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Performance Analysis of UDE based Controllers Employing Various Filters

Adarsh Kodhanda * **S. E. Talole** **

* *Ph.D. Student, Department of Aerospace Engineering, Defence Institute of Advanced Technology, Girinagar, Pune 411025, India (e-mail: adarshkodhanda@hotmail.com*

** *Professor, Department of Aerospace Engineering, Defence Institute of Advanced Technology, Girinagar, Pune-411025, India (e-mail: setalole@hotmail.com)*

Abstract: This work explores performance characteristics of Uncertainty and Disturbance Estimator (UDE) based controllers designed using various filters. Considering a second order uncertain plant, a controller is designed for nominal system to meet desired performance specifications. The controller is then augmented using UDE component to achieve robustness in the presence of uncertainties and disturbances. The UDE component is designed using four different filters proposed in the literature and time and frequency response analysis for the designs has been carried out on common basis to bring out their relative performance characteristics.

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1. INTRODUCTION

As practical systems are usually affected by plant uncertainties and unmeasurable external disturbances, robust control design has been an area of active research and therefore, a large number of approaches have been proposed in literature addressing the issue. One of the approach that has been explored widely for designing robust controllers for uncertain systems is based on the concept of uncertainty and disturbance estimation and compensation. The central idea in this approach is to estimate the effect of uncertainties and disturbances acting on the system and compensate the same by augmenting the controller designed for nominal system. To this end, various techniques have been proposed in literature to estimate the effect of uncertainties and disturbances Schrijver and van Dijk (2002); Moura et al. (1997); Talole et al. (2007a); Youcef-Toumi and Ito (1990); Talole et al. (2005, 2010).

Following similar concept as that of Time Delay Control (TDC) Youcef-Toumi and Ito (1990) and addressing certain issues associated with it, a novel Uncertainty and Disturbance Estimator (UDE) technique is proposed in Zhong and Rees (2004) wherein the effect of plant uncertainties and external disturbances is estimated by employing an appropriate filter. Since then, various theoretical and application results of UDE based control strategies have appeared in literature. For example, in Zhong et al. (2011), the authors have brought out the two-degree-of-freedom nature of the UDE based controllers and it is shown that, in addition to the known advantages over the TDC, the UDE-based control outperforms TDC under the same operational conditions. In Talole and Phadke (2008), UDE is used in addressing the issues of requirement of knowledge of uncertainty bound and chattering in sliding mode control. The UDE based robust control designs for uncertain linear and nonlinear systems with state delays are studied in Kuperman and Zhong (2009, 2011); Stobart et al. (2011). Results on extension of the UDE technique for uncertain nonlinear systems can be found in Deshpande and Phadke (2012). In Ren and Zhong (2013a), the UDE based robust control is investigated for a class of non-affine nonlinear systems in a normal form. An application of the UDE in robustification of Input-Output Linearization (IOL) controller is presented in Talole et al. (2007b); Talole and Phadke (2009); Talole et al. (2011) wherein the UDE estimated uncertainties are used in robustifying an IOL controller. In Chandar and Talole (2014), a new form of filter in UDE-based controller is proposed to cater for fast-varying uncertainties and disturbances.

Applications of the UDE based controllers have also been reported in the literature. An application of UDE in robustifying a feedback linearizing control law for a robot having joint flexibility is presented in Patel et al. (IIT Bombay, Mumbai, India, Dec., 2006) wherein the effect of joint flexibility is treated as a disturbance. Design of robust flight path angle tracking controller in aircraft Wu et al. (2012), trajectory tracking control of rigid link manipulators Kolhe et al. (2013), control of aircraft Su and Lin (2011b), design of a robust guidance law for tactical missiles Phadke and Talole (2012), robust control of variable-speed wind turbines Ren and Zhong (2013b), in control of a two axis active magnetic bearing for flywheel applications Kuperman et al. (2012), wing rock motion control Kuperman et al. (2011), active surge control of compression system Xiao and Zhu (2012), and active suspension scheme for vehicles Deshpande et al. (2014) are some more examples to cite.

At the heart of the UDE approach is the choice of an appropriate filter used for uncertainty estimation and there-

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fore, various filters have been proposed in the literature. In the original formulation of UDE in Zhong and Rees (2004), a first order filter is proposed. Extending the work further and in order to improve the estimation accuracy, a second order filter has been proposed in Deshpande et al. (2014). Suggestion for use of higher order filters can be found in Phadke and Talole (2012); Talole and Phadke (2009); Talole et al. (2011). Similarly, in Chandar and Talole (2014), a new form of filter designated as α filter is proposed to address the issue of fast varying disturbances. In this work, performance analysis of UDE based controllers using four filters has been carried out on common basis and the related results are presented. It is felt that the analysis will help in progressing further research in the UDE approach to make it more effective and efficient.

The remaining paper is organized as follows. The design of UDE based Controllers based on the considered filters as applied to a second order uncertain plant are presented in Section 2. Results on performance of the controllers are presented in Section 3. Simulation results using the controllers can be found in Section 4 and lastly, Section 5 concludes this work.

