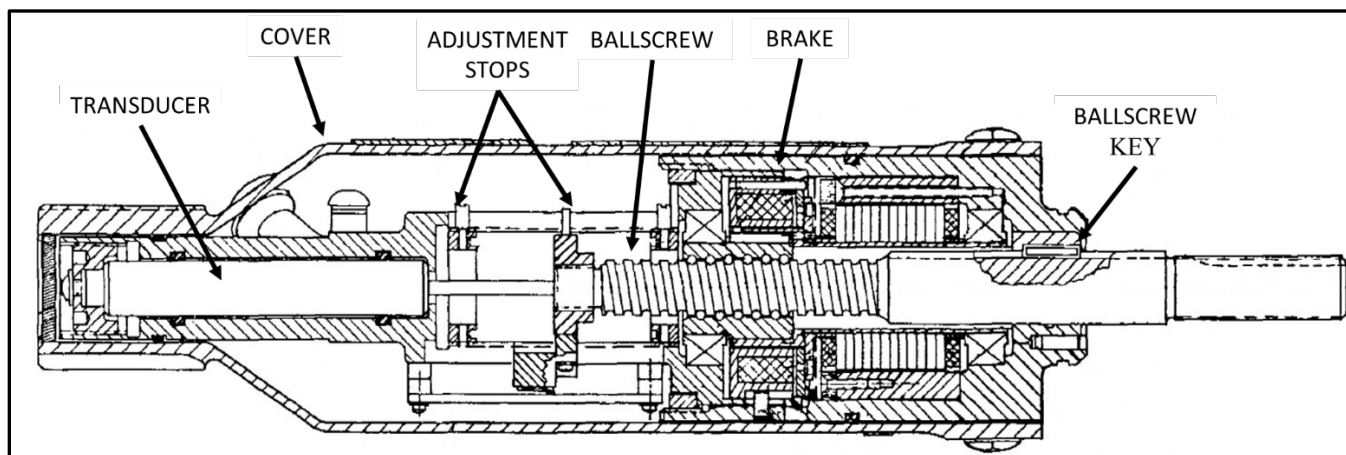
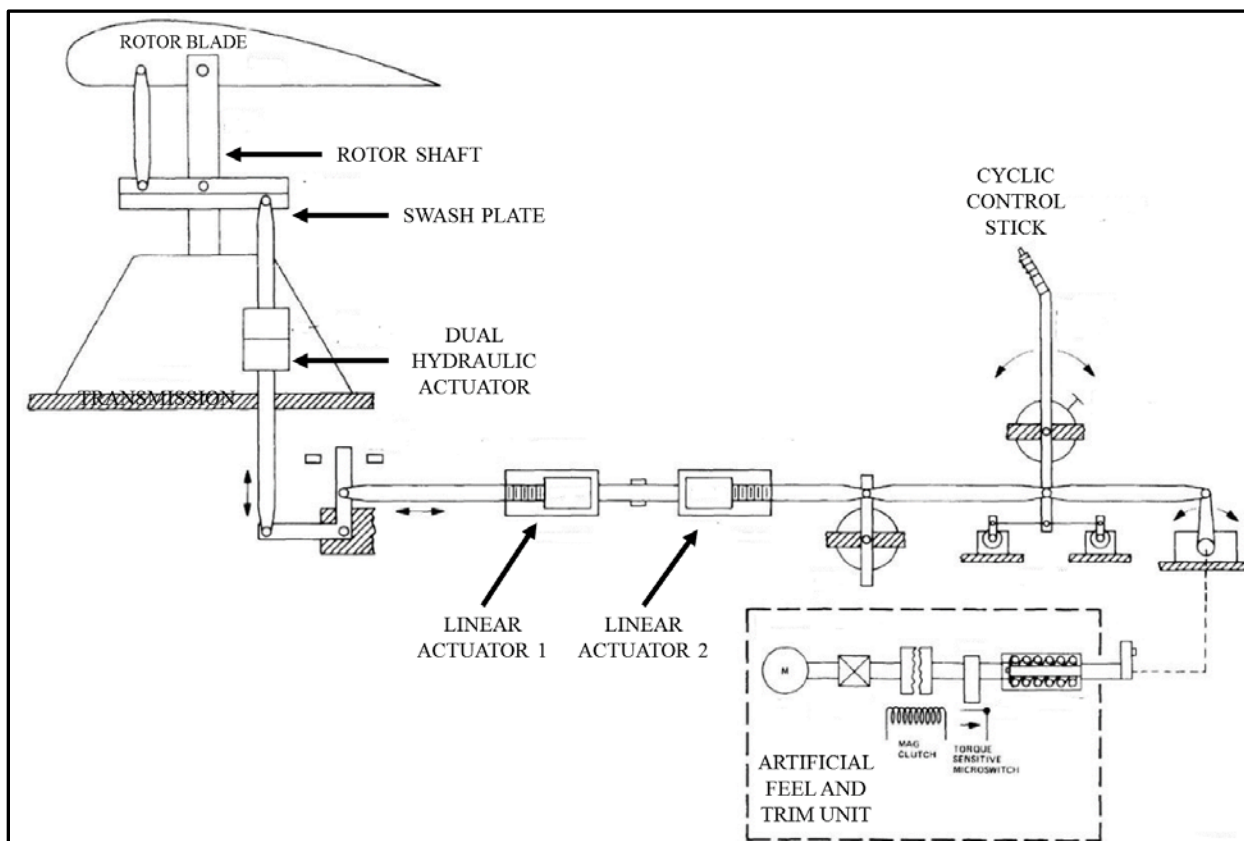


Figure 11 Schematic showing the location of the linear actuators in the control system



As previously stated, the pitch, roll and yaw linear actuators were removed from the helicopter on April 24, 2017, at the Wentworth Aircraft hangar at Airlake Airport (LVN), Lakeville, MN. The actuators were shipped to the Honeywell facility located in Boyne City, MI and examined on August 16 and 17th 2017. Reference Figure 12.

Figure 12 - Linear Actuators at Honeywell



D.7.3.1 Yaw Linear Actuator:

The visual inspections revealed that the yaw actuator, P/N 4012373-905, S/N 0506H036, was intact, three plastic zip ties (white) were observed attached to the outside of the unit, all safety wire remained present and intact, a “Honeywell” quality seal remained intact and covering the safety wire between the shear bolts in one location, the grommet for the wiring harness was cracked, gray paint was observed on a portion of the unit and no corrosion or bent pins was observed on the electrical connector. All shear bolts (6) appeared to be undamaged; there was no visual evidence of a fracture.

It was noted that the rear housing to ballscrew key for ballscrew anti-rotation, key P/N MS16555-618 was found protruding out from the unit. The housing material holding the pin in its location exhibited shearing and overload deformation, allowing the pin to protrude from the end of the housing by 0.050”.

