Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Paper Path Detection in Ink Jet Printers by Using Speed Perturbation Observer

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Abstract: As the speed of paper feeding processes in an ink jet printer is increased, the paper feeding mechanisms are usually prone to induce some paper transport problems such as paper jamming and slipping, and some mechanical problems such as gear cracking and chattering. Therefore, for ensuring printing qualities and for preventing destructive damages, the paper path detection in ink jet printers is required. In this paper, we explore the feasibility of using speed perturbation observer to detect paper path situations in an ink jet printer. Moreover, in comparing with the existing approaches, this paper presents an approach without additional sensors. The speed perturbation observer composed of a nominal plant, a low-pass filter, and an identification unit is developed to detect paper path situations during paper feeding processes. The design concept is based on the fact that external disturbances usually significantly affect the speed performances of an axial motion system. Since the paper feeding processes in ink jet printers are equivalent to that the interaction among paper and paper feeding mechanisms exerts external disturbances on the driven motor, it is interesting to detect paper path situations by estimating speed perturbations induced by different paper feeding actions. The proposed approach is implemented on an ink jet printer and two usual paper path situations are tested. The experimental results demonstrate that the proposed approach can accurately respond to the different paper path situations caused by different paper feeding actions.

1. INTRODUCTION

Ink jet printers are widely used in our living environment. However, as ink jet printers operate under higher speeds, the paper feeding mechanisms are usually more prone to induce some problems. Although well-designed paper feeding mechanisms (Kim and Cha, 2004; Koo et al., 1998) and well-controlled paper feeding systems (Bukkems et al., 2006; Sanchez et al., 2004; Krucinski et al., 1998) can provide reliable and stable paper feeding processes, some problems may occur and limit the running performances for a long period using an ink jet printer including paper sticking, jamming, and slipping. Some mechanical factors may also provide adverse effects on paper feeding processes including gear cracking, chattering, and wearing. Therefore, it is important to detect paper path situations during paper feeding processes for ensuring printing qualities and for preventing destructive damages.

Some researchers have proposed several approaches that can be applied to detect paper path situations in ink jet printers. Zhao et al. (2005) proposed a model-based monitoring and fault diagnosis method to efficiently detect and isolate incipient and abrupt faults in paper printing machines. In addition to the built-in sensors, audio and current sensors are deployed to detect fourteen paper path situations including paper jamming, paper slipping, gear cracking, and so on. Although the experimental results validate their approach, many sensors deployed for detecting paper path situations increases the production cost of an ink jet printer. Fung et al. (2002) proposed a fault detection method to detect cartridge situations in ink jet printers by applying neural networks and the motor fault detection scheme proposed by the authors. Although their approach can be applied to detect different paper path situations in ink jet printers, the computation complexity of neural networks makes their approach difficult to be implemented on an embedded system with limited computation resources. In practice, many sensors are usually added to paper feeding mechanisms for sensing and detecting paper path situations (Ishikawa, 1998; Chen and Chen, 2005). However, those approaches may have some problems including:

- one sensor usually detects only one paper path situation in real applications;
- many sensors in an ink jet printer substantially increase the production cost;
- the setup of sensors increases the design complexity of paper feeding mechanisms;
- many sensors usually increase the difficulty in maintaining an ink jet printer.

Therefore, it is desired to design a paper path detection method that uses few sensors and has little computation complexity. In this paper, based on the following two facts:

- external disturbances usually significantly affect the speed performances of an axial motion system; and

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10.3182/20080706-5-KR-1001.0931

- the paper feeding processes in an ink jet printer are equivalent to that the interaction among paper and paper feeding mechanisms exerts external disturbances on the driven motor,

the speed perturbation observer is designed to detect different paper path situations induced by different paper feeding actions.

