EXTENSIVE ANALYSIS OF HARDOVER AND TRIM-RUNAWAY FAILURES ON TLUH MATHEMATICAL MODEL BASED ON CS-29 REQUIREMENTS

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ABSTRACT

Flight control systems improve the handling qualities of helicopters based on their allowable control authority. However, in limited authority helicopters the control systems do not have high number of redundancy. Therefore, in the event of a flight control system failure a pilot must safely recover from the failure scenario. In such a case, the pilot should have enough time to react and recover back to the original flight condition. During the certifications process of a helicopter, failure scenarios should be demonstrated with piloted simulations and flight tests. Piloted tests consume too much time to analyze all the flight conditions that include control system failure. Therefore, desktop based simulation analyses can be conducted to determine the worst case regime and to obtain a statistical database related to control system failures. In this paper failure and actuator module that has been implemented is presented. Using implemented modules with an in-house development tool, actuator failure cases on TLUH based on Certification Specifications for Large Rotorcraft and Advisory Circular (CS/AC-29) are conducted. Results of the analyses are given in the final section. Results obtained from the piloted simulations conducted in system integration laboratory are compared with the results obtained from desktop based simulations.

1. NOTATION/ABBREVIATIONS

AFCS:	Automatic Flight Control System
cg:	Center of Gravity
FCC:	Flight Control Computer
KIAS:	Indicated Airspeed in Knots
Lat Cyc:	Lateral Cyclic Input
Lon Cyc:	Longitudinal Cyclic Input
LG_conf:	Landing Gear Configurations
MRA:	Main Rotor Actuator
SCAS:	Stability and Control Augmentation System
SerDetTime:	Servo Failure Detection Time
SIL	System Integration Laboratory
$t_{pilot:}$	Pilot Detection Time
TLUH	TAI Light Utility Helicopter
TOROS:	TAI Originated Rotorcraft Simulation
$V_{NE:}$	Never Exceed Speed
Δh:	Altitude Change
Δθ:	Body Pitch Angle Change
Δϕ:	Body Roll Angle Change
Δψ:	Body Yaw Angle Change
A:	Hydraulic piston area
B:	Viscous damping coefficient
c_v:	Flow coefficient
C_t:	Leakage coefficient
F_{ext}:	External force on the hydraulic actuator
K:	Bulk modulus of the hydraulic fluid
K_{ratio}:	Input- output ratio of the hydraulic actuator
M:	Mass on the hydraulic actuator
P_L:	Load pressure
P_s:	Supply pressure
Q_L:	Flow rate through the orifice
x_{plt}:	Pilot input to hydraulic actuator
V_t:	Volume of the cylinder chambers

2. INTRODUCTION

Turkish Light Utility Helicopter (TLUH) is being developed by Turkish Aerospace Industry Inc. TLUH has limited authority mechanical flight control system, four-axis autopilot, and dual-redundancy. In the control system, the actuator commands are divided into two channels by AFCS flight control computer (FCC) depending on their frequencies, high frequency ones for stability control augmented systems (SCAS) actuators, and low frequency ones for trim actuators.

TLUH is mathematically modelled with an in-house development tool (TOROS). Mathematical model constructed using TOROS is based on physical modelling of each rotorcraft structure individually in MATLAB-Simulink® environment. Complexity level of the model developed in TOROS allows it to be used for detailed prediction of whole flight envelope during the design phase. [1].

TOROS has capability of adding turbulence to flight simulations. Turbulence is modeled as disturbance input to collective, cyclic and pedal inputs; the methodology is adopted from turbulence models used in DLR [2]. During the failure test the effect of turbulence has been observed.

A failure module is implemented on TOROS to analyze possible failure modes. In this failure module, both SCAS failures and trim actuator failures can be injected. The failure modes that are modeled related to SCAS failures cover hardover, oscillation, and jam. Furthermore, the failure modes that are modelled related to trim actuator failures include trim-runaway, mismatch and jam.

In literature Batra N.N. et al. tested the hardover failure on Bell 214 piloted simulations. The aim was the investigation of pilot delay time and recovery techniques on helicopter response during hardover failure in AFCS [3]. Kalinowski K.F. et al. developed a pilot rating scale to evaluate the failure transients in fly-by-wire control system. Two piloted simulations conducted with hardover and slow-over failures which were injected on command path. According to degree of pilot effort Failure/Recovery rating scale developed [4]. Christensen K. et al. realized hardover failure on ARH-70A. Both simulations and flight tests have been conducted.to normalize pilot response time [5]. Hamers M. et al. have made runaway tests to define new flight-height envelope on EC135 research helicopter. By tuning the runaway limiter they have assessed the control authority of pilot [6].

The present study includes the analyses of hardover and trim-runaway failures on TLUH based on Certification Specifications for Large Rotorcraft and Advisory Circular (CS/AC-29) [7, 8]. During the analyses statistical approach is followed for turbulence effect and different flight conditions such as hover, forward flight, climb, and descent.

