LOAD LIMITING CONTROL: A PILOTED SIMULATION STUDY

Chams E. Mballo
PhD Candidate

Robert Walters
PhD Candidate

J.V.R Prasad
Professor

School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, Georgia, USA

Abstract

The aim of this paper is two fold; firstly, to integrate a previously developed life extending control scheme, viz., Load Limiting Control (LLC) scheme, with a visual cueing system, and secondly, to perform real-time piloted flight simulation experiments of the resulting architecture using the Georgia Tech Re-configurable Rotorcraft Flight Simulator. The piloted simulations assessed the effectiveness of the visual cue in limiting maneuver aggressiveness for component load limiting. Two maneuvers were considered in this study: a pitch doublet maneuver and a pull-up maneuver. From the results gathered during the experiment, it is found that, even though the implementation of an LLC scheme within a real system using a visual cueing architecture is viable, the time delay inherent in such a cueing paradigm can impede the overall performance of an LLC system.

NOMENCLATURE

Q, q	Pitch rate
T_p	Time horizon
u	Input vector
y_p	Load vector
$\tilde{x}$	State vector
XA, XB	Longitudinal and lateral sticks displacements
XC, XP	Collective stick and pedal displacements
δ_{cmd}	Command input
Δ	Variation from equilibrium
$()_{ext}$	Extremal value
$()_{limit}$	Limit value
$()_{max}$	Maximum value
$()_{pilot}$	Pilot control input vector
AFCS	Automatic Flight Control System
CM	Control Margin
Cmd	Command
LAC	Load Alleviation Control
LLC	Load Limiting Control
MPC	Model Predictive Control
PLn	n/rev Pitch Link Load, n=1, 2, 3...

1. 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. Because of the asymmetric air flow past the main rotor, the lift forces each blade generates vary depending on its location. This creates cyclic loading that occurs at the main rotor frequency of rotation (1/rev) and at higher harmonic frequencies (n/rev, n=2, 3, 4, etc.) which become important for vibration, fatigue and forward flight performance. Hence, many components in the rotor system are highly loaded with cyclic loads at and multiples of the rotor frequency. This causes significant high-cycle fatigue life usage, and therefore, reductions in component life. In addition, during aggressive maneuvers, the low-duration high magnitude cyclic loads may lead to small amounts of localized damage, for example, localized plasticity, at stress concentration regions. It is, therefore, crucial to develop control strategies that can guard against premature fatigue failure of critical helicopter components.

In the literature, the development of control strategies for component life extension took mainly the form of Load Alleviation Control (LAC). For instance, studies at Penn-State[1,2] developed load alleviation control schemes aimed at reducing component dynamic (e.g., peak-to-peak) loads, leading to reduced peak-to-peak stresses, and hence, potentially leading to a reduction in low cycle 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 other words, using an LAC design, the trade-off between maneuver performance and component load alleviation is always present irrespective of the aggressiveness of the maneuver.

An alternative control strategy for component life extension is the Load Limiting Control (LLC)[3]. The LLC scheme is a less conservative approach to component life extension compared to the LAC scheme. The LLC scheme trades maneuver performance for component load limiting only when needed, i.e., only during aggressive maneuvers, at the discretion of the pilot. Unlike the LAC scheme, the LLC scheme allows for pilots to prioritize between load limiting and maneuver aggressiveness. Previously, it has been shown how the proposed load limiting control scheme can be integrated within an Automatic Flight Control System (AFCS) to perform batch simulations[4]. The LLC scheme can be integrated within an AFCS in two ways[4]. One way is through a command limiting architecture (“Command limiting LLC"); another way is through a control limiting architecture (“Control limiting LLC").

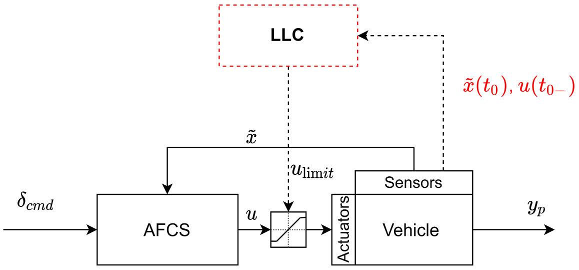


Figure 1: Load Limiting via control limiting.

