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An Adaptive Control Approach for Improving Control Systems with Unknown Backlash

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Abstract

Backlash is common in mechanical and hydraulic systems and severely limits overall system performance. In this paper, the development of an adaptive control scheme for systems with unknown backlash is presented. An adaptive backlash inverse based controller is applied to a plant that has an unknown backlash in its input. The harmful effects of backlash are presented. Compensation for backlash by adding a discrete adaptive backlash inverse structure and the gradient-type adaptive algorithm, which provides the estimated backlash parameters, are also presented. The supposed adaptive backlash control algorithms are applied to an aircraft with unknown backlash in the actuator of control surfaces. Simulation results show that the proposed compensation scheme improves the tracking performance of systems with backlash.

Key words: Adaptive control, Actuator nonlinearities, Backlash, Backlash inverse

1. Introduction

Actuator devices contain nonlinearities such as friction, dead-zone, saturation, backlash, and hysteresis. Many of these nonlinearities are not continuous, but rather discontinuous functions or even dynamic models. Backlash is a dynamic nonlinearity and is common in mechanical and hydraulic systems. The undesirable effects of backlash are the main factors that severely limit the performance of feedback systems.

These undesirable effects consist of non-differentiable nonlinearities and include the decrease of static output accuracy, poor transient performance, limit cycles, and instability (Santos and Vieira, 2008; Slotine and Li, 1991; Tao and Kokotovic, 1993; Tao and Kokotovic, 1996).

Mechanical solutions such as spring loaded split gear assemblies and dual motor systems can satisfactorily handle the backlash problem. However, they are expensive, energy consuming, and increase the weight of the system. Therefore, it is desirable to find ways to achieve backlash compensation without such mechanical devices.

A commonly used approach to cancel the harmful effects of nonlinearities is the implementation of their inverse characteristics into the controller structure. A compensated inverse dynamics approach using adaptive and robust control techniques is presented in Song et al. (1994). A backlash compensation system using dynamic inversion is described in Selmic and Lewis (2001).

A backlash inverse is used to reduce the harmful effects of the backlash in this paper. The parameter values of the backlash inverse are crucial to the control performance and, as such, they need to be estimated if the backlash is unknown or varies with time.

This paper is organized as follows: Section 2 presents the backlash compensation, that is, the backlash model and its inverse as well as the adaptive backlash inverse. Section 3 introduces the adaptive backlash inverse control model, the controller structure, and the applied adaptive law. Section 4

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analyzes the performance of our adaptive control approach through a numerical example and Section 5 presents the conclusions of this work.

2. Backlash Compensation

2.1 Backlash model

In contrast to the memoryless dead-zone, backlash has an element of memory and is dynamic. A widely accepted characteristic of backlash is shown Fig. 1, where $v(t)$ is the input, $u(t)$ is the output, and c_r>0 is the right "crossing," while c_l>0 is the left "crossing" (Tao and Kokotovic, 1996). Typically, the concept of backlash is associated with gear trains as the schematic representation of backlash, as shown in Fig. 1b.

The upward side is active when both $v(t)$ and $u(t)$ increase:

$u(t) = m(v(t)-c_r)$, $\dot{v}(t)>0$, $\dot{u}(t)>0$

The downward side is active when both $v(t)$ and $u(t)$ decrease:

$u(t) = m(v(t)-c_r)$, $\dot{v}(t)<0$, $\dot{u}(t)<0$

where m>0, $c_l<C_r$ are constant parameters. The motion on any inner segment is characterized by $\dot{u}(t) = 0$. A compact description of the continuous-time version of the backlash $B(\bullet)$ is given in Eq.(1)

$$\dot{u}(t) = \begin{cases} m\dot{v}(t)\ if\ \dot{v}(t) > 0\ and\ u(t) = m(v(t) - c_r)\ ,or \\ \quad if\ \dot{v}(t) < 0\ and\ u(t) = m(v(t) - c_l) \\ \quad 0\ \ otherwise \end{cases} \tag{1}$$

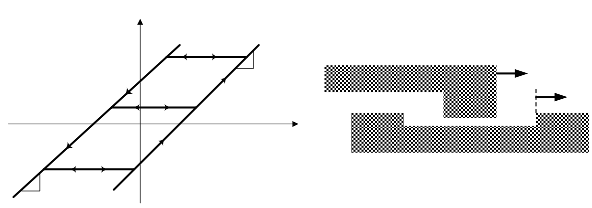

Fig. 1. (a) Backlash model, (b) Schematic representation.

