HELICOPTER MANEUVER PERFORMANCE WITH ACTIVE LOAD LIMITING

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Abstract
This paper expands on a previously developed real-time load limiting for critical helicopter components that are subjected to significant fatigue loading. The (structural) load limiting scheme, which is posed as an optimal control problem where estimate of control margin associated with the component load limit is used to arrive at load limiting, is developed within a Dynamic Inversion control architecture. The integration of the load limiting via Model Predictive Control (MPC) within the Dynamic Inversion environment is described in detail. The developed controller resulting from this integration is evaluated using nonlinear model simulations for its ability to limit harmonic pitch link loads and its direct effect on maneuver performance for test cases including attitude and rate command maneuvers.

1. NOMENCLATURE

Δ	Perturbation from trim
ψ	Non-dimensional time
x_B	Rigid body state vector
x_R	State vector of rezidualized model
A	LTI state matrix
B	LTI input matrix
C	LTI output matrix
D	LTI direct transition matrix
F(ψ)	LTP state matrix
G(ψ)	LTP input matrix
U	Augmented control vector
X	Augmented state vector
Y	Augmented output vector
u	Control vector
x	State vector
y	Output vector
$()_0$	Average or 0^{th} harmonic term
$()_{max}$	Maximum value
$()_{n/rev}$	n/rev magnitude component
$()_{nc}$	n^{th} cosine harmonic term
$()_{ns}$	n^{th} sine harmonic term
LAC	Load alleviation control
LLC	Load limiting control
MPC	Model predictive control

2. INTRODUCTION

A 2012 survey of the past 30 years, carried out within Augusta Westland Limited (AWL) Materials Technology Laboratory, concluded that fatigue failures account for approximately 55% of all premature failures in helicopter components[1]. The causes of low cycle fatigue are largely due to aircraft maneuvers,

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gust loading and through take-off and landing. 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[2] on the AH-64A Apache shows that many of the Grade-A Vital components are located in the rotor system, creating challenges for real time load monitoring of those components but also for the development of load alleviation/limiting control schemes.

Current methods for structural health and usage monitoring and load alleviation control rely on distributed sensing and operational monitoring to infer usage and estimate fatigue in critical components. Such inference process is affected by significant uncertainty given that sensors type and locations are often removed from hot spot areas characterized by maximum stresses. For example, past work[3] for limiting pitch link loads has used proxy models of the vibratory loading. A classic example is the Equivalent Retreating Indicated Tip Speed (ERITS) parameter, which has been correlated as a function of airspeed and normal load factor with vibratory pitch link loads from retreating blade stall onset, can be limited to indirectly constrain the pitch link loads.

Recent studies[4,5] at Georgia Tech have explored methods for approximating coupled body/rotor/inflow dynamics into linear time invariant form that is suitable for integrated flight/rotor controller development. The developed methods use harmonic decomposition to represent higher frequency harmonics as states in a LTI state space model, and they offer the potential for real-time estimation of the effect of control inputs on component dynamic loads. Such real-time estimation of component level dynamic loads provides the opportunity for real-time monitoring and the development of control schemes designed to alleviate/limit component loads by automatically limiting excessively aggressive maneuvers.

Recent studies[6,7] at Penn State have used the LTI modeling of coupled body/rotor/inflow dynamics of Refs. 4 and 5 for the development of life extending control schemes in the form of load alleviation control (LAC) strategies. The LAC strategies for component life extension aim 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 LAC scheme pursued in Refs. 6 and 7 considered a Linear Quadratic Control (LQR) solution for arriving at feedback control laws that trade between maneuver command following and load alleviation. As such, load alleviation is implicitly used in arriving at a compromise set of gains as a trade-off between maneuver performance and load alleviation. While the LAC pursued in Refs. 6 and 7 offers a computationally simpler scheme, it leads to a conservative design at the expense of reduced maneuver performance, as in the optimization of controller gains, no distinction is made in the aggressiveness of the maneuver. Further, in reducing peak-to-peak dynamic loads, no distinction is made between different harmonic load effects on accumulated component fatigue. A more effective control strategy for component life extension, albeit at a significant computational complexity, is to treat desired levels of component harmonic loads as limit boundaries, and hence, limit directly the fatigue life usage associated with harmonic loads, considering that higher harmonics represent greater number of cycles over time and harmonics that are close in frequency to the natural modes of a component result in a greater modal response.

Recent studies[8,9] at Georgia Tech were aimed at using the LTI models developed in Refs. 4 and 5 for the development of load limiting controllers (LLC). Specifically, the study of Ref. 8 focused on developing a controller using the local sensitivity method for limiting a selected harmonic load component(s) of a rotating blade root pitch link. It makes use of LTI model approximation of coupled body/rotor/inflow dynamics of a helicopter for the real-time estimation of component dynamic loads, which in turn is used for limiting or altering the pilot control inputs in order to achieve component load limiting during aggressive maneuvers.

The load limiting controller developed in Ref. 8 is based on the use of dynamic trim estimation algorithm which aims at calculating future steady state value of the limit parameter. This ability to estimate future steady state value of the limit parameter is essential in the early detection of limit violation. While the proposed use of dynamic trim method for component load limiting was seen to be promising, the performance of the LLC was seen to degrade due to loss of fidelity of the LTI model for large control inputs. As such, a Linear Quadratic Estimator using fixed system vibration load measurements is suggested as a viable method for reducing errors in LTI model predictions of pitch link harmonic loads.

