LOAD LIMITING CONTROL : A HANDLING QUALITIES ANALYSIS

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Abstract

The aim of this paper is to study the impact of two component load limiting controllers (LLC), viz., command limiting LLC and control limiting LLC, on the quantitative handling qualities specifications during pitch maneuvers in the forward flight regime. Specifically, the maximum achievable load factor, the pitch attitude quickness, the agility quickness, and the load quickness parameters are used as metrics to quantify the impact of both LLC schemes on the handling qualities performance of the helicopter. The pitch attitude and agility quickness criteria are used to quantify the agility of the helicopter. The load quickness is used to measure the performance of the component load limiting controllers by quantifying the build up of load on the component during maneuvering flight. Results demonstrate that both component load limiting controllers have similar impact on the pitch attitude quickness, load quickness, and maximum achievable load factor. Furthermore, it is observed that the command limiting LLC has less detrimental effect on the agility quickness when compared to the control limiting LLC.

1. NOMENCLATURE

Q_γ	Agility quickness
Q_θ	Pitch attitude quickness
Q_l	Load quickness
T_p	Time horizon
δ_{cmd}	Command input
δ_u	Control effector
γ	Flight path angle
θ	Pitch attitude
n_z	Load factor
q_c	Commanded pitch rate
F	Load
Y	Pitch Link load
g	Gravitational acceleration
q	Pitch rate
$()_{max}$	Maximum value
$()_{n/rev}$	n/rev Magnitude component
$()_{pk}$	Peak value
ADS	Aeronautical design standard
Cmd	Command
Ctrl	Control
LAC	Load alleviation control
LLC	Load limiting control
LTI	Linear time invariant
MPC	Model predictive control
MTE	Mission task element

2. INTRODUCTION

In forward flight, as the helicopter's main rotor rotates and simultaneously advances, a very complex aerodynamic environment dominated by large dynamic loads is created[1]. The large magnitude and high application rate of these loads are detrimental to many helicopter components as they are the main cause of premature fatigue failure. Critical helicopter components, classified as Grade-A Vital components by regulatory authorities, are subject to significant fatigue loading in which the failure would result in a catastrophic event. A list of fatigue critical components on the AH-64A Apache shows that many of the Grade-A Vital components[2] are located in the rotor system, creating challenges for real-time load and structural health monitoring of those components. Consequently, the operational structural life of such components is underestimated and more importantly, the development of load alleviation/limiting control schemes for component life extension becomes challenging.

In the literature, the development of control strategies for component life extension took mainly the form of Load Alleviation Control (LAC). For instance, a recent study at Penn-State[3,4] developed a load alleviation control scheme aimed at reducing component dynamic (e.g., peak-to-peak) loads, leading to reduced peak-to-peak stresses, and hence potentially leading to reduced fatigue life usage. The main drawback of using an LAC scheme for component life extension resides in its inability to discern between aggressive versus non-aggressive maneuvers. In using LAC no distinction is made in the aggressiveness of the maneuver. In order to circumvent this limitation, two Load Limiting Controllers (LLC) were proposed in Ref. 5 : namely control and command limiting LLC. The LLC schemes are designed to limit the control effector commands coming out of the flight controller and the pilot command inputs, only during aggressive maneuver, in order to achieve component load limiting. Hence, a clear distinction in the aggressiveness of the maneuver is taken into account. In Ref. 5, the LLC schemes are designed to limit a particular pitch link harmonic load during aggressive maneuvers. Even though the study of Ref. 5 shows the effectiveness of such schemes along with providing an initial understanding of the trade-off between component load limiting and maneuver performance, a comprehensive handling qualities analysis is needed to understand the impact of the LLC schemes on the handling qualities performance of the helicopter.

The focus of the current study is to assess the impact of the LLC schemes on the predicted handling qualities using ADS-33. The paper is organized as follows: First, a brief description of the LLC schemes used for component load limiting is presented. Next, we analyze the impact of the LLC schemes on the maximum achievable load factor. Following that, using the pitch attitude quickness and agility quickness parameters, a study of the impact of the LLC schemes on the agility of the helicopter is performed. Next, the effectiveness of the LLC schemes is evaluated using the load quickness parameter. Finally, concluding remarks are provided in order to summarize the main points of the study along with suggestions for future work.