2. UDE BASED CONTROLLERS USING VARIOUS FILTERS

In this work a hypothetical second order linear plant is considered in view of the laborious derivations involved in the theoretical performance analysis. However UDE based filters are used for robust control of various higher order and nonlinear systems and thus the insights from this study can be extended to them. The dynamics of the second order linear plant is given by

$$\ddot{y} = -a_1 y - a_2 \dot{y} + bu + d' \tag{1}$$

where d' represent external disturbance, if any. To account for plant parameter uncertainties, let $a_1 = a_{1o} + \Delta a_1$, $a_2 = a_{2o} + \Delta a_2$ and $b = b_o + \Delta b$ where a_{1o}, a_{2o} and b_o are the nominal values of the respective parameters, whereas Δa_1, Δa_2 and Δb are their associated uncertainties. Defining the total uncertainty as $d = -\Delta a_1 y - \Delta a_2 \dot{y} + \Delta bu + d'$, the dynamics of (1) is re-written as

$$\ddot{y} = -a_{1o} y - a_{2o} \dot{y} + b_o u + d \tag{2}$$

To address the issue of uncertainties and disturbances, the following UDE robustified controller Talole and Phadke (2009) is proposed

$$u = \frac{1}{b_o}(u_a + u_d + \nu) \tag{3}$$

where
$$u_a \stackrel{\triangle}{=} a_{1o} y + a_{2o} \dot{y} \tag{4}$$

$$\nu \stackrel{\triangle}{=} -k_d \dot{y} + k_p (r - y) \tag{5}$$

and $r(t)$ is the reference input and k_p and k_d are the controller gains. The quantity u_d represents that part of the control which compensates d. Now using (3) in (2) with u_a of (4) leads to

$$\ddot{y} = u_d + \nu + d \tag{6}$$

from where one has

$$d = \ddot{y} - u_d - \nu \tag{7}$$

In view of (7) and following the procedure given in Zhong and Rees (2004) and Talole and Phadke (2009), the estimate of d is obtained as

$$\hat{d} = G_f(t) * d = G_f(t) * (\ddot{y} - u_d - \nu) \tag{8}$$

where $\hat{d}$ is an estimate of d, $*$ is the convolution operator and $G_f(t)$ is chosen appropriate filter. Selecting $u_d = -\hat{d}$ and using (8) gives

$$u_d = -G_f(t) * (\ddot{y} - u_d - \nu) \tag{9}$$

and solving for u_d leads to

$$u_d = -\left\{ \frac{G_f(t)}{(1 - G_f(t))} \right\} * (\ddot{y} - \nu) \tag{10}$$

Having obtained u_d, and assuming that the disturbance d is compensated completely, one obtains closed loop dynamics as

$$\ddot{y} + k_d \dot{y} + k_p y = k_p r \tag{11}$$

Obviously, the gains k_d and k_p need to be chosen to satisfy given performance specifications. In next section, the u_d of (10) is designed using four different filters and expressions for the resulting controllers are presented.

2.1 Design-I

Firstly, the first order filter proposed in Zhong and Rees (2004) is considered. The filter is given as

$$G_1(t) = L^{-1} \left\{ \frac{1}{1 + s\tau} \right\} \tag{12}$$

where τ is the time constant of the filter. Obtaining the u_d in (10) using the filter (12), u_a of (4) and ν of (5), the controller of (3) can be obtained as Deshpande and Phadke (2012); Talole and Phadke (2009),

$$u_1 = \frac{1}{b_o} \left(a_{1o} y + a_{2o} \dot{y} - \frac{1}{\tau} \dot{y} + \nu + \frac{1}{\tau} \int \nu dt \right) \tag{13}$$

The controller of (13) will be referred to as the Design-I.

2.2 Design-II

In order to improve uncertainty estimation accuracy, higher order filters have been suggested in the literature Deshpande et al. (2014); Phadke and Talole (2012); Talole and Phadke (2009); Talole et al. (2011). For example, in Talole and Phadke (2009) while analysing closed loop stability using the first order filter of (12), it is shown that for constant uncertainty, i.e., $\dot{d} = 0$, the closed loop error dynamics exhibit asymptotic stability implying perfect uncertainty estimation. However, if $\dot{d}$ is not small but $\ddot{d}$ is, then a second order filter can provide asymptotic stability for the closed loop dynamics. Extending the argument, if $\dot{d} \neq 0$, but some k^{th} order derivative of d is zero, then asymptotic stability for the error dynamics can be guaranteed by choosing kth order filter of the form (14) , at the penalty of reduced stability margins of the system.

$$G_f(t) = L^{-1} \left\{ \frac{(1 + \tau s)^k - (\tau s)^k}{(1 + \tau s)^k} \right\} \tag{14}$$

It may be noted that for $k = 1$, one gets the first order filter of (12) as expected. In this work, the second and third order filters are considered as Design-II and Design-III respectively. With $k = 2$ in (14), one gets the second order filter as

$$G_2(t) = L^{-1} \left\{ \frac{1 + 2\tau s}{1 + 2\tau s + \tau^2 s^2} \right\} \tag{15}$$

and the corresponding UDE based controller of (3) using (4), (5) and (10) can be obtained as

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