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ASSESSMENT OF MANEUVER AIRLOADS WITH MODEL PREDICTIVE CONTROL

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ABSTRACT

In this present work, one of the most used comprehensive modeling and analysis software, Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics II (CAMRAD II), is coupled with linear model predictive control (Linear MPC) to generate time history of control input for analysis of maneuvering flight. Mathematical model of UH60 is implemented in CAMRAD II and model validation is presented by using the flight test results. After that, a linear model of UH60 is effectuated at 20knots forward speed. The linear model is linked with an optimization algorithm, sequential quadratic programming (SQP), and it is coupled with CAMRAD II to generate maneuvering flight. Finally, some acceleration-deceleration maneuvers are performed, and effect of length of control horizon is investigated on maneuver and on analysis time.

NOTATIONS

- e Error term between optimization results and target
- *o* Optimization results
- t Target
- $\Delta u, \Delta v, \Delta w$ Change of velocity components along x, y, z body axes
- $\Delta p, \Delta q, \Delta r$ Change of angular velocity components along x, y, z body axes
- $\Delta \phi, \Delta \theta$ Change of roll and pitch angles
- $\Delta \dot{u}, \Delta \dot{v}, \Delta \dot{w}$ Change of acceleration components along x, y, z body axes
- $\Delta \dot{p}, \Delta \dot{q}, \Delta \dot{r}$ Change of angular acceleration components along x, y, z body axes
 - $\Delta \dot{\phi}, \Delta \dot{\theta}$ Time derivative of roll and pitch angles
 - $\delta_{coll} \ \delta_{longcyc} \ \delta_{latcyc}$

 δ_{latcyc} Change of control inputs; collective, longitudinal cyclic, lateral cyclic, pedal δ_{pedal}

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INTRODUCTION

Calculation of loads is one of the main significant input for structural design of helicopters. Since, the structural sizing of the helicopter uses the calculated loads as basis. Calculation of helicopter loads can be divided in two part, steady flight loads and transient flight loads. Steady flight loads can be determined by trim analysis of the rotorcraft. However, determination of transient flight loads requires simulation analysis for a flight maneuver. These flight maneuvers can be obtained from the usage spectrum of the helicopter or certification specification for rotorcrafts. Therefore, maneuvering loads shall be calculated to learn how much load a helicopter carries its service life.

Simulation of the desired flight maneuvers to calculate loads of a helicopter and airframe requires a coupled analysis of aerodynamics, rotor dynamics and flight dynamics. To achieve that fidelity of simulation, aerodynamic modelling, elastic blade modelling and modelling of rotor dynamics with a proper flight condition and flight maneuver is required by a comprehensive evaluation. In literature, one of the most used comprehensive modeling and analysis software is Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics II (CAMRAD II) [Johnson, 1998; Johnson, 1994; H. Yeo, 2006].

CAMRAD II involves a combined free wake approach with elastic blade and models of rotor dynamics and it has a capability to analyze full helicopter trim and time simulation. On the other hand, it can perform non-linear flight simulation with the trace of time dependent pilot inputs. Flight simulation can be generated by creating pilot inputs manually. However, the manual process both takes time and makes concessions to the accuracy of the maneuver. Therefore, it is needed a control algorithm to generate the pilot inputs for a desired maneuver automatically. For open loop control, there are several approaches. Such as, inverse simulation method, model predictive control etc. [Kalkan & Tosun, 2019; Yücekayalı, Şenipek, & Ortakaya, 2019]. The main issue of analyzing flight maneuvers by CAMRAD II costs lots of time because of the complexity of the helicopter models in CAMRAD II. Using an inverse simulation method for CAMRAD II might be expensive because it needs to call CAMRAD II many times to find control input. It is needed that calling CAMRAD II as less as possible. Therefore, model predictive control is a good choice to generate pilot inputs to simulate desired flight maneuvers for CAMRAD II.

Model predictive control (MPC) defines the control methodology that utilizes a reference model to predict the future states of the plant and generates a sequence of inputs by incorporating an objective function with an optimizer. MPC requires a model describing the relation between the inputs and the states of the plant. There is a trade-off between the prediction model fidelity and the desired accuracy, efficiency and computational cost. This model is operated by the optimization algorithm to minimize a cost function while meeting related bounds and constraints. The optimized control set is then directed to the plant to observe the anticipated dynamic response of the plant. MPC is an advance control method for open loop systems and it became very popular in chemical industry [Patwardhan, Rawlings, & Edgar, 1990; Lee & Lee, 1997], robotics [Erez, 2013]. In terms of aerospace, there are application using model predictive control [Yücekayalı, Şenipek, & Ortakaya, 2019; Alexis, Nikolakopoulos, & Tzes, 2012; Alexis, Papachristos, Siegwart, & Tzes, 2016; Oettershagen, Melzer, Leutenegger, Alexis, & Siegwart, 2014].

