CONTROL AND NAVIGATION OF A HELICOPTER DURING TAIL ROTOR FAILURE

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Abstract

The objective of this study is to stabilize a helicopter after experiencing a tail rotor failure while in steady state conditions. This study takes the previous work of the authors several steps further by handling the stabilization after the tail rotor failure phase and investigating the effects of main rotor speed control and the reaction time to the failure. The trajectory optimization is used to generate the flight paths from a healthy steady condition to a faulty steady condition for different flight scenarios. The flight trajectory generation process is improved by implementing a stitched model. The obtained trajectories are used by the tracking controller as references and the nonlinear simulations are performed.

1. NOTATION

Symbols

U_0	Trim Velocity
$\|_{U_0}$	Value at Anchor Velocity U_0
$\|_{U}$	Value at Instantaneous Velocity U
$\boldsymbol{X}$	Total State Vector
$\boldsymbol{Y}$	Total Output Vector
$\boldsymbol{U}$	Total Control Vector
Ω	Main rotor speed of rotation, rad/s
$\dot{\Omega}$	Main rotor acceleration, rad/s^2
ϕ	Roll Angle, rad
θ	Pitch Angle, rad
ψ	Yaw Angle, rad
$\delta_{col}, \delta_{lon}, \delta_{lat}, \delta_{ped}$	Control Inputs, %

Acronyms:

TRF	Tail Rotor Failure
TRT	Trajectory Reaction Time
CRT	Controller Reaction Time
MR	Main Rotor

2. INTRODUCTION

The tail rotor is the primary anti-torque generator to balance the main rotor torque in conventional single main rotor helicopters. The control of the helicopter in the yaw-axis is achieved by changing the tail rotor collective, governed by the pedal. The control power in the yaw-axis could be lost as the result of an aerodynamic phenomenon known as the loss of tail rotor effectiveness, or simply because of a mechanical or structural failure. The tail rotor is the only source to generate anti-torque in low-speed flight conditions while the vertical fin is another contributor to anti-torque generation during high-speed flights. Due to lack of anti-torque sources, a tail rotor failure might result in catastrophic accidents, especially at low-speed flight regimes. Reference 1 shows that tail rotor failures have been the reason for 470 accidents suffered by commercial helicopters between 1963 and 1997. When the tail rotor failure happens, the forces and moments generated by the tail rotor disappear and the anti-torque generated by the main rotor cannot be balanced. The emergency procedure in this case is going into autorotation and landing the helicopter safely as soon as possible. Autorotation is normally utilized in engine failures since the engine cannot provide the torque necessary to rotate the main rotor but in tail rotor failure cases, it is the ideal solution as explained in Ref. 2 since there is no component to generate anti-torque.

The trajectory of a helicopter in tail rotor failure has been handled in numerous recent studies. Yan (Ref. 3) investigated the optimal landing trajectory and related control scheme for a helicopter in tail rotor drive failure. In this study, a helicopter model which experiences tail rotor drive failure during steady-state flight conditions is developed and used. After the tail rotor failure, an autorotation maneuver is initiated. The maneuver is described as a classical optimal control problem in rotorcraft and solved numerically by converting it into a nonlinear programming problem and applying the optimal control method. An optimal landing trajectory and control scheme are obtained. A model of Z11 is used to demonstrate the obtained approach and an optimal landing procedure is proposed for rotorcrafts in tail rotor failure. In another work, Yan (Ref. 4) focused on the control strategy and optimum landing trajectory for a helicopter in both high and low tail rotor pitch lockup conditions. The analyses are done by using a nonlinear flight dynamics model and a pilot model. The pilot model is used to perceive the situation and give the response. Since the pedal control is ineffective during both lockup conditions, the first-order derivatives of collective, lateral cyclic and longitudinal cyclic with respect to time are used as the control variables. A high-order nonlinear flight dynamics model of the UH-60A is used for the analyses. The objective is defined as finding a control strategy that guides the helicopter from its initial state to a target state, which is landing in this study, optimally. The optimal control problem is solved by numerical methods. The calculated optimal landing procedure is verified by comparing it with conventional autorotation test data of UH-60A. The results are used to recommend landing maneuvers for a safe landing in both tail rotor pitch lockup conditions.

There are also many studies on trajectory optimization for helicopters in autorotation. Meng (Ref. 5) worked on safe landing procedures for a helicopter under engine failure. In this study, a six-degree-of-freedom rigid body model is used for autorotation landing optimization. Steady-state flight conditions with zero-sideslip are assumed at the time of engine failure. The trajectory optimization problem is defined as reaching the ground with minimal horizontal and vertical velocities at touchdown. Then this optimal control problem is transformed into a nonlinear programming problem and an optimal solution is obtained numerically. The sample helicopter model is taken as UH–60A. Obtained optimal trajectory and control inputs using a six DoF model and point-mass model are compared and it is concluded that the optimal solutions show good agreement, resulting in reasonable control procedures and trajectories. Taamallah (Ref. 6) studied a trajectory planning and tracking system with online computational tractability for a small-scale helicopter UAV in autorotation. The trajectory planning and trajectory tracking are decoupled. The guidance module produces an optimal autorotation trajectory and the control module formulates the feedback controls by comparing the measured states and the states obtained from the guidance module. A high-order nonlinear and continuous-time flight dynamics model that represents a small-scale helicopter is used for simulations. The trajectory generation problem is converted from a dynamic problem to an algebraic problem by using flat parametrization. The high-order model is simplified for trajectory generation by using only the rigid body dynamics as the model and feeding the total aerodynamic forces and total moments as inputs. The tracking system focuses on control over position and velocity. The guidance and control systems are validated on a high-fidelity helicopter simulation. The results showed that vertical position and velocity control performance is excellent but there is room for improving the horizontal position and velocity tracking. Yomchinda (Ref. 7) focused on trajectory planning during the autorotative descent of autonomous rotorcraft. The problem is defined as obtaining a three-dimensional trajectory that takes the rotorcraft from the state where engine failure happened to a state where the rotorcraft is able to perform an autorotative flare and land safely. It is assumed that the touchdown location and the desired state at the destination are selected within the safe landing set. A modified three-dimensional Dubins path is used in this study. The path is divided into three autorotative segments which include a turn, a straight segment and another turn. Acceleration is allowed along each of the segments. The trajectory problem is solved using a nonlinear parameter optimization. The results yielded safe and feasible trajectories that can take the aircraft from an autorotation state to a safe landing condition near the selected landing site.

