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Two-layer observer based control for a class of uncertain systems with multi-frequency disturbances

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ABSTRACT

A novel disturbance estimation approach is presented for a class of uncertain systems subject to multiple-sinusoidal disturbances with unknown frequencies. Different from existing results on disturbance observer based control (DOBC), a new methodology with a two-layer observer structure is developed to effectively estimate and reject the disturbances. In the proposed control architecture, an auxiliary observer is derived to generate a disturbance representation in a parametric uncertainty form. Furthermore, the unknown parameters can be reduced to a constant vector with the dimension of the number of harmonic components in the disturbances. Then an augmented observer is designed to estimate the corresponding unknown parameters of the disturbances. As a result, the uncertain systems with disturbances constituting of multiple unknown-frequency sinusoidal components can be controlled within the DOBC framework, where asymptotic stability can be guaranteed. The proposed approach is successfully validated on a robotic manipulating example.

1. Introduction

Over the past decades, the rejection problem of neutral stable disturbances for nonlinear systems has attracted considerable attentions. Among the many elegant approaches, the disturbance observer based control (DOBC), originated from frequency domain methods for linear systems, has been widely investigated with many successful applications [1–7].

Recently, DOBC has been developed for the cases with uncertain nonlinearities as well as more sophisticated disturbances. Representative results along this line of research include a robust DOBC approach developed in [8] for systems with nonlinearities, and a composite hierarchical anti-disturbance control (CHADC) method can discussed in [9–11]. The readers can be referred to [13–16] and references therein for some recent advances in this area. Note that most existing DOBC approaches for nonlinear systems require the key information (such as frequency) of the disturbances [3,7–12]. It is still an open problem for DOBC design of uncertain nonlinear systems subject to disturbances with unknown frequencies and phases.

For other alternatives, such as output regulation methods and adaptive control approaches, the disturbances governed by exosystems with unknown parameters can be rejected in various situations. For linear systems, adaptive algorithms are proposed to handle multiple sinusoidal disturbances in [17,18]. An adaptive unknown disturbance rejection scheme for nonlinear systems is provided in [19] by a combination of feedforward compensation and an adaptive identification technique. In [20], the authors consider the adaptive regulation problem for linear MIMO systems subject to unknown sinusoidal exogenous inputs. The problem is then extended to the cases of disturbances with the uncertain order of their exosystems [21]. The semiglobal output regulation problem is addressed in [22] for nonlinear systems with unknown parameters in the exosystem using adaptive internal model. Global stabilization and disturbance suppression are achieved in [23] via output feedback with a new formulation of internal model. Output regulation with unknown linear exosystems is discussed in [24] for uncertain nonlinear systems in the output feedback form, where the uncertain part is restricted to a particular form such that the adaptive technique can be designed to identify the unknown parameter. In [25], the uncertain nonlinear systems described in [24] are extended to some bounded function cases, such as polynomial functions.

Although output regulation methods and adaptive compensation approaches have been well deployed with many significant

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theoretical results and successful applications, it is still a challenging topic to develop a feasible anti-disturbance control framework for nonlinear systems with both harmonic disturbances and uncertainties. In our previous work [26], single-frequency sinusoidal disturbances with unknown frequencies are estimated by constructing a generalized two-step observer for a class of multi-input–multi-output (MIMO) nonlinear system. For disturbances with a single frequency, the auxiliary observer can convert the problem to scalar estimation, which cannot be extended directly to the cases of multi-frequency disturbances. In the present paper, our primary motivation is to introduce a two-layer observer structure to excite and capture the disturbance characteristics, where the unknown signal can be represented in an observable form with appropriate coordinate transformation. In the presence of unmodeled dynamics, the proposed two-layer observer structure can be combined with feedback control design approaches to achieve desired control performance.

The rest of the paper is organized as follows. Section 2 describes the anti-disturbance control problem associated with a single-link robotic manipulator model. In Section 3, a two-layer disturbance observer is proposed, and a DOBC controller is designed for the composite systems with both disturbances and uncertainties in Section 4. In Section 5, the proposed method is applied to an example of a robotic manipulator, where numerical simulations demonstrate the advantages of the proposed scheme, followed by concluding remarks in Section 6.