Figure 13 Yaw actuator

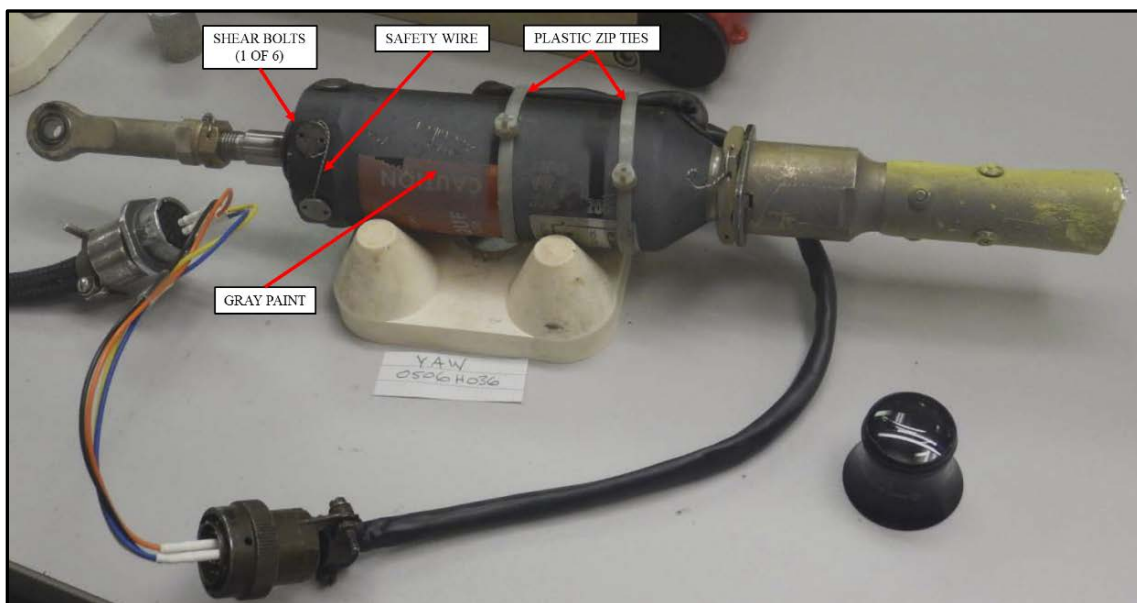
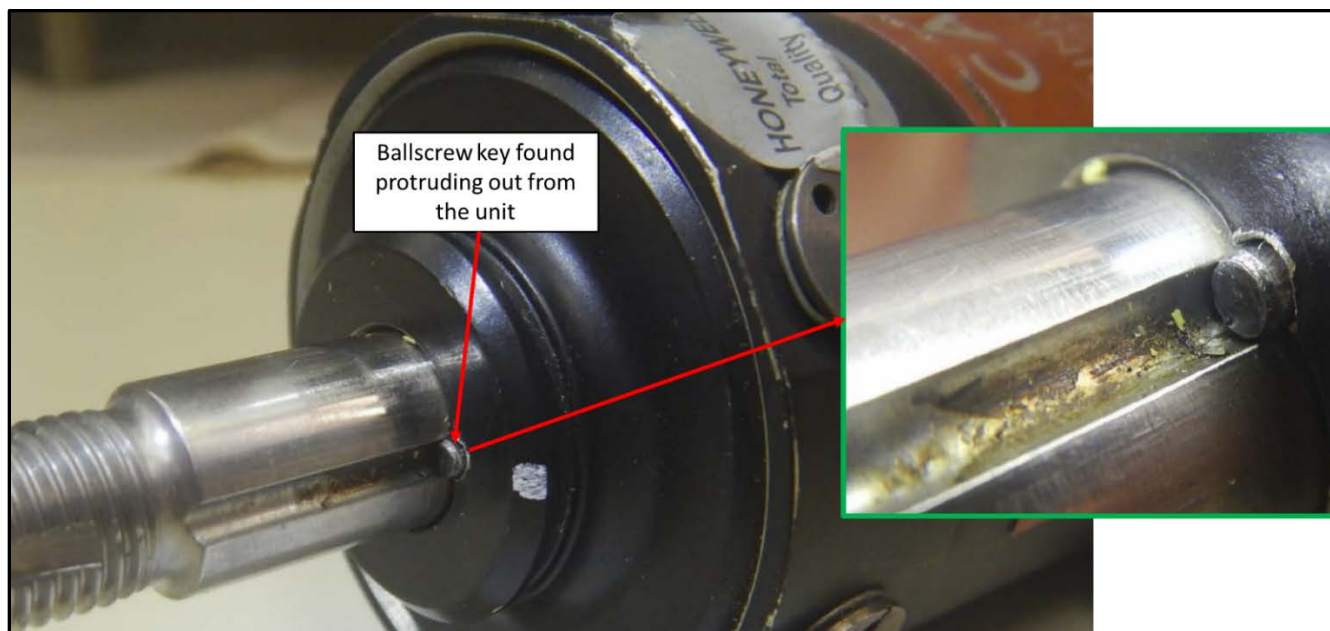
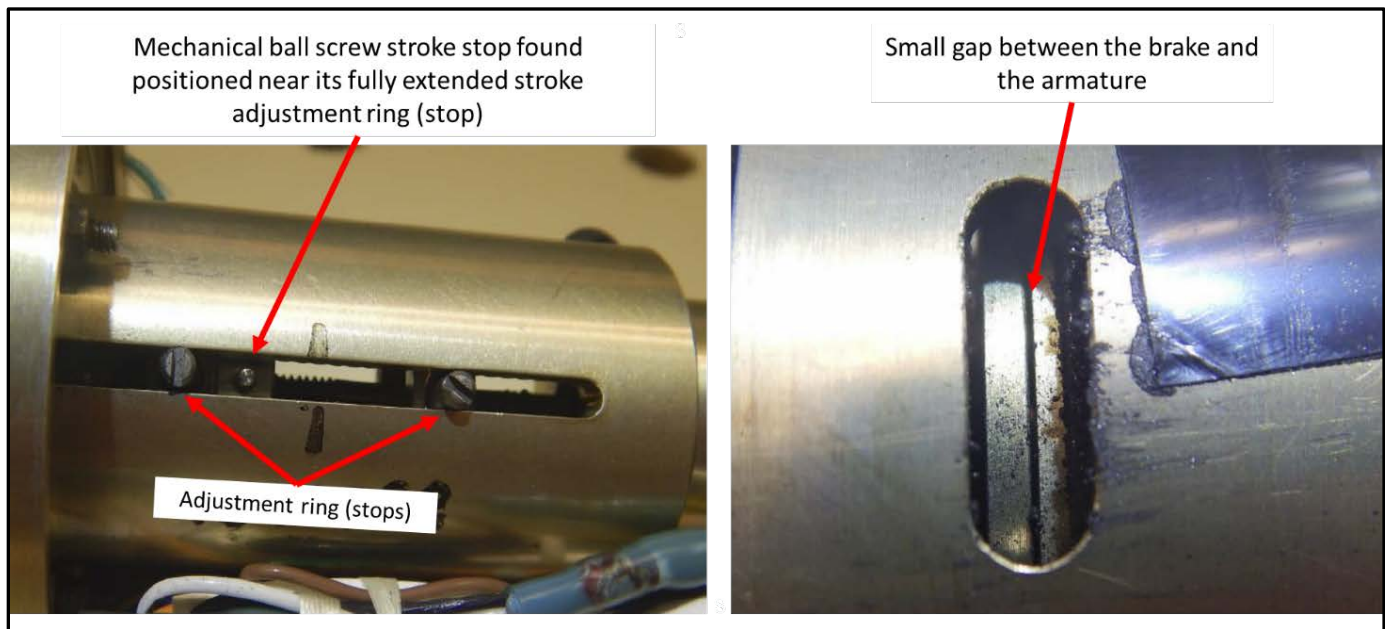


Figure 14 Photograph of ballscrew key



As shown in Figure 15, after removing the actuators housing, the mechanical ball screw stroke stop was found positioned near its fully extended stroke adjustment ring (stop). A small gap between the brake and the armature was observed, however, a minimum shim gap tool (0.025) could not be inserted between them.

