Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-21 (2016) 240–245

An Adaptive Disturbance Observer for Precision Control of Time-Varying Systems ⋆

Jungsu Choi, Hyunjin Choi, Kyoungchul Kong ∗
Dong Jin Hyun ∗∗

∗ *Department of Mechanical Engineering, Sogang University, Seoul, Korea 04107 (e-mail: {zz1zzy, hyunjin, kckong}@ sogang.ac.kr)*
∗∗ *Human Factors & Devices Research Team, Hyundai Motor Company, Korea 16082 (e-mail: mecjin@hyundai.com)*

Abstract: In this paper, a new adaptive disturbance observer (ADOB) approach is introduced to overcome the inherent interference problem between a disturbance observer (DOB) and a parameter adaptation algorithm (PAA); the PAA is applied to estimate the parameters of the nominal plant model inverse, such that the disturbance estimated by the DOB is remained small. Namely, the proposed ADOB is equivalent to an adaptive control method that recursively minimizes the ℓ_2 norm of the disturbance estimated by a DOB. Since the bounded ℓ_2 norm of the disturbance estimate can be interpreted as the guaranteed stability of the DOB loop, the stability of the proposed ADOB can be proved theoretically, as well as practically. In addition, the proposed method directly seeks the parameters of a nominal plant model inverse, and thus the model inversion process is no longer necessary. The proposed ADOB is verified by theoretical analyses and experimental results in this paper.

Keywords: Disturbance observer, parameter adaptation, time-varying systems

1. INTRODUCTION

Since the concept of a disturbance observer (DOB) was first introduced by Ohnishi (1987), the DOB has been refined by many control engineers (e.g., Kobayashi et al. (1996) and Kong et al. (2009b)) and applied in various applications such as robotic manipulators by Yang et al. (2012) and hard disc drives by White et al. (2000). The DOB is a simple but effective control method; it consists of only two components – an inverse of a nominal plant model and a filter, called the Q filter, as shown in Fig. 1. The DOB estimates a disturbance, which includes an exogenous disturbance and a model uncertainty, by comparing an output simulated by a nominal plant model with an actual measurement, and the estimated disturbance is fed back into the system for rejection of the disturbance. In this process, the model uncertainty, as well as the exogenous disturbance, is rejected, which makes the DOB-controlled system behave as the nominal plant model. Therefore, the DOB has been widely used as an inner-loop controller for model-based feedback and feedforward control methods as in Fig. 1, which is often called the two-degrees-of-freedom control; the model-based control methods can be designed based on the nominal plant model of the DOB, as in Kong et al. (2009a) and Yang et al. (2013).

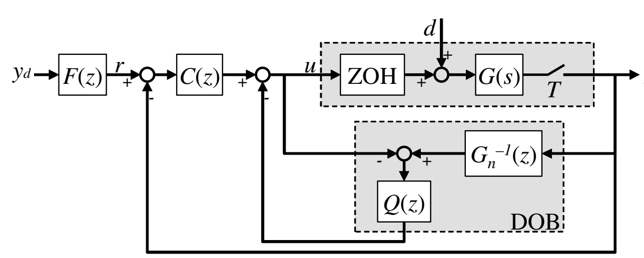

Fig. 1. Two-DOF control with a disturbance observer in discrete-time domain.

Given a nominal plant model, the performance and stability robustness of a DOB can be analyzed by the magnitude of model uncertainties. Applying small gain theorem, the stability of the DOB loop is guaranteed if the magnitude of the Q filter is smaller than that of a multiplicative model uncertainty in the entire frequency range. This condition introduces a tradeoff between the control performance and the stability robustness; the DOB cannot be effective for systems with large model uncertainties. For successful implementation of a DOB, therefore, a nominal plant model should be an accurate interpretation of the actual dynamics, which is often challenging in practice, in particular for time-varying systems.

1.1 *Efforts for identification of a nominal plant model*

Many efforts have been made to identify an appropriate nominal plant model for a DOB. Since every control en-

⋆ This research was supported by university-industry collaborative research project funded by Hyundai Motor Company.

2405-8963 © 2016, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.10.557

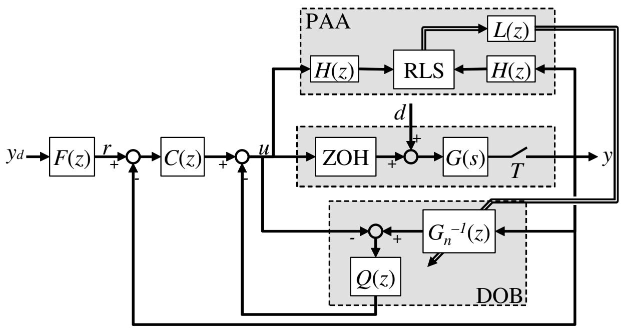

Fig. 2. Two-DOF control with a DOB and a PAA; $H(z)$ and $L(z)$ are filters for assuring the stability of the overall control system.