The design of the speed perturbation observer is derived from the design of the torque disturbance observer. In recent years, the disturbance observer is widely applied to motion control systems for observing and compensating perturbations caused by external disturbances. Katsura et al. (2005a, 2005b) proposed the acceleration-based control with a disturbance observer such that the force servoing and the position regulator can be integrated in the acceleration control loop for developing a medical forceps system. Yasui et al. (2005) proposed an adaptive disturbance observer design such that the engine system provides accurate and rapid speed control under all engine conditions. Yeh and Hsu (2004) proposed the perfectly matched feedback control design with a digital disturbance observer for improving the contouring accuracy of multi-axis motion control systems. However, some problems still exist on the realization of a disturbance observer on an ink jet printer.

The first problem in implementing the disturbance observer is the need of acceleration signal. In the present research, the acceleration signal is obtained from the double differentiation of the position signal. However, the double differentiation operator usually generates considerable noise superimposed on the acceleration signal, and a low-pass filter with narrow bandwidth is thus required for noise attenuation. The low-pass filter with narrow bandwidth not only slows down the estimation of external disturbances but also deteriorates the transient robustness of control systems. The second problem in implementing the disturbance observer is the need of an inverse nominal plant model. An inverse nominal plant model is generally required to precisely estimate external torque disturbances, and the continuous-time to discrete-time transformation methods must be applied to implement the disturbance observer on digital control systems. However, since the transformed inverse nominal plant model is usually with unstable poles if the continuous-time to discrete-time transformation is applied with improper sampling time (Astrom et al., 1984), the observer may lead to unstable computation in the applied digital control systems. Thirdly, to precisely estimate the external torque disturbances, a current sensor is usually required in implementing the disturbance observer on an inkjet printer, and this requirement may increase the production cost.

Thus, in contrast with the torque disturbance observer, for implementing an observer on an ink jet printer to detect paper path situations, this paper presents the design of the speed perturbation observer by considering the speed model of an axial motion system. In comparing with the disturbance observer design, the speed perturbation observer design uses the speed signal obtained from the single differentiation of position signal. Although the single differentiation operator generates noise superimposed on the speed signal, a conventional low-pass filter is applied to attenuate noise perturbations. The low-pass filter with suitable bandwidth provides good observing results and maintains the transient robustness of motion control systems. Moreover, the speed perturbation observer design does not use an inverse nominal plant model that may cause unstable computation in digital control systems. Because it is not required to precisely estimate the external torque disturbances in our approach, the speed perturbation observer does not use current sensor. Besides, since specific paper path situation usually exhibits some specific features on the observed perturbation signal, by using feature extraction and recognition algorithms, the identification unit included in the speed perturbation observer is developed to identify different paper path situations. Experimental results on an ink jet printer demonstrate that the proposed approach can successfully identify paper jamming and mechanical chattering situations during paper feeding processes without additional sensors.

This paper is organized as follows. Section 2 presents the design of the speed perturbation observer, and Section 3 details the design considerations. Section 4 demonstrates the proposed approach on an ink jet printer. Section 5 concludes this paper.

2. DESIGN OF SPEED PERTURBATION OBSERVER

Based on the speed model of an axial motion system, the speed perturbation observer is designed as shown in Fig. 1. T is the sampling time. $G(s)$ is the controlled plant model with equivalent inertia J and equivalent viscous friction coefficient B. $u^*(t)$ is the discrete driving force with uniform interval of T second. $\tau(t)$ is the torque command for the applied permanent-magnet direct-current (PMDC) motor. It's also the output signal of the zero-order hold $H(s)$ with input signal $u^*(t)$. $\tau_d(t)$ is the torque disturbance. Signals $w(t)$ and $\theta(t)$ are the rotating speed and the angular position of the applied PMDC motor, respectively. $\delta^*(t)$ is the measurement noise. $v^*(t)$ is the sampled rotating speed of the applied PMDC motor, and it usually contains the measurement noise $\delta^*(t)$. $d^*(t)$ is the estimated perturbation signal. $\hat{d}^*(t)$ is the filtered perturbation signal. It's also the output signal of the low-pass filter $LPF(z^{-1})$ with input signal $d^*(t)$. $GH(z^{-1})$ is an infinite impulse response (IIR) filter and it is also the z-transform of $[G(s)H(s)]^*$ (Kuo, 1992). Moreover, in the following paragraph, symbols $U^*(s)$, $T(s)$, $T_d(s)$, $W(s)$, $\Delta^*(s)$, $V^*(s)$, $D^*(s)$, and $\hat{D}^*(s)$ represent the Laplace transform of signals $u^*(t)$, $\tau(t)$, $\tau_d(t)$, $w(t)$, $\delta^*(t)$, $v^*(t)$, $d^*(t)$, and $\hat{d}^*(t)$, respectively.