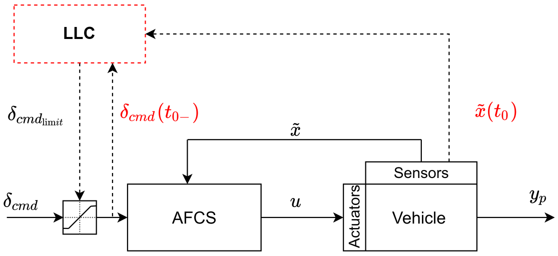


Figure 2: Load Limiting via command limiting.

Figures 1 and 2 show the control and command limiting architectures, respectively. From Figs. 1 and 2, it can be observed that the control limiting LLC (“Load Limiting via control limiting") architecture limits the control effector commands to achieve load limiting while the command limiting LLC (“Load Limiting via command limiting") architecture limits directly the pilot’s command to achieve load limiting.

Figures 3 and 4 show the performance of the control and command limiting LLC during a pitch rate doublet maneuver in forward flight at 120 knots. Figure 3 plots the pitch link load on the y-axis versus time on the x-axis for three conditions, no LLC, with control limiting LLC, and with command limiting LLC. The goal is to keep the 1/rev pith link load below a limit at 350 lbs as indicated by the horizontal black dashed line. The no LLC condition in solid dark blue exceeds the limit by 341 lbs (97 %). The command limiting (green) and control limiting (dashed light blue) exceed the limit by 14 lbs (4 %) and 26 lbs (7 %), respectively. Therefore, it may be concluded that both load limiting methods result in effective load limiting. From Fig. 4 it is observed that the command limiting LLC has less detrimental effect on the maneuver performance when compared to the control limiting LLC. This result shows that even thought the proposed LLC scheme comes with great benefits, one needs to be careful when integrating such a scheme within an AFCS. However, at the same time, the actual implementation of the load limiting via control limiting is much simpler as its architecture is independent of vehicle-specific flight control system.

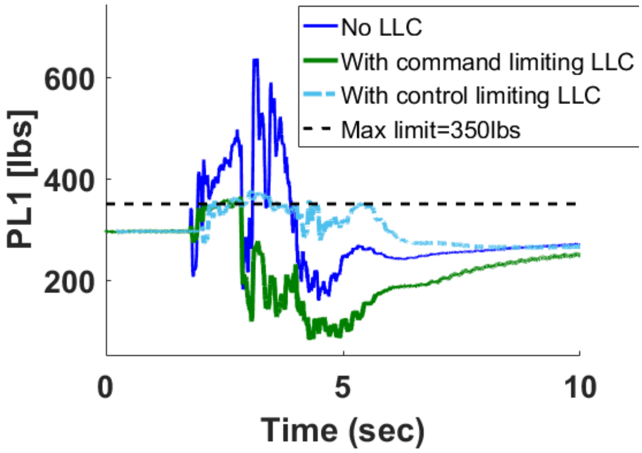


Figure 3: Variation of 1/rev harmonic component of reference blade pitch link load with and without LLC[4].

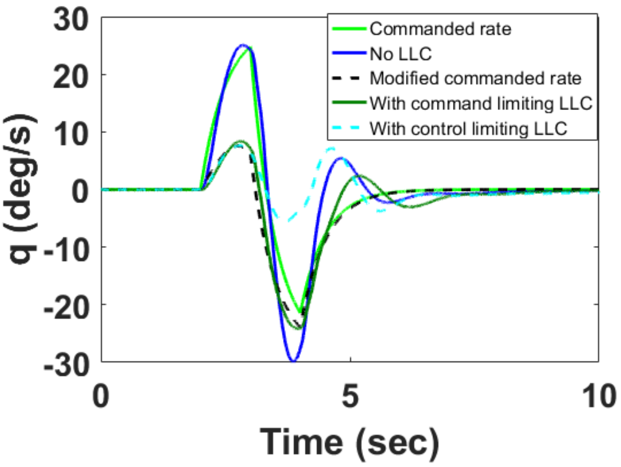


Figure 4: Body pitch rate response with and without LLC[4].