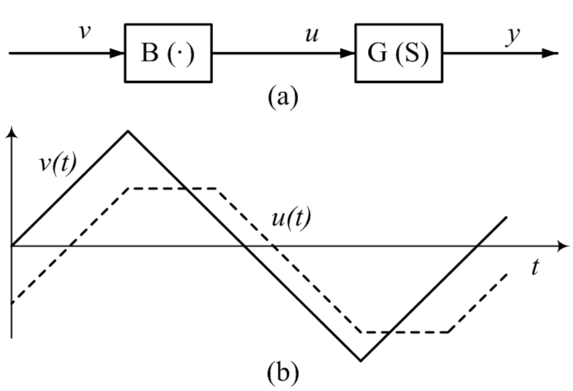

Fig. 2. Backlash response to a saw-tooth input.

The discrete-time version of the backlash model is also easy to visualize, as shown below:

$$v_l = \frac{u(t-1)}{m} + c_l,\ \ v_r = \frac{u(t-1)}{m} + c_r \tag{2}$$

$$u(t) = B(v(t)) = \begin{cases} m(v(t) - c_l) & if\ v(t) \le v_l \\ m(v(t) - c_r) & if\ v(t) \ge v_r \\ u(t-1) & if\ v_l < v(t) < v_r \end{cases} \tag{3}$$

where the values v_l and v_r are the v-axis projections of the intersections of the two parallel lines of slope m with the horizontal inner segment containing $u(t\text{-}1)$ (Tao and Kokotovic, 1996).

A further insight into the nature of backlash can be gained from the waveform of the output $u(t)$ when the input $v(t)$ is the saw-tooth signal in Fig. 2.

2.2 Backlash inverse model

The desired function of a backlash inverse is to cancel the harmful effects of backlash on system performance. The ideal backlash inverse $BI(\bullet)$ will make the traverse of this segment instantaneous and thus cancel this undesirable

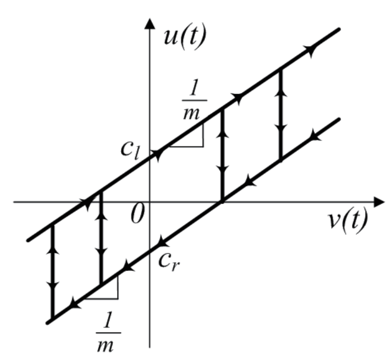

Fig. 3. Backlash inverse model.

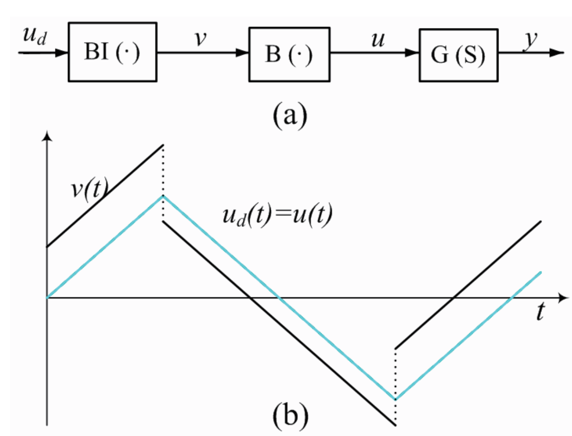

Fig. 4. Backlash inverse response to a saw-tooth input.

backlash effect, as shown in Fig. 3. That is, given a desired signal $u_d(t)$ for $u(t)$, a backlash inverse $BI(\bullet)$ is such that $u_d(t) = B(BI(u_d(t)))$ as shown in Fig. 4.