Stitched model architecture is studied on multiple applications. Tischler and Tobias (Ref. 8) developed a comprehensive model stitching simulation architecture that is capable of performing continuous, full-flight envelope simulations. The stitched model is constructed using individual linear models and trim data for specific flight conditions. It is considered a quasi-nonlinear simulation model and can accurately simulate off-nominal aircraft configurations. The model stitching architecture is applied to a business jet and a utility helicopter. Berger and Tischler (Ref. 9) obtained a full-envelope simulation model for Learjet-25, a twin-turbojet-powered business jet. The model is developed by applying the model stitching architecture based on a series of discrete linear point models and trim data. The obtained model is then compared with the flight test data which is not used during the model development.

Johnson and Kannan (Ref. 10) used neural network as the adaptive element to develop an adaptive controller for an autonomous helicopter. Their work differs from previous studies by that time by concentrating on tracking of position commands instead of attittude commands. Dynamic inversion is used to linearize the attitude and translational dynamics. Linear controllers are designed for these linearized dynamics. Online adaptation is provided by the use of a non-linearly parametrized neural network. Pseudocontrol hedging technique (PCH) is used to mitigate the problems caused by the use of adaptive element. Position tracking performane is improved by using a combination of gain selection and PCH and the making bandwith of the outer loop closer to the bandwidth of the inner loop.The controller is applied to an unmanend helicopter. The results show that the developed controller was able to correct the modeling error in altitude and translation dynamics. Flight tests illustrated that adaptation might correct model errors due to poor approximate models. Furthermore, since it does not conation any assumptions that limit the application to unmanned helicopters, desired response characteristics can be implemented to the design.

Reference 11 focuses the effect of total response time in total power failure, tail rotor control failure and tail rotor drive failure cases, which are time-critical emergencies. AFCS failures are also included since there may be time-critical situations. The pilot pool included U.K. Royal Air Force pilots and civilian pilots. The simulators for three different helicopters are used to obtain data. Pilots' failure detection time and response time are collected and analyzed together with visual, auditory and motion cues. Simulations without pilots are also run to see the outcome if there was no pilot to intervene. 90% of the failure simulations have resulted with the pilots being able to recover after failure. The average detection and response times are also obtained for the helicopter simulators under different failure conditions. Tail rotor drive failures are detected in approximately 1.5 seconds. The results showed that the failures that end with a crash involved significantly higher response times while having similar detection times. It is also observed that the response patterns of failed pilots differ qualitatively from majority of pilots who recovered. Failed pilots' collective controls were not simple and rapid but incorporated hesitations and reversals.

This paper focuses on the stabilization of a helicopter after experiencing a tail rotor failure. After reaching a steady-state flight condition, flight trajectories are generated that take the helicopter from this stable state to a different desired flight condition. Flight path generation is done by using OptimTraj (Ref. 12), an open-source trajectory optimization tool. This tool uses the direct collocation method to solve a trajectory optimization problem by defining an objective function, path constraints, boundary constraints and system dynamics. In the previous works of the author (Ref. 13 and Ref. 14), linear helicopter models that represent the system dynamics were utilized to reduce the computation time. In this study, these linear models are replaced by the quasi-nonlinear model obtained by using model stitching architecture. The stitched model is more complex, thus increasing the computation time. However, the accuracy gain proved to be higher than the time cost. Stabilization with tail rotor failure is performed for several scenarios. The trajectories for these cases are obtained with different combinations of variable/constant main rotor speed and instant/delayed control response to the failure to see the effect of these variables on trajectories. Response delays are implemented by two different methods. The first method is obtaining the trajectory with a delay in control responses and the other method is delaying the trajectory following of controller during the nonlinear simulation step. After obtaining an optimal path between the starting state and the desired flight condition, a tracking controller is used to follow it. State tracking is achieved by an LQI controller. The controllers are used in nonlinear model simulations. FLIGHTLAB Run-time model and SIMULINK are utilized in conjunction for the nonlinear model simulations.

3. HELICOPTER MODEL

In this paper, the generic nonlinear FLIGHTLAB model similar to Sikorsky UH-60A is utilized. For trajectory generation, instead of using linear models as in previous studies (Ref. 13 and Ref. 14), a quasi-nonlinear model which is mentioned as stitched model in (Ref. 8) is used in order to enhance the fidelity of the model.

The model stitching method utilizes a series of state-space models and the associated trim data of states and controls for a certain flight conditions, named as "anchor points", to obtain the quasi-nonlinear model.

The linear models and trim values of the anchor points are found by trimming and linearizing the nonlinear FLIGHTLAB model at the interested condition. The horizontal tail controller, pitch bias controller and SAS are switched off to reduce. The mechanical mixing of controls is also eliminated from the nonlinear model for the same reason.