Figure 15 Ballscrew and brake position



Power (24v) was applied to the brake and the brake/armature moved forward fully closing the gap and disengaging the brake; when power was removed, the brake/armature moved aft opening the gap and engaging the brake.

Power (22v) was applied to the motor to see if the motor would operate; the motor would not rotate in either the extend or retract position. A slight movement could be felt by hand when touching the motor housing when the direction (fore/aft) of the motor was changed. With the brake armature in either position (fore/aft), the motor could not be rotated to extend or retract the ball screw.

In order to investigate why the ball screw would not operate the circuit board was removed (desoldered) from the unit and the rear housing motor assembly was removed from the unit. Visual inspection found that the motor brush blocks were heavily worn and the ballnut was seized on the ballscrew (ballnut could not be rotated by hand). Score marks were observed on one side of the ball screw shaft key⁴.

No score marks were evident on the other face of the key way slot (left side when viewed as above). An axial load was applied to the ball screw and pliers were used to twist the ballnut to free the jammed condition. Once freed, the ballnut would move freely along the length of the ball screw. The rotation of the ballnut was rough and noisy.

The units front and rear housings were re-assembled and the brake and motor were electrically verified to function. The ballscrew would operate to both its full extend and retract stops. A final ATP was not performed due to the disassembly of the unit.

⁴ When looking down the end of the shaft with the threads of the shaft towards you, with the shaft key way slot facing up, the score marks were on the inside of the right face of the key way slot.

D.7.3.2 Roll Linear Actuators:

D.7.3.2.1 Left Roll Actuator:

The visual inspections revealed that the left roll actuator was intact, two plastic zip ties (white) were intact and were observed attached to the outside of the unit, all safety wire remained present and intact, the “FirstMark” quality seal remained intact and covering the safety wire between the shear bolts in one location, and no corrosion or bent pins was observed on the electrical connector. All shear bolts (6) appeared to be undamaged; there was no visual evidence of a fracture. The unit was identified as follows:

- P/N: 4012373-909 Model (SM-710)
- S/N: 05066993
- Mod: H,J,L,M,N,P
- Final Test: 06-23-2005

After removing the actuators housing, the mechanical ball screw stroke stop was found positioned up against its fully retracted stroke adjustment ring (stop). A minimum shim gap tool (0.027) could be loosely inserted between the brake armature and the coil.

Note: Normally, when the power is removed from the actuator, the brake is applied to stop rotation of the ballscrew. When unpowered, there normally is a gap of about 0.025” minimum between the brake and the armature. When power is applied, the armature is pulled to the magnet, the brake is disengaged (free to rotate the motor), and the gap is minimum/none.

Power (22v) was applied to the motor with the brake engaged and the motor operated, but would not rotate in either the extend or retract direction. A slight movement could be felt by hand when touching the motor housing and a slight movement could be seen when the direction (fore/aft) of the motor was changed.

Power (24v) was applied to the brake and the brake/armature moved forward closing the gap and disengaging the brake; when power was removed, the brake/armature moved aft opening the gap and engaging the brake. With the brake power applied (brake disengaged), the ball screw shaft could be moved in and out by hand. With power (24v) applied to the motor, the ball screw shaft was able to be operated to its full extend and retract stops.

The cover (housing) and all 6 shear bolts were re-installed onto the unit. The unit was then subjected to and passed its Acceptance Test Procedure (ATP). The unit was not disassembled.

D.7.3.2.2 Right Roll Actuator:

The visual inspections revealed that the right roll actuator was intact, no plastic zip ties were observed attached to the outside of the unit, all safety wire remained present and intact, the “FirstMark” quality seal remained intact and covering the safety wire between the shear bolts in one location, the grommet for the wiring harness was cracked, and no corrosion or bent pins was observed on the electrical connector. All shear bolts (6) appeared to be undamaged; there was no visual evidence of a fracture. The unit was identified as follows:

- P/N: 4012373-909 Model (SM-710)
- S/N: 05056894
- Mod: H,J,L,M,N,P
- Final Test: 5-13-2005

After removing the actuators housing, the mechanical ball screw stroke stop was found positioned approximately 0.01 inch from the fully extended stroke adjustment ring (stop). A minimum shim gap tool (0.027) could be loosely inserted between the brake armature and the coil.

Power (22v) was applied to the motor with the brake engaged and the motor operated, but would not rotate in either the extend or retract direction. A slight movement could be felt by hand when touching the motor housing and a slight movement could be seen when the direction (fore/aft) of the motor was changed.

Power (24v) was applied to the brake and the brake/armature moved forward closing the gap and disengaging the brake; when power was removed, the brake/armature moved aft opening the gap and engaging the brake. With the brake power applied (brake disengaged), the ball screw shaft could be moved in and out by hand. With power (24v) applied to the motor, the ball screw shaft was able to be operated to its full extend and retract stops. During motor operation, the unit sounded louder than expected.

The cover (housing) and all 6 shear bolts were re-installed onto the unit. The unit was then subjected to and passed its Acceptance Test Procedure (ATP). The unit was not disassembled.

D.7.3.3 Pitch Linear Actuators:

D.7.3.3.1 Left Pitch Linear Actuator:

The visual inspections revealed that the left pitch actuator was intact, one plastic zip tie (white) was intact and was observed attached to the outside of the unit, all safety wire remained present and intact, the "FirstMark" quality seal remained intact and covering the safety wire between the shear bolts in one location, the wiring harness grommet was broken and no corrosion or bent pins was observed on the electrical connector. All shear bolts (6) appeared to be undamaged; there was no visual evidence of a fracture. The unit was identified as follows:

- P/N: 4012373-908 Model (SM-710)
- S/N: 04066217
- Final Test stamp sticker: 06-29-2004

After removing the actuators housing, the mechanical ball screw stroke stop was positioned about (0.045 inch) from the full extend stroke adjustment ring (stop). A minimum shim gap tool (0.027) could be loosely inserted between the brake armature and the coil.

Power (22v) was applied to the motor with the brake engaged and the motor operated, but would not rotate in either the extend or retract direction. A slight movement could be felt by hand when touching the motor housing and a slight movement could be seen when the direction (fore/aft) of the motor was changed.

Power (24v) was applied to the brake and the brake/armature moved forward closing the gap and disengaging the brake; when power was removed, the brake/armature moved aft opening the gap and engaging the brake. With the brake power applied (brake disengaged), the ball screw shaft could be moved in and out by hand. With power (24v) applied to the motor, the ball screw shaft was able to be operated to its full extend and retract stops.

The cover (housing) and all 6 shear bolts were re-installed onto the unit. The unit was then subjected to and passed its Acceptance Test Procedure (ATP). The unit was not disassembled.