In this study, CAMRAD II is used as a black box analysis tool for non-linear plant of model predictive control. For predictive stage, nonlinear model consumes lots of computation time. Therefore, linear model is coupled with CAMRAD II to gain analysis time in using optimization. Firstly, mathematical model of UH60 is implemented in CAMRAD II due to existence of lots of research data on UH60 and nonlinear model of UH60 is validated with flight test. Secondly, a linear model of this helicopter is combined with a constrained optimization method. The reason of the constrained optimization is to avoid unrealistic control input for linear model. Finally,

linear model generates the control input and sends to CAMRAD and CAMRAD feeds back the states to linear model until CAMRAD II reaches the desired flight maneuver.

METHOD

The methodology developed in this study is a combination of optimal control operating over an objective function generating the flight maneuver with a non-linear helicopter model. A model predictive control approach using with the linear model of the helicopter. A flow chart is depicted with Figure 1.



Figure 1 Flowchart of Linear Model Predictive Control

For this approach, CAMRAD II is used for a nonlinear plant.

CAMRAD II

CAMRAD II is a comprehensive aeromechanical analysis tool of rotorcrafts that includes multibody dynamics, nonlinear finite elements and rotorcraft aerodynamics.

This program is used for research, conceptual design, detailed design and development. Performance, loads, vibration etc. might be calculated by CAMRAD II. It has also capability of trim, transient and flutter analysis. CAMRAD II is used in industry and research area for helicopters [Jones & Kunz, 2001; Silbaugh, Kang, Floros, & Singh, 2014; Meyn, 2018].

In this study, mathematical model of UH-60 is implemented in CAMRAD II and it is used with rigid blade and uniform flow solver [Hilbert, 1984; Howlett]. Pitch angle, power curve, collective and longitudinal cyclic of the mathematical model is compared with the flight test [Datta, Chopra, & Gessow, 2002] and it is presented at Figure 2.



Figure 2 Mathematical Model Verification with Flight Test

For the analyzing of desired flight maneuvers, the transient analysis capability of CAMRAD is used. It is needed that a control input history to activate transient analysis. For the generation of control input, linear model predictive control approach is used.

Model Predictive Control

Model predictive control (MPC) defines the control methodology that utilizes a reference model to predict the future states of the plant and generates a sequence of inputs by incorporating



Figure 3 Model Predictive Control Scheme (Dai, Xia, Fu, & Mahmoud, 2012)

an objective function with an optimizer. MPC requires a model describing the relation between the inputs and the states of the plant. There is a trade-off between the prediction model fidelity and the desired accuracy, efficiency and computational cost. This model is operated by the optimization algorithm to minimize a cost function while meeting related bounds and constraints. The optimized control set is then directed to the plant to observe the anticipated dynamic response of the plant.

An illustration of the model predictive control scheme is depicted with Figure 3. In every optimization stage, the linear model is analyzed by control inputs that are generated by optimization algorithm for prediction horizon. Then, optimal inputs

are sent to non-linear plant along control horizon. The states of the non-linear plant are fed back to linear system and optimization loop is activated again. This linear model – nonlinear model loop is continued until nonlinear model reaches the desired flight maneuver.

The definition for the flight maneuver of interest is sent to the predictive stage where optimal control input is generated. Then the control input history is sent to the non-linear plant and with the results of the non-linear plant, the states are fed back to linear model.

For linear model predictive control, a linear model of helicopter shall be used. In this work, a linear model of UH-60 which is linearized at 20kt forward flight speed [Howlett; Padfield, 2018].

$\Delta \dot{u}$		ΓΔu ⁻	1				
Δŵ		Δw					
Δġ	= A	Δq	+ B	$egin{bmatrix} oldsymbol{\delta}_{coll} \ oldsymbol{\delta}_{longcyc} \end{bmatrix}$			
$\Delta \dot{\theta}$		$\Delta \hat{\theta}$					(1)
$\Delta \dot{v}$		Δv		δ_{latcyc}		(1)	
Δp̈́		Δp		$\left[\delta_{pedal} \right]$			
$\Delta \dot{\phi}$		$\Delta \phi$		1			
LAr		$L\Delta r$	I				

