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Resetting disturbance observers with application in compensation of bounded nonlinearities like hysteresis in piezo-actuators

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ABSTRACT

This paper presents a novel nonlinear (reset) disturbance observer for dynamic compensation of bounded nonlinearities like hysteresis in piezoelectric actuators. Proposed Resetting Disturbance Observer (RDOB) utilizes a novel Constant-gain Lead-phase (CgLp) element based on the concept of reset control. The fundamental limitations of linear DOB which results in contradictory requirements and in a dependent design between DOB and feedback controller are analysed. Two different configurations of RDOB which attempt to alleviate these problems from different perspectives are presented and an example plant is used to highlight the improvement. Stability criteria are presented for both configurations. Performance improvement seen with both RDOB configurations compared to linear DOB is also verified on a practical piezoelectric setup for hysteresis compensation and results analysed.

1. Introduction

Real world is nonlinear and plants are often represented by their nominal linear model. All existing nonlinearities are generally considered as input disturbances and are handled by the disturbance rejection capability of the overall feedback system. Linear controllers are designed based on the nominal linear plant estimate and in the absence of a disturbance observer (DOB), the effect of nonlinearities have to be dealt solely by the disturbance rejection property of the controller. In some cases where the nonlinearities are significantly high to be handled by the controller, overall system in best case gets inaccurate and, in worst case can be unstable. One such nonlinear system is a piezo-actuator where high nonlinearity exists due to its hysteresis. Piezo-actuators have become increasingly popular in high precision motion control applications (Gu, Zhu, & Su, 2014; Woronko, Huang, & Altintas, 2003), and literature focusing on hysteresis compensation specifically in piezo-actuators through DOB can be found in Abidi, Sabanovic, and Yesilyurt (2004), Gu et al. (2014), Ruderman and Bertram (2014), Sofla, Rezaei, Zareinejad, and Saadat (2010) and Yi, Chang, and Shen (2009). In general, suppression of similar nonlinear effects has been widely studied using various techniques in literature and can be broadly classified into two categories namely, model-based techniques and control based techniques.

Models used in the model-based techniques can be either physics principles-based, differential equation based, mathematical operator based, fuzzy logic based and so on (Al Janaideh, Feng, Rakheja, Su, & Rabbath, 2009; Al Janaideh, Su, & Rakheja, 2010; Gu, Zhu, Su, Ding, & Fatikow, 2016; Hassani, Tjahjowidodo, & Do, 2014; Janaideh & Farhan, 2009; Jiles & Atherton, 1986; Krejci & Kuhnen, 2001; Rakotondrabe, 2012). They operate on a similar mode by modelling the nonlinearity and using the inverse which is connected in series to have a feedforward connection such that the nonlinearity gets cancelled. The main advantage of this approach is that it is a feedforward compensation scheme and can hence not cause instabilities. However, an equally major drawback is that it is not generalizable since a new model has to be identified for each device and worse for every new operating condition and this significantly limits its utilization in industrial applications. Additionally, the achievable accuracy is determined by the accuracy of nonlinearity estimate. These techniques are not analysed in this work due to their lack of robustness.

On the other hand, control based techniques can be classified into two categories namely, feedforward and feedback. Feedforward control strategy is same as model-based technique. However, the feedback approach does not need the hysteresis model and is hence generalizable resulting in enhanced compensation of nonlinearity with a single compensation architecture operating at all different operating points. This strategy generally considers nonlinearities to be bounded input disturbances and attempts to reject them. This methodology can be further classified into two categories, one which estimates considered

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nonlinearity as disturbance using linear state estimation (Yi et al., 2009) and, another which uses nominal linear plant model and attenuates all other dynamics including actual input disturbance (Du, Li, Thum, Lewis, & Wang, 2010). It is not clear as to why nonlinearity is estimated as nonlinear disturbance using linear estimation techniques in the first approach since this limits its performance. However, the performance of the second approach is more limited by fundamental properties of linear control systems and not the approach itself and this second approach is the focus of our work.

Linear disturbance observers (DOB) suffer from the fundamental limitations. One of the limitations comes from the contradictory requirements for disturbance rejection and noise attenuation placed on the disturbance estimating filter (DEF) which is an integral part of DOB (Schrijver & Van Dijk, 2002). Another is that, although ideally design of feedback controller and DOB should be separable, the limitation on sensitivity function results in a dependence as explained in detail in the next section. This paper presents novel nonlinear DOB configurations to specifically tackle these limitations and the nonlinearity used for this purpose is reset control.

Reset control is a nonlinear control technique which has been the focus of research for many decades starting from Clegg in 1958 (Clegg, 1958). The phase advantage of reset has been used to overcome limitations of linear control in recent years (Baños & Barreiro, 2011; Zheng, Guo, Fu, Wang, & Xie, 2008). Its simplicity along with the fact that it can be approximated and analysed in frequency domain using describing function gives it a great advantage over other nonlinear techniques. Several works exist where reset has been used for performance improvement in high precision motion control (Li, Du and Wang, 2011; Li, Guo and Wang, 2011). However, application of reset in DOB for performance improvement does not exist to the best of authors' knowledge. In this paper, reset control is applied for the first time in DOB to improve performance. A novel reset element 'Constant-gain Lead-phase' is used for this purpose and two different approaches are considered to improve performance resulting in two different novel configurations being presented.