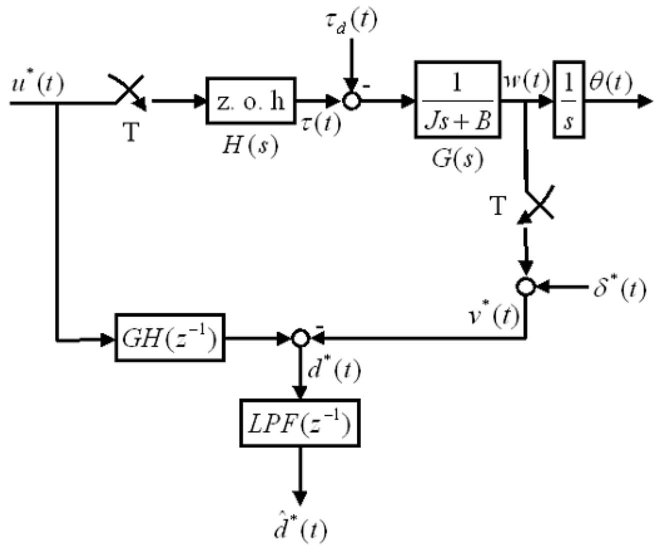

Fig. 1. Structure of the speed perturbation observer

By applying the speed perturbation observer as shown in Fig. 1, the estimated perturbation signal can be derived as

$$D(z^{-1}) = GT_d(z^{-1}) - \Delta(z^{-1}) \quad (1)$$

where $D(z^{-1})$, $GT_d(z^{-1})$, and $\Delta(z^{-1})$ are the z-transform of $D^*(s)$, $[G(s)T_d(s)]^*$, and $\Delta^*(s)$, respectively. Eq. (1) denotes the estimated perturbation signal $d^*(t)$ contains the filtered disturbance $GT_d(z^{-1})$ and measurement noise $\delta^*(t)$. Suppose the measurement noise $\delta^*(t)$ is high frequency noise, and the low-pass filter $LPF(z^{-1})$ is applied to degrade the adverse effects caused by measurement noise, the filtered perturbation signal is thus obtained as

$$\hat{D}(z^{-1}) = LPF(z^{-1})GT_d(z^{-1}) - LPF(z^{-1})\Delta(z^{-1}) \quad (2)$$

where $\hat{D}(z^{-1})$ is the z-transform of the signal $\hat{d}^*(t)$. For low-pass filter designed with suitable cutoff frequency, Eq. (2) can be rewritten as

$$\hat{D}(z^{-1}) \cong LPF(z^{-1})GT_d(z^{-1}) \quad (3)$$

Clearly, Eq. (3) denotes that the signal $\hat{d}^*(t)$ can be represented as the output signal of an equivalent system with input signal $\tau_d(t)$. Fig. 2 shows the equivalent system of Eq. (3), and it also shows that the filtered perturbation signal $\hat{d}^*(t)$ can respond to the perturbation speed induced by the external disturbance $\tau_d(t)$. Since the paper feeding processes in an ink jet printer are equivalent to that the interaction among paper and paper feeding mechanisms exerts different external disturbances on the applied PMDC motor, the speed perturbation observer shown in Fig. 1 can be used to detect different paper path situations.