The linear models are stitched along the total airspeed and the pressure altitude. 60, 80, 100 and 120 kt level flight trim conditions at 2000 and 4000 ft altitude are chosen as the anchor points for the level flight transition scenarios. On the other hand, for the transition to autorotation scenario, stitching is performed along the z-body velocity and the pressure altitude. In this case, linear model of 80 kt level flight and linear model of 80 kt autorotation condition for 2000 and 4000 ft altitude are implemented as anchor points.

Noting that the x-body airspeed and the total airspeed can be used interchangeably, the general representation of corresponding perturbation dynamic response around an anchor point with trim x-body airspeed U_0 is given as,

(1) $$\dot{x} = A|_{U_0} x + B|_{U_0} u$$

(2) $$y = C|_{U_0} x + D|_{U_0} u$$

where A, B, C and D are stability and control matrices from the state-space model of that anchor point. The total values of state vector X and the total values of output vector Y at the instantaneous x-body airspeed U are given as,

(3) $$\dot{\boldsymbol{X}} = A|_U(\boldsymbol{X} - \boldsymbol{X_0}|_U) + B|_U(\boldsymbol{U} - \boldsymbol{U_0}|_U)$$

(4) $$\boldsymbol{Y} = C|_U(\boldsymbol{X} - \boldsymbol{X_0}|_U) + D|_U(\boldsymbol{U} - \boldsymbol{U_0}|_U) + \boldsymbol{Y_0}|_U$$

The state and control vectors are chosen as follows,

(5) $$x = [\Omega \quad \phi \quad \theta \quad u \quad v \quad w \quad p \quad q \quad r]^T$$

(6) $$u = [\delta_{\mathrm{col}} \quad \delta_{lon} \quad \delta_{lat} \quad \delta_{ped} \quad \dot{\Omega}]^T$$

Since the pedal has no effect on the helicopter because of the failure, main rotor speed is added into the states and the man rotor acceleration is added into the controls, allowing the directional control of the helicopter to be enhanced.

Tail rotor failure is implemented to the stitched model by injecting the forces and moments due to the failure as a user-defined external forces and moments which can be seen in Figure 1. The stitched model calculates aerodynamic, gravitational and external forces and moments according to the present stitching parameters. The total forces and moments are used in order to compute the helicopter accelerations by using rigid body equations. To implement the failure, the tail rotor hub forces and moments are taken from FLIGHTLAB for the condition at which tail rotor fails. The obtained forces and moments acting on the center of gravity are subtracted from the total forces and moments so that the effect of tail rotor is nullified.

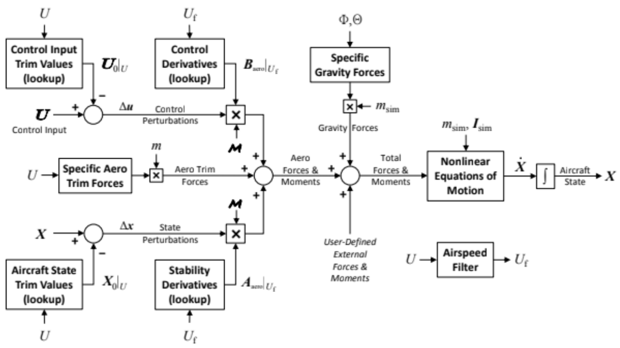

Figure 1: Schematic of Stitched Model Architecture

The Run-time System of FLIGHTLAB allowed utilizing the generic nonlinear model for the simulations. SIMPHONY module of FLIGHTLAB is used to generate a black-box model called FCM model that can be interfaced with external systems such as SIMULINK. An interface script is prepared to drive the FCM model and regulate the input-output signals. It transfers the data to the shared memory of SIMPHONY via UDP communication protocol.

4. TRAJECTORY GENERATION

Flight path generation is achieved by using OptimTraj (Ref. 12). The constraints of the optimization problem are defined as the terminal states of the helicopter in TRF, objective function and state & control bounds. The initial states of the scenarios are steady flight conditions with a properly functioning tail rotor. The final states are the objected steady flight conditions with tail rotor failure. The investigated flight scenarios are tabulated in Table 1.

The optimization tool generates the optimum state and control trajectories that take the helicopter from the state when the tail rotor failure occurs and brings it to the stable flight condition with failure still present.

100 kt level flight condition is chosen as an initial condition because it is a usual cruise condition for a utility helicopter. Additionally, the generic model in FLIGHTLAB can be stabilized in this condition with a large sideslip angle thanks to the vertical fin creating enough anti-torque to balance the main rotor torque. The same phenomena apply for 80 kt level condition too. Moreover, it is a suggested airspeed for autorotation for conventional helicopters. Therefore, when the vertical fin is not enough for creating an anti-torque, autorotation option is considered.

The system dynamics used in the trajectory optimization problem are provided by stitched model architecture. The stitched model is a quasi-nonlinear model based on previously defined linear models at anchor points and trim data and allows continuous, full flight envelope simulations. Using the stitched model over the set of linear models in previous works (Ref. 13 and Ref. 14) enhances the trajectory generation process since it is a more advanced and accurate helicopter model; however, this comes with a penalty in process time. Despite not being in the scope of this study, this penalty is compensated by the improvements in obtained results.

For state navigation, the minimum time objective function is implemented. The reasoning behind this decision is the fact that a helicopter with TRF should be stabilized as quickly as possible since the helicopter is in highly unstable state and it may be unrecoverable in a few seconds.