Thus far, the performance of LLC scheme has only been assessed in batch simulations. In this paper, the main focus is the integration of the LLC scheme with a visual cueing system and real-time piloted simulation evaluations of the resulting architecture. More specifically, the implementation of the load limiting via control limiting scheme within the Georgia Tech Re-configurable Rotorcraft Flight Simulator and piloted simulation evaluations are considered.

The paper is organized as follows: First, a brief description of the LLC scheme is presented. Next, the integration of the LLC scheme with a visual cueing system is discussed. Following that, real-time piloted simulation evaluations are carried out in order to assess the effectiveness of the visual cue in limiting maneuver aggressiveness for component load limiting. Finally, concluding remarks are provided in order to summarize the main points of the study along with suggestions for future work.

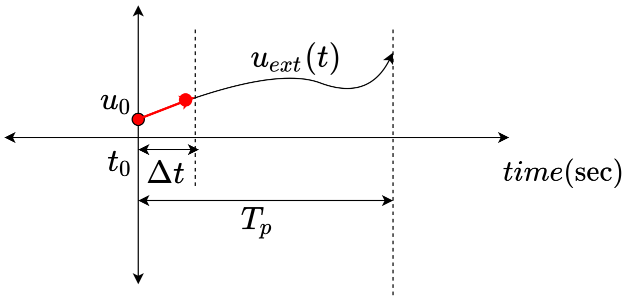
2. LLC SCHEME

Given a load limit (y_{max}) that is not to be exceeded, the LLC scheme uses an on-board dynamical model representative of the true vehicle dynamics, a cost function defined over a finite time horizon of T_p, and an optimizer to compute, at each instant in time, future extremal control input (u_{ext}) that would lead the component harmonic load (y_p) to reach its limit, without exceeding it. This process is illustrated in Fig. 5. Hence, the LLC scheme treats the load limit (y_{max}) as a limit boundary and uses Model Predictive Control (MPC) to arrive at an optimal control profile that would give rise to a harmonic load response reaching the limit boundary within a time horizon of T_p. The shaded area in Fig. 5b gives a graphical representation of the cost function used by the LLC scheme. The calculated extremal control profile is used to form the quantity known as Control Margin (CM). The control margin is given by the following equation

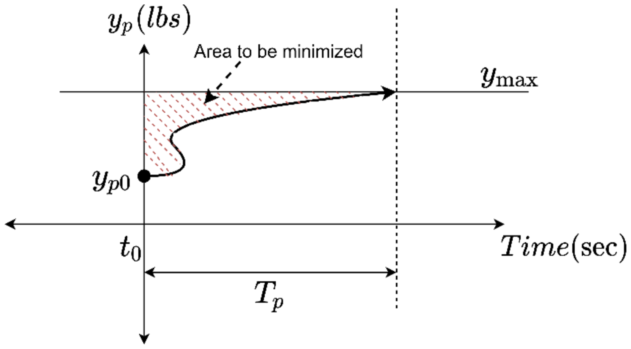
$$(1) \quad CM(t) = u_{ext}(t_0 + \Delta t) - u_{pilot}(t)$$

The control margin is an important quantity that can be provided to the pilot in the form of a cue. This would inform the pilot, at each instant in time, of how much control deflection is allowed before the harmonic load exceeds the maximum limit. The LLC scheme can also be used as an automatic load limiting system[4]. In this case, the extremal control input estimates (i.e., allowable control travel estimates) are directly used to automatically constrain the pilot control inputs to keep the selected harmonic load within the desired maximum value. If integrated with a cueing system, the LLC scheme comes with the benefit of allowing the pilot to prioritize between load limiting and maneuver aggressiveness. Therefore, the pilot has the choice to follow the cues to avoid load limit exceedance or disregard them in situations where maneuver performance at the expense of component load limit violations may become a priority.