In contrast, the load limiting control strategy developed in Ref. 9 is based on the use of Model Predictive Control (MPC) for the estimation of available control margin by treating the selected limit value of component harmonic load magnitude as a limit boundary. The proposed load limiting controller scheme makes use of an on board reduced order LTI model to compute, at each instant in time, extremal control input, and hence available control margin, that would result in the component load to reach its limit boundary without exceeding it. The extremal control inputs so calculated are then used as cues to the pilot. This load limiting strategy via cuing allows for pilot's decision to prioritize between load limiting and maneuver aggressiveness. The present study is focused on implementing the load limiting strategy of Ref. 9 within a Dynamic Inversion controller and evaluating the impact of the load limiting on helicopter maneuver performance for test cases involving attitude and rate command maneuvers. However, the cuing strategy is omitted in this study. The paper is organized as follows: First, a brief description of the methodology used for extraction of the higher order LTI and reduced order LTI models used in the development of the load limiting via MPC is presented. Next, the integration of the load limiting control law within the Dynamic Inversion Controller is described. Following that, a study of the impact of load limiting on helicopter maneuver performance is analyzed using nonlinear model simulations. Finally, concluding remarks are provided in order to summarize the main points of the study along with suggestions for future work.

3. HIGHER ORDER LTI MODELS

A description of the extraction of a higher order LTI model from a high-fidelity nonlinear model of a helicopter is presented in this section. Following the method described in Ref. 5, an LTI model using harmonic decomposition of LTP states, with a first order representation (i.e., separate displacement and velocity states), is developed from a full vehicle nonlinear (NL) FLIGHTLAB®,[10] model of a generic helicopter with elastic blade mode shapes and a 33-state Peters-He dynamic inflow model. The LTI model has previously been validated against a nonlinear rotorcraft model and found to be of sufficient fidelity[5]. Considering an LTP model of the form given in Eqs. (1) and (2), harmonic decomposition for the extraction of LTI model assumes the approximation for the state vector, x ,in Eq.(3)

$$\dot{x} = F(\psi)x + G(\psi)u \tag{1}$$

$$y = P(\psi)x + R(\psi)u \tag{2}$$

$$x = x_0 + \sum_{n=1}^{N}[x_{nc}cos(n\psi) + x_{ns}sin(n\psi)] \tag{3}$$

where x_0 is the average component and x_{nc} and x_{ns} are respectively, the n/rev cosine and sine harmonic components of x. Likewise, the control u is expanded in terms of harmonic components as

$$u = u_0 + \sum_{m=1}^{M}[u_{mc}cos(m\psi) + u_{ms}sin(m\psi)] \tag{4}$$

and the output y is expanded in terms of harmonic components as

$$y = y_0 + \sum_{l=1}^{L}[y_{lc}cos(l\psi) + u_{ls}sin(l\psi)] \tag{5}$$

where y_0 is the average component and y_{lc} and y_{ls} are respectively the l^{th} harmonic cosine and sine components of y. An LTI approximation of the LTP model given by Eqs. (1) and (2) can be obtained by substituting for harmonic expansions[4,5] of x, u and y, i.e.,Eqs. (3), (4), and (5) into Eqs. (1) and (2). The resulting equations can be represented in state-space matrix form by defining an augmented state vector as:

$$X = [x_0^T..x_{ic}^T..x_{is}^T..x_{jc}^T..x_{js}^T..]^T \tag{6}$$

and the augmented control vector as

$$U = [u_0^T..u_{mc}^T u_{ms}^T..]^T \tag{7}$$

where x_0 is the zeroth harmonic component, x_{ic}, x_{is} are the i^{th} harmonic cosine and sine components of x, and u_0 the zeroth harmonic and u_{mc}, u_{ms} are the m^{th} harmonic cosine and sine components of u, respectively. The state equation of the resulting LTI model is

$$\dot{X} = [A]X + [B]U \tag{8}$$

Likewise the augmented output vector of the LTI model is defined as:

$$Y = [y_0^T..y_{lc}^T y_{ls}^T..]^T \tag{9}$$

Then the output equation of the LTI model can be written as

$$Y = [C]X + [D]U \tag{10}$$

Detailed expressions for the LTI model matrices A, B, C and D are developed in Ref. 5. The LTP model extracted through linearization from the NL model includes 8 body states, 33 inflow states (Peters-He Finite state inflow with 4 harmonics and a maximum radial variation power of 8), and 48 multi-blade coordinate (MBC) rotor states that include rigid flap, rigid lead-lag and coupled elastic modes. Thus, the total number of LTP states is 89. Each of these LTP states is then decomposed into 0-8/rev harmonic components, resulting in 1513 total LTI model states. It should be noted that all 0-8 harmonics may not be required to achieve acceptable fidelity in the LTI model[5]. The nonlinear model is trimmed at 120 knots.

4. CONTROLLER DESIGN

A dynamic inversion control law is used as the aircraft control system. Dynamic inversion is very attractive as it eliminates the need to gain schedule controllers in order to cover the entire flight envelop[11]. For structural load limiting, a load limiting controller is implemented within the control system architecture. The model prediction part of the load limiting scheme requires the use of an on-board model. Further, the initial values of on-board model states from measurements are needed for model predictions. As such, the reduction of the full-order LTI model to a reduced order model using a two-time scale method is described next.