A =	-0.0104	0.0374	-0.6020	-9.7600	-0.0224	-0.0574	0	-0.0596		10.5981	-9.7631	0.3582	-4.7737
	-0.1460	-0.3834	10.9719	0.2286	-0.0255	0.1282	-0.9969	-0.0914		-80.5337	-8.0664	0.4943	-4.2333
	0.0036	0.0113	-0.8910	0	0.0366	0.2894	0	-0.0297		0.9778	7.1188	-0.1370	0.0827
	0		0.9948	0	0	0	0	-0.1016	R –	0	0	0	0
	0.0181	0.0069	-0.0006	0.0234	-0.0583	0.4444	9.7565	-10.1136	0 =	0.6769	0.3078	10.4155	5.2728
	0.0763	0.0053	-1.7300	0	-0.1295	-3.6040	0	0.0443		-1.1032	0.9970	47.9585	10.0323
	0	0	-0.0024	0	0	1.0000	0	0.1021		0	0	0	0
	-0.0184	-0.0122	-0.7563	0	0.0281	-0.2857	0	-0.3662		2.1508	-0.1835	9.3052	-7.3713

Optimization

Optimization algorithm is based on linear model, and optimal controls are generated for the linear model which satisfies constrains and objective. Constrains are set to control inputs and optimization algorithm tries to find minimum objective between these constrains.

Objective function is set as following configuration;

$$e = abs(t - o)$$
(2)
$$J = e^T Q e$$

The optimization algorithm, sequential quadratic programming (SQP), is set to minimize this objective function.

RESULTS

In this chapter, several results are presented to show consistence of this control approach on CAMRAD II.

For the following maneuver, control horizon is set to 1 second, and prediction horizon is set to 3 seconds for a CAMRAD II analysis. A smooth acceleration type maneuver is presented in Figure 4. Helicopter attitudes, flight path and air speeds are plotted. In this maneuver, the helicopter aims to reach 40knots forward speed without losing altitude. Therefore, control pushes the longitudinal cyclic to forward and pulls the collective up to gain forward velocity.



Figure 4 20Knots to 40Knots Acceleration Maneuver Path and States

A sensitivity analysis is performed for this approach as given in Figure 5. Prediction horizon is set to 3 seconds and, 1 second, 0.5 second, 0.2 second and 0.1 second of the prediction horizons are set as control horizon. It is seen that giving more disturbance chance to controller makes the approach more unstable.



Figure 5 Comparison of the Flight States with Different Control Horizon

Another comparison is done for the computational time of this approach as given in Figure 6. Decreasing of the control horizon, or in other way, disturbance increasing the of controller on nonlinear plant increases the computation time and optimization iterations. It causes increase on computation time of this coupled approach.

Following maneuvers are used with a control horizon 1 second and prediction horizon 3 seconds.



Figure 6 Computational Time of the Analyses

A deceleration maneuver is performed similar to acceleration maneuver in Figure 7. In this maneuver, flight simulation is aimed to decrease helicopter forward speed to 20 knots from 40 knots. Helicopter decreases its forward speed by pitching up while keeping the altitude as constant as possible.



Figure 7 40Knots to 20Knots Deceleration Maneuver Path and States

Another acceleration maneuver is performed and depicted with Figure 8. This maneuver is initiated from hover position to 10 knots side velocity, increasing the roll angle and holding the altitude constant to the best of its ability.



Figure 8 Hover to 10Knots Acceleration Maneuver to Left Path and States

Last maneuver, is an acceleration from hover to 20 knots forward speed presented in Figure 9. This maneuver has almost similar control input characteristics as in 20 knots to 40 knots

acceleration. Helicopter changes its attitude as pitch down and tries to accelerate while keeping the altitude constant as possible.



Figure 9 Hover to 20Knots Acceleration Maneuver Path and States

CONCLUSION

At the predictive stage, a linear mathematical model of UH60 is coupled with the optimization algorithm [Hilbert, 1984; Padfield, 2018]. This enables to perform fast optimization to generate maneuver history for maneuvering flight conditions. This approach permits to create flight maneuvers automatically.

It is evaluated that, analysis stability of the non-linear plant is effected by the length of the control horizon. Decreasing of the control horizon has two disadvantages; increasing the instability and increasing the whole analysis time.

In this study, a methodology is introduced to generate a maneuvering flight for a highly complex non-linear plant with using linear model predictive control. While performing the analyses, it is observed that the assignation of the objective function, weight coefficients and types of the penalty functions have a significant influence on the generation of the history of the control input. There are some possibilities to improve the performance of this approach;

- A learning algorithm for the linear model,
- Adaptive prediction and control horizon can be implemented to increase performance,
- Feedback of the time-derivative of the states to linear model.

To conclude, this approach seems as a promising method to create control history automatically and fast for an open loop non-linear plant used as black box models.

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