Hysteresis compensation for piezo-actuators is considered for application of proposed schemes. It must be noted that the work focuses on overcoming fundamental limitations of linear DOB through the introduction of reset. Although hysteresis compensation has been chosen as the application example, advancement on this front is not considered. As such, comparison of proposed scheme with advanced compensation schemes tailored for hysteresis compensation of piezo-actuators is not considered. The proposed schemes are only compared with linear DOB to show that the identified fundamental limitations are overcome.

The structure of the paper is as follows. The basics of nonlinear plant with bounded input disturbance and stability criteria of the feedback disturbance observer scheme proposed in Yi et al. (2009) are studied in Section 2, along with limitations of linear approach. The preliminaries of reset control along with design concept of 'Constant-gain Lead-phase' (CgLp) element are explained in Section 3. In Section 4, CgLp is used to present two novel Resetting Disturbance Observer (RDOB) configurations. A simple example plant is used to show that these overcome limitations of linear DOB. In Section 5, hysteresis compensation in piezo-actuator is considered and results from the experimental set-up are provided for validation of proposed RDOB.

2. Nonlinear plant model and linear disturbance observers

A plant having nonlinearities such as hysteresis, creep, or electromagnetic effects can be modelled as a combination of linear plant P and bounded disturbance d depicting the nonlinearities as shown in Fig. 1 (Schrijver & Van Dijk, 2002). The boundedness of disturbance is an important criterion and for instance, hysteretic nonlinearities can be proven to be bounded using Duhem model (Yi et al., 2009). Similarly, other mentioned nonlinear effects can also be proven to follow the bounded input bounded output (BIBO) property and this model holds for any other BIBO nonlinear effects.

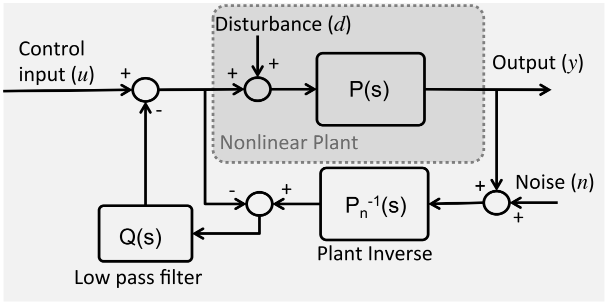

Fig. 1. Disturbance observer architecture.

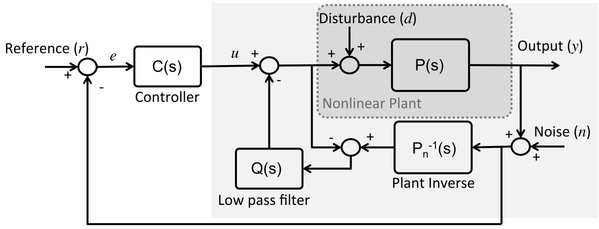

Fig. 2. Full DOB with controller.

Disturbance observer has been proposed in Shahruz (2000) to compensate for large nonlinear effects. This is also capable of suppressing other input/output disturbances and unmodelled dynamics. A good DOB is capable of ensuring that the plant behaves like the nominal linear plant model and this linearization further allows for a relaxation on the robustness constraint of the feedback controller and also enhances the overall performance. The traditional compensation architecture of the disturbance observer as suggested in Schrijver and Van Dijk (2002) is shown in Fig. 1. Here, P_n is the nominal linear model estimate of the plant and Q is the disturbance estimating filter (DEF).

2.1. General required behaviour of Q-filter

The transfer functions from the various inputs u, n, d to output y of the compensated scheme are derived in Schrijver and Van Dijk (2002) as

$$H_{uy} = \frac{PP_n}{Q(P-P_n)+P_n} \tag{1}$$

$$H_{ny} = \frac{PQ}{Q(P-P_n)+P_n} \tag{2}$$

$$H_{dy} = \frac{PP_n(1-Q)}{Q(P-P_n)+P_n} \tag{3}$$

Assuming $P = P_n$

$$H_{uy} = P_n \tag{4}$$

$$H_{ny} = Q \tag{5}$$

$$H_{dy} = P_n(1-Q) \tag{6}$$

In the case of a perfect match as above, H_{uy} is equal to P_n (nominal plant) and hence the feedback controller that is used in conjunction with DOB (see Fig. 2) sees only P_n. In this ideal scenario, DOB and feedback controller C can be designed independently (also known as separation property).

Some required properties of DEF Q can also be ascertained from the above equations. From Eq. (6), complete disturbance rejection requires Q to be as close as possible to unity. However, from Eq. (5), complete noise attenuation requires Q to be as close as possible to zero. These two requirements contradict each other and thereby limit the performance of compensation scheme. In the case under consideration,