D.7.3.3.2 Right Pitch Linear Actuator:

The visual inspections revealed that the right pitch actuator was intact, two plastic zip ties (black) were observed attached to the outside of the unit, all safety wire remained present and intact, the “FirstMark” quality seal remained intact and covering the safety wire between the shear bolts in one location, the grommet for the wiring harness was cracked, and no corrosion or bent pins was observed on the electrical connector. All shear bolts (6) appeared to be undamaged; there was no visual evidence of a fracture. The unit was identified as follows:

- P/N: 4012373-908 Model (SM-710)
- S/N: 90078694
- No Final Test date sticker

After removing the actuators housing, the mechanical stroke stop was approximately 0.01 inches from the fully extended stroke adjustment ring (stop). A minimum shim gap tool (0.027) could be loosely inserted between the brake armature and the coil.

Power (22v) was applied to the motor with the brake engaged and the motor operated, but would not rotate in either the extend or retract direction. A slight movement could be felt by hand when touching the motor housing and a slight movement could be seen when the direction (fore/aft) of the motor was changed.

Power (24v) was applied to the brake and the brake/armature moved forward closing the gap and disengaging the brake; when power was removed, the brake/armature moved aft opening the gap and engaging the brake. With the brake power applied (brake disengaged), the ball screw shaft could be moved in and out by hand. With power (24v) applied to the motor, the ball screw shaft was able to be operated to its full extend and retract stops. During motor operation, the unit sounded louder than expected.

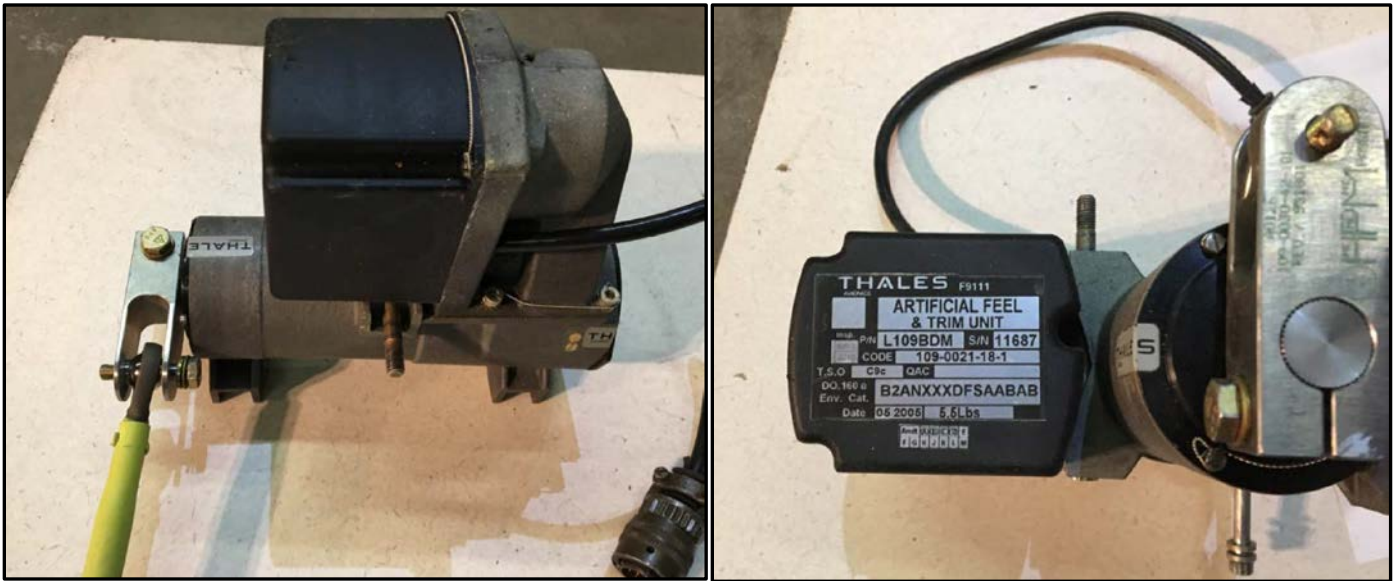
The cover (housing) and all 6 shear bolts were re-installed onto the unit. The unit was then subjected to and passed its Acceptance Test Procedure (ATP). The unit was not disassembled.

D.7.4 Artificial Feel & Trim Actuator - Roll:

As previously stated, the roll force/feel trim actuator, S/N 11687, was removed from the helicopter on April 24, 2017 at the Wentworth Aircraft hangar at Airlake Airport (LVN), Lakeville, MN. Reference Figure 16. The actuator was shipped to the Thales Italia S.p.A, located in Vergiate, Italy for examination.

On July 14, 2017, visual examination and functional testing were conducted on the actuator by Thales in the presence of a representative from Leonardo Helicopters. Results of the examination showed that there were no mechanical or electrical malfunctions with the actuator and that it passed its acceptance testing.

Figure 16 Artificial feel & trim unit as photographed at the wreckage facility



D.7.5 Helipilot Computers:

The helicopter was equipped with two Helipilot computers having part number 1010063A03-00AD and serial numbers 0668 and 0669. Reference Figure 17 and 18. Both computers were removed from the helicopter on April 24, 2017 at the Wentworth Aircraft hangar. The units were then shipped to Leonardo Airborne and Space Systems located in Nerviano (MI), Italy for examination.

Figure 17 Helipilot computers as photographed at the wreckage facility



Figure 18 Photograph of the front of the Helipilot computers showing their identification tags



On July 18, 2017, the examination of both Helipilot computers was conducted by UTC Aerospace Systems in the presence of representatives from the ANSV, and Leonardo Helicopters.

D.7.5.1 Examination of Helipilot Computer S/N 0668 at UTC Aerospace Systems:

D.7.5.1.1 Visual Inspection:

A visual inspection of the exterior of the computer revealed that the case assembly was structurally deformed in several locations. To gain access to the interior of the unit for inspecting the integrity of the circuit card assemblies, the computer's cover assembly was removed. After it was removed, inspection revealed that the YAW circuit card was unmated from the connector of the mother board (MB) due to the mechanical deformation of the chassis; the other circuit cards (ROLL, PITCH & GAIN) remained properly connected to the MB. The four circuit cards were removed from the computer and placed on the table to perform a more detailed visual inspection. This inspection did not identify any significant mechanical damage, electrical or burn failures of the components located on the circuit boards or with the circuit boards.

D.7.5.1.2 Functional Testing:

Prior to performing functional testing on the computer, power-on and power verification checks were performed to check the integrity of the computer and its circuits. These checks found that the all circuits were within specification according to the Integrated Test Specification document⁵.

⁵ Reference Integrated Test Specification document IT4025008-928 Rev. B.
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A test was then performed to verify the control of the "Servo Amplifiers" output signal from the actuator. This test did not show any anomalies and the detected data were in accordance with Integrated Test Specification requirements.⁶

Testing was then performed that simulated the computer installed in the helicopter. The purpose of these tests was to check that the computer provided the correct command signal to position the linear actuators (pitch, roll, and yaw) when the computer received signals from the pitch/roll gyroscope or the rate gyro. To perform this test, the respective gyroscope was manually moved in two directions for each axis (pitch, roll, and yaw). The tests performed were successful and all "channels" (pitch, roll, and yaw) worked properly.

Based on the results of the testing, computer, S/N 0668, was found without any functional problems.