2. Problem formulations

We consider the anti-disturbance control problem of a single-link robotic manipulator represented by the following model:

$$M\ddot{q}+V_m\dot{q}+G(q)=\tau+d \tag{1}$$

where $q\in R$ is the joint angular position, $\tau\in R$ is the torque applied to the joint, M is the bounded positive definite mass (or inertia) term, V_m is the viscous friction coefficient, and $G(q)$ is the gravity term. We suppose that the joint angular position q and the joint angular velocity $\dot{q}$ are measurable. The disturbance term d in (1) is assumed to be a combination of multiple unknown sinusoidal signals represented as:

$$\begin{cases} d=d_1+d_2+\cdots+d_m \\ d_i=\Phi_i\ \sin(\omega_i t+\varphi_i) \end{cases} \tag{2}$$

where $\Phi_i,\omega_i,\varphi_i$ $(i=1,2\ldots m)$ are unknown constant parameters. Therefore the harmonic disturbance in the control input path is multi-sinusoidal signal with unknown amplitudes, phases and frequencies that can be also formulated by the following exogenous system:

$$\begin{cases} \dot{w}=\Gamma w \\ d=Vw \end{cases} \tag{3}$$

where $w\in R^{2m}$, $\Gamma\in R^{2m\times 2m}$ has all its eigenvalues on the imaginary axis, and $V\in R^{1\times 2m}$ is the proper unknown matrix. For simplicity, we denote

$$\Gamma=\begin{bmatrix}\Gamma_1 & 0 & 0\\ 0 & \ddots & 0\\ 0 & 0 & \Gamma_m\end{bmatrix},\quad V=[V_1\ V_2\ \cdots\ V_m] \tag{4}$$

and without loss of generality, suppose that $[\Gamma_i,V_i]$ $(i=1,2\ldots m)$ has observable canonical form described as

$$\Gamma_i=\begin{bmatrix}0 & 1\\ -\omega_i^2 & 0\end{bmatrix},\quad V_i=[1\ \ 0] \tag{5}$$

In this paper we would like to address the problem of rejecting multi-sinusoidal disturbances of unknown parameters for nonlinear uncertain systems. In particular, we consider the uncertainty of (1) obeying

$$h(\dot{q},q):=V_m\dot{q}+G(q)=h_1(\dot{q},q)-\Delta h(\dot{q},q),$$

where $h_1(\dot{q},q)$ and $\Delta h(\dot{q},q)$represent known and uncertainty parts in $h(\dot{q},q)$ respectively. For any pair of $\begin{bmatrix}q\\ \dot{q}\end{bmatrix}$ and $\begin{bmatrix}\overline{q}\\ \dot{\overline{q}}\end{bmatrix}$, the nonlinear uncertain term is supposed to satisfy

$$\begin{cases} \Delta h(0,0)=0 \\ \|[\Delta h(\dot{q},q)-\Delta h(\dot{\overline{q}},\overline{q})]\| \\ \le\left\|\begin{bmatrix}U_{11} & 0\\ 0 & U_{12}\end{bmatrix}\left(\begin{bmatrix}q\\ \dot{q}\end{bmatrix}-\begin{bmatrix}\overline{q}\\ \dot{\overline{q}}\end{bmatrix}\right)\right\| \end{cases} \tag{6}$$

where U_{11} and U_{12} are given constant weighting matrix. Note that the model discussed in the present paper can be easily extended to more general nonlinear systems for anti-disturbance control.

3. Two layer disturbance observer design

The block diagram of proposed strategy can be shown in Fig. 1, where the nominal feedback controller is designed to guarantee stability of the closed loop system in the absence of disturbances. To deal with disturbances with multiple unknown sinusoidal components, a two-layer disturbance observer is introduced constituting of an auxiliary observer and an augmented observer structure. The auxiliary observer yields a disturbance presentation in a parametric uncertainty form, and the augmented observer is constructed to obtain the unknown parameters related to multi-sinusoidal disturbances, with which the disturbance generator provides an estimate of the disturbances according to the relations between ξ, θ_o and d.

3.1. Auxiliary disturbance observer

We first recall some recent results in the literature [3,8,9,7], and notice that the disturbance observer cannot be constructed directly if the information of disturbance frequencies is not available. For the case of single-frequency disturbances, a possible solution, as discussed in [26], can be derived based on a representation of the disturbance by a nonlinear function related to an unknown scalar. The situation of those with multi-frequency disturbances is more complicated because the unknown parameters are now in a vector form, which prevents us from designing disturbance observers based on existing results. In this paper, a novel two layer observer structure is explored to estimate disturbances with multiple unknown frequency components. We start with the following result on a representation of disturbance $d(t)$.

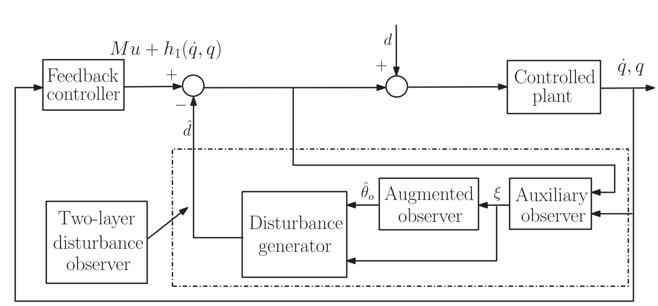

Fig. 1. Block diagram of the proposed control architecture.