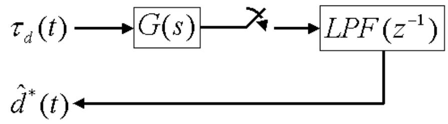

Fig. 2. The equivalent system with input signal $\tau_d(t)$ and output signal $\hat{d}^*(t)$

3. DESIGN CONSIDERATIONS OF SPEED PERTURBATION OBSERVER

3.1 Modeling Error Analysis

As shown in Fig. 1, in order to make the filtered perturbation signal $\hat{d}^*(t)$ can exactly respond to the perturbation speed induced by the external disturbance $\tau_d(t)$, the IIR filter $GH(z^{-1})$ should be the z-transform of $[G(s)H(s)]^*$. However, the controlled plant model $G(s)$ is usually unknown in advance, and thus we must replace the filter $GH(z^{-1})$ with the nominal filter $G_nH(z^{-1})$ in the design of the speed perturbation observer. The IIR filter $G_nH(z^{-1})$ is the z-transform of $[G_n(s)H(s)]^*$, and $G_n(s)$ is the nominal plant model. By replacing the filter $GH(z^{-1})$ with the nominal filter $G_nH(z^{-1})$, the estimated perturbation signal $D(z^{-1})$ becomes

$$\begin{aligned} D(z^{-1}) = &\left[G_nH(z^{-1}) - GH(z^{-1})\right]U(z^{-1}) \\ &+ GT_d(z^{-1}) - \Delta(z^{-1}) \end{aligned} \quad (4)$$

Eq. (4) shows that Eq. (1) is obtained when the nominal plant model $G_n(s)$ is exactly the same as the controlled plant model $G(s)$. By applying the low-pass filter $LPF(z^{-1})$ as shown in Fig. 1, the filtered perturbation signal is obtained as

$$\begin{aligned} \hat{D}(z^{-1}) = &LPF(z^{-1})\left[G_nH(z^{-1}) - GH(z^{-1})\right]U(z^{-1}) \\ &+ LPF(z^{-1})GT_d(z^{-1}) - LPF(z^{-1})\Delta(z^{-1}) \end{aligned} \quad (5)$$

For low-pass filter designed with suitable cutoff frequency, Eq. (5) can be rewritten as

$$\begin{aligned} \hat{D}(z^{-1}) \cong &LPF(z^{-1})\left[G_nH(z^{-1}) - GH(z^{-1})\right]U(z^{-1}) \\ &+ LPF(z^{-1})GT_d(z^{-1}) \end{aligned} \quad (6)$$

Define the uncertainty function $P_e(z^{-1})$ as

$$P_e(z^{-1}) = LPF(z^{-1})\left[G_nH(z^{-1}) - GH(z^{-1})\right] \quad (7)$$

Eq. (6) can be rewritten as

$$\hat{D}(z^{-1}) \cong P_e(z^{-1})U(z^{-1}) + LPF(z^{-1})GT_d(z^{-1}) \quad (8)$$

Based on the equivalent system as shown in Fig. 2, the modified equivalent system of Eq. (8) is shown as Fig. 3.

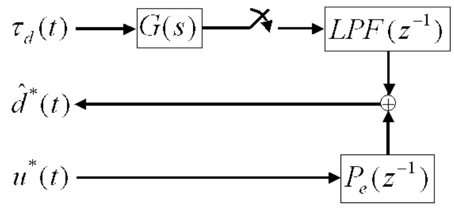

Fig. 3. The modified equivalent system

Clearly, the uncertainty function $P_e(z^{-1})$ is induced by the modeling error $[G_nH(z^{-1})-GH(z^{-1})]$, and it usually affects the filtered perturbation signal such that the observer can not exactly respond to the perturbation speed induced by the external disturbance $\tau_d(t)$. However, because the frequency response of the modeling error $[G_nH(z^{-1})-GH(z^{-1})]$ is usually in high frequency range, the adverse effects caused by modeling error can be reduced by applying the low-pass filter $LPF(z^{-1})$ with suitable design of cut-off frequency.