4.1. Reduced Order LTI Model

A reduced order LTI model is obtained via residualization using a two-time scale representation of the full-order LTI model in terms of slow and fast states[12]. Residualization is a process based on singular perturbation theory in which a reduced order model is obtained from the higher order LTI model. Through residualization, the LTI model low frequency and steady state are accurately captured but high frequency dynamics are neglected[12]. The residualized LTI model is derived from a quasi-steady representation of the fast dynamics of the full order LTI model. It is assumed that the fast states reach their equilibrium instantaneously with respect to the slow states. What follows is a derivation of the new reduced order dynamical system and functional relationship that maps the controls and slow states to the limit parameters via the use of residualization. For this study, specific harmonic components of pitch link loads are selected as limit parameters.

$$X = \begin{bmatrix} X_s \\ X_f \end{bmatrix} \tag{11}$$

where X_s=slow states and X_f=fast states We therefore have the following dynamical system

$$\begin{bmatrix} \dot{X}_s \\ \dot{X}_f \end{bmatrix} = \begin{bmatrix} A_s & A_{sf} \\ A_{fs} & A_f \end{bmatrix} \begin{bmatrix} X_s \\ X_f \end{bmatrix} + \begin{bmatrix} B_s \\ B_f \end{bmatrix} U \tag{12}$$

As per the assumption that the fast states reach steady state very quickly, we can set $\dot{X}_f$ =0 and solve for X_f

$$A_{fs}X_s + A_f X_f + B_f U = 0 \tag{13}$$

$$X_f = A_f^{-1}[-A_{fs}X_s - B_f U] \tag{14}$$

By substituting for X_f from Eq.(14) into Eq.(12) the dynamic equation for the residualized system becomes

$$\dot{X}_s = [\hat{A}]X_s + [\hat{B}]U \tag{15}$$

where

$$\hat{A} = A_s - A_{sf}A_f^{-1}A_{fs} \tag{16}$$

$$\hat{B} = B_s - A_{sf}A_f^{-1}B_f \tag{17}$$

The output equation is also rewritten in terms of the slow states and control as

$$Y = \begin{bmatrix} C_s & C_f \end{bmatrix} \begin{bmatrix} X_s \\ X_f \end{bmatrix} + \begin{bmatrix} D \end{bmatrix} U \tag{18}$$

$$Y = [\hat{C}]X_s + [\hat{D}]U \tag{19}$$

where

$$\hat{C} = C_s - C_f A_f^{-1}A_{fs} \tag{20}$$

$$\hat{D} = D - C_f A_f^{-1}B_f \tag{21}$$

Using the residualization procedure described above, a 10^{th} order reduced order LTI model is considered. The reduced order model is derived with slow states consisting of 0^{th} harmonic components of body velocities (U, V, W), body angular velocities (P, Q, R), body pitch and roll attitudes, (θ,ϕ), also and the 0^{th} harmonics of the longitudinal (β_{1c_0}) and lateral flapping (β_{1s_0}). The resultant slow state vector is defined as

$$X_s = [x_{B_o}^T \, \beta_{1c_0} \, \beta_{1s_0}]^T \quad (22)$$

The obtained 10^{th} order model allows for capturing the low-frequency cyclic flap mode in addition to the body modes as part of the slow dynamics

A study conducted in Ref. 8 assesses the fidelity of different reduced order LTI models for prediction of blade root pitch link loads, vehicle angular rate and body velocity component responses. It was concluded that the reduced 10^{th} order LTI model provided a relatively good representation of the higher order LTI model in the prediction of 1/rev harmonic of pitch link loads, and hence, a 10^{th} order LTI model is used in this study for the synthesis of the load limiting controller via MPC.

4.2. Dynamic Inversion Control Law

The dynamic inversion controller[11] makes use of linearized aircraft model, such as in Eqs. 8 and 10. The linear models were generated about different airspeeds ranging from 0 knots to 160 knots with an increment of 20 knots. A block diagram representation of the controller is shown in Fig. 1.

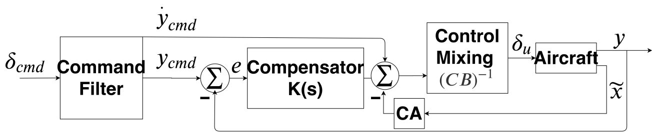

Figure 1: Dynamic Inversion control law.

In this control architecture, the signal y is forced to follow the reference signal y_{cmd}. The matrices A, B and C as stated earlier are function of airspeed. A PID controller is used for compensation. The transfer function in the command filter dictates the desired dynamics of the closed loop or the nature of the desired response type. One instance of response type is Attitude Command/Attitude Hold (ACAH). ACAH response relates a pilot stick displacement to a vehicle attitude. Another response type is Rate Command/Attitude Hold (RCAH). RCAH response relates a pilot stick displacement to a vehicle angular rate. The selection of the response type heavily depends on the usable cue environment[13] (UCE).

It is important to note that the command model has design parameters that are tuned manually to meet desired aircraft response to piloted inputs as characterized by ADS-33 requirements[13].

4.3. Model Predictive Control (MPC)

The use of model predictive control for the estimation of control margins associated with vehicle performance limit boundaries was developed in Ref. 14. In this section, we adopt the control margin estimation via MPC towards the development of a load limiting control scheme by making use of a model predictive receding horizon control formulation as previously done in Ref.9. The load limiting control scheme makes use of an on-board reduced order LTI model to compute, 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 calculated extremal control inputs are then used as bounds on the control inputs coming out of the control mixing. A block diagram representation of the load limiting scheme via MPC integrated within the Dynamic Inversion control architecture is shown in Fig. 2.