The discrete-time model of the backlash inverse is represented by the following mapping:

$$v(t) = BI(u_d(t)) = \begin{cases} v(t-1) \; if \; u_d(t) = u_d(t-1) \\ \frac{u_d(t)}{m} + c_l \; if \; u_d(t) < u_d(t-1) \\ \frac{u_d(t)}{m} + c_r \; if \; u_d(t) > u_d(t-1) \end{cases} \quad (4)$$

In this paper, the continuous-time version of the backlash inverse model is not shown. This is because the discrete-time version has the following advantages. The discrete-time backlash inverse does not require knowledge of $sign(\dot{u}_d(t))$ for implementation. This makes a discrete-time adaptive inverse controller more practical than a continuous-time adaptive controller, because such signal derivative knowledge is often unavailable in applications. In addition, modern control systems are most frequently implemented with digital controllers so that a discrete-time treatment is closer to actual practice (Tao and Kokotovic, 1996).

2.3 Adaptive Backlash inverse

The backlash inverse $BI(\bullet)$ defined by Eq. (4) can be approximated by replacing the vertical jumps between its upward and downward lines by continuous curves with bounded gains. When the backlash parameters m, c_l, c_r are unknown, we can use their estimates $\hat{m}, \hat{c}_r, \hat{c}_l$ to design a backlash inverse estimate: $v(t) = \widehat{BI}(u_d(t))$, characterized by

$$v(t) = \widehat{BI}(u_d(t)) = \begin{cases} v(t-1) \;\; if \; u_d(t) = u_d(t-1) \\ \frac{u_d(t)}{\hat{m}} + \hat{c}_l \; if \; u_d(t) < u_d(t-1) \\ \frac{u_d(t)}{\hat{m}} + \hat{c}_r \; if \; u_d(t) > u_d(t-1) \end{cases} \quad (5)$$

In the next section, we use an adaptive backlash inverse $BI(\bullet)$ as part of the proposed adaptive control algorithm for plants with an unknown backlash $B(\bullet)$.

3. Adaptive Backlash Inverse Control

3.1 Discrete-time adaptive Backlash inverse

In this section, the adaptive backlash inverse control structure and the applied adaptive law are presented. The goal of this section is to design a discrete-time adaptive backlash inverse controller to achieve asymptotic tracking, despite the presence of backlash.

Let us consider a plant whose linear part is $G(s) = k_p / s$, where k_p is a known constant, assuming that the backlash slope $m>0$ is known, but its width is unknown. The linear part of the plant in discrete-time is given by:

$$y(t+1) = y(t) + u(t) \quad (6)$$

In the absence of backlash, our design objective to stabilize the closed loop system and make the plant output $y(t)$ track a given reference signal $y_m(t)$ may be achieved by the controller:

$$u_d(t) = -y(t) + y_m(t+1) \quad (7)$$

In the presence of backlash we use this controller along with an adaptive scheme designed to update the backlash inverse $v(t) = \widehat{BI}(u_d(t))$ on-line, as shown in Fig. 5.

Since, by assumption, m is known and $c_r = -c_l = c$, we let $\hat{m}(t) = m$ and $\widehat{mc_l}(t) = -\widehat{mc_r}(t) = \widehat{mc}(t)$ and introduce:

$$\phi(t) = \theta(t) - \theta^*, \;\; \theta(t) = \widehat{mc}(t), \;\; \theta^* = mc \quad (8)$$

As such, the backlash inverse error equation becomes:

$$u(t) - u_d(t) = \phi(t)\omega(t) + d_b(t) \quad (9)$$

where $\omega(t) = \widehat{\chi_r}(t) - \widehat{\chi_l}(t)$ is the regressor.

For the tracking error, $e(t) = y(t) - y_m(t)$, from Eq. (6) –(8), we obtain the expression:

$$e(t) = \theta(t-1)\omega(t-1) - \theta^*\omega(t-1) + d_b(t-1) \quad (10)$$

An important quantity for use in the discrete-time adaptive law is the estimation error, defined as:

$$\varepsilon(t) = e(t) + \theta(t)\omega(t-1) - \theta(t-1)\omega(t-1) \quad (11)$$

Using Eq. (11), our update law for $\theta(t)$ based on the gradient-type algorithm is:

$$\theta(t+1) = \theta(t) - \frac{\gamma\omega(t-1)\varepsilon(t)}{1+\omega^2(t-1)} + f(t), 0 < \gamma < 2 \quad (12)$$

where γ is the constant gain and the modifying term $f(t)$ is found by:

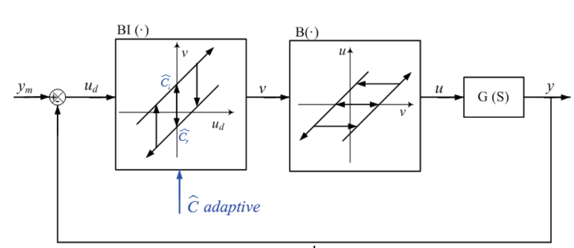

Fig. 5. Adaptive backlash compensation scheme.

$$f(t)=\begin{cases}0 & \text{if } \theta(t)+g(t)\in[\theta^a,\theta^b]\\ \theta^b-\theta(t)-g(t) & \text{if } \theta(t)+g(t)>\theta^b\\ \theta^a-\theta(t)-g(t) & \text{if } \theta(t)+g(t)<\theta^a\end{cases} \quad (13)$$

$$g(t)=-\frac{\gamma\omega(t-1)\varepsilon(t)}{1+\omega^2(t-1)} \quad (14)$$

with the constants θ^a, θ^b being the lower and upper bounds of the known backlash parameter $\theta^* = mc$: $\theta^a \le mc \le \theta^b$. These are determined from a priori knowledge of mc. A natural constant is that $\theta^a>0$ since $mc\ge 0$. This projection $\theta(t)$ of ensures that $\widehat{mc}(t)\ge 0$.

A detailed proof of this is given by Tao and Kokotovic (Tao and Kokotovic, 1996), along with the stability and tracking properties of the closed loop system.

4. Numerical Example

It can be seen that some aircraft experience limit cycle oscillations (LCOs) related to actuator nonlinearities (Mattos, 2008; Ross et al., 1979). This LCO of aircraft limits the performance of feedback systems and degrades aircraft handling qualities. Therefore, it can be seen as advantageous to eliminate such oscillations. One of the actuator nonlinearities, backlash, can also induce limit cycles and instability (Slotine and Li, 1991). According to Mattos (Mattos, 2008) the adaptive controller is designed to eliminate small amplitude, self induced oscillations due to actuator nonlinearities of Russian Su-37 aircraft.

This section presents the numerical example of the aircraft showing limit cycles and actuator nonlinearity in flight in order to show the effectiveness of the proposed adaptive backlash algorithms. Figure 6 shows the I/O of the actuator, which is the relation between control command and the deflection of control surface based on the flight data.

The backlash characteristics of the aircraft shown in Fig. 6 are similar to those shown in Fig. 1. These characteristics appear only in the specific aircraft and limited flight envelope as a form of LCO. The magnitudes and flight conditions are intentionally not included. We insert the backlash model in the horizontal tail actuator of the linear longitudinal model in order to compare the flight data and review the possibility of adaptive backlash compensation. Figure 7 shows the aircraft response when backlash is applied. The parameters of unknown backlash $B(\bullet)$ are selected as follows, $m=1$, $c_l=-0.08$, $c_r=0.08$.

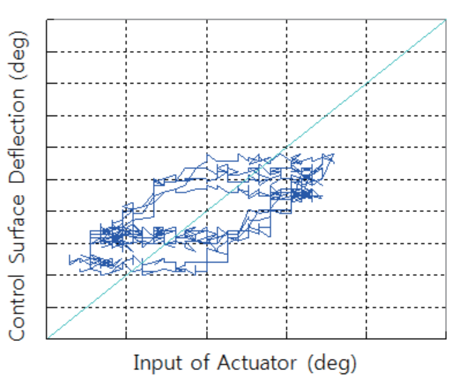

Fig. 6. Flight data input of actuator vs. control surface deflection.

In order to eliminate the above harmful effects of backlash, we first apply the backlash inverse to the fixed type, not the adaptive type. This is because the signal, which is needed for the error equation for adaptive control from the aft backlash, cannot be used directly in a real aircraft control system.

The detailed parameters of the fixed backlash inverse are as follows, $m = 1$, $c_l = -0.04$, $c_r = 0.04$. The differences of parameters between the backlash and the fixed backlash inverse are identified as the backlash model error and the variances from aircrafts and time. Figure 8 shows the aircraft response with the above backlash and the fixed backlash inverse.