The cost function for minimum time is,

(7) $$\min_{t_0, t_F, x(t), u(t)} \int_{t_0}^{t_F} t \, dt$$

Grid number is selected as 50 for the trajectory generation process since the average solution length is about 5 seconds and having 50 grids results in approximately 0.1 seconds long time steps, which is desirable for simulations and solutions.

The reaction time to TRF is implemented in OptimTraj by forcing the controls until the desired grid number to the initial values. Hence, the flight trajectory is optimized by taken into account the reaction time. These cases are labeled as TRT.

After the offline process of obtaining the optimum path from occurrence of failure to a steady flight condition with TRF, the trajectory is given as a reference to the controller for tracking.

Table 1: Investigated Flight Conditions.

Flight Case	From	To
1	100 kt Level Flight	100 kt Level Flight
2	80 kt Level Flight	80 kt Level Flight
3	80 kt Level Flight	80 kt Autorotation

5. TRAJECTORY TRACKING

In this paper, linear quadratic regulator with integral action is selected for tracking the helicopter states (Ref. 15). Trajectory tracking is the main topic of Reference 134 and it contains detailed explanation about the process.

In this study, the advantage of main rotor speed control is also investigated. The weighting matrix for the state error, Q, and the weighting matrix for the input effort, R, are selected according to existence of the utilization of main rotor speed control. If the main rotor speed can be controlled, the tracked states are chosen as,

(8) $$x = [\Omega \;\; \phi \;\; \theta \;\; v]^T$$

If the main rotor speed cannot be controlled, the tracked states are chosen as,

(9) $$x = [\; \phi \;\; \theta \;\; u \;\; v]^T$$

Since roll and pitch angles mostly drive the movement of the helicopter and the sideslip angle has an important effect on the steady conditions in TRF, ϕ, θ and v are the common tracked states of both controller.

The reaction time to TRF is implemented in the controller by shifting the references and keeping the controls until the desired time as the initial values. When the reaction time is reached, the controller is allowed to produce input. These cases are labeled as CRT.

6. RESULTS AND DISCUSSION

In this study, the effects of CRT, TRT and the advantage of having the main rotor speed control are investigated. For the maximum reaction time is taken as 0.5 seconds since it is assumed that TRF is detected by a failure detection algorithm in the controller of the helicopter and reacts immediately with a full control authority. The main rotor speed control limit is determined as bounding the main rotor speed between 95% and 105% which are acceptable values for conventional helicopters. Although the final time for the objected terminal condition is found as about 5 seconds by OptimTraj for all cases, the nonlinear simulations are performed for 10 seconds in order to capture the convergence of the helicopter to the steady state.

Firstly, nonlinear simulations are performed for different controller reaction time. In order to have comparable results, Flight Case 1 with main rotor speed control for zero TRT is selected. As it can be seen in Figure 2 and Figure 3 the performance of the controller degrades as the reaction time increases and the time for convergence becomes longer. The similar comments can be made for the response of the main rotor speed; however, it is not given for the sake of simplicity.

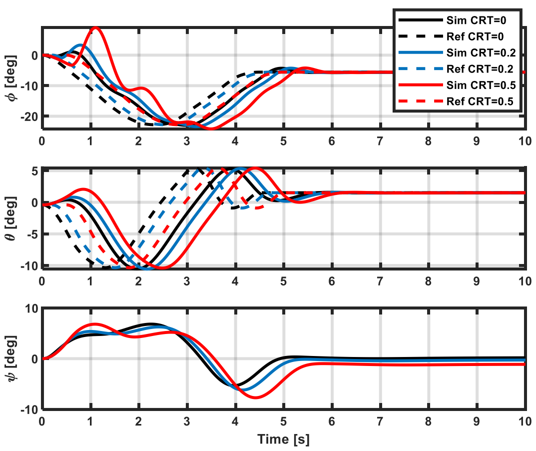

Figure 2: Case 1 – CRT Comparison of Euler Angles

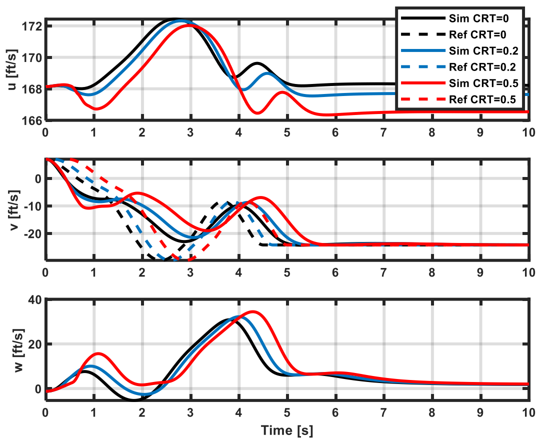

Figure 3: Case 1 – CRT Comparison of Velocities

Secondly, nonlinear simulations are performed for different trajectory reaction time. Flight Case 1 with main rotor speed control for zero CRT is selected to make comparisons. As it can be seen in Figure 4 and Figure 5, the initial response of the helicopter to TRF is captured by OptimTraj. However, as the reaction time increases, the calculated flight trajectories differs from the nonlinear simulation. The reason for that could be that the linearity decreases and the high order dynamics of the nonlinear model cannot be captured by the stitched model. Additionally, using a low grid number in trajectory optimization plays a role in this situation and degrades the fidelity. As linearity decreases the performance of the controller also degrades as expected and the time for convergence becomes longer. The similar comments is applicable for the response of the main rotor speed.