3. LOAD LIMITING SCHEMES

In this section, a brief overview of the load limiting controllers (LLC) developed in Ref. 5 and the simulation model used in this study are presented. Two load limiting controllers were developed in Ref. 5. The first one is a control limiting LLC whereas the second proposed strategy is a command limiting LLC.

3.1. Control Limiting LLC

The control limiting LLC scheme of Ref. 5 is based on a model predictive receding horizon control formulation. Using an on-board reduced order linear time invariant (LTI) model, the control limiting LLC scheme computes, at each instant in time, future extremal control input that would result in the component load to reach its limit boundary without exceeding it. The on-board dynamical model provides a means to obtain a mapping from the control effector commands to the component load. A 10^{th} order LTI model, derived from a higher order linear time invariant model, is used as the on-board model. The calculated extremal control inputs are then used as bounds on the control inputs coming out of the flight controller (control effectors commands). A block diagram representation of the load limiting scheme via control limiting integrated within a flight controller is shown in Fig. 1.

In Fig. 1, $x(t_0)$ represents the current values of the reduced order LTI model state vector and $\delta\tilde{u}(t_{0-})$ represents control vector prior to input at t_0. It is assumed that the reduced order LTI model states are available from on-board measurements and the estimated trim values of the limit parameter are assumed to be known. Note that the on-board reduced order model uses these measurements in order to estimate the component loads at t_0. The extremal control inputs are obtained by solving at each time instant a constrained optimization problem of a quadratic cost function using the reduced order LTI model as can be seen in Eqs. 1 and 2 (see Ref. 5 for more details)

(1)

$$min_{\delta u_{limit}}[J],\ J = \int_{t_0}^{t_o+T_p} L(\|Y_{harm}\|_2, \delta u_{limit})dt$$

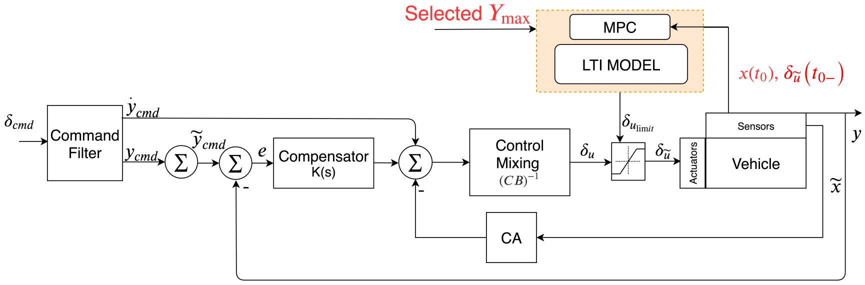


Figure 1: Control limiting LLC (Ref. 5).

subj:

(2) $\|Y_{harm}\|_2 \leq y_{max}$

The solution to the optimal control problem provides estimates of the control margin boundaries associated with harmonic pitch link load limits and are used to bound the control input from the flight controller.

3.2. Command Limiting LLC

The command limiting LLC scheme, similar to the control limiting LLC, is based on a receding horizon model predictive control formulation. Using an onboard model that provides a mapping between the pilot command input and the harmonic pitch link loads, the command limiting LLC scheme solves the optimization problem shown in Eqs. 3 and 4 to generate estimates of available command margin. Using these command margin estimates, the input to the controller is constrained to keep harmonic pitch link loads within a desired maximum value. A block diagram representation of the load limiting scheme via command limiting integrated within a flight controller is shown in Fig. 2. A more detailed explanation of this scheme can be found in Ref. 5.