The trade-off is more direct between maneuver performance and load limiting in an LAC scheme through a proper choice of weightings between maneuver command following and resulting harmonic loads. For the LLC scheme, the trade-off between maneuver performance and resulting harmonic loads is indirect via the choice of user specified value of harmonic load limit. In addition, the LLC scheme limits the maneuver performance only when load exceedance is likely to occur. Therefore,



(a) Extremal control profile



(b) Load profile

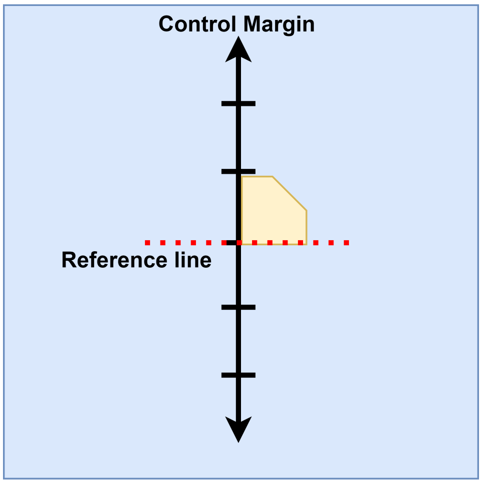
Figure 5: LLC scheme.

for non-aggressive maneuvers that do not cause load exceedance, no trade-off is required. Unlike the LAC scheme, the LLC scheme allows to limit component dynamic loads within a prescribed maximum value (y_{max}). This prescribed maximum value can be wisely selected to reflect a threshold above which significant fatigue damage on the component is very likely to occur. Another important property of the proposed LLC scheme is its ability to estimate future values of the limit parameter. This is essential in the early detection of limit violation. The early detection of limit violation allows the pilot to have enough time to take preventive actions. More details on the LLC scheme can be found in Refs. 3 and 4.

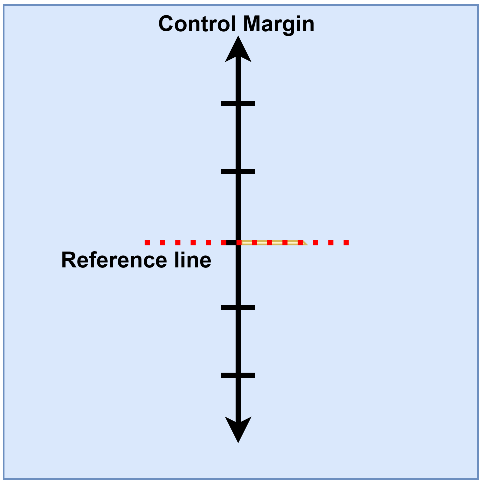
3. LLC SCHEME VIA CUEING

In this section, the integration of the LLC scheme with a visual cueing system is discussed.

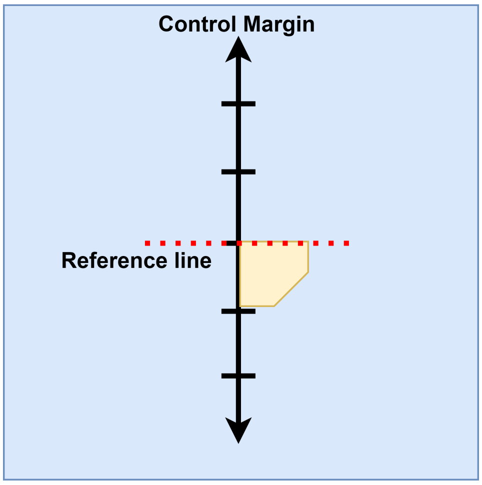
In this cueing-based implementation of the LLC scheme, the control margin (i.e., Eq. 1) is computed in real-time and provided to the pilot in the form of a visual cue. A former US. Army Black Hawk pilot conducted the piloted study presented in this paper and helped in the design of a visual cue strategy that would lead to minimal effects on the pilot attention and no increase in pilot workload. Based on his comments, the 2D visual cue shown in Fig. 6 was implemented.



