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Brief paper

Adaptive input shaping for manoeuvring flexible structures using an algebraic identification technique☆

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ABSTRACT

Input shaping is an efficient feedforward control technique which has motivated a great number of contributions in recent years. Such a technique generates command signals with which manoeuvre flexible structures without exciting their vibration modes. This paper presents a novel adaptive input shaper based on an algebraic non-asymptotic identification. The main characteristic of the algebraic identification in comparison with other identification methods is the short time needed to obtain the system parameters without defining initial conditions. Thus, the proposed adaptive control can update the input shaper during each manoeuvre when large uncertainties are present. Simulations illustrate the performance of the proposed method.

1. Introduction

Applications, such as those of the aerospace industry, have motivated the use of very light weight structures. Their advantages may be an increase in the speed of the system without the need to use large actuators, or a reduction in transport costs, among others. However, when flexible structures are manoeuvred, undesirable vibrations appear at the end of the trajectory. Thus, control systems are included and designed to suppress such vibrations.

Input shaping (IS) is an efficient technique through which to generate command signals that do not excite the flexible vibration modes, whilst the final position is attained without steady-state errors (Singer & Seering, 1990; Smith, 1958). In order to overcome system uncertainties, robust, learning or adaptive input shaping (AIS) approaches have been proposed in recent years. When large variations in the system parameters are present, the use of a Robust IS which is not combined with an adaptive or learning technique might not be appropriate since the duration of the command signal could be excessive (Singhose, Derezinski, and Singer (1996), Singhose, Porter, Tuttle,and Singer (1997), among others). Furthermore, learning IS is not suitable for non-repetitive manoeuvres (Park & Chang, 2001; Park, Chan, Park, & Lee, 2006). AIS should therefore be used in these cases. The performance of AIS depends on the identification procedure used. AIS may, therefore, be developed in the frequency domain (Tzes & Yurkovich, 1993), or in the time domain (Bodson, 1998; Cutforth & Pao, 2004; Rhim & Book, 2001).

Tzes and Yurkovich (1993) use the time-varying transfer function estimation (TTFE) approach to adjust the time intervals of the input shaping impulses on-line. However, TTFE has a high computational load and needs a high number of periods to obtain the system parameters with sufficient precision. This has motivated a great number of more recent approaches in AIS based on time domain identification. Methods developed in the time domain have several limitations such as: the estimation must be carried out after each manoeuvre (Rhim & Book, 2001) or the steady-state position is not guaranteed unless the shaper is updated between manoeuvres (Bodson, 1998). The solution proposed in Cutforth and Pao (2004) presents an AIS technique based on the learning rule expounded in Park and Chang (2001). This AIS can update the shaper during and after the manoeuvres. However, initial conditions must be defined and the adaptation can only take place during one part of the reference signal. Therefore, the utilization of this method for the adaptation of the IS during the manoeuvre when large system uncertainties occur is not appropriate.

In this work, we propose a novel AIS that is able to update the IS during the manoeuvre and is robust to large system

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uncertainties before each manoeuvre. In order to update the IS, the new controller parameters are calculated from the identification of the natural frequency and the damping ratio of the system. Such an identification is carried out by a non-asymptotic algebraic estimator developed in continuous time. This method is used for fast constant parameter identification, state estimation in feedback control systems and signal processing problems (see Fliess, Join, and Sira-Ramírez (2008) and Fliess and Sira-Ramírez (2008)). The main advantages of the algebraic estimator for the proposed application are (see Chapter 3 of Fliess and Sira-Ramírez (2008)): (a) it works on-line and it is able to achieve an estimation in a time which is less than half the period of that of the vibration mode; and (b) it does not require any assumption concerning the statistical distribution of the unstructured noise.

This paper presents an AIS for a damped flexible system with a single dominant vibration mode. In Section 2, the dynamic model assumed in this work is presented. In Section 3, the AIS control scheme is explained. In Section 4, the deduction of an algebraic estimator for a system with a single dominant vibration mode is expounded. Section 5 includes two examples of applications with which to illustrate the performance of this AIS approach. Finally, some conclusions and suggestions for future works are given in Section 6.

2. System model

The system model considered in this paper is a second order system with the following transfer function

$$\frac{Y(s)}{U_c(s)} = \frac{K_f\omega_f^2}{s^2 + 2\xi_f\omega_f s + \omega_f^2}, \tag{1}$$

where $Y(s)$ is the output, $U_c(s)$ is the input, ξ_f is the damping ratio, ω_f is the natural frequency, and K_f is the gain of the system. The assumed model can be used in the following situations: (1) when the system response is essentially governed by one vibration mode; (2) when the rigid-body motion and the other significant vibration modes can be suppressed by a filter; and (3) when the input and output of the model are chosen in order to isolate the rigid-body motion and suppress the other significant vibration modes.

