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An Affine Parameter Dependent Controller for an Autonomous Helicopter at Different Flight Conditions

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Abstract: In this paper we address the design of a controller that achieves stabilization and reference tracking at different flight conditions for an unmanned helicopter. The controller proposed is in the form of an H-infinity gain-scheduler, and is used for stabilization and reference tracking, for the 4 axis autopilot. (heave, pitch, roll and yaw control) A nonlinear helicopter model has been built, trimmed and linearized at different flight conditions. Based on the linearized models an approximate affine parameter dependent model has been constructed. Then, a linear parameter dependent controller is synthesized which stabilizes the affine parameter dependent helicopter model. By doing so, a single controller achieves stabilization and reference tracking of a family of linear models by scheduling the controller gains based on the online measurement of the scheduling parameter, which is the forward velocity. Moreover, the affine parameter dependent controller is fitted into the nonlinear helicopter model. It is seen that this single parameter dependent controller successfully stabilizes the nonlinear helicopter model at different flight conditions.

Keywords: Nonlinear Modeling, H-infinity control, Parameter Dependent Control, Gain Scheduling.

1. INTRODUCTION

Aerial vehicles have complex nonlinear behavior which changes significantly at different fight conditions. Generally speaking, control design is based on classical design rules and nonlinear variations on the system dynamics are usually handled by the standard gain scheduling techniques by simply tuning the controllers at different flight conditions. Specifically, helicopters are highly unstable and complex systems whose dynamics changes with variations on the flight conditions. Thus the need for a gain scheduled controller becomes more evident.

In (Bates D. and Postlethwaite I., 2002), a mixed sensitivity $\mathcal{H}_\infty$ controller is designed based on a linearized model of a Bell 205 helicopter as a design example. In (Postlethwaite I., Prempain E., Turkoglu E., Turner M. C., Ellis K., and Gubbels A.W., 2005), $\mathcal{H}_\infty$ controllers are designed using the linearizations extracted from nonlinear model of the Bell 205 helicopter. It has been noted that $\mathcal{H}_\infty$ controllers provided satisfactory stabilization of the helicopter and yielded desirable handling qualities in flight testing. Moreover, in (Luo C., Liu R., Yang C., and Chang Y., 2003), an $\mathcal{H}_\infty$ flight control system is also designed to improve its stability, maneuverability and agility. Resulting $\mathcal{H}_\infty$ flight control system is then fitted into the nonlinear model of a helicopter to simulate nonlinear dynamic response.

In (Pei H., Hu Y., and Wu Y., 2007), a robust gain-scheduling algorithm is introduced by employing local multi-variable LQR controllers which are designed at each operation point, for a given performance index. For the controllers between two neighbor operating points, a scheduling scheme is employed for the control gain interpolation. In (Abulhamitbilal E. and Jafarov M., 2011), a flight control system with gain scheduled LQ optimal controllers are designed based on look-up tables. Gain scheduling is simply accomplished by changing the values of the control matrix according to predefined conditions. However, it should be stressed that the creation of separate control laws is laborious compared to the self scheduling method which forms an automatic interpolation law.

In the 90's Linear Parameter Varying (LPV) control has been presented as a reliable alternative to classical gain-scheduling for multivariable systems; typical well known examples can be found in (Shamma J. S. and Cloutiert J. R. , 1993) and (Apkarian P., Gahinet P., and Biannic J.M., 1994). Gain scheduling is a standard method to design controllers for dynamical systems over a wide performance envelope. In (Asif A. and Smith R., 2000), LPV control design techniques are also applied to the attitude control of the X-33, a single-stage-to-orbit (SSTO) prototype vehicle. A multivariable LPV controller was designed using $\mathcal{H}_\infty$ synthesis for F/A-18 in (Balas G.J.,Mueller J.B., and Barker J., 1999). This type of controller was chosen because the change in dynamics of the aircraft state-space matrix and input matrix are approximately affine functions of forward velocity. The results show that the LPV controller performed the specified objectives and is therefore a sufficient controller for the F/A-18 model.

In (Balas, 2002) two different approaches are proposed that can be used to obtain reliable LPV models. Unfortunately,

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there is no proposed way of obtaining quasi LPV models either by state transformation or function substitution for a nonlinear helicopter model. Generally, control designers use a family of linear, time-invariant (LTI) plants at different points of interest throughout the operational envelope in order to obtain a reliable LPV model. Jacobian linearization method is applicable to the widest class of nonlinear systems, since it is valid for any nonlinear system that can be linearized around its equilibrium points. Thus, Jacobian linearization approach can be used to obtain an affine parameter dependent model of nonlinear helicopter model. Based on the locally linearized family of systems, it is straightforward to construct a parameter dependent model that captures the nonlinear behavior. Hence, gain scheduling enables synthesis of global controllers based on interpolation of a family of locally linearized controllers.