(a) Nominal case with control margin



(b) Case with zero control margin



(c) Case with negative control margin

Figure 6: 2D visual cue.

The 2D-cue shown in Fig. 6 is a vertical bar. One side of the vertical bar is aligned with a fixed reference line, whereas the other side is free to move vertically. Hence, the height of the vertical bar changes with time. The width of the vertical bar is fixed and selected by the pilot to enhance the effectiveness of the visual cue. At each instant in time, the vertical bar enables the pilot to gauge the amount of control deflection required to take the harmonic load of interest from its current value to its limit. When the vertical bar has a height equal to zero (i.e., Fig. 6b: both sides of the vertical bar are at the reference line), the control margin is zero. A zero control margin value implies that the harmonic load (i.e., 1/rev load) is at the load limit. When the vertical bar is below the reference line (i.e., Fig. 6c), this implies a negative control margin which represents load exceedance (i.e., the harmonic load exceeded the maximum load value). On the other hand, a positive control margin illustrated by the vertical bar being above the reference line (i.e., Fig. 6a) implies that the load limit is not exceeded.

4. REAL-TIME PILOTED SIMULATION

In this section, the LLC scheme via cueing is implemented within the Georgia Tech Re-configurable Rotorcraft Flight Simulator and piloted simulation evaluations are carried out.

The Georgia Tech Re-configurable Rotorcraft Flight Simulator is a fixed-base simulator utilizing the cockpit of a OH-58D helicopter. The simulator imagery is generated using the UNIGENE image generation software and displayed onto a 16 feet diameter and 270° screen. The flight dynamics is generated using FLIGHTLAB®. Furthermore, the simulator is equipped with a mechanically linked control system with no advanced features (i.e, no ACAH/RCAH modes). A picture of the simulator is shown in Fig. 7.

Figure 7: The Georgia Tech Re-configurable Rotorcraft Flight Simulator.

Real-time piloted simulation evaluations were carried out by considering two maneuvers at a forward flight speed of 120 knots in order to assess the effectiveness of the visual cue in limiting maneuver aggressiveness for component load limiting. For both maneuvers, the LLC scheme is tuned to limit the rotating pitch link 1/rev load to a maximum value of 350 lbs.

The first maneuver is a pitch doublet maneuver. During this maneuver, the pilot is asked to keep both the collective stick and pedal at their trim values and avoid lateral motion. This is done because the LLC scheme is currently only tuned to act on the longitudinal cyclic channel. In Fig. 8 an overlay of the actual longitudinal control input from the pilot and estimated control limit (corresponding to component load limit) as a visual cue to the pilot are shown. The changes in other control inputs from trim are very small, and hence, not shown. The resulting pitch rate response is shown in Fig. 9. In this case, the pilot is asked to ignore the visual cue for load limiting provided to him (i.e., cue-off case), resulting in the rotating pitch link 1/rev load to exceed the selected limit of 350 lbs (shown in Fig. 12). In Fig. 10, the simulation is repeated, except in this case, the pilot is asked to limit the control input, whenever necessary, to the estimated control limit provided to him in the form of a visual cue (i.e., cue-on case), resulting in the 1/rev load to be roughly limited to the selected maximum value (shown in Fig. 12). It is important to note that for the purpose of component life extension, slight load exceedance is acceptable since the user defined max limit is a soft limit rather than a hard limit. For the cue-on case, as for the cue-off case, the changes in other control inputs from trim are very small, and hence, not shown.The pitch rate response for the case with cue-on is shown in Fig. 11. As expected, the vehicle response with cue-on shown in Fig. 11 becomes restricted compared to that for the cue-off shown in Fig. 9, thus trading vehicle maneuver performance with component load limiting.