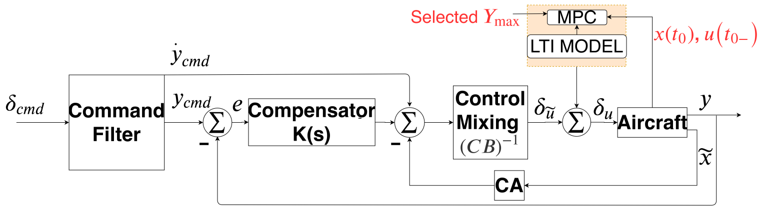

Figure 2: Dynamic Inversion control law with active load limiting.

In Fig. 2, $x(t_0)$ represents the current values of the reduced order LTI model state vector and $u(t_{0-})$ 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 proposed load limiting control scheme calculates the extremal control input by solving at each time instant a constrained optimization problem of a quadratic cost function using the reduced order LTI model. As mentioned before, the reduced order model is derived from a full-order LTI model via the process of residualization[12]. The determination of extremal control boundary associated with component load limit is posed as a receding horizon model predictive algorithm and is formulated in terms of the following optimal control problem:

$$min_U[J], J = \int_{t_0}^{t_o+T_p} L(\|Y_{harm}\|_2, U)dt \quad (23)$$

subj:

(24) $$\dot{X_s} = [\hat{A}]X_s + [\hat{B}]U$$

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

(26) $$U_{min} \leq u(t_{0-}) + U \leq U_{max}$$

where $\|Y_{harm}\|_2$ is the two norm or magnitude of the specific pitch link harmonic load and y_{max} is a selected value of its limit.

The cost function integrand is defined as follows:

(27) $$L(\|Y_{harm}\|_2, U) = (\|Y_{harm}\|_2 - y_{max})^T * Q(\|Y_{harm}\|_2 - y_{max}) + (U - u(t_{0-}))^T * R(U - u(t_{0-}))$$

where Q and R are symmetric positive definite matrices of design coefficients that penalize the limit parameter tracking error in reaching its boundary in the selected time horizon, T_p, and control activity, respectively. y_{max} is a user selected value of pitch link harmonic load limit. The expression for the two norm of the specific pitch link harmonic load is given by:

(28) $$\|Y_{harm}\|_2 = \sqrt{(y_{1c_{(trim)}} + \Delta y_{1c})^2 + (y_{1s_{(trim)}} + \Delta y_{1s})^2}$$

The limit parameter, $\|Y_{harm}\|_2$, is the total harmonic load (i.e., trim + change from trim). Due to the computational benefit that comes with solving a convex optimization problem, it is beneficial to transform the posed optimization problem into a quadratic form. The posed optimization problem can be transformed as such by performing a linear approximation of Eq. 28 as

(29) $$\|Y_{harm}\|_2 \overset{\text{approx}}{\approx} a + b\Delta y_{1c} + c\Delta y_{1s}$$

where a, b and $c \in \mathbb{R}$ and are given by

(30) $$a = \sqrt{(y_{1c_{(trim)}})^2 + (y_{1s_{(trim)}})^2}$$

(31) $$b = \frac{y_{1c_{(trim)}}}{\sqrt{(y_{1c_{(trim)}})^2 + (y_{1s_{(trim)}})^2}}$$

(32) $$c = \frac{y_{1s_{(trim)}}}{\sqrt{(y_{1c_{(trim)}})^2 + (y_{1s_{(trim)}})^2}}$$

The MPC formulation expressed by Eq. 23 through Eq. 28 makes use of Eq. 29 as a representation of the magnitude of the harmonic pitch link load we are trying to limit.

The solution to the optimal control problem provides estimates of the control margin boundaries associated with pitch link load limits and are used to bound the control input from the control mixing. For computational efficiency, and more importantly real-time application of such a methodology, it is beneficial to convert the infinite dimensional optimal control problem into a finite dimensional one. This is done through the use of the direct transcription method[15] where the continuous optimal control is approximated into a discrete form. The discrete form is obtained by using a judiciously selected time discretization method over a grid of N time nodes that span the interval [t_0,t_0+Tp]. The solution to this convex optimization problem can be solved efficiently and in real-time by using the convex optimization solver described in Ref. 16. The integration of the load limiting control scheme within the dynamic Inversion architecture provides a framework to study in more depth the trade-off between structural load limiting and maneuver performance.

5. RESULTS

In this section, an investigation of the performance of the proposed dynamic inversion controller with active load limiting is shown. Specifically, limiting of the 1/rev pitch link load is considered. Moreover, the impact of such load limiting on the maneuver performance is also investigated. For this study, the prediction horizon Tp is arbitrarily set to 0.0065 seconds. Likewise, the number of grid points N is arbitrary set at 10, representing a time discretization interval of 0.00065 seconds. The high fidelity full vehicle nonlinear model (NL) in FLIGHTLAB®, from which the higher order LTI model is generated, is used as the aircraft model (truth model). Two simulations were conducted. The first maneuver is an attitude command maneuver where the flight control system is set to give an Attitude Command Attitude Hold (ACAH) response in the pitch axis. The second maneuver is a rate command maneuver where the flight control system is set to give a Rate Command Attitude Hold (RCAH) response in the pitch axis. As described in the previous section, the load limiting control scheme applies bounds to the input coming out of the control mixing, based on the MPC solution. Hence, unlike in Ref. 9, no bound is set on the command inputs from the pilot.