3.2 The Low-Pass Filter Design

Similar to the torque disturbance observer, the low-pass filter $LPF(z^{-1})$ is the central in the design of the speed perturbation observer. As shown in Fig. 1, the main concern in designing the low-pass filter $LPF(z^{-1})$ is for reducing the adverse effects caused by measurement noise. However, referring to the modified equivalent system as shown in Fig. 3, if the frequency response of the modeling error $[G_nH(z^{-1})-GH(z^{-1})]$ is considered, the low-pass filter $LPF(z^{-1})$ must be designed with suitable bandwidth for reducing the adverse effects caused by the modeling error $[G_nH(z^{-1})-GH(z^{-1})]$. Thus, in this paper, the low-pass filter $LPF(z^{-1})$ is designed for reducing the adverse effects caused by measurement noise and modeling error. Fig. 4 shows the design concept of the low-pass filter $LPF(z^{-1})$.

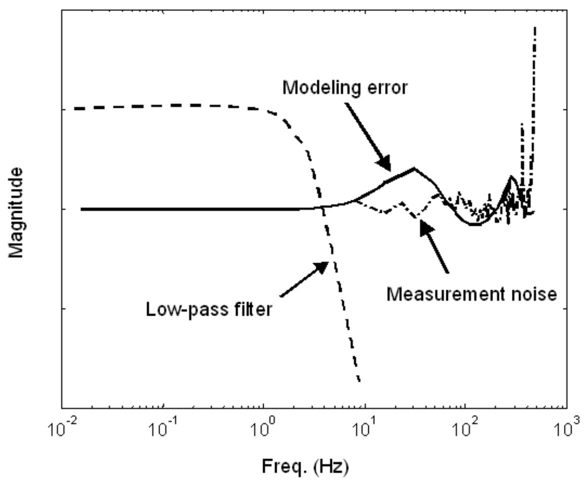

Fig. 4. The consideration for designing the low-pass filter $LPF(z^{-1})$

3.3 Design of Identification Unit

The observer shown in Fig. 1 estimates the speed perturbation caused by external disturbances that are induced by different paper path situations such as paper sticking, paper jamming, paper slipping, parts cracking, parts chattering, and parts wearing. In practice, for some applications, only the speed perturbation induced by specific paper path situation is the main concern in an ink jet printer. For instance, the estimation of the speed perturbation caused by parts cracking could be used to index a serious situation in an ink jet printer. Actually, it is possible to identify the speed perturbation caused by specific paper path situation if some mechanical factors and motion properties are known in advance by several motion tests.

Fig. 5 shows the structure of the identification unit developed in this paper. By using the filtered perturbation signal $\hat{d}^*(t)$, the identification unit with feature extraction and comparison is applied to distinguish the speed perturbation caused by specific torque disturbance. In this paper, the different torque disturbances are caused by the different paper path situations. For instance, $F_{\text{sticking}}{}^*(t)$, $F_{\text{jamming}}{}^*(t)$, $F_{\text{cracking}}{}^*(t)$, and $F_{\text{chattering}}{}^*(t)$ denote the sampled load torques caused by paper sticking, paper jamming, parts cracking, and parts chattering, respectively.

