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FLIGHT ENVELOPE PROTECTION SYSTEM FOR A HELICOPTER IN AUTOROTATION

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ABSTRACT

In this study, a flight envelope protection system is developed for a helicopter in autorotation to prevent main rotor speed limit exceedance. In an emergency condition, helicopter autorotation can be a challenging task to apply. Fatal accidents may occur due to loss of control during the autorotative flight. It is crucial to keep the helicopter inside the operational flight envelope to ensure safety. During autorotation, one of the most important limitations is the rotor speed boundaries. In this paper, a rotor speed estimation model is developed using a neural network based algorithm for a helicopter in autorotation. Using the lead estimate, the collective input margin and pitch angle margin are calculated. Two flight envelope protection methodologies are proposed using these margins. These strategies are shown through simulations to be successful in preventing the rotor speed limit exceedance.

NOMENCLATURE

Ω	Rotational speed of the rotor
ϕ, θ, ψ	Euler rotations defining the orientation of the helicopter
σ_{coll}	Collective stick input
σ_{long}	Longitudinal cyclic input
$V_{xhub}, V_{yhub}, V_{zhub}$	Local hub velocities
$pred$	Predicted

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INTRODUCTION

During autorotation, rotor speed boundaries are critical flight envelope limits and crucial for flight safety. The pilot should keep the rotor rpm between the maximum and minimum rpm limits. Very high rotor speeds might cause structural damage, whereas very low rotor speeds might cause loss of lift force, or loss of control, leading to fatal accidents. This paper proposes two methodologies to prevent rotor speed limit exceedance by calculating margins for the two limit parameters.

Aircraft have several performance limitations that should not be exceeded to prevent decrease in overall flight safety and control authority [Gratton, 2018]. These limitations are generally related to aerodynamic, structural, power, and control. The research on flight Envelope Protection Systems (EPS) aim to decrease this workload by cueing the pilots during flight through visuals, aural warnings or other equipment. In [Binet et al., 2009] a semi-empirical approach was used for the calculation of Vortex Ring State (VRS) parameters and it is implemented in the ground simulator for tactile cueing. The study showed the cue allowed the pilots to rapidly reach a sink rate that would prevent exceeding the safe limits. In [Sahasrabudhe et al., 2006], the collective control margin is calculated for continuous torque limits during non-emergency flight. The system cues the pilot to a variety of envelope limits of transient and continuous transmission torque limits. It uses a neural network algorithm to predict the collective control margin due to torque limit during powered flight.

Few studies on limit avoidance during autorotation in literature are done using linear models of rotor speed[Sahani & Horn, 2004]. Linear models are not accurate enough for the estimation of a highly nonlinear parameter such as the rotor rpm. Also, these studies do not provide a margin for the rotor speed, but they propose a control input sequence to stay at a nominal rpm value. The rotor speed limit margin estimation and limit avoidance during autorotative flight is new in this paper.

In this study, the method by [Sahani & Horn, 2004] for torque estimation is adapted to estimate the rotor speed during autorotative flight. Using helicopter models, the response of rotor rpm to state and control input changes are investigated. Then, the rotor speed is estimated using a neural network-based algorithm. A collective control margin and pitch angle margin are calculated in real-time during flight simulation using the estimation models. These margins are used to cue the pilot model during autorotative flight simulation and it is shown that the rotor rpm limits can be avoided.

METHOD

Helicopter Mathematical Model

The helicopter model is developed using physics-based functions. The model libraries that are used were developed in Aerotim Engineering LLC [Yavrucuk et al., 2010]. They have proven high fidelity and reliability for helicopter flight simulation through certified flight simulators. The performance of these methods at autorotative flight conditions is also proved to be realistic through pilot testing, hence the same methods are used in this study.

In autorotation and an event of engine failure, the clutch mechanism enables the rotor to drive the tail rotor. The clutch switch is the important section of this model. The difference between the rotor speed and engine speed determines whether the engine is clutched or not. If the difference is less than zero, this means the engine drives the rotor, the clutch is used as a rigid link. If the difference is greater than zero, the engine is de-clutched. This means the engine is slower than the main rotor and freewheeling is required. Since the losses are very small, they are neglected. The rpm is driven by the aerodynamic torque in the model.