5.1. Attitude command maneuver

For this maneuver, the transfer function in the command model is appropriately selected to give an Attitude Command/Attitude Hold response type (see Ref. 11 for details). The longitudinal cyclic stick input from the pilot is taken to be desired pitch attitude command input.

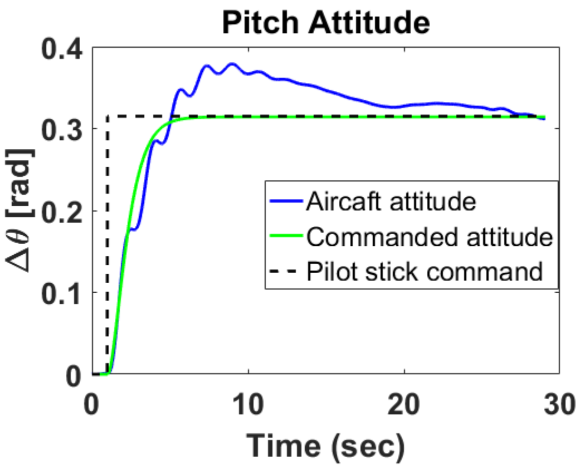

Figure 3: Body pitch attitude response comparison between pilot stick command and aircraft response.

In order to test the attitude command/attitude hold capability of the Dynamic Inversion controller, simulation results with LLC turned off is first considered. Figure 3 shows the pilot stick command, the commanded attitude and the resulting aircraft attitude. As a result of the step input command from the pilot, the aircraft is commanded to reach a specified attitude and hold it approximately constant until removal of the step input. This is indeed the case as the aircraft pitch attitude is seen to converge to the desired attitude. It is also important to note that subsequent to the start of the pilot stick command, the aircraft attitude is approximately constant (about 0.36 rad) between 6 and 12 seconds following the step input. We therefore can conclude that we meet level 1 handling quality for an Attitude Command/Attitude Hold system, as described in the ADS -33 handbook[17]. Figure 4 shows the reference blade root pitch link 1/rev load magnitude resulting from the pitch attitude command of Fig. 3.

The dynamic inversion controller is seen to work as expected. In what follows, we investigate the trade-off between load limiting and maneuver performance for the attitude command/attitude hold

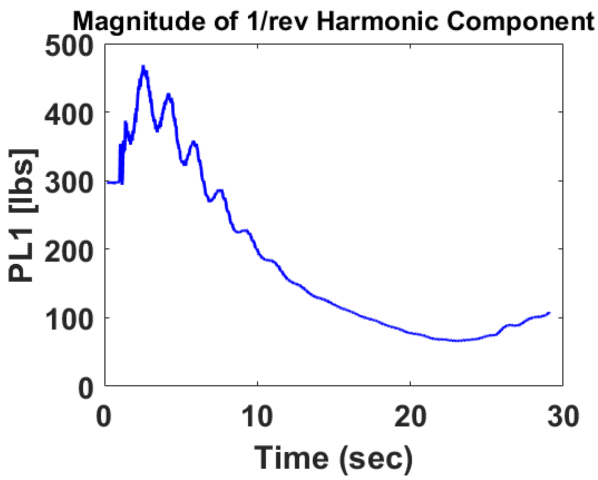

Figure 4: Variation of 1/rev harmonic component of reference blade pitch link load without LLC.

maneuver when the LLC is turned on. The limit for the pitch link 1/rev load magnitude is arbitrarily set to 350 lbs. Simulation results of the reference blade root pitch link 1/rev load magnitude without (labeled 'No LLC') and with the proposed load limiting control scheme (labeled 'With LLC...') are shown in Fig. 5 for the case of the step pitch attitude command of Fig. 3.

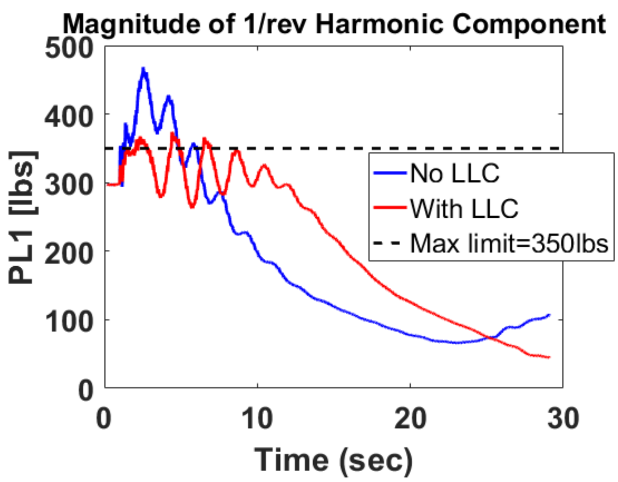

Figure 5: Variation of 1/rev harmonic component of reference blade pitch link load with and without LLC.

It can be observed from Fig. 5 that the 1/rev magnitude of the pitch link load approximately stays within the selected limit of 350 lb. However, slight load exceedance is noticed. This is due to the fact that even though the reduced order LTI models used in the formulation of the proposed load limiting scheme can be used for real-time component load estimation, the estimated loads may have to be corrected for error due to LTI model approximation and nonlinearities[18,19,20]. As such, to large input the on-board linear model is expected to loose fidelity. It is therefore normal that some limit exceedance is expected since the on-board model is used to compute the control limit boundary corresponding to the load limit boundary. The root mean square values of limit exceedance for the case with no LLC and with LLC are evaluated to be, respectively, 58.02 lbs and 11.09 lbs (80.87% reduction).