In this paper, there are two phases for designing the identification unit. In the first phase, by applying the speed perturbation observer as shown in Fig. 1, some features are extracted from the filtered perturbation signal $\hat{d}^*(t)$. Then, the extracted features are stored in database for further applications. For instance, if paper jamming occurs in paper feeding processes, the signal $\hat{d}^*(t)$ will rise to a larger value than that estimated under normal conditions. The magnitude of the filtered perturbation signal $\hat{d}^*(t)$ is therefore an important feature in applications. After taking some experiments, features with different paper path situations are obtained and stored in the database as shown in Fig. 5. The second phase is applied for on-line identifying and indexing different paper path situations. As shown in Fig. 5, the identification unit extracts features from the filtered perturbation signal $\hat{d}^*(t)$, and then compares with the features stored in database. Therefore, a specific paper path situation can be successfully identified if the on-line extracted features are similar to those stored in database. For instance, the identification unit indexes paper jamming situation if the on-line extracted features are similar to those obtained by paper jamming experiment.

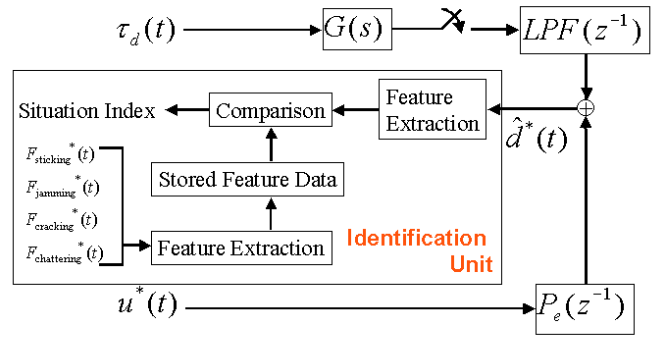

Fig. 5. Identification unit with feature extraction and comparison

4. EXPERIMENTAL RESULTS

The experimental setup for the present study is shown in Fig. 6. The applied experiment system consists of a DSP controller and an ink jet printer. The DSP controller has built-in a high-performance TI TMS320F2812 digital signal controller, which is capable of implementing control laws at a sampling period of 1 ms. The ink jet printer consists of a DC motor, a gear set, and some rollers to transmit paper from the lower paper tray to another paper tray. In this paper, the DC motor is controlled by the DSP controller for testing the proposed approach.

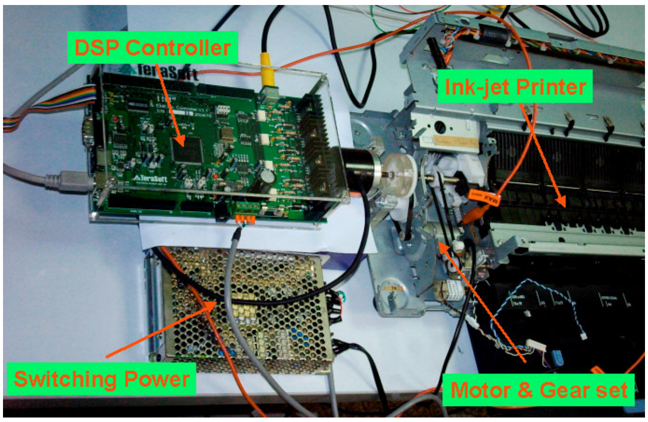

Fig. 6. Experimental setup

For testing the performances of the proposed approach, two usual paper path situations, paper jamming and mechanical chattering, are tested on the experiment system as shown in Fig. 6. According to the frequency analysis, a 4th-order low-pass filter with bandwidth 3.25 $^{rad}/_{sec}$ is designed as

$$LPF(z^{-1})=\frac{\begin{pmatrix}0.5845+2.3381z^{-1}+3.5071z^{-2}\\+2.3381z^{-3}+0.5845z^{-4}\end{pmatrix}\times10^{-7}}{\begin{pmatrix}1\text{-}3.9179z^{-1}+5.7571z^{-2}\\\text{-}3.7603z^{-3}+0.9212z^{-4}\end{pmatrix}}$$

Fig. 7 shows the experimental results for detecting paper jamming situation. Clearly, the observer accurately responses paper jamming situation at 3 seconds after starting printing process. The response time that depends on the low-pass filter design is about 1 second. In the experiment, the magnitude of the filtered perturbation signal $\hat{d}^*(t)$ is an important feature. Normally, without paper jamming, the magnitude of the signal $\hat{d}^*(t)$ is within 10 units. However, the magnitude is increased to approximately 120 units when the paper jamming situation occurs. Thus, the magnitude with 10 units can be a feature for indexing paper jamming situation. Although an overshoot occurs as shown in Fig. 7, it does not affect the detection result for paper jamming situation.