Rotor Speed Estimation Model

The investigation of the rotor speed response to the given inputs or change in parameters is performed by first developing and using a pilot model. The pilot model is a PID controller that works on four channels consisting of longitudinal, lateral, directional, and vertical controllers. The total control inputs acting on the helicopter model are saturated with real limitations of the control system so that the inputs are not unrealistic.

The main rotor speed is investigated after a given step input change in pitch angle reference to the helicopter model trimmed in autorotation. The rotor speed converged to a steady-state value as the pitch angle reached its new steady-state value. Some examples of the behavior are presented in Figure 1. The same procedure was performed for the collective input. Figure 2 shows example rotor speed response to given step collective input. Results show that the rotor speed is steady-state critical [Gürsoy, 2016] to a pitch angle change and also to a given collective input.

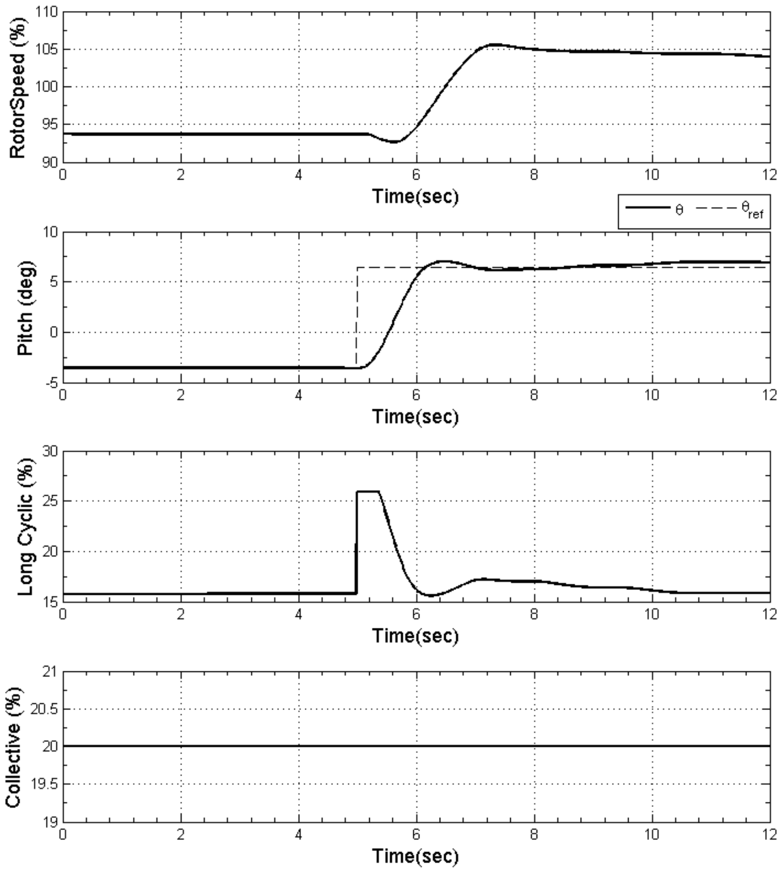

Figure 1: Helicopter model response to given pitch up reference at 90 kts forward autorotation