(3)
$$min_{\delta limit}[J], J = \int_{t_0}^{t_o+T_p} L(\|Y_{harm}\|_2, \delta limit)dt$$

subj:

(4) $\|Y_{harm}\|_2 \leq y_{max}$

The effectiveness of both LLC schemes is evaluated in Ref. 5. Figures 3 and 4, extracted from Ref. 5, show sample results wherein the LLC schemes are designed to limit the magnitude of 1/rev pitch link load. The LLC schemes keep the magnitude of 1/rev pitch link load within the desired maximum value as can be seen in Fig. 3. As a result of the load limiting, the pitch rate profile is attenuated as can be observed in Fig. 4.
Even though the results in Ref. 5 clearly show that both LLC architectures lead to a loss in maneuver performance (as can be seen in Figs. 3 and 4), a more comprehensive handling qualities analysis is needed to better understand the impact of both LLC schemes on the predicted handling qualities. In this paper, we consider the study of the impact of limiting the magnitude of 1/rev pitch link load on the predicted handling qualities during pitch maneuvers in forward flight. The limit for the magnitude of 1/rev pitch link load is arbitrarily set to 350 lb.

3.3. Nonlinear Simulation Model

This research makes use of FLIGHTLAB® (Ref 6) for the development of the bare-airframe high fidelity nonlinear model of a generic single main rotor helicopter, similar in size and weight of the UH-60. The nonlinear helicopter model is approximately 17000 lbs of weight with an articulated rotor system with elastic blades. In order to accurately capture the rotor loads, the nonlinear model includes flexible blades with representative in-plane, out of plane bending and torsional modes. Furthermore, the model uses a 33 state Peters-He dynamic inflow model, complete non-linear aerodynamic look-up tables for airframe and rotor blade aerodynamics coefficients, swashplate and tail rotor actuator models, and the Bailey tail rotor model.

4. MAXIMUM ACHIEVABLE LOAD FACTOR

The maximum achievable load factor ($n_{z_{max}}$) can be used as a metric to quantify the impact of the LLC schemes on the handling qualities during pitch maneuvers in forward flight (Ref. 7). To quantify the impact of the LLC schemes on the handling qualities using the maximum achievable load factor metric, we consider a step pitch rate command input

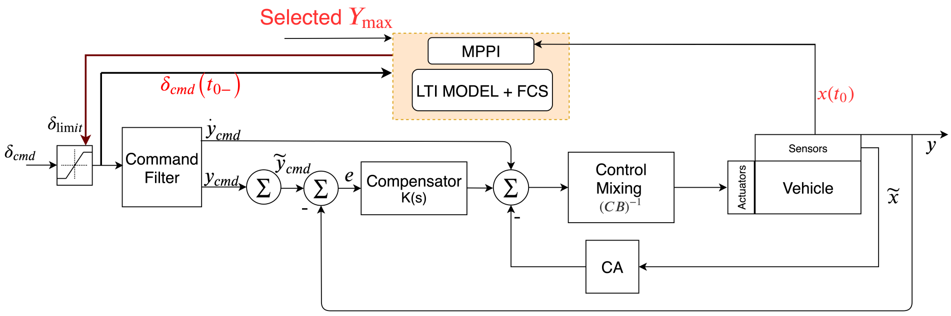


Figure 2: Command limiting LLC (Ref. 5).

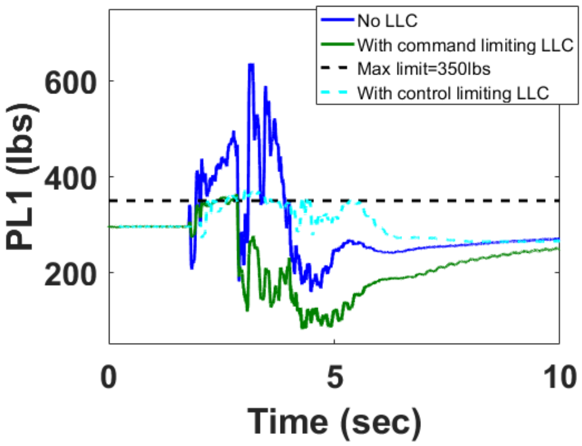


Figure 3: Magnitude of 1/rev pitch link load with and without LLC (Ref. 5).