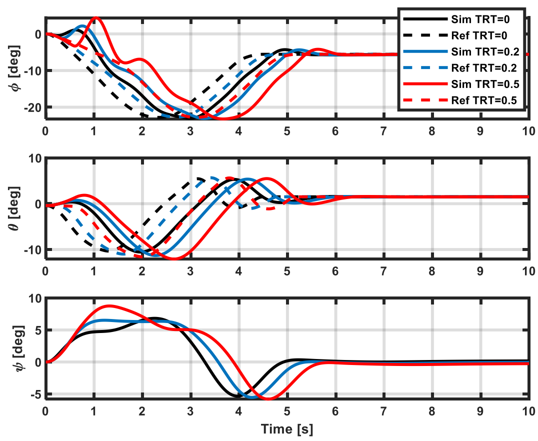

Figure 4: Case 1 – TRT Comparison of Euler Angles

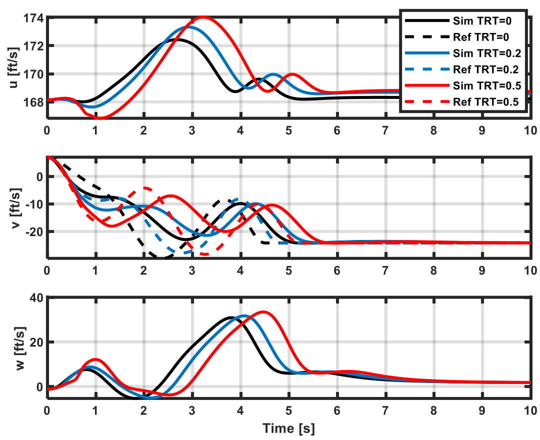

Figure 5: Case 1 – CRT Comparison of Velocities

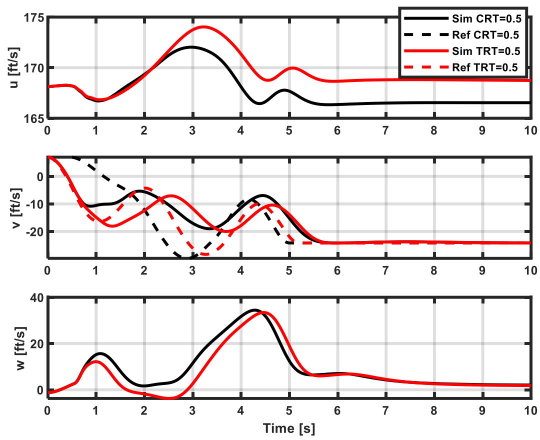

Figure 7: Case 1 – CRT vs. TRT for Velocities

Thirdly, the reaction time implementation methods are compared for Flight Case 1 with main rotor speed control. Figure 6 and Figure 7 shows that although TRT implementation is better to guess the behavior of the helicopter with 0.5 seconds reaction time, the advantage in the references is not very effective in the controller performance. In both case, the helicopter reached the steady condition in similar time.

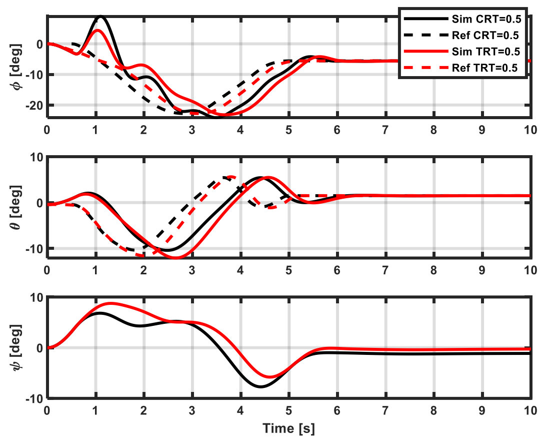

Figure 6: Case 1 – CRT vs. TRT for Euler Angles

And finally, the results of having main rotor speed control are compared by not having main rotor speed control for Flight Case 1. Figure 8, Figure 9 and Figure 10 show that having main rotor speed control increases helicopter control and maneuverability. If the main rotor speed can be controlled, the helicopter in TRF can be trimmed in a desired condition shorter time. The main rotor speed control especially increases the directional control of the helicopter which is the main goal of this investigation. Note that the tracked states are different for the simulations.