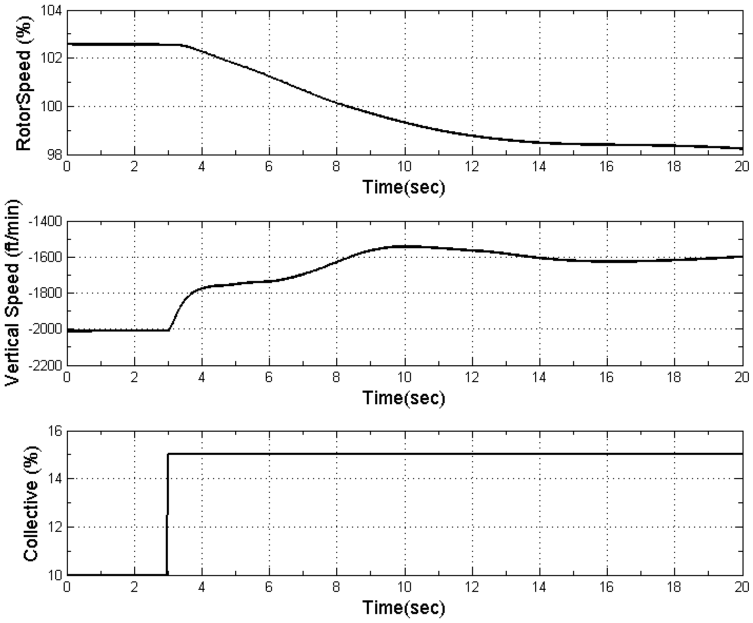

Figure 2: Helicopter model response to given collective up input at 65 kts in forward autorotation

In accordance with these results, the rotor speed ($\boldsymbol{\Omega_{pred}}$) is estimated by a function based on the pitch angle $\boldsymbol{\theta}$, pilot collective input $\boldsymbol{\sigma_{coll}}$, and the rotor hub velocities $\boldsymbol{V_{xhub}}, \boldsymbol{V_{yhub}}, \boldsymbol{V_{zhub}}$ on the x, y, and z axes.

$$\Omega_{pred} = f(\sigma_{coll}, \theta, V_{xhub}, V_{yhub}, V_{zhub}) \tag{1}$$

A neural network algorithm is developed to estimate this relation. A dynamic trim database for autorotation flight is generated and the neural network model is trained offline using this trim database [Sahani & Horn, 2004]. The developed neural network in this study is a three-layer feed-forward network that was trained using MATLAB [Demuth & Beale, 1994]. Figure 3 shows the steady-state response of the trained neural network.

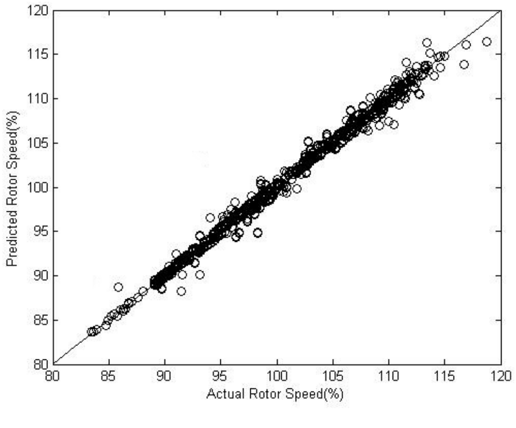

Figure 3: Neural network approximation of steady-state rotor speed

The neural network is implemented into the helicopter simulation as shown in Figure 4. A pilot model is used to track the pitch angle reference. The result in Figure 5 shows that the neural network algorithm can calculate a lead estimate of the rotor speed which can be used to predict before it reaches the limit boundary.