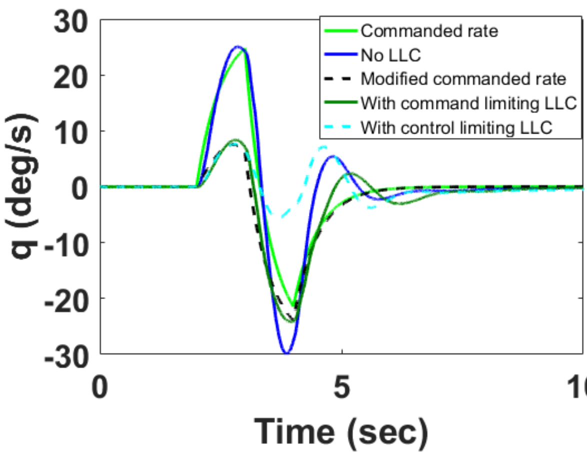


Figure 4: Body pitch rate response with and without LLC (Ref. 5).

of magnitude 34.4 deg/s. The maximum achievable load factor for the cases with control limiting LLC ("Ctrl LLC"), with command limiting LLC ("Cmd LLC), and without LLC ("No LLC) resulting from this step command input are recorded and compared. Figures 5 and 6 show the load factor and magnitude of 1/rev component of pitch link load resulting from the step pitch rate command input. The maximum achievable load factor for the cases with control limiting LLC ("Ctrl LLC"), with command limiting LLC ("Cmd LLC) and without LLC ("No LLC) was determined (Table 1). With the baseline controller ("No LLC") a maximum load factor of 2.45 is achieved whereas for the cases with control and command limiting LLC the maximum achievable load factor drops to 1.24 (49.4% reduction) and 1.27 (48.2% reduction) respectively.

It can be concluded that for a load limit of 350 lb. the control and command limiting LLC have similar impact on the maximum achievable load factor.

Table 1: Maximum Achieved Load Factor

Cases	$n_{z,max}(g)$
No LLC	2.45
With control limiting LLC	1.24 (-49.4%)
With command limiting LLC	1.27 (-48.2%)

5. PITCH ATTITUDE QUICKNESS

In the pitch axis, an important flying qualities criterion is the pitch attitude quickness. The pitch attitude quickness parameter gives a measure of the agility of the helicopter during vertical maneuvers. It does so by measuring the ability of the helicopter to perform rapid and precise moderate-amplitude pitch attitude changes (i.e., $5^o < \theta < 30^o$) during pitch maneuvers (Ref. 8). The pitch attitude quickness parameter (Q_θ) is defined as the ratio of the peak pitch rate (q_{pk}) to the peak attitude angle change ($\Delta\theta_{pk}$)

$$Q_\theta = \frac{q_{pk}}{\Delta\theta_{pk}} \qquad (5)$$

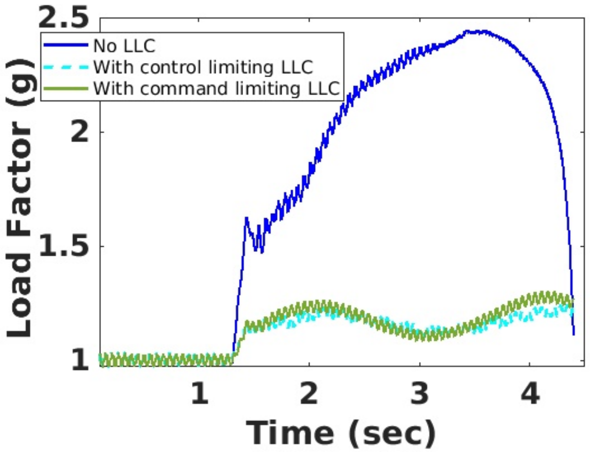


Figure 5: Load factor with and without LLC.