3. ACTUATOR MODULE

Actuator module includes SCAS, trim and main actuator mathematical models. The dynamics of each actuator and the relation between them are covered in this module. In total, there are three main rotor actuators attached to the non-rotating part of the swash plate and one tail rotor actuator attached to the slider shaft

Hydraulic Actuator

The hydraulic actuator system is modeled as a third order system based on [9] with a feedback link modification. Two states come from the movement of the output rod and one from pressure function between the chambers.

The flow rate through the orifice is controlled by the input and feedback rod;

(1) $$Q_L = c_v\sqrt{P_s - P_L}\,(x_{plt} - K_{ratio}y)$$

The rate of change of pressure is;

(2) $$\dot{P}_L = \frac{4K}{V_t}(Q_L - C_t P_L - A\dot{y})$$

The acceleration of the output rod is;

(3) $$\ddot{y} = \frac{(AP_L - B\dot{y} - F_{ext})}{m}$$

The equations are linearized around $x_{plt\,trim}$ and $P_{L\,trim}$

(4) $$\begin{Bmatrix} \dot{P}_L \\ \ddot{y} \\ \dot{y} \end{Bmatrix} = R \begin{Bmatrix} P_L \\ \dot{y} \\ y \end{Bmatrix} + Q x_{plt}$$

Where R and Q are as follows;

$$R = \begin{bmatrix} (-\frac{c_v}{2} x_{v\,trim}(P_s - P_{L\,trim})^{-\frac{1}{2}} - C_t)\frac{4K}{V_t} & -A\frac{4K}{V_t} & -c_v\sqrt{P_s - P_{L\,trim}}\frac{4K}{V_t}K_{ratio} \\ \frac{A}{m} & -\frac{B}{m} & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

(5) $$Q = \begin{bmatrix} c_v\sqrt{P_s - P_{L\,trim}}\frac{4K}{V_t} \\ 0 \\ 0 \end{bmatrix}$$

(6) $$x_{v\,trim} = (x_{plt\,trim} - K_{ratio}y_{trim})$$

It is found out that system consists of second order mode above 50 Hz and a first order mode around 5 Hz. An equivalent first order system with position and rate limit is generated for simulations. Rate limit is a function of force on the actuator.

The inputs are transformed to actuator axis from multi blade coordinates (MBC) before feeding into the block. Then, the outputs are transformed to MBC and sent to rotor modules. Mixing matrix for main rotor is generated based on positions of actuators with respect to swash plate center and positions of pitch links with respect to rotor hub center.

SCAS Actuator

On the main actuators there are dual redundant limited authority SCAS actuators. Actuators can be centered after the detection of the failure. These servos are modeled as second order systems with individual and common limits. Common limit guarantees the total contribution is within the limited authority. Individual limits are selected based on the desired response at failures. Wind-up logics to inner states are implemented in both limiting conditions.

Type of connection (series or parallel) is an option in the model. If servos are connected in parallel, common output is summation of all servos. Average of the actuators is fed as common output at serial connection.

Trim Actuator

Trim actuators are full authority low rate limited actuators that are driven by AFCS. Trim actuators control speed instead of position and provides position data with an angular resolver. Firstly, the resolver data was used to identify the dynamics of the servo. It was possible to get low frequency correlation and nonlinearities such as dead-zone. However, it was found to be too noisy even after filtering to estimate natural frequency. Hence, an external gyro is attached to get direct rate output. The model - test comparison with the illustration of the model is shown in Figure 1.

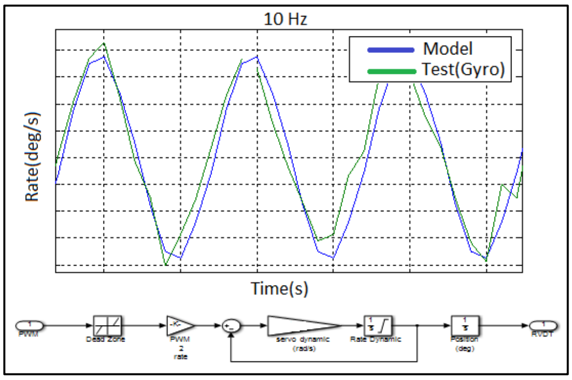

Figure 1 Parallel actuator model- test comparison

4. FAILURE MODULE

Failure module in TLUH mathematical model consists of SCAS actuator and trim actuator failure injection logic. SCAS actuators failure types include hardover, oscillation and jam. Among these failure types hardover is selected as the critical one. When compared to the other failure scenarios the frequency to encounter hardover failures is higher [10]. The hardover failure is injected to selected SCAS actuator in one channel. Both hardover directions can be simulated in analysis. When the hardover is recognized, the faulty actuator initiates center and lock procedure. The important point here is how flight characteristics are affected within the hardover recognition time.