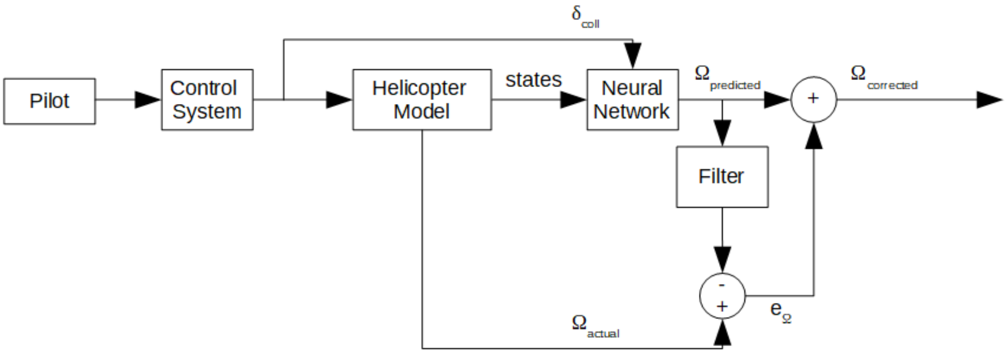

Figure 4: Schematic representation of rotor speed estimation algorithm

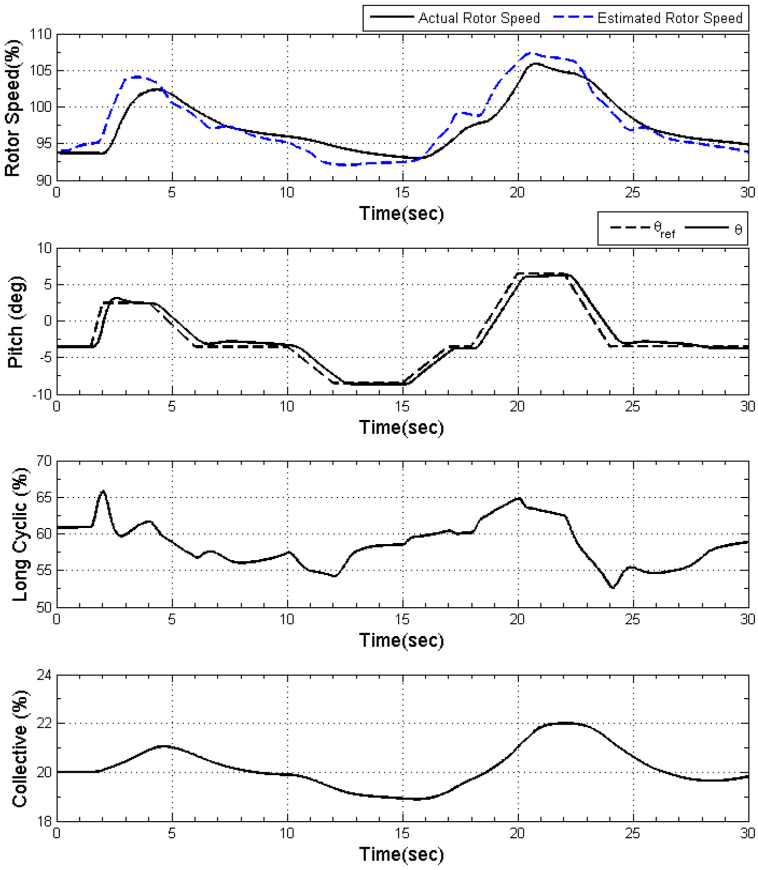

Figure 5: Neural network estimation performance for a given pitch reference and response of the helicopter in autorotation

Limit Margin Estimation

The calculation of the limit and control margins require to linearize the neural network model. The approximation can be written as [Horn et al., 2001],

$$\begin{bmatrix} \Delta\sigma_{coll} \\ \Delta\theta \end{bmatrix} \approx \left(\Delta\Omega - \dot{\Omega}\Delta t\right) \begin{bmatrix} \dfrac{\dfrac{\partial f}{\partial \sigma_{coll}}}{\left(\dfrac{\partial f}{\partial \sigma_{coll}}\right)^2 + \left(\dfrac{\partial f}{\partial \theta}\right)^2} \\ \dfrac{\dfrac{\partial f}{\partial \theta}}{\left(\dfrac{\partial f}{\partial \sigma_{coll}}\right)^2 + \left(\dfrac{\partial f}{\partial \theta}\right)^2} \end{bmatrix} \tag{2}$$

The critical control margin, $\boldsymbol{\Delta\sigma_{coll}}$**,** is the difference between the current control position and the related limit boundary. The critical limit margin, $\boldsymbol{\Delta\theta}$**,** is the difference between the current pitch angle and its value at the related limit boundary. $\boldsymbol{\Delta\Omega}$ represents the difference between the value of the rotor speed at the limit boundary and its current value. Δt is an arbitrary time margin that can be selected ensuring the limit is not exceeded. The partial derivative terms represent the sensitivity of the neural network model output to the given control inputs. They are calculated by perturbing the network model at several trim points.

Limit Protection Algorithm

The pitch limit margin cue is simulated in this study such that the pitch angle reference given to the pilot model is saturated with calculated upper and lower pitch angle margins. The pitch angle limit avoidance algorithm is shown in the block diagram in Figure 6. The collective cue is assumed as a hard stop tactile cueing. The calculated control margin is used to saturate the pilot model collective input. This control limiting algorithm is shown schematically in Figure 7.