Figure 6, where the control input with LLC turned off and the associated control bounds from the MPC are compared, shows that the control input exceeds the predicted control limit several times. It is interesting to note from Figs. 5 and 6 that, with LLC turned off, load exceedance occurs whenever the control input exceeds the computed control limit.

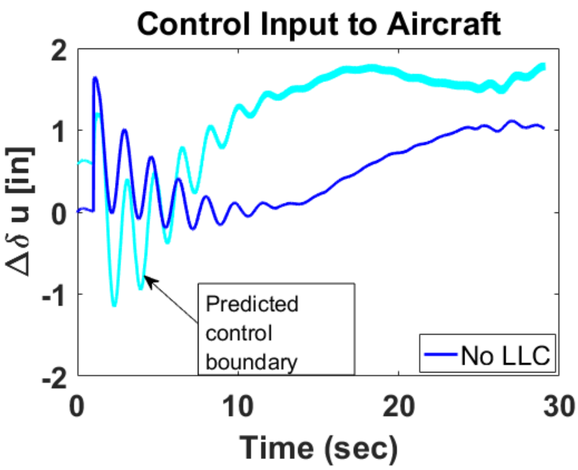

Figure 6: Change in inches of control input without LLC.

However, when the LLC is turned on, it can be seen that the control input from the control mixing rides the predicted control boundary whenever load exceedance is detected as can be see from Figs. 5 and 7, and hence, limiting the selected harmonic component magnitude of the pitch link load within the selected value. It is important to note that the predicted control bound from the LLC scheme is dynamic in nature, as it depends, at any given instant in time, on the current state of the vehicle. As such superposition of the control input plots with and without LLC do not give us valuable information.

The effect of the load limiting control strategy on the helicopter maneuver performance can be illustrated by comparing the achieved pitch attitude for the case with and without LLC. Figure 8, where the pitch attitude variation with and without LLC are

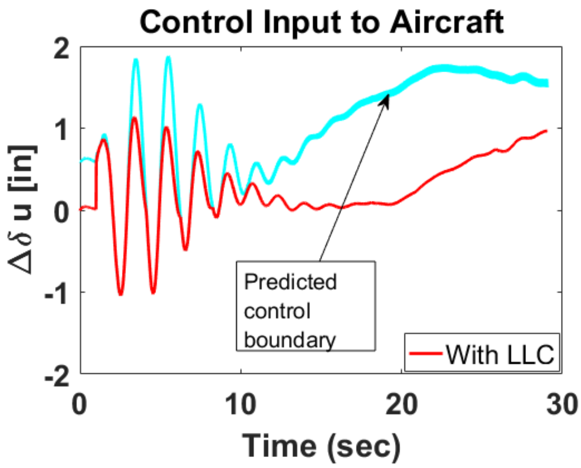

Figure 7: Change in inches of control input with LLC.

compared, shows that with LLC turned on, the desired pitch attitude is achieved. The only trade-off between load limiting and maneuver performance resides in the time needed to reach the desired attitude. With LLC turned on, the maneuver aggressiveness is limited in order to limit the resulting 1/rev magnitude of pitch link load, which, in turn, causes the desired pitch attitude to be reached with some delay.

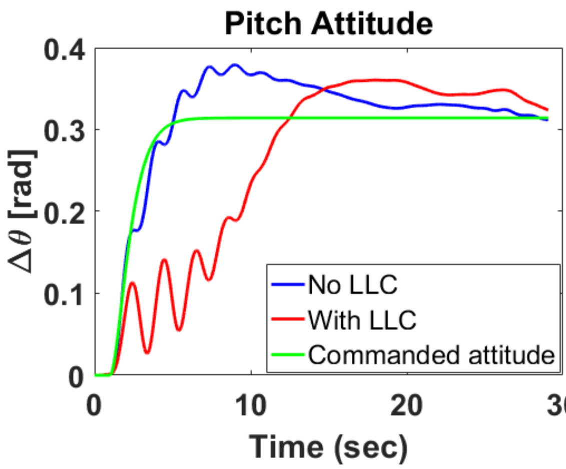

Figure 8: Body pitch attitude response with and without LLC.

5.2. Rate command maneuver

For this maneuver, the transfer function in the command model is appropriately selected to give a Rate Command/Attitude Hold response (see Ref. 11 for details). The pilot control input is taken to be pitch rate command as show in Fig. 9. The pulse input has a duration of 7 seconds.

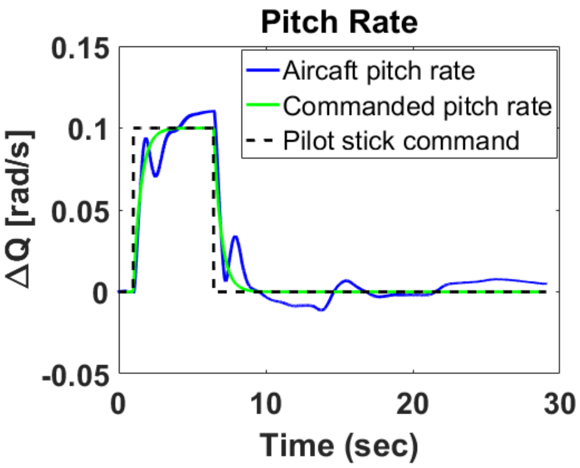

Figure 9: Body pitch rate comparison between pilot stick command and aircraft response.