gineer faces the fundamental question given above during the implementation of a DOB, every control engineer may have his/her own solutions for identification of an appropriate nominal plant model. For examples, Kong and Tomizuka (2013) proposed a systematic way to adjust the parameters of a nominal plant model to obtain improved stability robustness in the discrete-time domain. Chen et al. (2000) used a nonlinear nominal plant model to enhance the stiffness of a robot manipulator. Although the DOB with a nonlinear nominal model, often called a nonlinear DOB, may improve the effectiveness of the disturbance rejection function of a DOB, the closed-loop dynamics of the DOB becomes nonlinear, which makes it difficult for linear feedback and feedforward control methods to utilize a "nominalized" plant model.

1.2 Adaptive DOB: a DOB with parameter adaptation

Another solution for identifying model parameters is parameter adaptation by recursive least squares, which is particularly useful for linear time-varying systems, or piecewise linear systems. However, selection of adaptation parameters, such as an adaptive gain or a forgetting factor, requires hands-on experiences and thus is challenging for non-experts. Since a low adaptive gain results in a low adaptation speed, tracking control performance may be deteriorated in a transient response when the adaptation gain is low. On the other hand, the increase of the adaptive gain for expeditious adaptation makes the overall system too sensitive to the model change and disturbances, so the system response oscillates and may even be unstable in systems with continuously time-varying dynamics. Therefore, an upper limit of the adaptive gain should be taken into account in practice to limit the adaptation speed. In order to solve such problems, various adaptive control methods have been proposed by Miller and Davison (1991), Ydstie (1992), and Bartolini et al. (1999). In particular, $\mathcal{L}_1$ adaptive control methods proposed by Cao and Hovakimyan (2008) and Jafari. et al. (2013) are noteworthy; it applies a lowpass filter to a control input and the estimated parameters by recursive least squares. Therefore, the $\mathcal{L}_1$ adaptive control enables an increased adaptive gain, such that the tracking performance can be maintained even in a transient response.

In our previous work by Hyun et al. (2013), an adaptive disturbance observer (ADOB) shown in Fig. 2 that intuitively incorporates a DOB with a parameter adaptation algorithm (PAA) was introduced. The motivation of the ADOB was simple; when a plant exhibits nonlinear dynamics but is piecewise linear, a linear time-varying (LTV) nominal plant model can be used for the DOB. More specifically, the ADOB method has been inspired from the following arguments:

(1) If a nominal plant model is accurate and there is no exogenous disturbance, the DOB does not influence the control performance and stability. This also implies that the stability of the DOB is guaranteed.
(2) If a nominal plant model is accurate but an exogenous disturbance, which is independent from the state variable of the plant dynamics, is exerted, the DOB is able to estimate the disturbance and to reject in the frequency range where $Q(e^{j\omega T}) \approx 1 + 0j$.
(3) If a nominal plant model is inaccurate and an independent exogenous disturbance exists, the DOB is able to estimate a lumped disturbance that includes both the model mismatch and the exogenous disturbance. The larger the model mismatch, the poorer the stability robustness of the DOB loop.
(4) If a nominal plant model is accurate enough but the exogenous disturbance is not independent from the state variables of the plant dynamics, the stability robustness of the DOB loop is deteriorated due to the disturbance correlated with the state variables. In this case, therefore, the nominal plant model should be designed taking account of the correlation between the disturbance and the state variables. In this case, the resultant nominal model parameters may not be an accurate interpretation of the dynamic characteristics of the plant.

Consequently, a nominal plant model should be as accurate as possible and take account of the plant dynamics and the disturbance dynamics, if any. Identifying the plant and disturbance dynamics is, however, very difficult in practice, and moreover, the disturbance dynamics is time-varying because it can be defined only when a disturbance correlated with the state variables exists. Therefore, one of the most intuitive solutions to address this issue is an adaptation of the parameters of a nominal plant model in the DOB system.

A recursive least squares method can be applied for the parameter adaptation of the LTV nominal plant model [see Eleftheriou and Falconer (1986)]. Additional filters were introduced, as $H(z)$ and $L(z)$ in Fig. 2, to assure the stability of the overall control system; in $H(z)$ filters both the input and output signals, and $L(z)$ is a lowpass filter for slowing down the change rate of the model parameters. In particular, tuning of $L(z)$ is critical, because the stability of the overall ADOB is vulnerable in a transient response. Similar approaches have been applied to practical applications; for example, a similar concept was numerically simulated by Kim et al. (2008), where the inertias of a two-link robotic manipulator were identified by a PAA while the robot was controlled by a DOB. The proposed work was effective, but the number of parameters to be updated was limited.