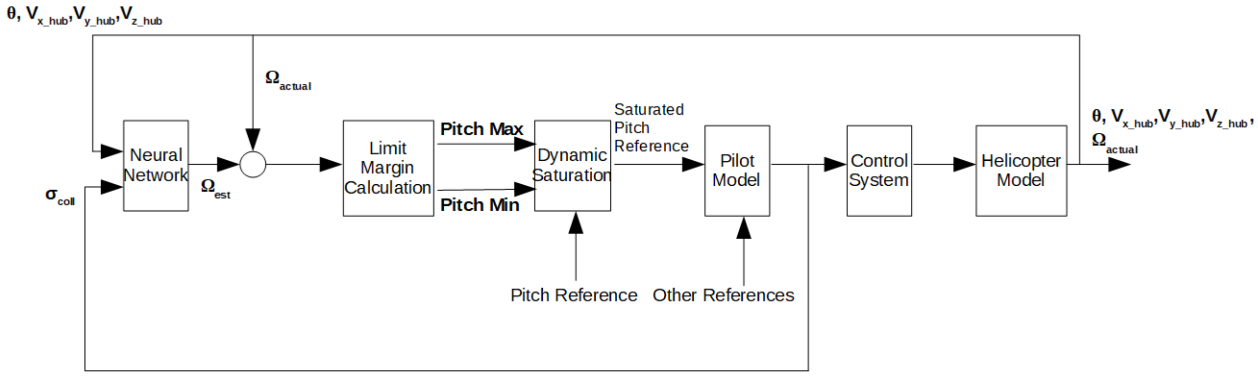

Figure 6: Block diagram representation of avoiding calculated pitch angle limit margin

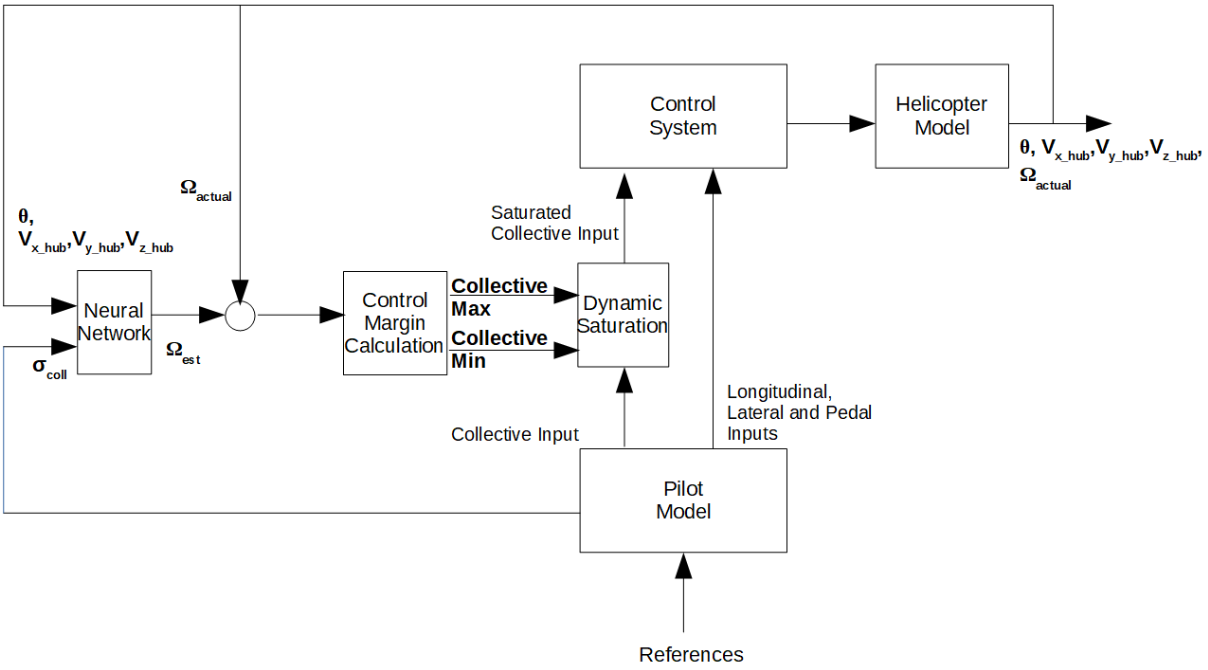

Figure 7: Block diagram representation of collective control limiting flight envelope protection