Similar to the previous maneuver case, the rate command/attitude hold capability of the Dynamic Inversion controller is tested first by turning off the LLC. As a result of the rate command pulse, the aircraft is commanded to reach a specified pitch rate, and subsequent to the pulse, keep the pitch attitude constant as can be seen in Figs. 9 and 10. Figure 11 shows the reference blade root pitch link 1/rev load magnitude resulting from the longitudinal cyclic pulse input of Fig. 9. The pilot commands a maximum pitch rate of 0.1 rad/s while the aircraft reaches a maximum pitch rate of 0.11 rad/s. The dynamic inversion controller is therefore seen to perform as designed.

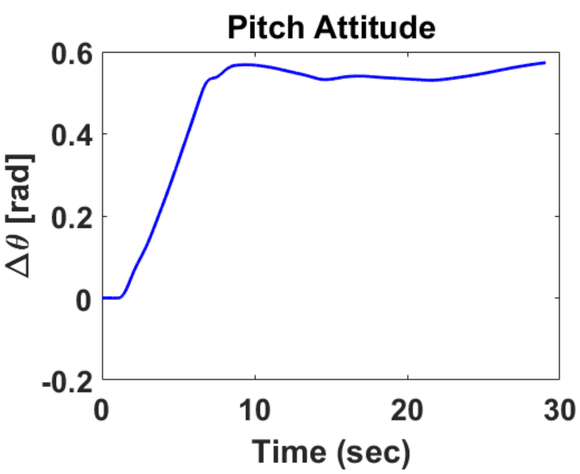

Figure 10: Body pitch attitude response without LLC.

In what follows, we investigate the trade-off between load limiting and maneuver performance for

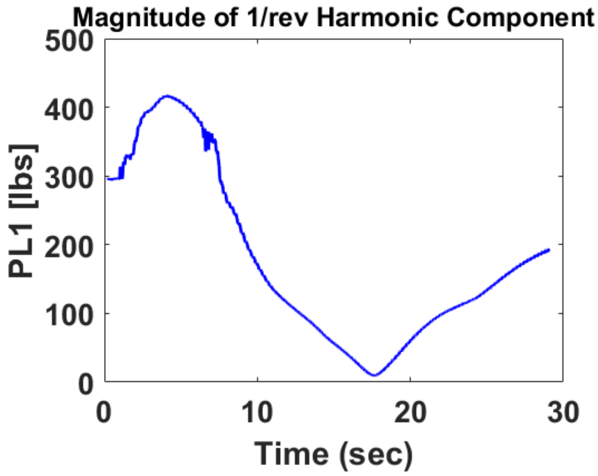

Figure 11: Variation of 1/rev harmonic component of reference blade pitch link load without LLC.

the rate command/attitude hold maneuver when the LLC is turned on. For consistency and ease of performance comparison with attitude command/attitude hold maneuver results, the limit for the pitch link 1/rev load magnitude is kept at 350 lbs. Simulation results of the reference blade root pitch link 1/rev load magnitude without (labeled 'No LLC') and with the proposed load limiting control scheme (labeled 'With LLC...') are shown in Fig. 12 for the case of the pitch rate command pulse of Fig. 9.

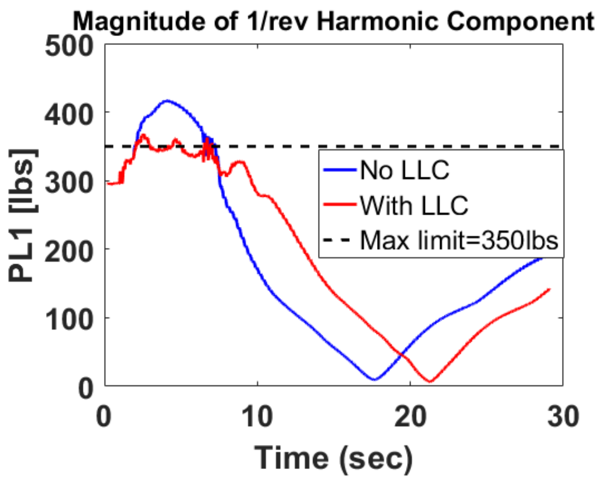

Figure 12: Variation of 1/rev harmonic component of reference blade pitch link load with and without LLC.

It can be observed from Fig. 12 that the 1/rev magnitude of the pitch link load stays approximately within the selected limit value of 350 lb. The root mean square values of limit exceedance for the case with no LLC and with LLC are evaluated to be, respectively, 46.98 lbs and 8.710 lbs (81.46% reduction). Figures 13 and 14 show the plots of control input variation with and without the load limiting. These plots demonstrate once again the effectiveness of the LLC scheme. When LLC is turned on, no control input limit exceedance is noticed in Fig. 14, and hence, no load limit violation is seen in Fig 12.

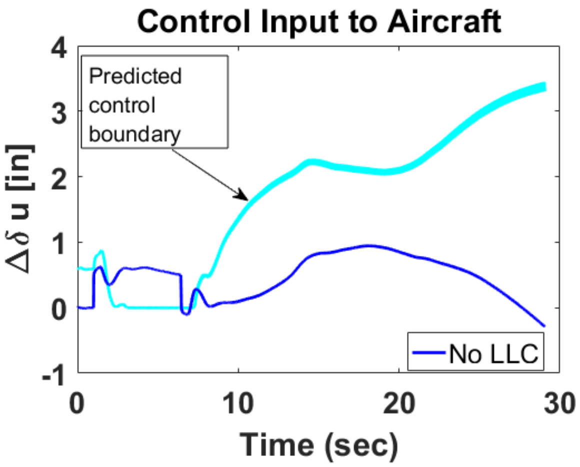

Figure 13: Change in inches of control input without LLC.