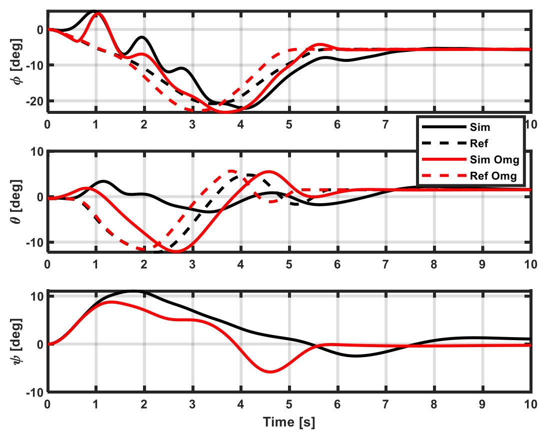

Figure 8: Case 1 – MR Speed Control Comparison of Euler Angles

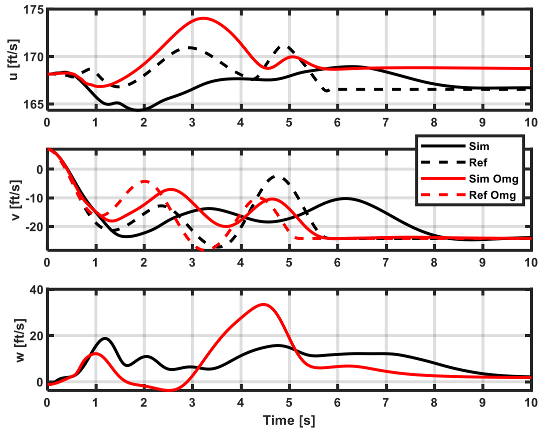

Figure 9: Case 1 – MR Speed Control Comparison of Velocities

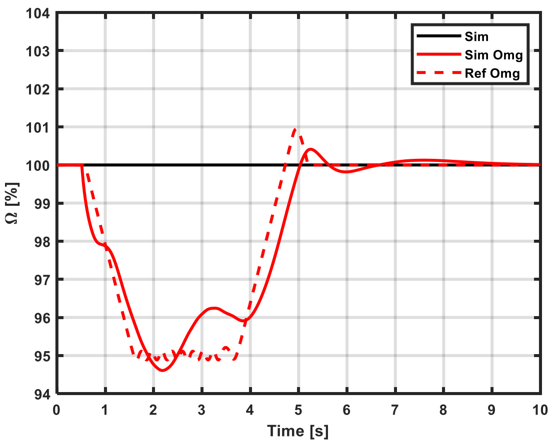

Figure 10: Case 1 – MR Speed Control Comparison of MR Speed

Since applying a reaction time would be more realistic, the study is performed for three flight cases for 0.5 seconds reaction time by implementing as TRT. The results for the flight cases are given in Appendix. The helicopter in TRF could be trimmed for all three cases successfully.

7. CONCLUSION

The results indicate that it is possible to stabilize the helicopter experiencing TRF during level flight. Suitable transition into stable level flight or stable autorotation depends on the forward speed of the helicopter at the moment of failure. If the forward speed is adequately high, vertical fin can generate enough anti – torque to stabilize the helicopter in level flight condition; however, in low forward speed, helicopter must perform autorotation to eliminate the need for anti-torque.

A new quasi-nonlinear stitched model based on nonlinear UH-60A model is developed with the aim of increasing the fidelity and accuracy of the trajectory generation.

Directional control is established by changing main rotor speed because of the lack of tail rotor. The main rotor speed is also included in the state matrix to represent its effects.

This stitched model is implemented to OptimTraj and trajectories from healthy steady flight conditions to steady conditions with TRF are obtained for different scenarios. The objective of this process was reaching the new trim condition in minimum time.

An LQI controller is designed to track the helicopter states and perform trim transition. The controller guided the nonlinear model by taking the generated trajectories as reference and following the selected states. The states to be tracked are selected based on the maneuver.

Three different scenarios consisting of different initial and final flight conditions with TRF are presented. The helicopter flying at steady level conditions experienced TRF and stabilized at new steady conditions. Two of these three scenarios took the helicopter to the steady level flight conditions at the same forward speed. In the third case, the helicopter is stabilized at autorotation condition after TRF.

The effect of the main rotor speed control is investigated. The same scenario is evaluated with both variable and constant main rotor speed. The generated trajectories and the results of nonlinear simulations are compared.

The impact of reaction time on stabilization of the helicopter is examined. The response delay is implemented by two separate methods and the results are compared.

Based on the results obtained in this study, it can be stated that:

1. The helicopter experiencing TRF in steady level flight can be stabilized at new steady flight conditions. The transition to steady level flight or steady autorotation at the same forward speed is successfully performed.

2. The LQI controller can be used to follow the states and bring the helicopter to desired trimmed condition.
3. Being able to control and change the main rotor speed reduces the time required to stabilize the helicopter after TRF. Although stabilization with constant main rotor speed is possible, it takes longer to reach the trim condition.
4. Implementing the reaction time in trajectory generation process and implementing the reaction time in the controller yield similar results. For both methods show that as the reaction time increases, it becomes harder to stabilize the helicopter and takes more time. The states tend to diverge when the response is delayed.