RESULTS AND DISCUSSION

Pitch Angle as a Limit Parameter

A smooth pitch up maneuver is performed using the developed pilot model in autorotation. The pilot model tracks the given pitch angle reference with the longitudinal cyclic. The roll angle and heading are kept at the trim state by the pilot model using the lateral cyclic and pedal inputs. The collective input tracks the given vertical speed reference. The high and low rotor rpm limits are 110% and 90%. These are the safe boundary limits during autorotation. The results are shown without the envelope protection in Figure 8. The helicopter is trimmed at a steady-state autorotation point where the rotor speed is close to the high rotor rpm limit. The trim point is at 6000ft height, the helicopter is trimmed at a 95 knots airspeed and -3800 ft/min vertical speed autorotation. A smooth pitch up reference is given. Collective is held constant. The dashed red lines in pitch angle plot are the calculated pitch angle limit margins. The margins are calculated at each time step and they change with the changing helicopter states and control inputs. As can be seen from the figure, the pitch angle limit margin is exceeded when the rotor speed limit is exceeded.

Figure 9 shows the same maneuver with the use of envelope protection algorithm that limits the pitch angle reference. As can be seen from the figure, the given pitch angle reference is saturated using the calculated limit margin. The pilot model tracks the saturated pitch angle reference. This prevents the rotor speed to exceed the limit.