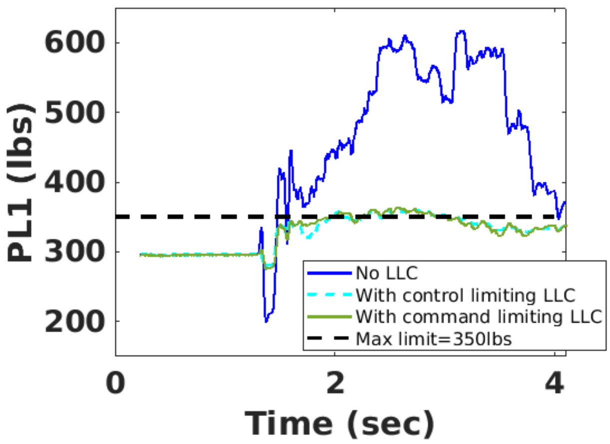


Figure 6: Magnitude of 1/rev pitch link load with and without LLC.

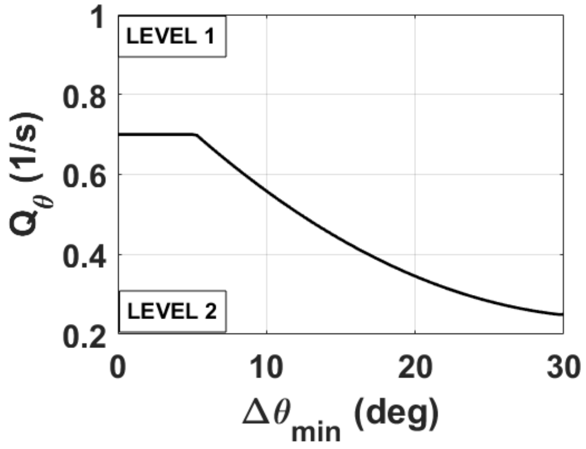


Figure 7: ADS-33 level 1-2 pitch attitude quickness boundary for a general MTE.

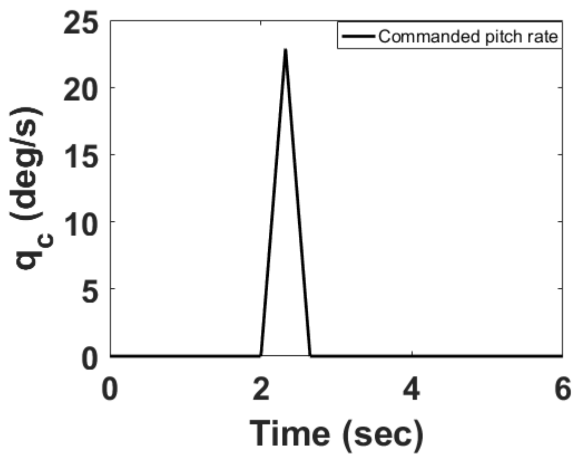


Figure 8: Pulse command input of 0.65 sec.

The ADS-33 handling qualities boundary associated with the pitch attitude quickness is defined as a function of the minimum attitude change ($\Delta\theta_{min}$). Figure 7 shows the handling qualities boundary for the pitch attitude quickness for a general MTE at hover and low speed (Ref. 8).

For a helicopter with a flight controller that provides a rate command response type in the pitch axis, the pitch attitude quickness parameter can be computed from the response of a pulse command input (Ref. 9). Figure 8 shows a typical ADS-33E-PRF pulse command input.

Figures 9 and 10 show the pitch rate and attitude responses resulting from the pulse command input of Fig. 8. From Figs. 9 and 10, the values of peak pitch rate (q_{pk}), peak attitude angle change ($\Delta\theta_{pk}$), and minimum attitude change ($\Delta\theta_{min}$) can be extracted. The pitch attitude quickness can then be obtained from pulse command input responses of different durations. The impact of both the command and control limiting LLC on the agility of the helicopter can be assessed by comparing the pitch attitude quickness with and without LLC. Figure 11 shows the pitch attitude quickness for the cases with control limiting LLC ("Ctrl LLC"), with command limiting LLC ("Cmd LLC") and without LLC ("No LLC"). Looking at Fig. 11, one main conclusion can be drawn. The control and command limiting LLC result in identical loss in agility. In addition, for both control and command limiting LLC the pitch attitude quickness remains within level 1. It is important to note that although the pitch attitude quickness parameter is only defined at hover and low speed, it still remains a good metric to quantify the change in handling qualities introduced by the command and control limiting LLC (Ref. 7) .