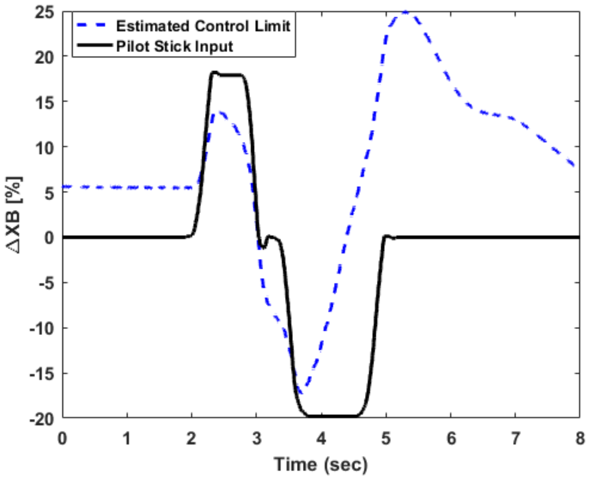


Figure 8: Pilot longitudinal stick input with cue-off.

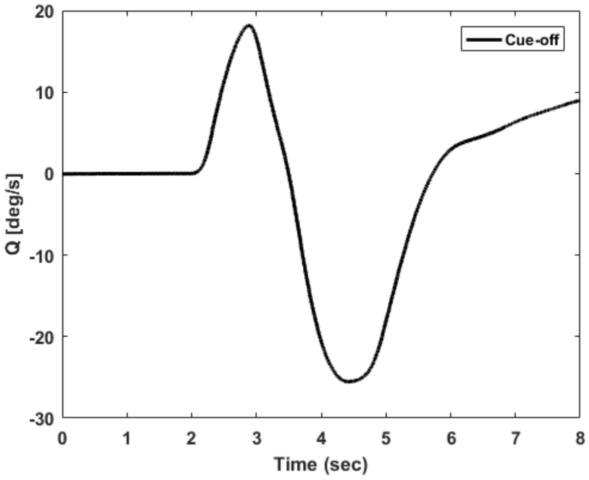


Figure 9: Pitch rate response with cue-off.

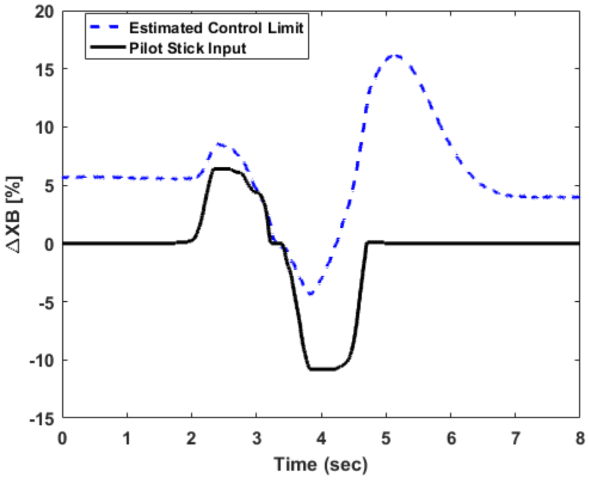


Figure 10: Pilot longitudinal stick input with cue-on.

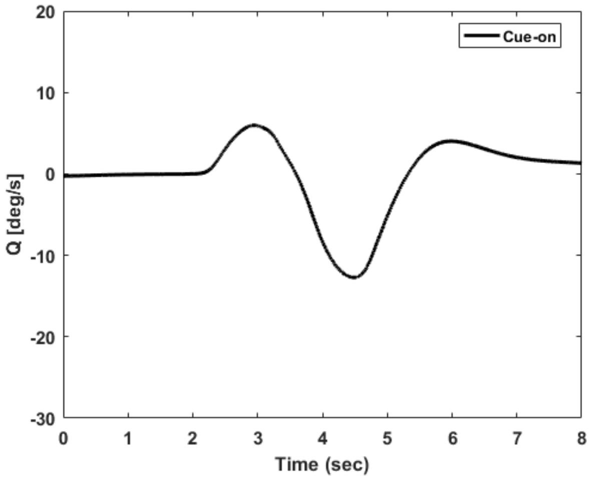


Figure 11: Pitch rate response with cue-on.