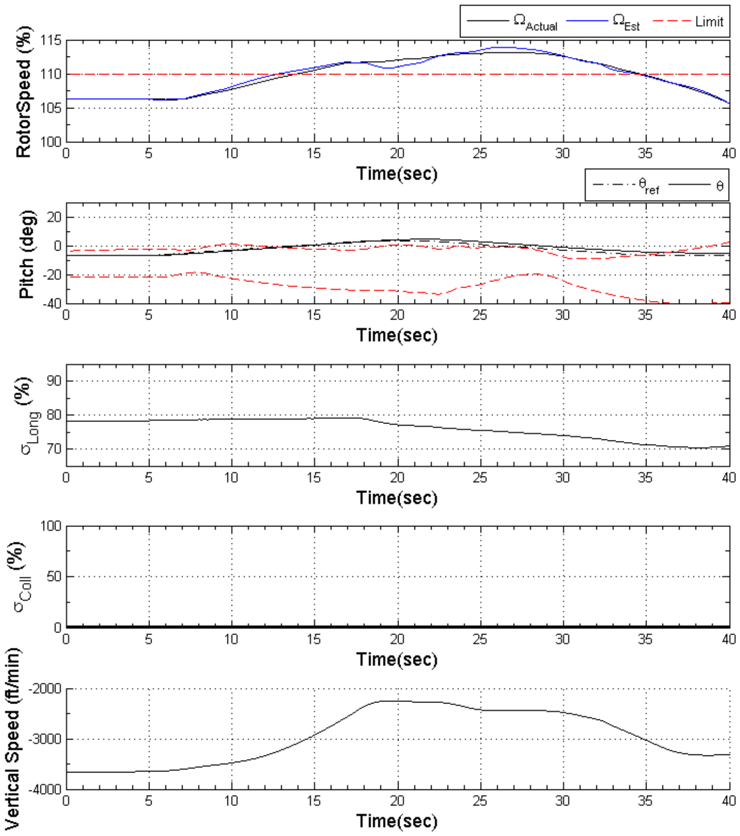

Figure 8: Smooth pitch up maneuver in autorotation, without envelope protection

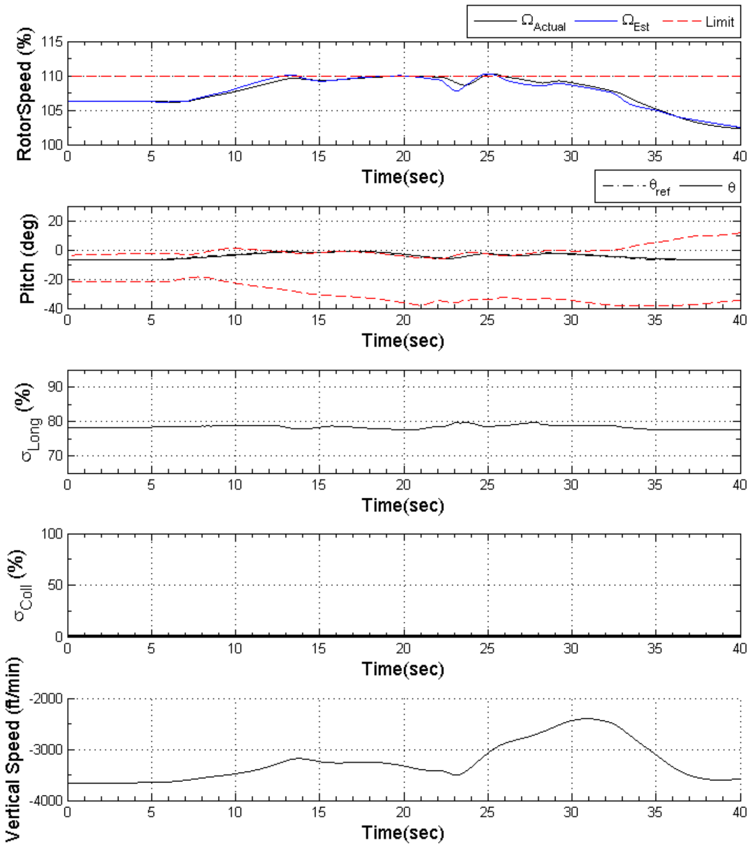

Figure 9: Smooth pitch up maneuver in autorotation, with envelope protection using pitch angle

Collective Input as a Control Limit

A collective cue is also calculated for envelope protection and a maneuver is performed. Both pitch angle and vertical speed references are given to the pilot model at the same time. The control margins for the collective control were calculated. The collective control input is saturated using these calculated margins. Figure 10 shows the maneuver without the use of envelope protection algorithm. Figure 11 shows that the envelope protection algorithm prevents the rotor rpm limit avoidance by saturating the collective control input.

