µ-Synthesis and Hardware-in-the-loop Simulation of Miniature Helicopter Control System

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Received: 6 February 2013 / Accepted: 26 January 2014 / Published online: 21 February 2014
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Abstract The aim of this paper is to describe in detail the µ-synthesis of a miniature helicopter integral attitude controller of high order and to present results from the hardware-in-the-loop simulation of this controller implementing Digital Signal Processor. The µ-controller designed allows to suppress efficiently wind disturbances in the presence of 25% input multiplicative uncertainty. A simple position controller is added to ensure tracking of the desired trajectory in 3D space. The results from hardware-in-the-loop simulation are close to the results from double-precision simulation of helicopter control system in Simulink®. The software platform developed allows to implement easily different sensors, servoactuators and control laws and to investigate the closed-loop system behavior in presence of different disturbances and parameter variations.

Keywords Miniature helicopter control · µ-synthesis · Hardware-in-the-loop simulation · Digital signal controller

1 Introduction

In recent years, there is a continuing interest in the development of robust control systems for unmanned small/miniature helicopters. Two major techniques to design robust controllers are most frequently used: the $H_\infty$ optimization and the µ-synthesis [9, 30]. The $H_\infty$ optimization is usually preferred in robust control design because it produces controller of smaller order which facilitates its implementation. This design method is usually applied in the version of $H_\infty$ loop shaping or in some form of mixed-sensitivity design [1]. $H_\infty$ loop shaping is applied to the hover control of Yamaha R-50 helicopter and validated in real flight as described in [18]. The same approach is used in [3] to control a 3-DOF miniature helicopter and in [17, 24] for robust control of the longitudinal and lateral dynamics of the full-scale Bell 412 helicopter. Other versions of $H_\infty$ optimization are also possible. For instance, in [7] a state-feedback $H_\infty$ control law combined with reduced-order observer is designed and successfully implemented to control a small-scale unmanned helicopter. It should be pointed out that the loop shaping design method is suitable for the case of unstructured uncertainties but can not ensure robust performance in the general case of unstructured and
structured (parametric) uncertainties. This is a common disadvantage of all $H_\infty$ optimization methods. In contrast, the $\mu$-synthesis which is based on the use of the structured singular value \cite{32} may ensure robust stability and robust performance in the presence of exogenous disturbances, noises and different type of uncertainties. This synthesis requires a linearized model of the helicopter dynamics and may include several weighting functions that shape the exogenous signals and represent the performance requirements to the closed-loop system. Successful implementation of the $\mu$-synthesis in case of Yamaha R-50 helicopter is reported in \cite{28} and a similar design is described in \cite{31}. In both cases the linearized helicopter model developed by Mettler \cite{21} is used and an input multiplicative uncertainty of 10\% is assumed in the helicopter model. The controller designed in \cite{31} is of 28th order. The high order of the controller obtained is usually pointed out as a disadvantage of $\mu$-synthesis. However, with the appearance of powerful processors in the recent years this peculiarity of the $\mu$-synthesis does not pose a serious difficulty.

The technique of the hardware-in-the-loop (HIL) simulation is a low cost effective technique to test the hardware and software of actual helicopter controller, which allows to access the closed-loop system performance in case of strong disturbances, noises and parametric variations. This technique makes possible to examine rapidly different control laws reducing in the same time the danger of accidents during real flight experiments \cite{6,27}. Hardware-in-the-loop simulation may be done efficiently by using the Simulink Coder\textsuperscript{®} \cite{29} and Embedded Coder\textsuperscript{®} \cite{11} developed by The MathWorks, Inc. which are implemented together with MATLAB\textsuperscript{®} and Simulink\textsuperscript{®} in the design and simulation process, see for instance \cite{12}.

The aim of this paper is to present in detail the $\mu$-synthesis of a high order integral attitude controller of a miniature helicopter and to demonstrate results from the hardware-in-the-loop simulation of this controller implementing a Digital Signal Processor. The $\mu$-controller designed allows to suppress efficiently wind disturbances in the presence of 25\% input multiplicative uncertainty. A simple position controller is added to ensure tracking of a desired trajectory in the 3D space. The results from hardware-in-the-loop simulation are close to the results from the double-precision simulation of helicopter control system in

![Fig. 1 Helicopter variables in body frame coordinate system](image)