D.7.5.2 Examination of Helipilot computer S/N 0669 at UTC Aerospace Systems:

D.7.5.2.1 Visual Inspection at UTC Aerospace Systems:

A visual inspection of the exterior of the unit revealed that the chassis and cover assembly had sustained more damage, especially in the area of mother board, than the chassis and cover of computer S/N 0668. To gain access to the interior of the unit for inspecting the integrity of the circuit card assemblies, the computer's cover assembly was removed. After removing the cover, it was revealed that the computer contained debris of various kind (stones / dirt / twigs) inside it. In addition, with the exception of the GAIN card, the YAW, PITCH and ROLL cards were found unmated from the mother board due to the mechanical deformation of the chassis.

The four circuit cards were removed from the computer and placed on the table to perform a more detailed visual inspection. An inspection of the YAW circuit card revealed that it exhibited extensive physical damage; it contained many broken components and its circuit board was found "cracked" near the screw attachment locations. A component on the ROLL circuit card had a small case dent (compatible with the accident). None of the four cards had evidence of electrical or burn damage on their components or circuit boards.

Due to the damage to the chassis and to the YAW circuit card, the investigation team decided to only perform functional testing on the ROLL and GAIN cards by using an exemplar chassis assembly.

D.7.5.2.2 Functional Testing:

The ROLL and GAIN circuit cards were inserted into an exemplar chassis (which included PITCH and YAW circuit cards) and the chassis was installed onto the test bench.

Prior to performing functional testing on the computer (specifically the ROLL and GAIN circuit cards), power-on and power verification checks were performed to check the integrity of the computer and its circuits. These checks found that the all circuits were within specification according to the Integrated Test Specification document⁷.

⁶ Reference step 5.11 of Integrated Test Specification document IT4025008-928 Rev. B.

⁷ Reference Integrated Test Specification document IT4025008-928 Rev. B.

A test was then performed to verify the control of the "Servo Amplifiers "output signal from the actuator. This test did not show any anomalies and the detected data were in accordance with Integrated Test Specification requirements.⁸

Testing was then performed that simulated the computer installed in the helicopter. The purpose of these tests was to check that the computer provided the correct command signal to position the linear actuators (pitch, roll, and yaw) when the computer received signals from the pitch/roll gyroscope or the rate gyro. To perform this test, the respective gyroscope was manually moved in two directions for each axis (pitch, roll, and yaw). The tests performed were successful and all "channels" (pitch, roll, and yaw) worked properly.

Based on the results of the testing, the ROLL channel of computer, S/N 0669, was found without any functional problems.

D.7.6 Examination of Flight Director Computer at UTC Aerospace Systems:

The helicopter was equipped with one P/N 1010067A01-00AA, S/N 0020, flight director computer. The computer was removed from the helicopter on April 24, 2017 at the Wentworth Aircraft hangar. The computer was shipped to Leonardo Airborne and Space Systems located in Nerviano (MI), Italy for examination. Reference figure 19.

Figure 19 Flight director computer as photographed at the wreckage examination



⁸ Reference step 5.11 of Integrated Test Specification document IT4025008-928 Rev. B.
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On July 18, 2017, an examination was conducted on the Helipilots by UTC Aerospace Systems in the presence of representatives from the ANSV, and Leonardo Helicopters.

An external visual inspection of the exterior of the unit revealed that the cover assembly and chassis were heavily damaged and deformed. The removal of the cover was particularly difficult; it had to be opened with some force (also by using a shear to cut the heads of the attachment screws). Once removed, a visual inspection of the interior of the unit revealed the circuit cards were also damaged.

The circuit cards were removed from the unit and placed on a table to perform a more detailed visual inspection: the inspection showed considerable mechanical damage to the components located on all of the circuit cards. However, none of the circuit cards had evidence of electrical or burn damage on their components.

Based on the inspection of the circuit cards and the chassis, the investigative team agreed not to perform a functional test on the unit or individual circuit cards.

D.7.7 Main Rotor Actuators:

The three (red, blue, and yellow) main rotor actuators were removed from the helicopter on April 24, 2017 at the Wentworth Aircraft hangar. All three actuators were shipped to their manufacturer, UTC Aerospace Systems, located in Brugherio, Italy for examination and functional testing. Reference Figures 20 and 21.

On July 19, 2017, visual examination and functional testing were conducted on the actuators by UTC Aerospace Systems in the presence of representatives from the ANSV, EASA, and Leonardo Helicopters.

Figure 20 Identification labels for the three actuators



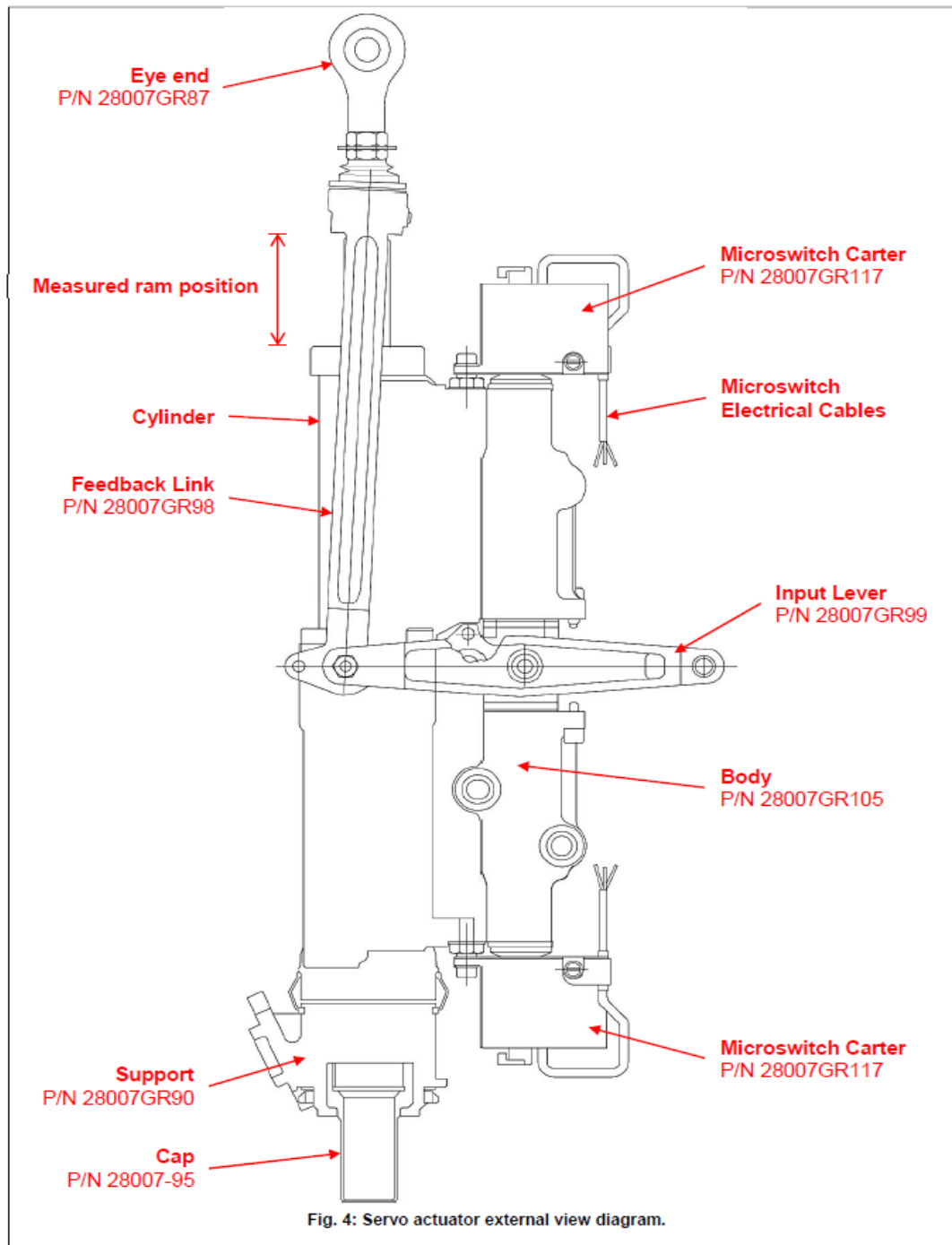
Figure 21 Main rotor actuators - at the wreckage examination



D.7.7.1 Visual Inspections of Actuators at UTC:

After removing the actuators from their shipping container, a thorough visual inspection was performed on each of the actuators in their “as received” condition. Reference Figure 22 and 23. A varying level of dirtiness (both soil and hydraulic fluid⁹) was observed on their external surfaces. As received, the three servo actuators remained connected with their electrical cables¹⁰. The results of this visual inspection are provided in Table 7.