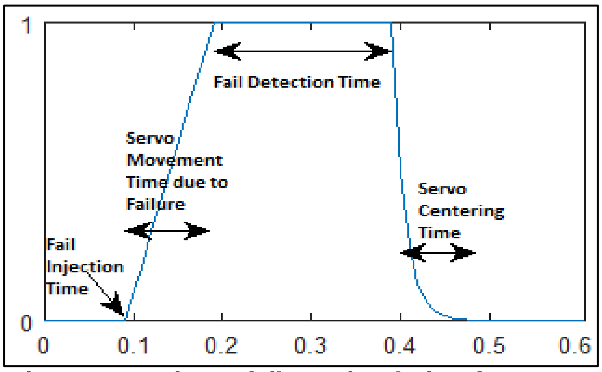

Figure 2 Hardover failure simulation for SCAS actuator

For trim actuator failures similar injection logic is implemented. Trim-runaway, mismatch and jamming failure types are covered in this failure module. Within these failure types trim-runaway is selected as the critical one. When trim-runaway failure occurs, full speed of trim actuator is fed to selected channel. Both trim-runaway directions are simulated in analysis. Piston movement due to trim-runaway failure continues and deviations in flight states accumulate until pilot reacts to this situation. The total response time of the pilot is determined according to attentiveness of the pilot with hands-on and hands-off situation [11].

5. FLIGHT CONDITIONS

The flight conditions are determined based on regimes which are indicated in CS-29-Appendix B IFR requirements. These flight regimes cover cruise, climb and descent conditions. Moreover, hover case is included to analyses. In this way, the selected conditions cover most of the usage spectrum of a helicopter.

Table 1 Flight Conditions for Actuator Failure

Flight Condition	KIAS	ALT
Hover	0	1000 ft
Forward Flight	80,100,120, 140,160	1000 ft
Climb	70,100,120	1000 ft with 1000 ft/min Climb rate [8]
Descend	70,100,120	1000 ft with 1000 ft/min Descend rate [8]

Table 2Weight-Cg Configuration

Weight	Center of Gravity
Min-Mid-Max	Max Aft-Max forward

The flight conditions given in **Table 1** with the weight-cg conditions including their corresponding inertia values given in **Table 2** are be analyzed.

6. COMPUTER SIMULATION RESULTS

Flight conditions and mass-cg configurations presented in previous section are analyzed for different turbulence for SCAS and trim actuator and different servo detection time for SCAS actuators. More than thousand cases have been simulated in computed environment. To be more precise SCAS actuator cases are; 12 Flight conditions, 5 mass-cg-inertia configurations, 4 SCAS actuators, 2 hardover directions, 2 different servo detection time, and 2 different turbulence conditions. Totally 1920 cases have been analyzed. Trim actuator cases are; 12 Flight conditions, 5 mass-cg-inertia configurations, 4 different channels, 2 trim-runaway directions and 2 turbulence conditions. Totally 960 cases have been analyzed. In order to represent all the cases, a simulation sample is given in **Figure 4**. In **Figure 4**, calculation procedures of error in roll, pitch, yaw angles and altitude are shown. These values have been used in elaborating the effects of turbulence and servo detection time values on failure tests.

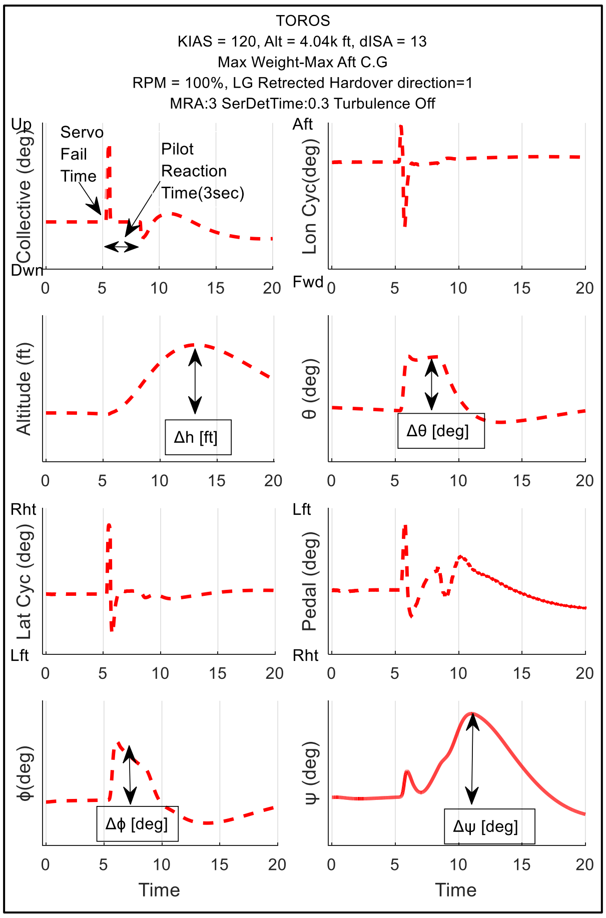

Figure 4 Third main rotor actuator hardover failure at 120 knot forward flight condition with maximum weight – aft c.g configuration in calm weather condition(Turbulence off)