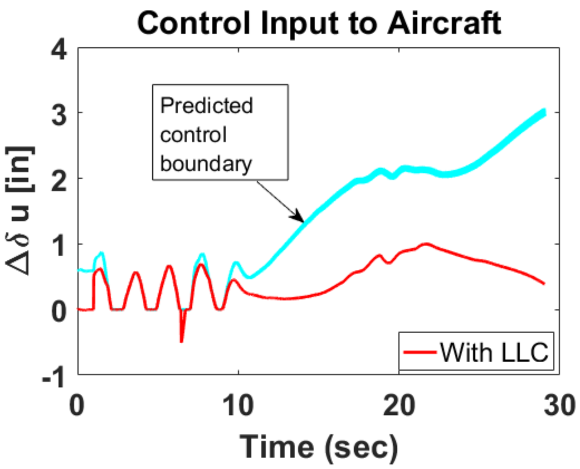

Figure 14: Change in inches of control input with LLC.

The study in Ref. 9 shows that load limiting comes at the expense of reduced pitch rate maneuver performance. This finding is confirmed with Fig. 15 where the variation of body pitch rate response with and without LLC are compared. With LLC turned on, the resulting pitch rate is reduced, whenever necessary, in order to arrive at load limiting. Nevertheless, Fig. 16, wherein the pitch attitude responses with and without LLC are compared, shows that the same pitch attitude is reached in both cases, albeit at a slower rate for the case with LLC.

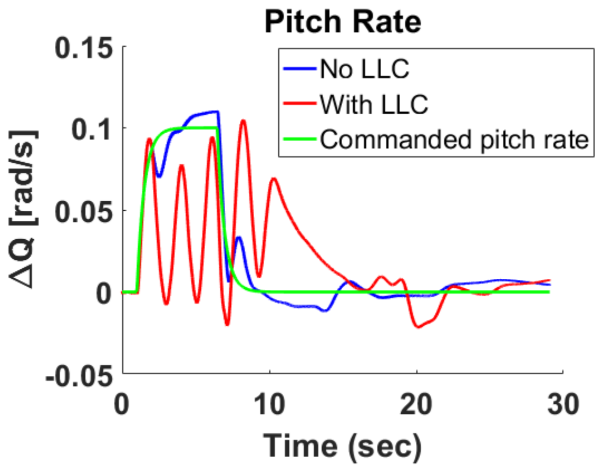

Figure 15: Body pitch rate response with and without LLC .

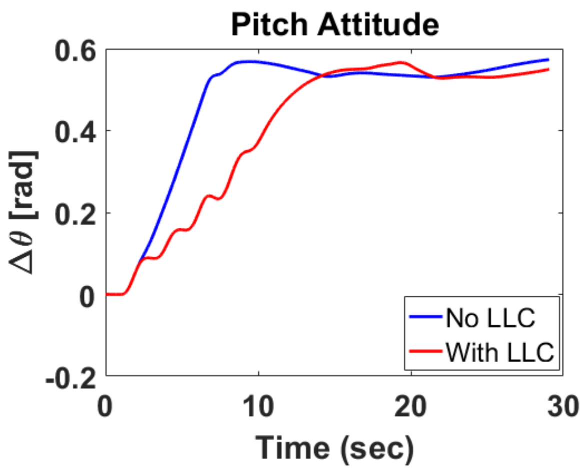

Figure 16: Body pitch attitude response with and without LLC.

6. CONCLUDING REMARKS AND FUTURE WORK

An approach for real time load limiting using model predictive control (MPC) for limiting helicopter component loads during aggressive maneuvers is presented in which higher order linear time invariant (LTI) model of a helicopter coupled body/rotor/inflow dynamics and the notion of residualization are used. The load limiting scheme is implemented within a Dynamic Inversion control architecture in order to fully understand the tradeoff between load limiting and maneuver performance. The proposed Dynamic Inversion with active load limiting controller is evaluated using nonlinear model simulations for its ability to limit an individual harmonic component of blade root pitch link loads arising from attitude and rate command maneuvers. The proposed controller is also evaluated in its ability to perform the desired maneuver while performing active load limiting. The presented results show promise in the ability of the proposed load limiting control (LLC) scheme to limit harmonic components of the pitch link loads through a reduction in the aggressiveness of the maneuver. For both the Attitude Command Attitude Hold (ACAH) and Rate Command Attitude Hold (RCAH) maneuver cases considered, it is seen that the vehicle pitch rate response is altered by the Load Limiting Control (LLC) in order to keep the 1/rev harmonic load of the rotating pitch link within a selected limit value. This, in turn, results in degraded attitude response during the transient part of the maneuver, while holding the required steady state attitude during the hold mode part.

While the proposed Dynamic Inversion with active load limiting control law via MPC shows promise based on the results presented in this paper, more work is needed in establishing the performance of the proposed load limiting scheme when one chooses to limit different harmonic components of loads. Further, future work needs to consider the use of higher harmonic control inputs for limiting individual harmonic components of pitch link loads.

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