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8. APPENDIX

i. Healthy 100 kt Level Flight to 100 kt Level Flight with TRF

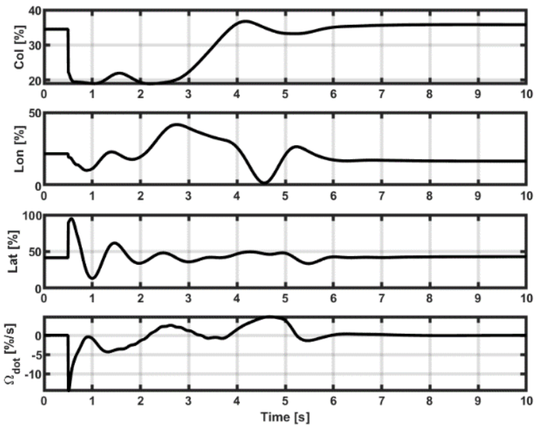

Figure 11: Case 1 – Control Inputs

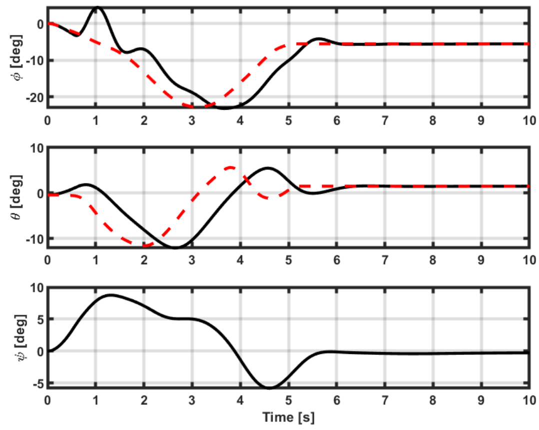

Figure 12: Case 1 – Euler Angles

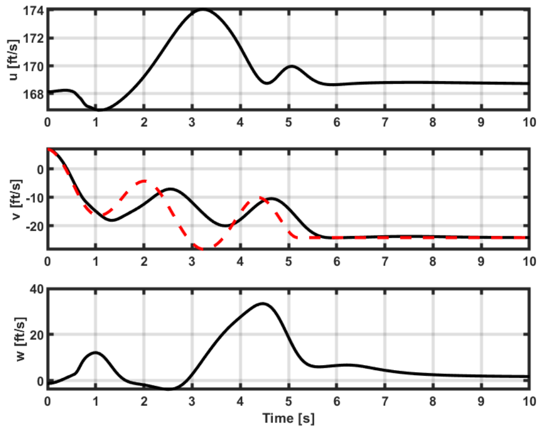

Figure 13: Case 1 – Body Velocities

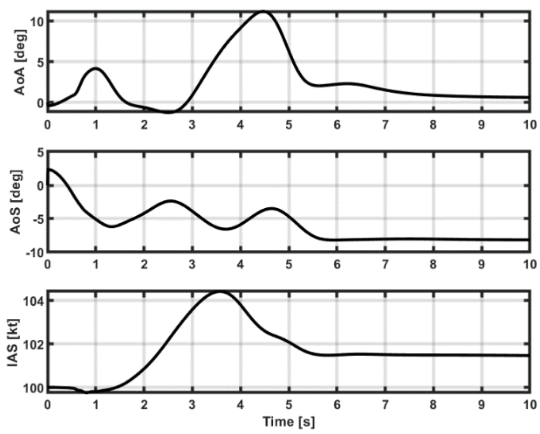

Figure 14: Case 1 – Air Data Parameters

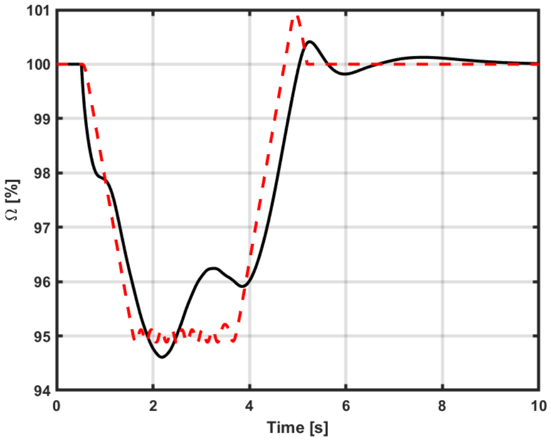

Figure 15: Case 1 – Main Rotor Speed

ii. Healthy 80 kt Level Flight to 80 kt Level Flight with TRF

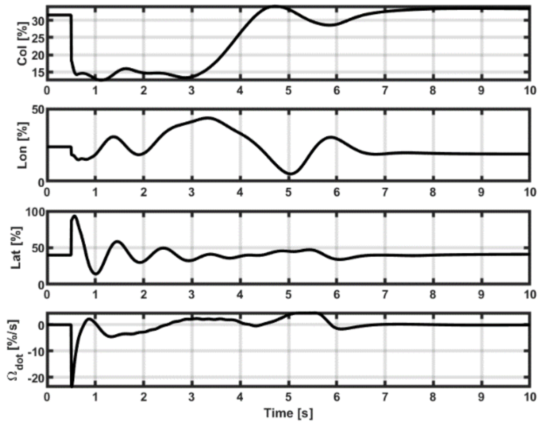

Figure 16: Case 2 – Control Inputs

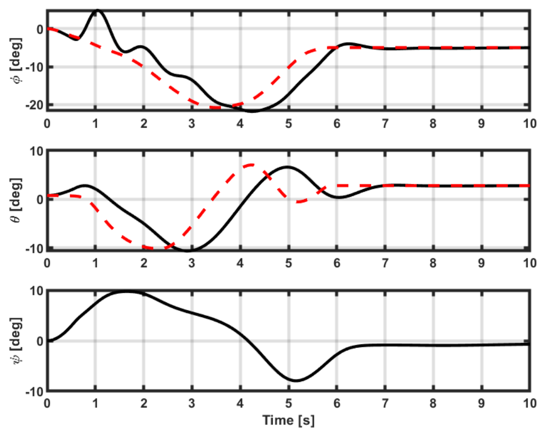

Figure 17: Case 2 – Euler Angles