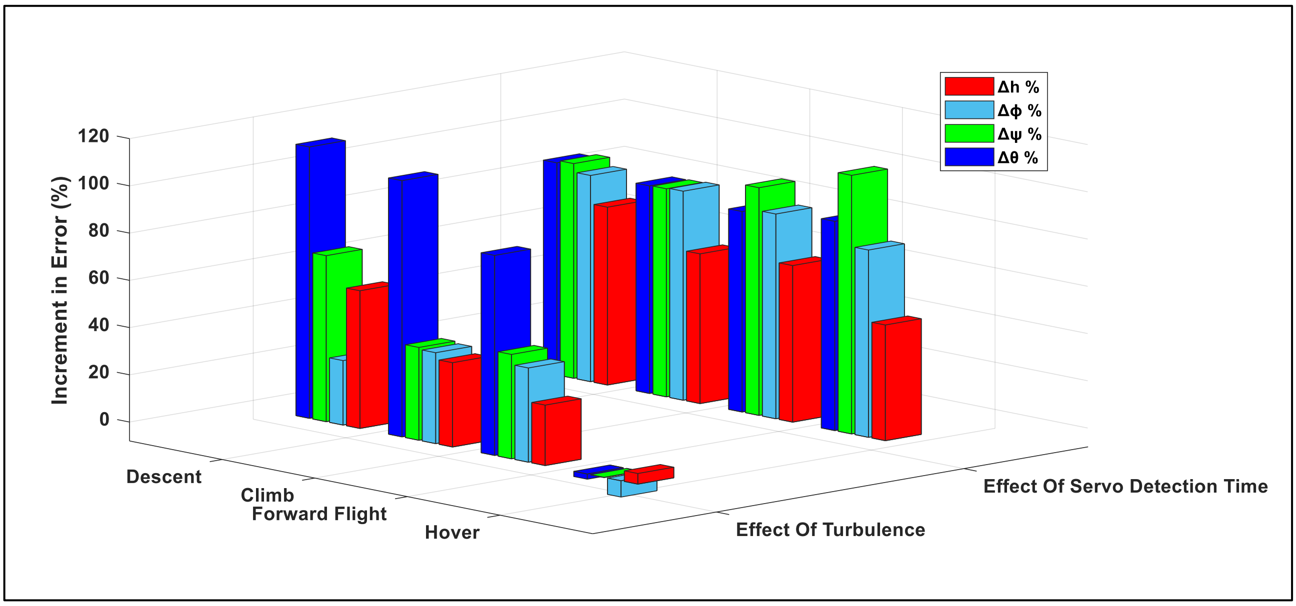

Figure 3 Effect of Servo Detection Time and Turbulence on SCAS Actuator Failure Analyses

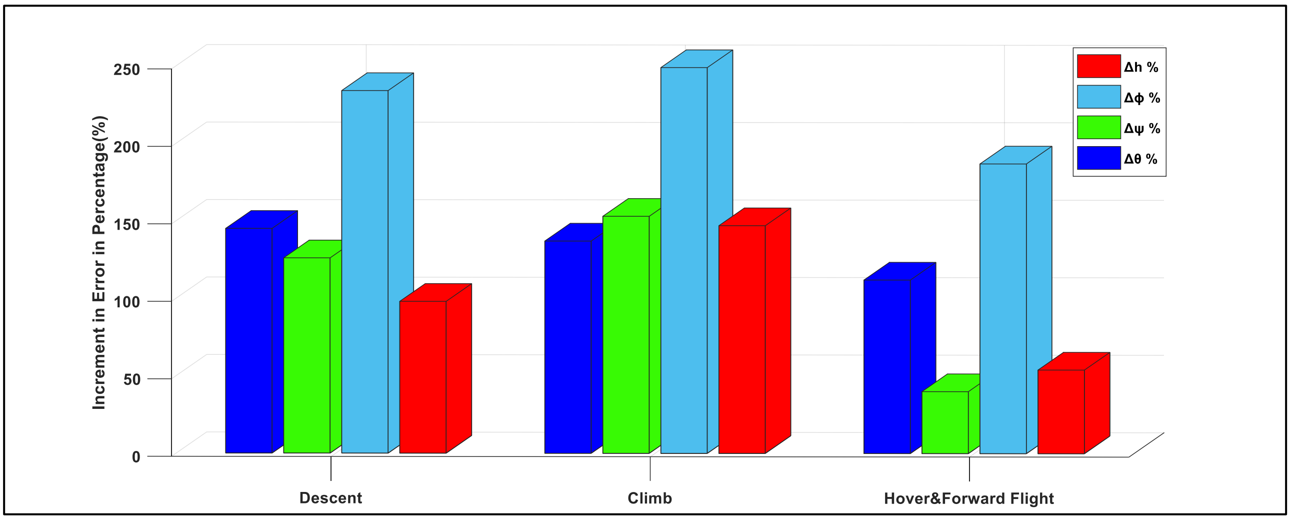

Figure 5 Effect of Turbulence on Trim Actuator Failure Analyses

TOROS simulation model does not include pilot model. Because of that issue, the Attitude hold mode engagement is introduced to model the pilot. Pilot response time is selected as 3 seconds. The requirement is between 1 and 3 seconds. In order to be on conservative side, 3 second pilot response time is chosen in these analyses. During simulation up to pilot response time, Attitude hold mode is closed. After pilot response time, attitude hold mode is engaged and the error in the Euler angles is tried to be minimized which occurred during servo failure. Furthermore, altitude hold mode is opened after pilot response time to minimize altitude change as if pilot react the failure.