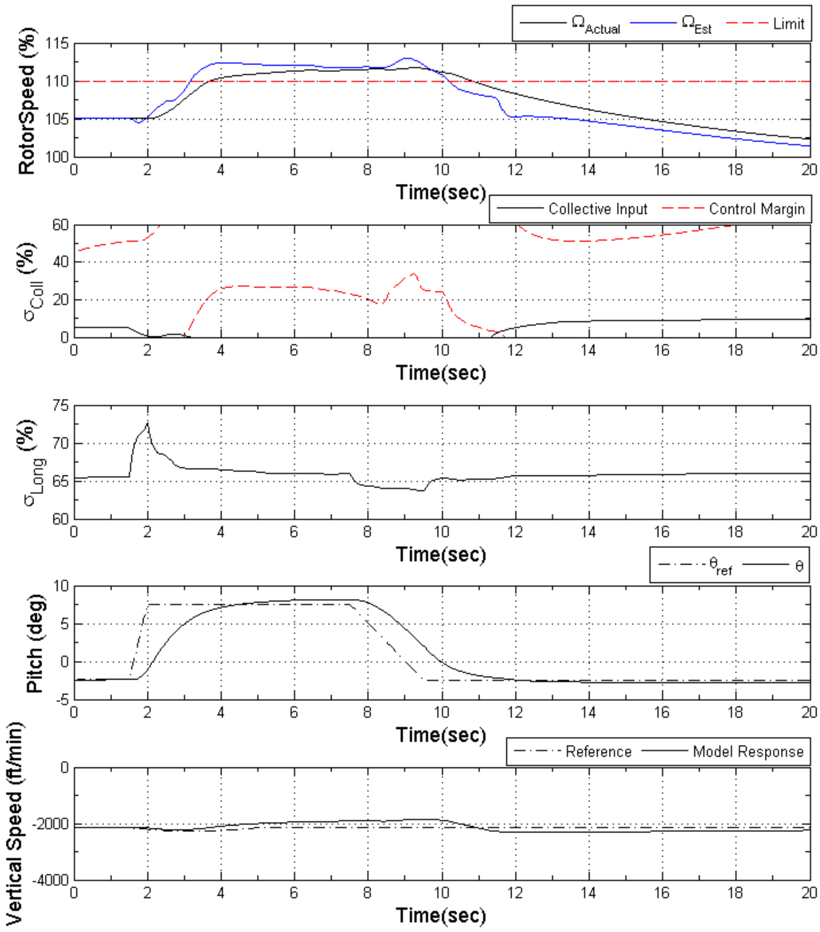

Figure 10: Pitch up maneuver in autorotation, without envelope protection

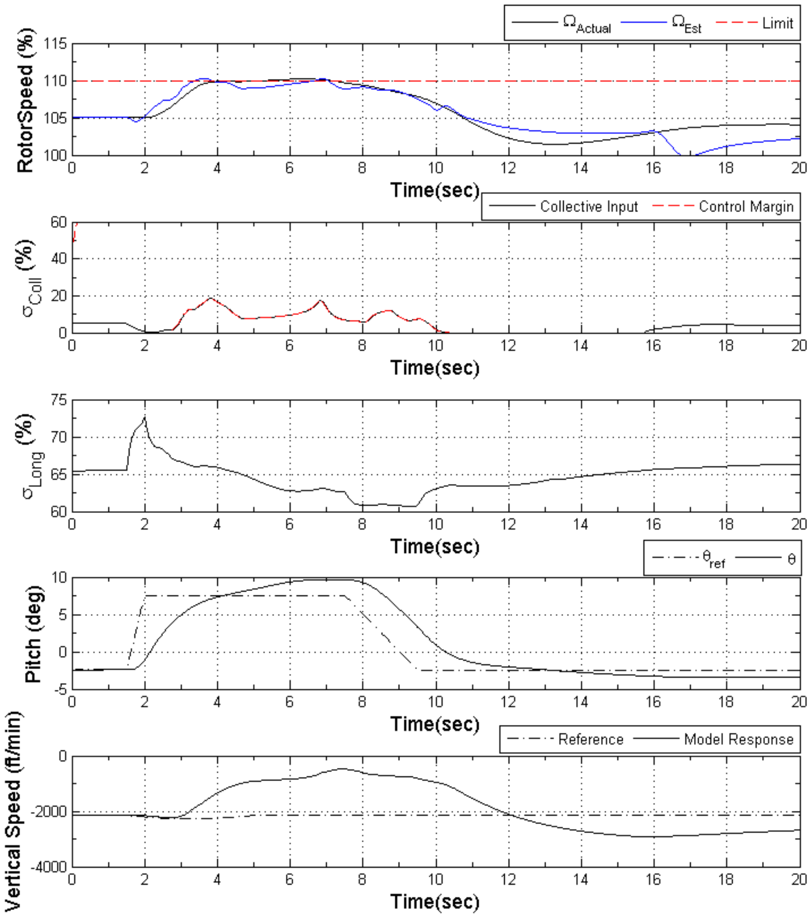

Figure 11: Pitch up maneuver in autorotation, with envelope protection using collective

CONCLUSION

A rotor speed estimation model is developed using a neural network based algorithm for a helicopter in autorotation. The estimation model is based on collective input, helicopter pitch angle, and the local hub velocities. This estimation model is used to predict the limit exceedance. Using the lead estimate, the collective input margin and pitch angle margin are calculated. Two flight envelope protection methodologies are proposed using these margins. Simulations are presented with a high-fidelity nonlinear helicopter model. In simulations, the proposed envelope protection strategies are shown to be effective in preventing the rotor speed limit exceedance.

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