3. Control strategy

The proposed AIS control scheme contains a robust IS, an algebraic estimator with which to obtain ω_f and ξ_f from $u_c(t)$ and $y(t)$ and a criterion to update the robust IS parameters (see Fig. 1). A prior knowledge of the system model is needed to design the robust IS, whose time control can be minimized once the uncertainty in ω_f and ξ_f are known (Pao & Singhose, 1998). The time control of any robust IS can be decreased by combining it with the AIS technique. The decrement in time control achieved by the proposed AIS is tested in this paper with a robust IS designed through the use of the so-called derivative method of a zero vibration (ZV), which can be written as

$$C(s) = \left(\frac{1+z\mathrm{e}^{-sD}}{1+z}\right)^p, \tag{2}$$

where $z = \mathrm{e}^{-\xi_f\pi/\sqrt{1-\xi_f^2}}$, $D = \pi/\omega_f\sqrt{1-\xi_f^2}$, and p is a design parameter which increases the controller robustness. Note that, $p = 1$ corresponds to a ZV IS, $p = 2$ is equivalent to zero vibration and derivative (ZVD) IS, and so on (Singer and Seering (1990), for example).

In order to explain the control strategy, let us define the unshaped input as $u(t) = u_1(t) + u_2(t) + \cdots + u_m(t)$, where each

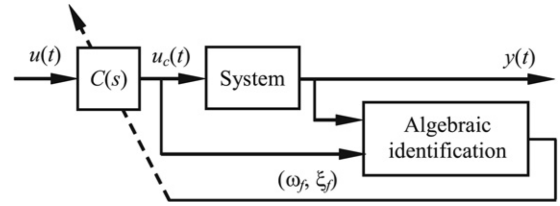

Fig. 1. Control scheme of the AIS.

manoeuvre can be expressed as $u_i = (1(t-T_{i-1}) - 1(t-T_i))u(t)$. The values of T_{i-1} and T_i are the instants in time at which each manoeuvre starts and finishes respectively, and $1(t)$ is a unit step. The shaped command is calculated by $u_c(t) = u_{c1}(t) + u_{c2}(t) + \cdots + u_{cm}(t)$, where each $u_{ci}(t)$ is obtained with a different IS as follows

$$U_{ci}(s) = U_i(s)C_i(s) = U_i(s)\left(\frac{1+z_i\mathrm{e}^{-sD_i}}{1+z_i}\right)^{p_i}. \tag{3}$$

During each manoeuvre, the proposed AIS: (a) fixes the value of p_i and z_i in T_{i-1}, (b) estimates ω_f and ξ_f during the manoeuvre, (c) updates D_i before $T_{i-1} + D_i$ and (d) calculates z_{i+1} for the next manoeuvre. The value of each p_i depends on the expected estimation error of ω_f and ξ_f. As will be seen in Sections 4 and 5, the performance of the estimation, which allows us to obtain ω_f and ξ_f before $T_{i-1} + D_i$ with a sufficient precision, depends on the SNR of the measured signals.

4. Algebraic identification

The objective of this section is to identify the parameters of Eq. (1) which are needed to update each IS defined by Eq. (3). The proposed estimator considers a constant value of K_f. Note that this consideration can be assumed in many real applications, such as single-link flexible manipulators. If one vibration mode is considered and the input and the output of the estimator are the joint and the tip angle respectively, Eq. (1) with a constant value of $K_f = 1$ can be considered as a system model (see Feliu and Ramos (2005), e.g.). The algebraic estimator with which to identify the values of ω_f and ξ_f is explained as follows. The following manipulations, which are based on operational calculus (see Mikusinski and Boehme (1987), e.g.), describe how the algebraic method works.

4.1. Noise free case

In order to make the deduction of the estimator equations more understandable, we first assume that signals are noise free. Consider Eq. (1) when expressed as a second order differential equation

$$\ddot{y}(t) + 2\xi_f\omega_f\dot{y}(t) + \omega_f^2 y(t) = K_f\omega_f^2 u_c(t). \tag{4}$$

The Laplace Transform of (4) is given by

$$s^2Y(s) - sy(0) - \dot{y}(0) + \alpha_1(sY(s) - y(0)) + \alpha_2(Y(s) - K_fU_c(s)) = 0. \tag{5}$$

It is quite straightforward to verify that

$$\xi_{f,est} = \frac{\alpha_1}{2\sqrt{\alpha_2}}, \qquad \omega_{f,est} = +\sqrt{\alpha_2}, \tag{6}$$

where $\omega_{f,est}$ and $\xi_{f,est}$ are the estimated values of ω_f and ξ_f. According to Fliess, Mboup, Mounier, and Sira-Ramírez (2003), this system is weakly identifiable since the unknown parameters can be made available through algebraic manipulations. Most estimation algorithms encounter the problem of setting the values