From all the data obtained from these cases, usually the most critical SCAS for TLUH is the third main rotor actuator. Furthermore, among the trim-runaway failure cases, longitudinal cyclic failure is found to be the most critical.

Figure 3 and Figure 5 are given in order to visualize the entire set of tests that has been conducted. In these figures, the effect of having turbulence and changing servo detection time from 0.3s to 0.5s on failure cases are presented. These effects have presented in percent increment in Euler angles and altitude. These values obtained as a mean increment in that particular error for both failure direction and each failure channel.

As it can be seen from Figure 3, turbulence has minimal effect on hover condition. However, the change in pitch angle due to failure is nearly doubled for descent, climb and forward flight conditions. Pitch angles due to failure in calm weather deviates around 1.5 degrees from trim condition; and these values increased up to 3 degrees for turbulent cases.

The effect of increase in servo detection time from 0.3seconds to 0.5 seconds has also been presented in Figure 3. This parameter directly increases the effect of the failure by extending failed actuator application time on the helicopter. Increasing detection from 0.3 seconds to 0.5 seconds means roughly 66% increment for its effectiveness. However, this effect has increased the change in Euler angles around 80%, and altitude around 55%. Moreover, trim-runaway analyses have been conducted only for different turbulence effects. Change in roll angle is effected much quite significantly from turbulence. Roll angles due to failure in calm weather deviates around 1 degree from trim condition; and these values increased up to 2.5 degrees for turbulent cases.

It must be noted that these values are percentage increase in Δ deviation from the trim condition. In comparison of two set of data, the Δ change could be doubled but at the same time could still be small. Histogram graphs can be an effective tool to visualize when the number of test points is numerous. In this paper forward flight cases has been selected as the representative for failure cases. Therefore, statistical analyses for the forward flight are also given in Figure 6, Figure 7, Figure 8, Figure 9, Figure 10 and Figure 11. In these statistical analyses, altitude and pitch angle deviation (Δh & $\Delta\theta$) during failure for all forward flight cases have been shown. The effect of turbulence and servo detection time can be perceived from a different point of view in these statistical plots.

- **SCAS Actuator Statistical Analyses**

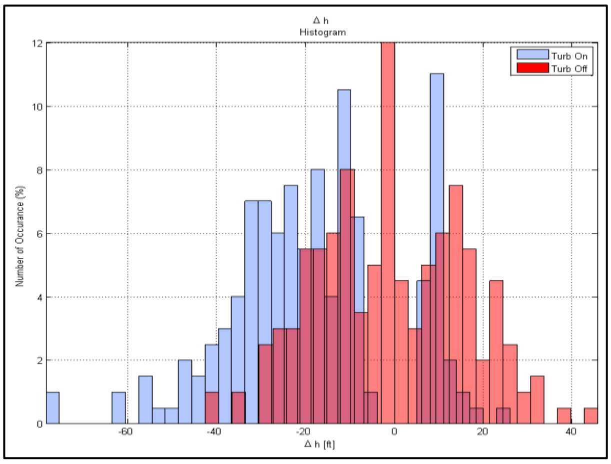

Figure 6 SCAS Actuator Failure Forward Flight Turbulence On & Off Δh Histogram

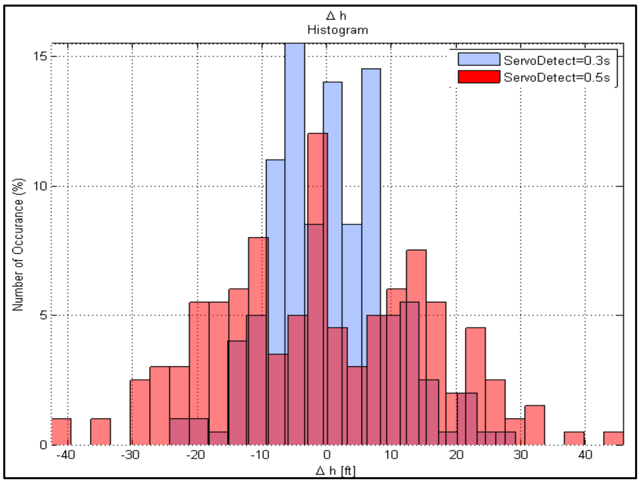

Figure 7 SCAS Actuator Failure Forward Flight Servo Detection time 0.3s & 0.5s Δh Histogram