To eliminate the effects of backlash model error and the variances from aircrafts and time, we apply the adaptive backlash inverse algorithm presented in Section 3. The constant gain, γ of adaptive law is selected as 0.56. The signal aft backlash for adaptive law is satisfied of the purpose of this study directly. Further study are ongoing to generate the error equation using the difference of aircraft responses between the reference aircraft and the real aircraft. Fig. 9 shows the aircraft response when both backlashes are applied with the adaptive backlash inverse.

It can be seen from the adaptive inverse examples that the backlash inverse parameters approximately reach the same values of the backlash parameters, once the difference between them converge to zero.

5. Conclusions

The characteristic of backlash, the mathematical model, and the backlash inducing LCO mechanism are presented in this paper. Feasibility is shown by comparison with flight data. A discrete-time adaptive backlash inverse based controller is developed for an aircraft that has an unknown backlash at its input. We verify through simulations that the backlash inverse parameter values reach the backlash parameter values in a short time interval. This means that an adaptive inverse can cancel the effect of an unknown nonlinearity, and thus improve system tracking performance.

As a future project, we intend to augment the adaptive state

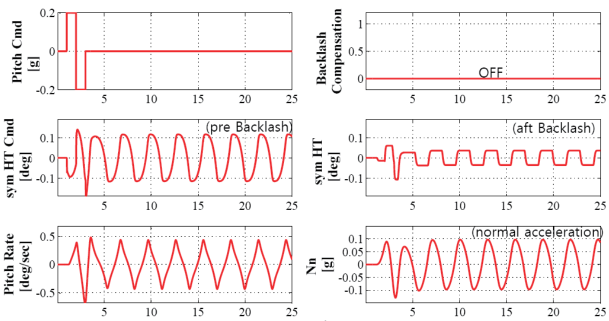

Fig. 7. Aircraft response when backlash is applied in horizontal tail actuator.

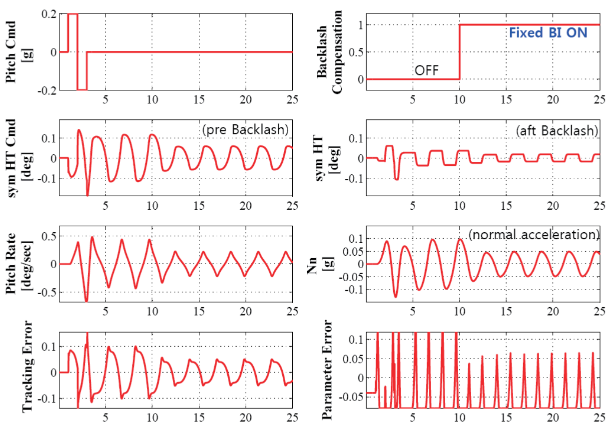

Fig. 8. Aircraft response both backlash are applied with fixed backlash inverse.

feedback control based on neural networks to the actuator nonlinearities of an aircraft. This approach is expected to be flexible with regard to various actuator nonlinearities.

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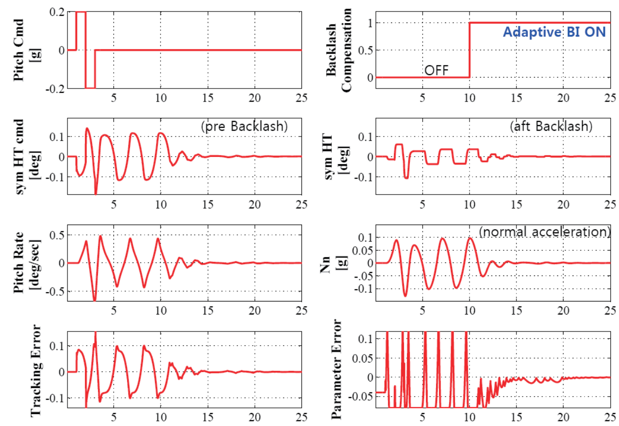

Fig. 9. Aircraft response when both backlash are applied with adaptive backlash inverse.

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