Figure 22 Schematic of a main rotor actuator



⁹ The actuators were shipped from Wentworth without a protective cap on the hydraulic ports of each actuator.

¹⁰ To remove the three main rotor actuators from the helicopter, a few electrical wires had to be cut.

Figure 23 Visual inspection of the unit's S/N 4006 (left image), 6021 (center image) and 8011 (right image).



Table 7 Results of visual inspections

	Left actuator (red position) P/N 304-28007-00 S/N 4006	Right actuator (yellow position) P/N 305-28007-00 S/N 6021	Forward actuator (blue position) P/N 306-28007-00 S/N 8011
Missing parts	No missing parts were detected, apart from the red support identification label.	No missing parts.	No missing parts.
External damage	Two deep scrapes on the cap and a clear bending deformation of both Microswitch carters were observed. The eye-end was also contacting the spool end	Two deep scrapes on the fixed-end valve body were observed. In addition, a plastic deformation of the fixed end Microswitch carter was clearly visible	No external damages, apart from a clear bending deformation of the fixed-end Microswitch carter, which was contacting the spool end
Support conditions	Broken (support side lugs were missing).	Broken (support side lugs were missing). Also, the bent teeth of the lock washer were either clearly deformed or broken due to a sudden over torque and rotation between the locked parts	No significant damage observed.
Lock wire	All present.	All present.	All present.
Input lever functionality	No jamming detected. Lever movement was free along the entire spool stroke but with an input force slightly higher than usual.	No jamming detected. Lever movement was free and smooth along the entire spool stroke.	No jamming detected. Lever movement was free along the entire spool stroke but with an input force slightly higher than usual.
Ram	No deformations of The eye end, ram, cylinder or outer glands were observed. Piston position: approximately 67% (72.9 mm) of the stroke.	No deformations of The eye end, ram, cylinder or outer glands were observed. Piston position: fully retracted .	No deformations of The eye end, ram, cylinder or outer glands were observed. Piston position: approximately 30% (34.4 mm) of the stroke.

D.7.7.2 Supports:

D.7.7.2.1 Visual Examination:

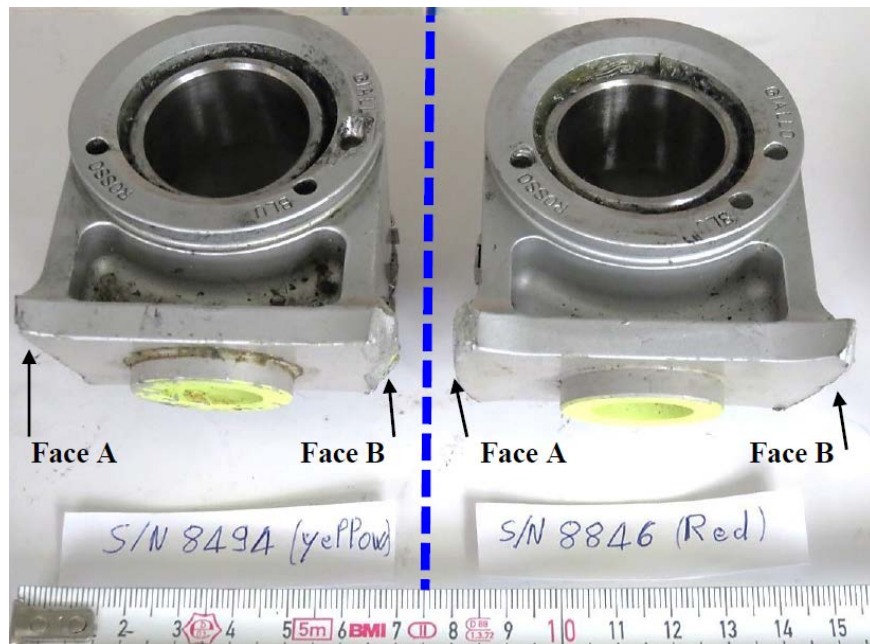
A visual examination of the broken support assemblies (Red and Yellow actuators) revealed that the surface of the fractures had the appearance of a static failure due to a sudden overload.

The two broken supports were subjected to a dedicated investigation at Leonardo Helicopter (LHD) facilities, to confirm the type of failure (fatigue or static rupture). Based on this, the supports of the servo actuators S/N 4006 and 6021 were delivered to LHD at the end of the main rotor actuator investigation. It should be noted that the broken lugs of the supports were not included in the received package and consequently will not undergo examination at LHD.

D.7.7.2.2 Fractographic Examination:

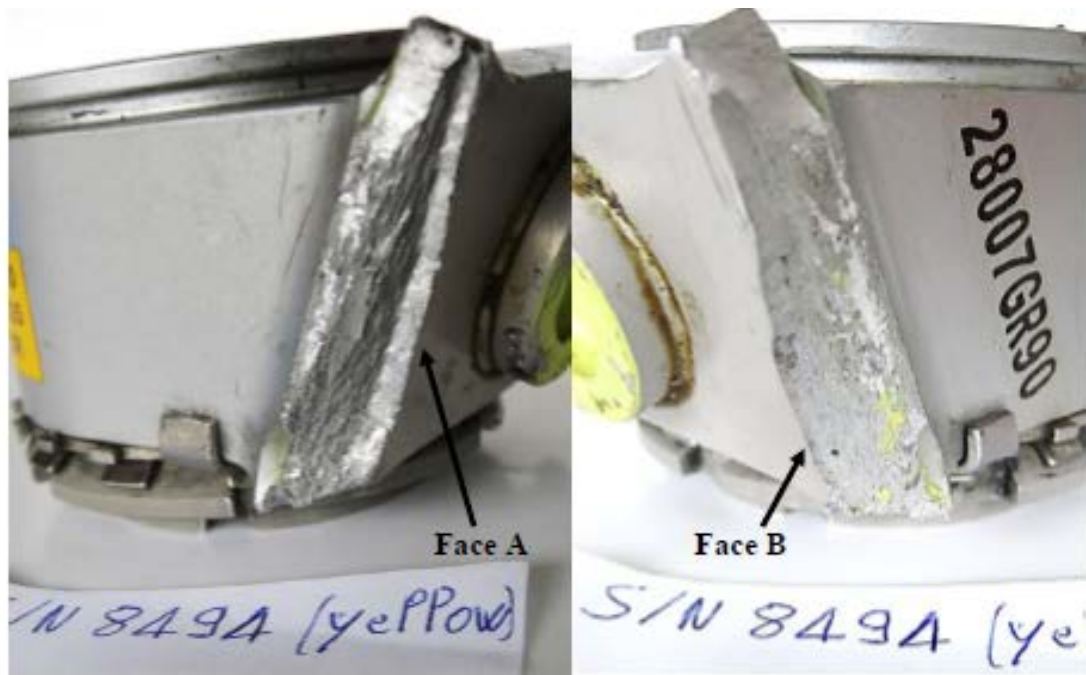
According to a report, dated 9/26/2017, from Leonardo Helicopter, the scope of their investigation was to determine the type of fracture morphology (fatigue or overload) that was present on the fracture surfaces of the wings that were found broken on the Yellow (S/N 8494 with 609.3 flight hours) and Red (S/N 8846 with 113.6 flight hours) main rotor servo actuator attachments removed from the A109S S/N 22014 R/M N91NM. Reference Figure 24.