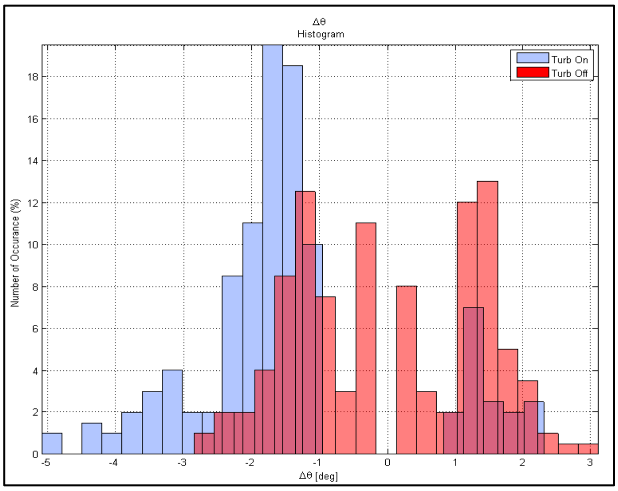

Figure 8 SCAS Actuator Failure Forward Flight Turbulence On & Off Δθ Histogram

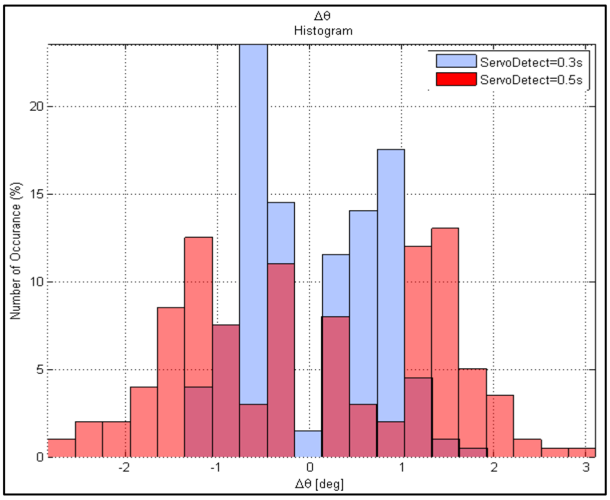

Figure 9 Forward Flight Servo Detection time 0.3s & 0.5s Δθ Histogram

- **Trim Actuator Statistical Analyses**

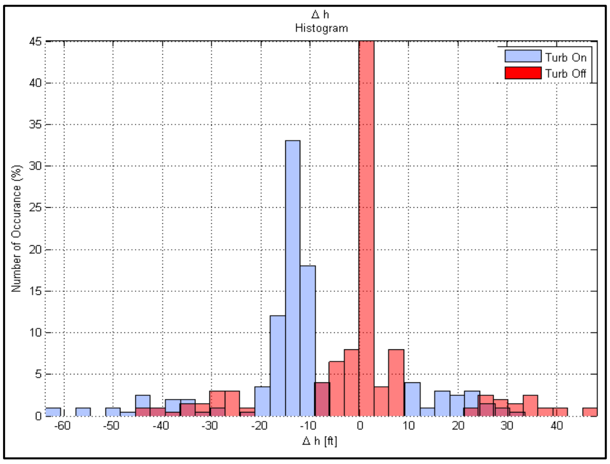

Figure 10 Forward Flight Turbulence On & Off Δh Histogram

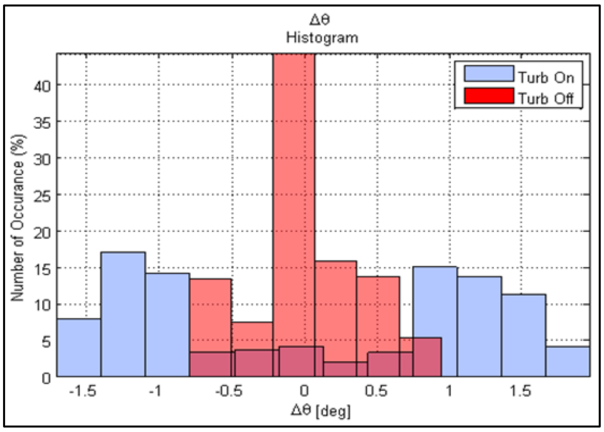

Figure 11 Trim Actuator Failure Forward Flight Turbulence On & Off Δθ Histogram

Among the 1920 test points that have been conducted with computer simulations, usually the most critical failure is found as the third main rotor actuator failure. The critical direction changes depending on the maneuver-weight-cg conditions. Helicopters usually have less rolling inertia then pitching inertia; therefore, a SCAS actuator acting on lateral axis have more significant effect than a SCAS actuator solely acting on longitudinal axis. For TLUH, 3rd main actuator acts (MRA) both on longitudinal and lateral axes, such that it generate the most unstable effect. Therefore, the deviations obtained from a failure in 3rd MRA usually have larger values from other SCAS actuator failures.

In trim actuators, it is found that each particular trim actuator is found to be critical for their corresponding Euler angle. However, among all the statistical data that has been gathered, the deviations due to longitudinal cyclic failure has been found critical more than the other trim actuator failures. It has been known that one of the longitudinal stability modes has low damping. This might be the reason for this outcome. Phugoid mode is excited due to failure in longitudinal cyclic failure.