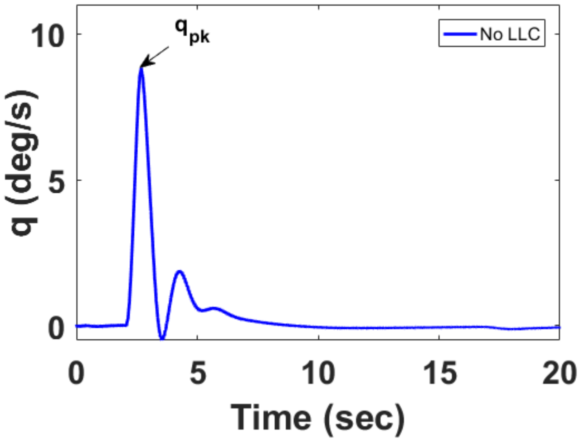


Figure 9: Body pitch rate response.

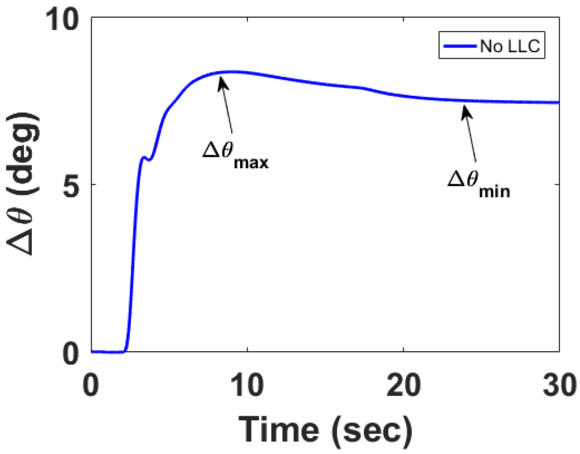
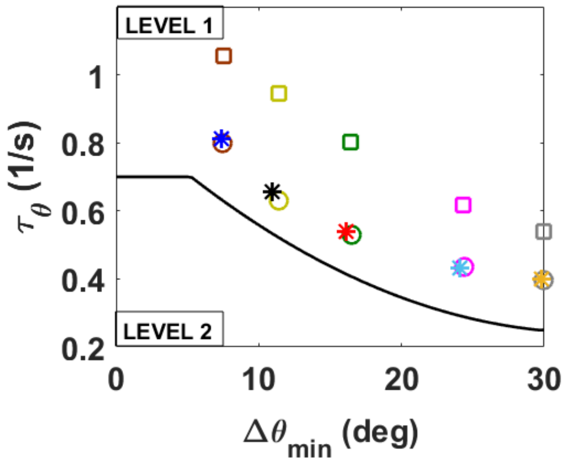
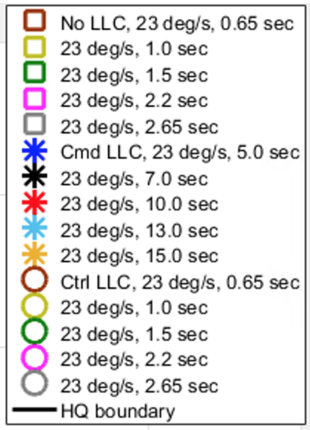


Figure 10: Body pitch attitude response.



(a) Pitch attitude quickness with and without LLC.