Figure 24 View of the two main rotor actuator attachments as arrived in Leonardo's laboratory

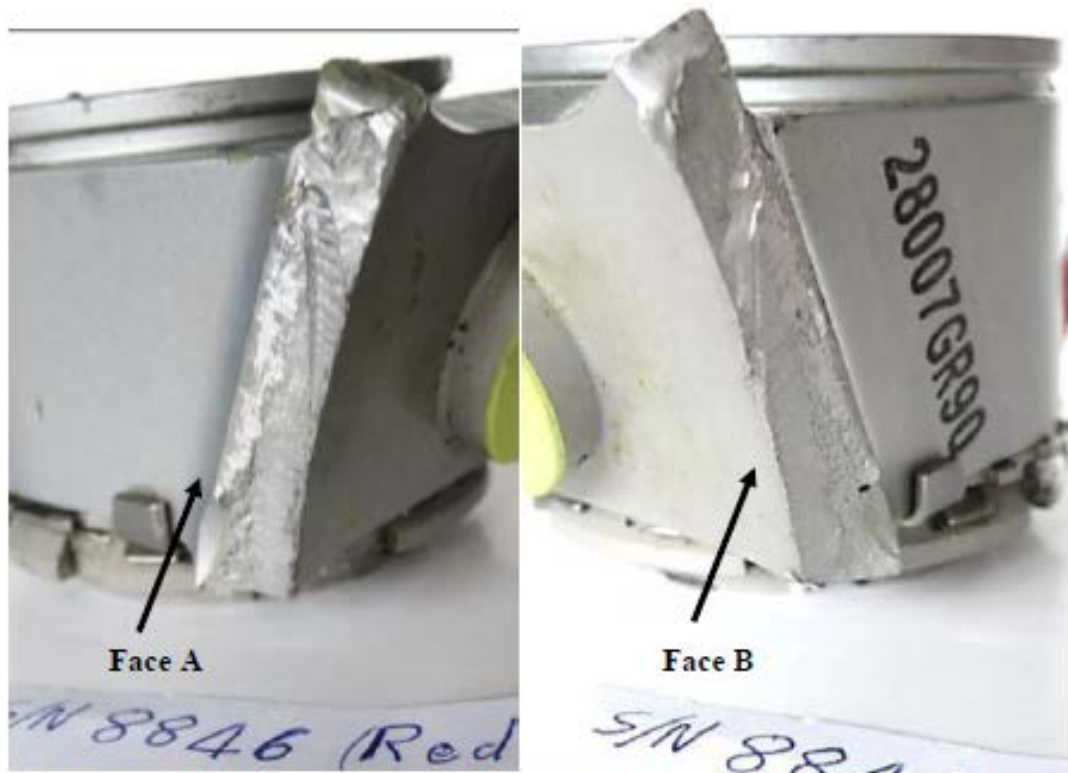


The macroscopic aspect of the four fracture surfaces were characterized by sliding of the material with significant roughness aspect of the same fracture surfaces. Reference Figure 25. The S.E.M. investigations conducted in a central zone for every fracture surface, evidenced that the modality of the cracks is by overload as indicated by the presence of dimples. Reference Figure 26.

Figure 25 photos of yellow and red support surfaces

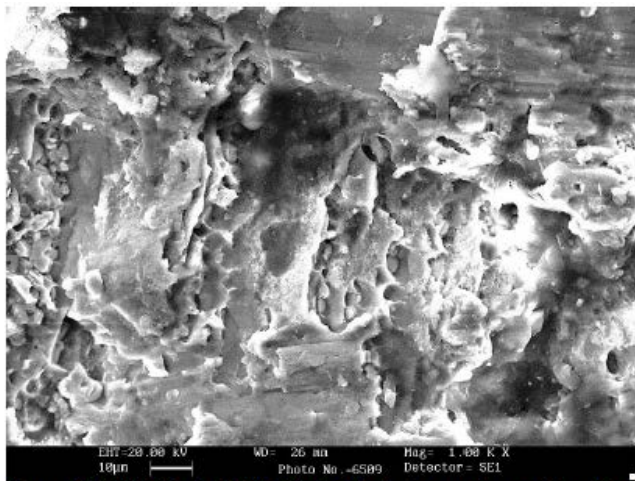


Picture n°2 S/N 8494 (Yellow) View of the Face A and B (named in laboratory for identification)

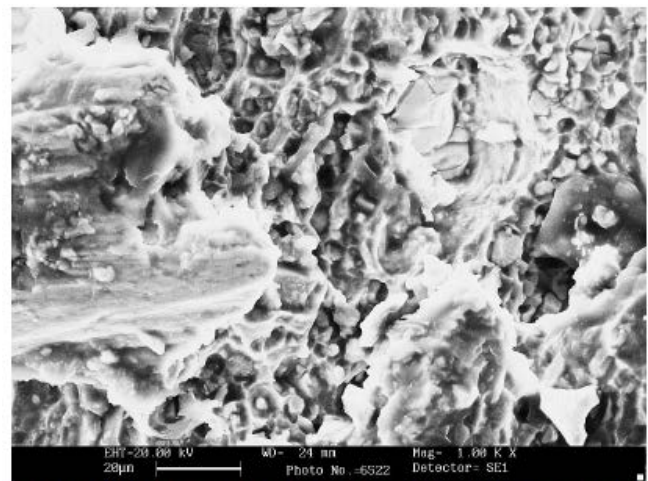


Picture n°3 S/N 8846 (Red) View of the Face A and B (named in laboratory for identification).