Effects of turbulence and servo detection time on actuator failure cases are investigated. For each channel, effects of increasing the turbulence and increasing the servo detection time on Euler angles and altitude have been discovered. Comprehending the effects and deviation amounts for any kind of failure without actually testing the model with a pilot can save immerse amount of time, energy and money. However, the reality of these results obtained from computer simulations must be confirmed with tests conducted including a real pilot. The comparison is presented in the following chapter.

7. SYSTEM INTEGRATION LABORATORY TEST WITH PILOT – COMPUTER SIMULATION COMPARISON

Figure 12 System Integration Laboratory

Among the several simulator failure experiments, three critical SCAS failure cases are presented. Since the most critical SCAS is found to be the third main rotor actuator, the cases to be compared are chosen with a failure in third main rotor actuator. Flight conditions are hover, 120 knot and 160 knot forward flight cases. Weight-Cg Configuration is chosen as the most critical configuration; max weight with max aft c.g. Turbulence is off and servo detection time is 0.3 seconds in these comparisons. Pilot has been requested to not to act following the failure at least 3 seconds. In the computer simulations this number is exactly 3 seconds. One of the most significant difference between the computer simulation and simulator test is preference in flying with zero sideslip angle or zero roll angle. In the computer simulations, the trim condition has been defined for zero sideslip angle, whereas pilots tend to fly the helicopter around zero roll angle.

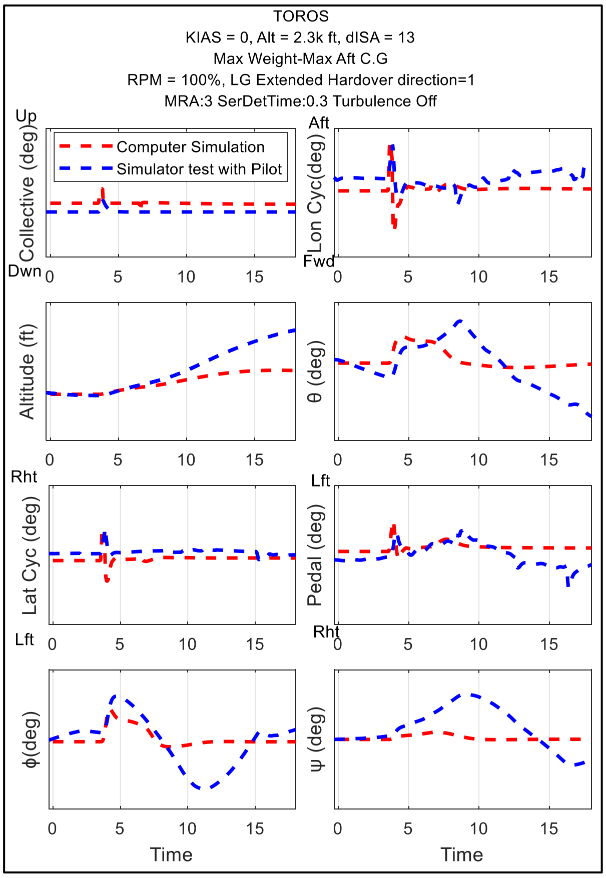

Figure 13 Hover – Maximum weight/max Aft Cg 3rd Main Rotor Actuator Failure without Turbulence Computer Simulation and System Integration Laboratory test with pilot comparison (Hardover Direction=1)

For the hover test, the pilot could not hold Euler angles as well as the computer simulation. The system is not highly damped at hover condition.

Therefore, a small amount of excessive control input might generate oscillations in that particular channel. In **Figure 13**, the pilot and the computer simulation has a difference of 4 degrees in roll and yaw angles and 8 feet in altitude.

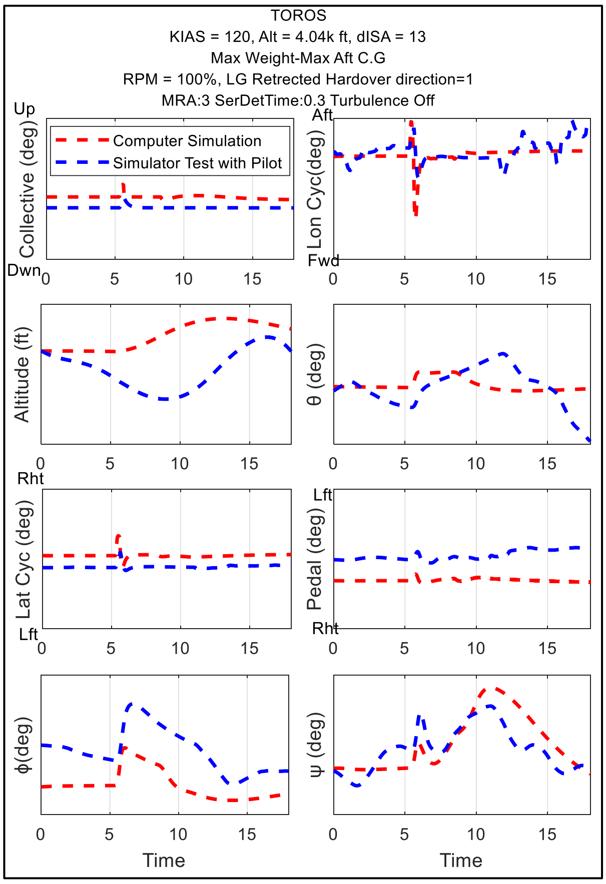

Figure 14 Forward Flight (KIAS=120) – Maximum weight/max Aft Cg 3rd Main Rotor Actuator Failure without Turbulence Computer Simulation and System Integration Laboratory test with pilot comparison (Hardover Direction=1)