In this paper, we develop a mathematical simulation model of an autonomous helicopter based on information of a Yamaha R-50 model helicopter given in (Munzinger, 1998). In Section 2, development of a minimum complexity helicopter simulation math model has been carried out in SIMULINK environment. Jacobian linearization is used to create a family of plants linearized with respect to a set of equilibrium points that represent the flight envelope of interest. The resulting model will be a local approximation to the dynamics of the nonlinear plant around a given set of equilibrium points. An affine parameter dependent system is obtained in Section 3 by using the family of linearized plants. Section 4, the mixed sensitivity $\mathcal{H}_\infty$ controller synthesis approach is summarized. Based on the affine parameter dependent helicopter model an affine parameter dependent controller is designed in Section 5 which stabilizes the closed-loop system and provides reference tracking to the pilot reference commands in different flight conditions by scheduling the controller based on the online measurement of scheduling parameter. Finally in Section 6, the parameter varying controller is tested on the all trimmed models at different equilibrium/linearization points. Lastly, the affine parameter dependent controller is fitted into the nonlinear helicopter model and it is seen that is stabilizes the system and provides reference tracking to the pilot commands.

2. NONLINEAR HELICOPTER MODEL

The helicopter is a highly unstable system for which a controller is needed to be able to achieve flight. The controller should make the helicopter model stable within the entire flight envelope in a simulation. As the main objective is to control the dynamical behavior of the helicopter, it is necessary to derive a representative model that reacts in the same manner as a real helicopter. In that respect a very accurate model is preferred, but the complexity increases with model accuracy. A highly complex model will limit the capability of real-time simulation. The nonlinear model must approximate the behavior of the actual helicopter system as closely as possible. The modeling approach mainly based on the NASA report in (Heffley R.K. and Mnich M.A. , 1988).

The helicopter is considered to be a rigid body, free to move in three directions and to rotate about all three axes, hence having 6 degrees of freedom (DOF). Basically, two different helicopter reference-frames are defined throughout the helicopter modeling: body fixed reference frame and earth fixed frame. All of these are right-handed coordinate systems. For deriving equations of motion, it is convenient to define a body fixed frame following the attitude and position of the helicopter. The x axis of the body frame is defined to point in the helicopter longitudinal direction. The y axis is defined to point to the right (lateral direction) when seen from above, and the z axis downwards and perpendicular to the other axes. The helicopter uses the main and tail rotor to perform these movements. By altering the pitch of the blades, the magnitude and orientation of the resulting thrust force can be controlled. The position and attitude of the helicopter are controlled through the following 4 control inputs commanded by the pilot: collective, longitudinal cyclic, lateral cyclic and pedal.

The modeling of the helicopter will be performed using a top-down principle. The entire model consists of three parts which comprise the nonlinear helicopter model. The nonlinear model is implemented in SIMULINK, for testing of the devised controller.

2.1 Thrust and Flapping equation

The blades of the main rotor generate the needed lift to the helicopter. This is done by accelerating the air downwards and thereby generates a counter force upwards. Main rotor thrust can be given as

$$T_{MR} = (\omega_b - v_i)\frac{\rho\Omega R^2 aBc}{4} \tag{1}$$

and induced flow v_i depends on main rotor thrust as follows

$$v_i{}^2 = \sqrt[2]{\left(\frac{\hat{v}^2}{2}\right)^2 + \left(\frac{T_{MR}}{2\rho A}\right)^2} - \frac{\hat{v}^2}{2} \tag{2}$$

where

$$\omega_b = \omega_r + \frac{2}{3}\Omega R u_{coll}$$
$$\omega_r = w + (\beta_{1c} + i_s)u - \beta_{1s}v$$
$$\hat{v}^2 = u^2 + v^2 + \omega_r(\omega_r - v_i).$$

A more detailed analysis on main rotor thrust equations can be found in (Munzinger, 1998) and (Hald U.B. ,Hesselbæk M.V. ,Holmgaard J.T. , Jensen C. S. ,Jakobsen S. L., and Siegumfeldt M., 2005). The main rotor thrust equations need to be solved iteratively, since T_{MR} depends on v_i and vice-versa. T_{MR} is calculated numerically by iterating the solutions of T_{MR} and v_i. Iterative solution for main rotor thrust and inflow needs to be solved by iteration in each time sample. This iteration is repeated until the values of T_{MR} and v_i have settled. Approximately 5 iterations are enough to ensure that the values have settled as advised in (Pettersen R., Mustafic E., and Fogh M., 2005). These iterations are carried out in a single sample step time when the model is simulated in SIMULINK.

Tail rotor thrust is not modeled and it is assumed that the tail rotor thrust force can be instantaneously applied by the pedal input in order to counteract the torque made by the main rotor.