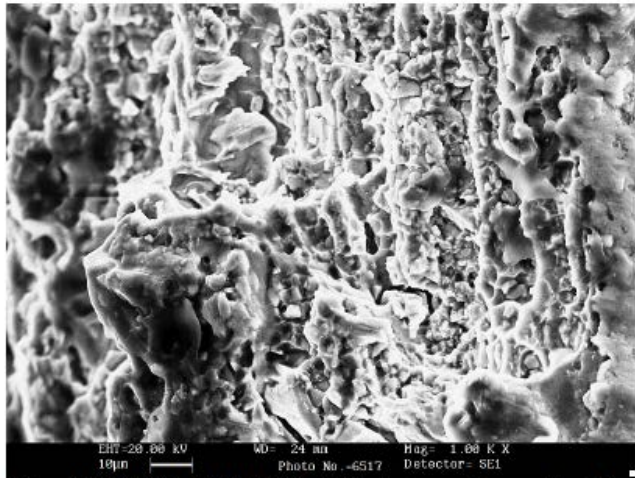
Figure 26 SEM photos of yellow and red support surfaces



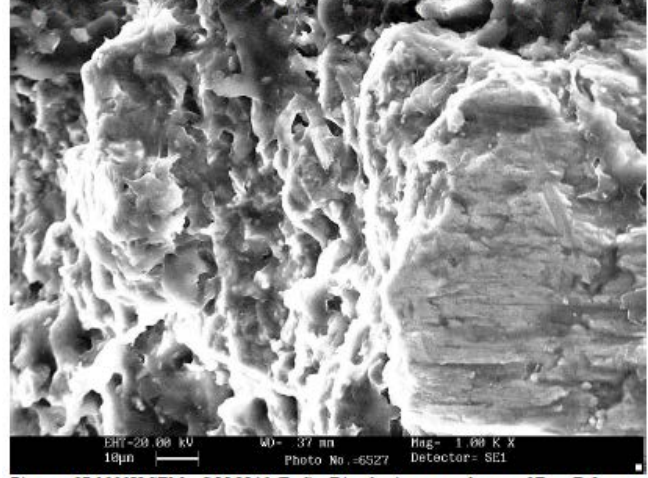
Picture n°4 1000X SEM S/N 8494 (Yellow) - Dimples in a central zone of Face A fracture.



Picture n°6 1000X SEM S/N 8846 (Red) - Dimples in a central zone of Face A fracture.



Picture n°5 1000X SEM S/N 8494 (Yellow) - Dimples in a central zone of Face B fracture.



Picture n°7 1000X SEM S/N 8846 (Red) - Dimples in a central zone of Face B fracture.

D.7.7.3 Pre-Functional Testing:

Prior to installing an actuator on the test bench, its cap, support and its spherical joint which was located on the fixed side of the actuator had to be removed. The breakout torque of the cap, which should be 30 - 45 Nm, and the oscillation torque of the spherical joint, which should be 8.8 - 10.3 Nm, were recorded during the support disassembly phase. The results of the disassembly are provided in Table 8.

Table 8 Results of support examination

	Left actuator (red position) P/N 304-28007-00 S/N 4006	Right actuator (yellow position) P/N 305-28007-00 S/N 6021	Forward actuator (blue position) P/N 306-28007-00 S/N 8011
Cap breakout torque [30 - 45 Nm]	Negligible (out of tolerance)	Negligible (out of tolerance)	Slightly lower than expected
Spherical joint oscillation torque [8.8 - 10.3 Nm]	No anomalies	~20.6 Nm (out of tolerance)	No anomalies

D.7.8 Functional Testing:

Functional tests were performed according to the applicable procedure NC 745-3 Issue 5, to check each unit's functionality and to determine the need for fault isolation and disassembly. Testing was performed with hydraulic fluid as per MIL-PRF-5606, at a temperature ranging from 36°C to 38°C.

The following is a brief description of the tests that were performed:

- **Initial operating cycles:**
Some full-stroke cycles were performed with the supply pressure initially limited to ~10 bar (~145 psi) for safety reasons, the pressure was then increased to ~50 bar (725 psi) and finally up to the actuator's nominal operating pressure of 103 bar (1,500 psi), with both hydraulic systems pressurized.
- **Single-system operations:**
Correct functionality of the two hydraulic sections verified by means of some operating cycles at nominal pressure (103 bar or 1500 psi) supplied to system 1 only, then repeating the test with pressure supplied to system 2 only.
- **Operating Cycles** (as per ATP, paragraph. 3.7.):
25 full-stroke cycles at nominal pressure (103 bar or 1500 psi), with both hydraulic systems pressurized. Requirements:
 - Smooth and linear movement, free from any hard sliding or jamming;
 - Leaks: ≤ 1 drop from outer glands and ≤ 2 drops from central glands in 25 cycles.
- **Internal Leakage** (as per ATP, paragraph. 3.8.2.):
Two sections individually tested for internal leakage at nominal pressure (103 bar or 1,500 psi), with the control valve in neutral position, then commanding an extension and a retraction of the ram with the control valve fully open.
- **Input Load** (as per ATP, paragraph. 3.9.1.)
Measurement of the force on the input lever required to make the ram start moving at nominal pressure (103 bar or 1500 psi). Requirement: $0.0 \leq 0.6 \text{ kg}$ ($\leq 1.32 \text{ lbf}$).

According to UTC Aerospace Systems, each of the three actuators completed and passed the tests listed above. For this reason, disassembly of the units was not performed. The results of the functional testing are provided in Table 9.

Table 9 Results of functional testing

	Left actuator (red position) P/N 304-28007-00 S/N 4006	Right actuator (yellow position) P/N 305-28007-00 S/N 6021	Forward actuator (blue position) P/N 306-28007-00 S/N 8011
Initial operating cycles with supply pressure limited to ~10 bar, then ~50 bar, then 103 bar. (both hyd. systems pressurized).	- Ram movement was smooth and linear. - Ram speed was normal. - Piston stroke was fully covered. - No external leakage observed.		
Operating cycles with a pressure of 103 bar supplied to system 1 only, then to system 2 only.	Same as above		
Operating Cycles as per ATP, para. 3.7. Requirements: ≤ 1 drop/25 cycles from outer glands ≤ 2 drops/25 cycles from central glands	Compliant Measured central glands leakage was 2 drops/25 cycles.	Compliant Measured central glands leakage was < 1 drop/25 cycles.	Compliant Measured central glands leakage was < 1 drop/25 cycles.
System 1 Internal Leakage as per ATP, para. 3.8.2.1.	Compliant Neutral: 44 cm ³ /min Extended: 50 cm ³ /min Retracted: 18 cm ³ /min <i>Required ≤ 230 cm³/min</i>	Compliant Neutral: 55 cm ³ /min Extended: 20 cm ³ /min Retracted: 17 cm ³ /min <i>Required ≤ 230 cm³/min</i>	Compliant Neutral: 34 cm ³ /min Extended: 38 cm ³ /min Retracted: 18 cm ³ /min <i>Required ≤ 230 cm³/min</i>
System 2 Internal Leakage as per ATP, para. 3.8.2.2.	Compliant Neutral: 56 cm ³ /min Extended: 8 cm ³ /min Retracted: 24 cm ³ /min <i>Required ≤ 230 cm³/min</i>	Compliant Neutral: 44 cm ³ /min Extended: 18 cm ³ /min Retracted: 20 cm ³ /min <i>Required ≤ 230 cm³/min</i>	Compliant Neutral: 40 cm ³ /min Extended: 16 cm ³ /min Retracted: 20 cm ³ /min <i>Required ≤ 230 cm³/min</i>
Input Load as per ATP, para. 3.9.1. <i>Required ≤ 0.6 kg</i>	Extension: 1.13 kg Retraction: 1.28 kg After displacing the Microswitch carter to avoid any contact with the spool end: Extension: 0.32 kg Retraction: 0.28 kg	Within tolerance and not recorded. No hard sliding or excessive friction observed.	Extension: 0.94 kg Retraction: 1.20 kg After displacing the Microswitch carter to avoid any contact with the spool end: Extension: 0.35 kg Retraction: 0.41 kg

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