In Forward flight cases, the main difference is, as mentioned previously, flying with zero sideslip or flying with small roll angle. Furthermore, at the failure instant, the helicopters flown in system integration laboratory(SIL) tests have marginal translational and rotational acceleration. However, in the computer simulations, the accelerations at that instant are around zero. Therefore, the lateral and pedal control inputs at the beginning of the tests were not equal. On the other hand, the response of the pilot and the helicopter in SIL is quite similar with the tests conducted in computer simulations. For 120 knots forward flight case, in **Figure 14**, the pilot and the computer simulation has a difference of 5 degrees in roll angle and 20 feet in altitude. For 160 knots forward flight case, in **Figure 15**, this difference is 4 degrees in yaw 7degrees in roll angles, and 30 feet in altitude. Pitch angle difference is less than 2 degrees in all the presented comparison cases.

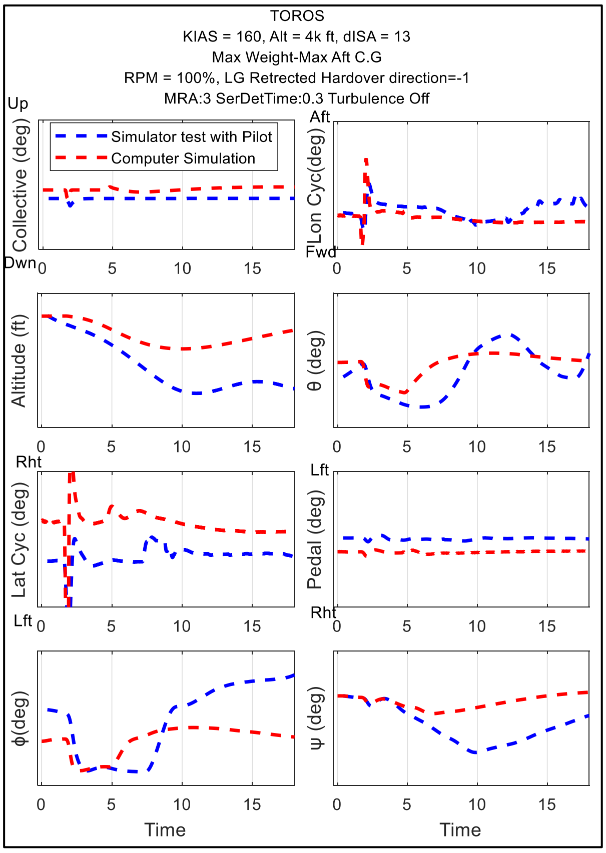

Figure 15 Forward Flight (KIAS=160) – Maximum weight/max Aft Cg 3rd Main Rotor Actuator Failure without Turbulence Computer Simulation and System Integration Laboratory test with pilot comparison (Hardover Direction=-1)

8. CONCLUSION

In this work, the analyses of SCAS and Trim actuator failures are conducted based on Certification Specifications for Large Rotorcraft and Advisory Circular (CS/AC-29). In the CS-29, it is required to test failures in cruise, descent and climb conditions. In this work, hover is added as a flight condition to cover up most of the flight regime. In CS-29, it is required to measure the altitude change resulting from failure. In these analyses, statistical approach is followed, effect of servo monitor/detection time, turbulence and flight conditions are investigated.

From the results of aforementioned testing conditions, the following outcomes have been obtained:

- Monitoring the actuators and detecting that a particular actuator is working in an incorrect manner as fast as possible are essential. Decreasing the detection time decreases the effect of the failure significantly.

- In a turbulent environment, the results from any failure is much severe than a failure in calm environment. The deviations from trim condition are doubled in moderate turbulent environment.
- For TLUH, the most critical SCAS actuator is found to be 3rd main rotor actuator. The most significant trim actuator is the longitudinal cyclic actuator.
- From the comparison with computer simulations and SIL tests with pilot, one can claim that the procedure used in computer simulation is a crude but similar representation of the tests with pilot.

For the future work, analyses with different pilot reaction time must be conducted. Rather than only focusing on the most significant and common failure modes such as trim-runaway and hard over; other possible failure modes should be conducted with the same statistical approach. Furthermore, hardover cases without SCAS actuator centering must be investigated. Finally, lane failure cases must be investigated. In lane failure cases, an FCC can give a faulty input to 2 different SCAS actuator at the same time.

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