(b) Legend

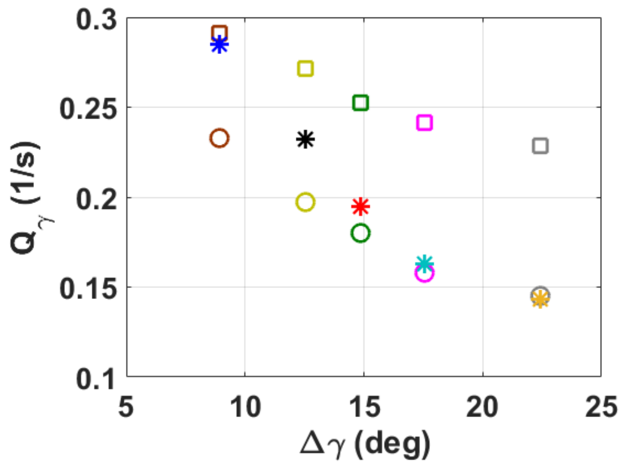
Figure 11: Impact of control and command limiting LLC on the pitch attitude quickness

6. AGILITY QUICKNESS

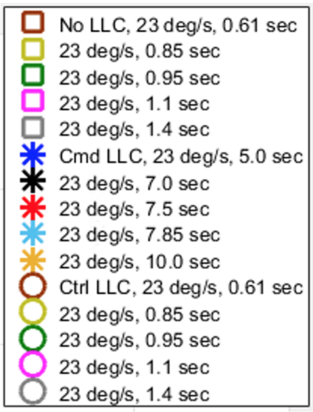
An alternative parameter that can be used to quantify the agility of a helicopter in forward flight is the agility quickness parameter. The agility quickness parameter is a metric introduced in Ref. 10 as a replacement for the conventional ADS-33 pitch attitude quickness parameter. In forward flight, during maneuvers in the vertical axes, the pilot is far more interested in the flight path angle change than in the pitch attitude change (Refs. 10, 11). Hence, in forward flight, the agility of a helicopter in the pitch axes should be related to the flight path angle instead of the pitch attitude angle. The agility quickness parameter, Q_γ, is defined as follows

$$Q_\gamma = \frac{\dot{\gamma}_{pk}}{\Delta\gamma} \tag{6}$$

where $\dot{\gamma}_{pk}$ is the peak values of the rate of change of the flight path angle during a specific maneuver and $\Delta\gamma$ is the change in flight path angle. It can be readily seen that the agility quickness parameter has the same units as the pitch attitude quickness parameter which facilitates their comparison. For a helicopter with a flight controller that provides a rate command response type in the pitch axis, the agility quickness parameter can be computed from the response of a pulse command input in the pitch axes. Similar to the pitch attitude quickness, the agility quickness can be obtained from pulse command input responses of different durations. The impact of both the command and control limiting LLC on the agility of the helicopter can be assessed by comparing the agility quickness with and without LLC. Figure 12 shows the agility quickness for the cases with control limiting LLC ("Ctrl LLC"), with command limiting LLC ("Cmd LLC") and without LLC ("No LLC"). It can be observed from Fig. 12 that the command limiting LLC performs better than the control limiting LLC. At low to medium flight path angle changes, the agility of the helicopter is less compromised with the command limiting LLC when compared to the control limiting LLC. At large flight path angle changes, the agility is near-identical. Hence, using the agility quickness parameter, we can conclude that the command limiting LLC has less detrimental effect than the control limiting LLC on the agility of the helicopter.



(a) Agility quickness with and without LLC



(b) Legend

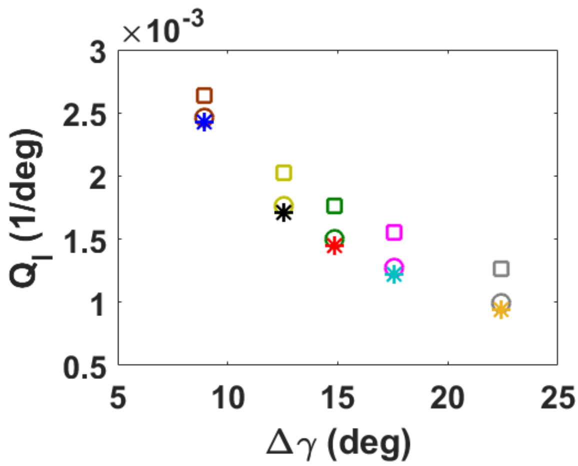
Figure 12: Impact of control and command limiting LLC on the agility quickness.