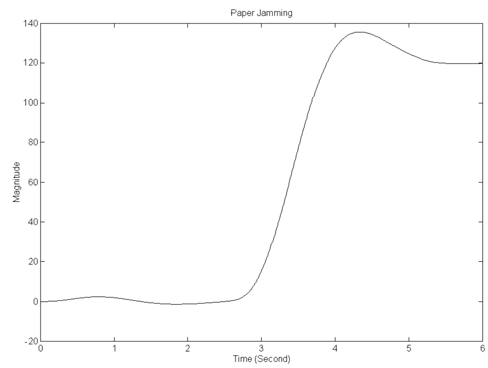

Fig. 7. The speed perturbation caused by paper jamming

Fig. 8 shows the experimental results for detecting mechanical chattering situation. Clearly, the observer accurately responses the mechanical chattering situation at 3 seconds after starting printing process. The response time is about 1 second. In comparing with Fig. 7, the filtered perturbation signal $\hat{d}^*(t)$ with different waveforms can denote different paper path situations. As shown in Fig. 8, not only the magnitude of the signal $\hat{d}^*(t)$ is increased to approximately 60 units, but also some fluctuations are detected when mechanical chattering situation occurs. Therefore, the magnitude and the fluctuations of the filtered perturbation signal $\hat{d}^*(t)$ are both the important features in applications. In the experiment, as shown in Fig. 8, the observer indexes mechanical chattering situation when the magnitude of the signal $\hat{d}^*(t)$ is over 10 units and the number of fluctuations is over 5 times.

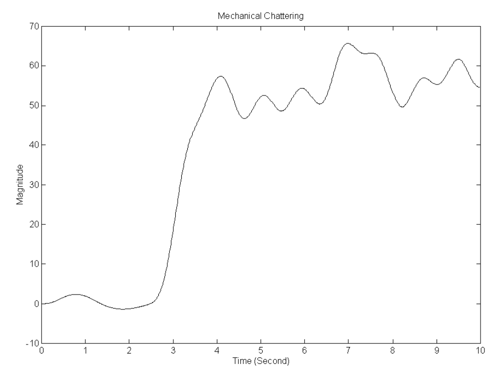

Fig. 8. The speed perturbation caused by parts chattering

5. CONCLUSIONS

Because paper transmission problems usually occur for a long period using an ink jet printer, the detection of paper path situations is thus required for ensuring printing qualities and for preventing destructive damages. Although many researchers have proposed several advanced detection methods, a simple detection method with few sensors is still preferred in most applications by considering the production cost of an ink jet printer. However, the paper path detection method with few sensors usually limits detection performances because few sensors only provide little information about paper path situations during paper feeding processes. Therefore, it is interesting to design a detection method that can detect some paper path situations without additional sensors. In this paper, the speed perturbation observer is proposed to detect paper path situations in an ink jet printer. In comparing with the existing approaches, the proposed approach detects several paper path situations without additional sensors. Moreover, in comparing with the torque disturbance observer, the speed perturbation observer is less sensitive to measurement noise and modeling error, and can provide stable computation in digital control systems. By applying feature extraction and comparison methods, an identification unit is included for identifying specific paper path situations in an ink jet printer. Experimental results demonstrate that the proposed approach provides good detection results and is feasible for detecting specific paper path situations in ink jet printers. In the future, based on the requirement of end users, a dynamic database and a tele-monitoring system will be developed for on-line extracting and automatically storing features from the detection signals of the proposed speed perturbation observer.

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