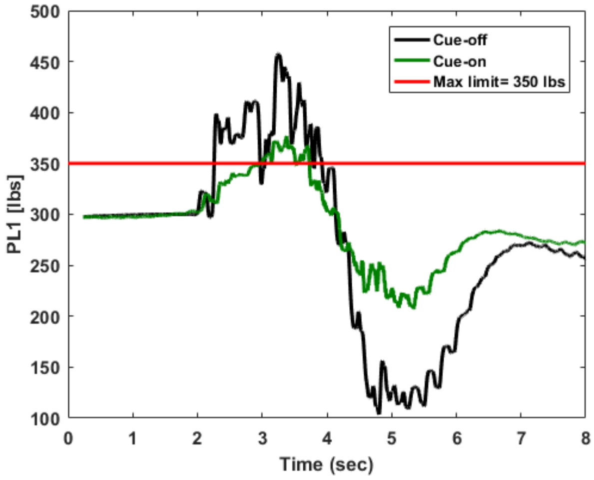


Figure 12: Variation of 1/rev harmonic component of reference blade pitch link load.

The second maneuver is a pull-up maneuver. This maneuver has a duration of 9 seconds and is performed to test the ability of the pilot to track the visual cue. Initially, the pilot is asked to ignore the visual cue (i.e., cue-off case). The pilot is then asked to repeat the same maneuver but this time to pay attention and track the visual cue to the best of his ability (i.e., cue-on case). In Figs. 13 and 14, an overlay of the actual longitudinal control input from the pilot and estimated control limit as a visual cue to the pilot are shown for the cue-off and cue-on cases, respectively. For the cue-on case, It can be observed that the pilot tracks the visual cues fairly well. One important observation is that when the cue changes rapidly due to vehicle speed changes, the pilot's ability to track the cue slightly degrades. This can be attributed to the time delay inherent in a visual cueing system. For the cue-off case, the pilot control input exceeds the estimated control limit. Figure. 15 shows the rotating pitch link 1/rev load resulting from both runs. It may be noticed that when the pilot uses the visual cue, the 1/rev load stays near the load limit. Due to the significant speed change introduced by the maneuver under consideration, the prediction from the on-board dynamical model deteriorates. This explains the noticeable load exceedance for the cue-on case. It is important to note that the LLC scheme is a fixed-point controller extracted at a true air speed of 120 knots. Therefore, the LLC scheme might not perform well when the aircraft's speed deviates far away from 120 knots. Adopting a control scheduling methodology would allow to take into account the variation in operating point, and hence, improve the performance of the LLC scheme.

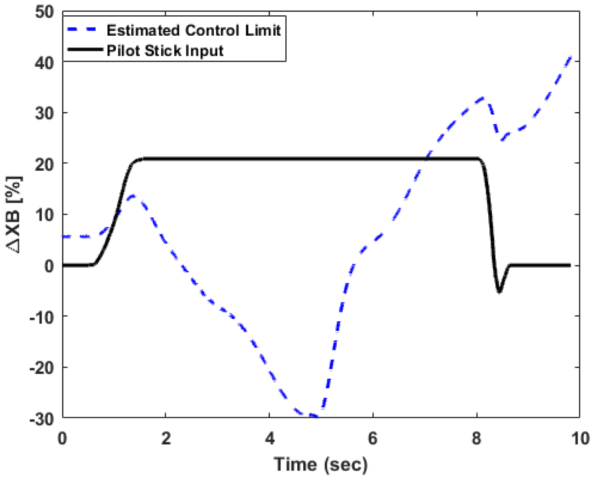


Figure 13: Pilot longitudinal stick input with cue-off.

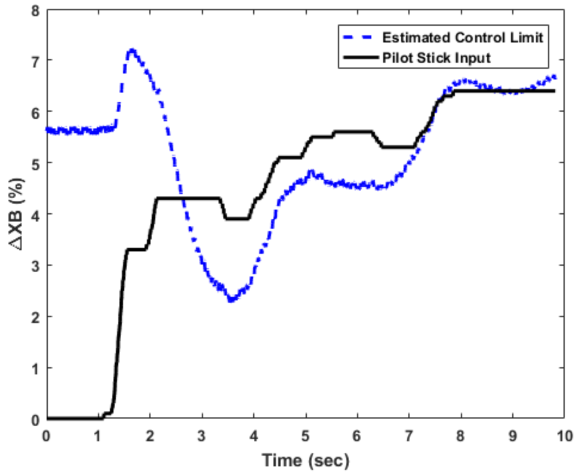


Figure 14: Pilot longitudinal stick input with cue-on.