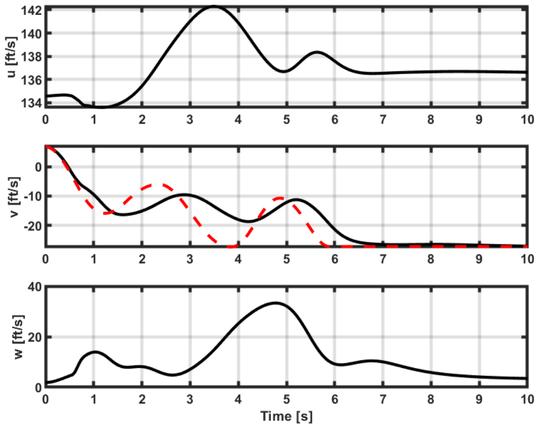

Figure 18: Case 2 – Body Velocities

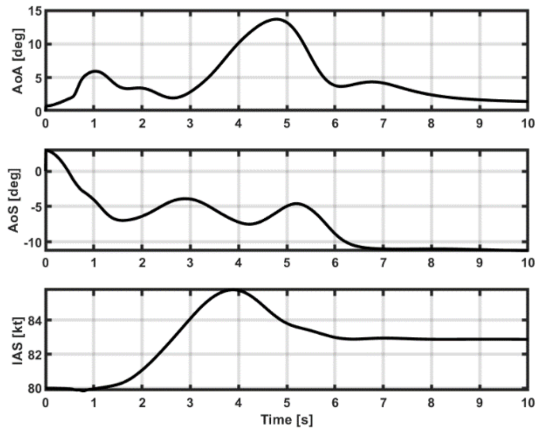

Figure 19: Case 2 – Air Data Parameters

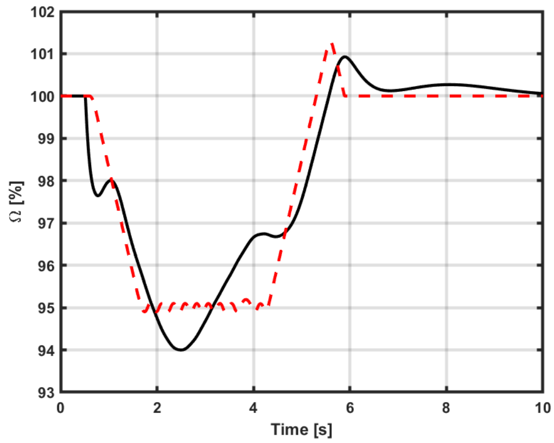

Figure 20: Case 2 – Main Rotor Speed

iii. Healthy 80 kt Level Flight to 80 kt Autorotation with TRF

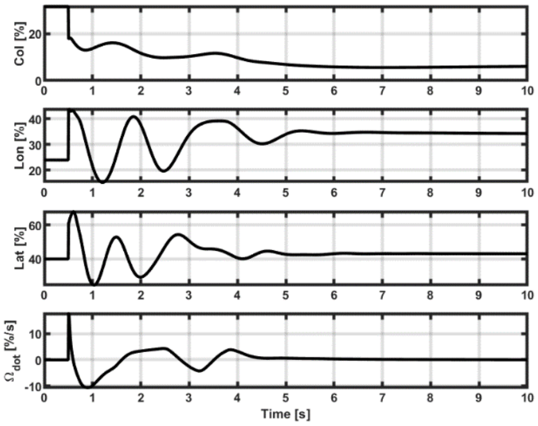

Figure 21: Case 3 – Control Inputs

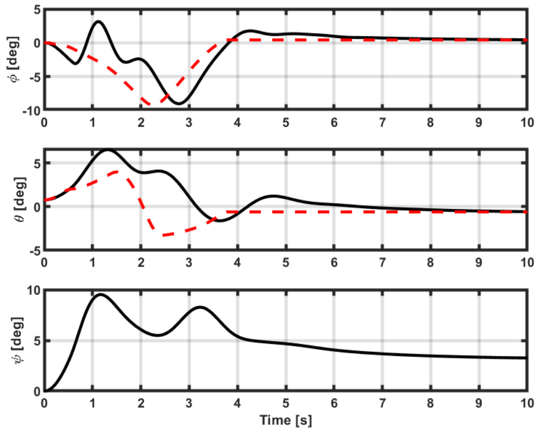

Figure 22: Case 3 – Euler Angles

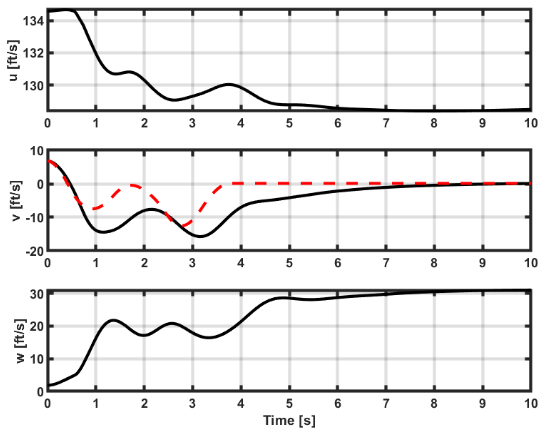

Figure 23: Case 3 – Body Velocities

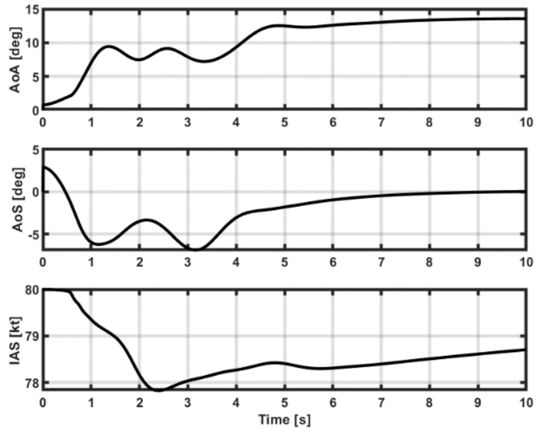

Figure 24: Case 3 – Air Data Parameters

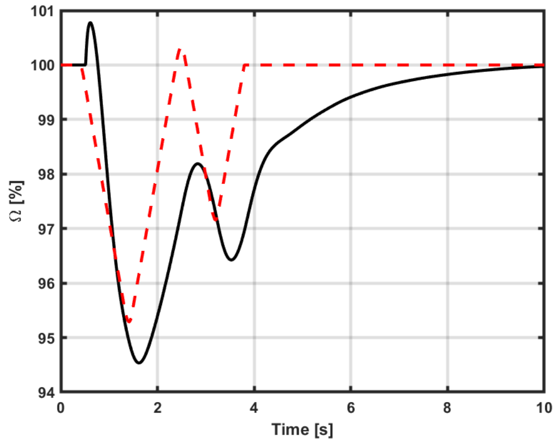

Figure 25: Case 3 – Main Rotor Speed

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