7. LOAD QUICKNESS

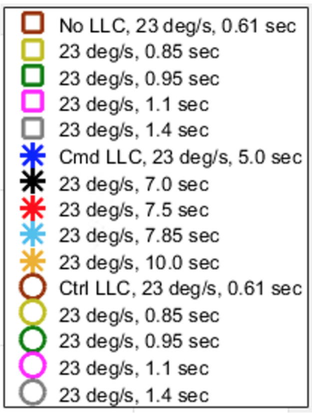
The load quickness parameter is a handling qualities metric for structural loading during maneuvering flight (Refs. 10, 7, 11). It was introduced to quantify the build up of loads in the rotor during maneuvering flight (Refs. 10 and 11). Therefore, this metric can be used to quantify the effectiveness of the load limiting schemes. The load quickness parameter is given as follows:

$$Q_l = \frac{|F|_{max}}{W\Delta\gamma} \quad (7)$$

where F is the maximum absolute value of the load during a specific maneuver, W is the weight of the helicopter, and $\Delta\gamma$ is the flight path angle change. Similar to the pitch attitude quickness, the load quickness can be obtained from pulse command input responses of different durations. Figure 13 shows the load quickness for the cases with control limiting LLC ("Ctrl LLC"), with command limiting LLC ("Cmd LLC") and without LLC ("No LLC"). It can observed that the 1/rev load build-up on the pitch link for the control and command limiting LLC is near-identical



(a) Load quickness with and without LLC



(b) Legend

Figure 13: Impact of control and command limiting LLC on the load quickness.

8. DISCUSSION

The Command limiting LLC can be implemented with a soft-stop that would allow the pilot to override it for safety reasons. In addition, since it is not in the loop, it does not affect the overall stability of the system. Hence, for the command limiting LLC, stability will not be sacrificed to avoid the excessive build-up of load on the component during maneuvering flight. On the other hand, while the control limiting LLC can affect the overall stability of the system, it allows to set an absolute load limit and not exceed it, no matter what the control system or pilot commands.

In light of the results obtained in this paper, it is seen that the command limiting LLC and control limiting LLC have similar performance in component load limiting. In addition, the command limiting LLC allows for more rapid changes in the flight path angle when compared to the control limiting LLC. Hence, the command limiting LLC allows for a more agile aircraft when compared the control limiting LLC. It is important to note that when designing either a command limiting LLC or control limiting LLC scheme for component load limiting, the agility quickness and load quickness parameters can be used to optimize between component load limiting and helicopter maneuverability.

9. CONCLUDING REMARKS

The handling qualities analysis of two component load limiting schemes is presented in this paper. This paper is aimed at understanding the impact of control and command limiting LLC on the handling qualities performance of the helicopter. The load limiting controllers used in this study were designed to limit the magnitude of 1/rev pitch link load to a maximum value of 350lb. The maximum achievable load factor, the pitch attitude quickness, the agility quickness, and the load quickness are time-domain metrics that are used in this paper to perform the handling qualities analysis. The pitch attitude and agility quickness parameters are used to quantify the agility of the helicopter. The load quickness parameter is a handling qualities metric that pertains to the build up of load in the rotor during maneuvering flight. It is found that the impact of the control and command limiting LLC on the maximum achievable load factor is near-identical. Same conclusion is observed for the pitch attitude quickness and load quickness. As for the agility quickness, the command limiting LLC performed better when compared to the control limiting LLC. More specifically, It is seen that the command limiting LLC led to less detrimental effect on the agility quickness when compared to the control limiting LLC.

While this work provides a better insight on the impact of the different LLC schemes on the predicted handling qualities, more work is needed in establishing the impact of component load limiting on the predicted handling qualities when one chooses to limit different harmonic components of loads.

10. ACKNOWLEDGMENTS

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