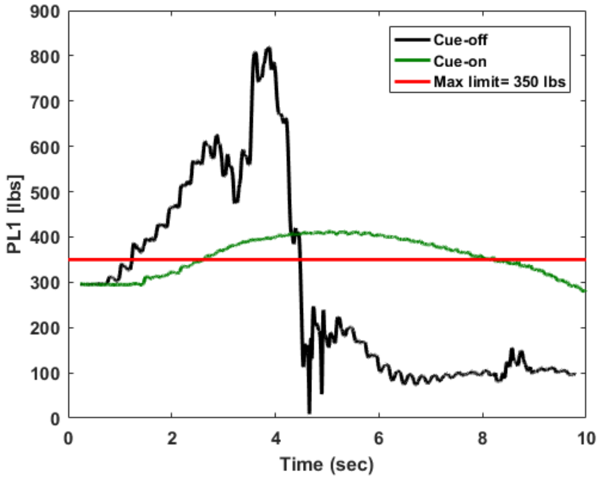


Figure 15: Variation of 1/rev harmonic component of reference blade pitch link load.

5. CONCLUDING REMARKS

A previously developed load limiting control strategy for limiting helicopter component loads during aggressive maneuvers, namely the Load Limiting Control (LLC) scheme, is integrated with a visual cueing system. The resulting architecture is implemented within the Georgia Tech Re-configurable Rotorcraft Flight Simulator, and real-time piloted flight simulation experiments are carried out to assess the effectiveness of the visual cue in limiting maneuver aggressiveness for component load limiting. More specifically, Control Margin (CM) cues are visually provided in real-time to the pilot for their use in limiting the aggressiveness of the maneuver for a selected value of the rotating pitch link 1/rev harmonic load limit.

In this investigation, two maneuvers are considered. The first one is a pitch doublet maneuver while the second one is a pull-up maneuver. For both maneuvers, it is shown that the visual cue is effective in keeping the 1/rev harmonic pitch link load roughly within the desired maximum load limit of 350 lbs. From the piloted simulation experiments, an important finding is that the time delay inherent in a visual cueing system can impede the overall performance of an LLC system.

Evaluation of the proposed LLC scheme through a visual cueing architecture while shown to be viable, for slow to moderate maneuvers, pilot's ability to follow the visual cue was seen to degrade for more aggressive maneuvers. Further work is needed to evaluate the effectiveness of LLC scheme using more intuitive cues such as tactile cueing where it is expected that such a cueing system may perform better.

6. ACKNOWLEDGMENTS

This research was partially funded through the U.S. Army/Navy/NASA Vertical Lift Research Center of Excellence at Georgia Tech under the direction of Mahendra Bhagwat of the US Army Futures Comment, Agreement No. W911W6-17-2-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.

REFERENCES

[1] U. Saetti and J. Horn, "Load Alleviation Flight Control Design Using High-Order Dynamic Models," *Journal of the American Helicopter Society*, vol. 65, pp. 1–15, July 2020.

[2] U. Saetti, J. F. Horn, T. Berger, and M. B. Tischler, "Handling-Qualities Perspective on Rotorcraft Load Alleviation Control," *Journal of Guidance, Control, and Dynamics*, vol. 43, pp. 792–1804, Oct. 2020.

[3] C. E. Mballo and J. V. R. Prasad, "Real Time Rotor Component Load Limiting via Model Predictive Control," in *Proceedings of the* 75^{th} *Annual Forum of the American Helicopter Society*, May 2019.

[4] C. E. Mballo and J. V. R. Prasad, "Trade-off between Maneuver Performance and Component Load Limiting," in *Proceedings of the* 76^{th} *Annual Forum of the American Helicopter Society*, Oct. 2020.