Event-Based Discontinuous Control for Harmonic Drive System
With the Damping Enhancement of Acceleration Feedback

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Abstract - This paper presents an event-based discontinuous control scheme for harmonic drive transmission. It is composed of two control strategies, namely, the motor-side PD control refined by load-side acceleration feedback, and the output torque control. Switching between these two modes is based on the external working condition of HD. This intends to generate appropriate control actions according to the actual problems of HD, which are different and closely dependent on its external conditions. Extensive experiments are conducted on a single link device driven by AC motor and harmonic transmission to test the performance of the proposed scheme.

I. Introduction

Harmonic drives are advantageous for robots and other mechatronic systems because they provide high speed-reduction ratios with lightweight, compact package, little backlash and high efficiency. However, harmonic drive system also suffers from resonant vibration, periodical transmission error, output ripple and poor back-drivability. These drawbacks will lead to poor tracking performance of its payload, especially when high motion speed is required and only motor-side sensors are available.

Recently, Modelling[1,2], sensing[3,4], as well as compensating techniques[5-9] have been extensively investigated into harmonic drive to improve its tracking performance. Generally, the critical problems which restrict a harmonic drive being extensively used in high performance servo system, exist in the following three aspects.

One is the transmission error[10, 11]. In most applications this position error itself is not significant, because the resulted link error is much smaller after divided by the high gear ratio. But it causes ripples on the gear output shaft as a derivative of the transmission error. The predominating frequencies of these ripples become second multiples of the input shaft turning frequency, namely, the frequencies are closely dependent on the rotation-speed of the motor shaft, and consequently on the desired trajectory. This problem will become special critical if the ripple frequency comes into a resonance with one of the system eigen-frequencies. Speed fluctuations will be largely amplified in such a case and often exceed allowable level for vibrations.

The second one is the compliance[12]. Although it has been revealed that the stiffness of a harmonic drive is fairly high (40000Nm/rad in [13]), the compliance of a harmonic drive will also lower the resonant frequencies of the mechanical chain. So the maximum velocity of the joint has to be strictly restricted to avoid the speed ripple coincide the resonance.

The third one is related with the poor back-drivability, which is due to the large gear ratio and internal friction of a harmonic drive[12, 14]. This results in several other problems of HD, such as difficulty in force control within both contact transition and force tracking phase, poor hand-by-hand teach ability, dangerous to both mechanical components and human operator whenever unexpected contact occurs, etc. On the other hand, poor back drivability also appears advantages instead of its drawbacks in force response. It will act as a kind of 'isolator' between motor shaft and its payload. Uncertainties in the payload will be significantly reduced when they reach motor shaft.

In this paper, we propose a discontinuous control scheme for harmonic drive, which decides its control actions according to the external conditions of HD in real time. Our motivation comes from the fact that the problems related with HD and needed to be overcome by its controller, are different with its working conditions. In trajectory tracking phase, improvements in tracking accuracy are prefered and our emphases should focus on how to resist the resonance and the output ripple of HD while maintaining its advantages of 'uncertainty-isolator'. But in the contact transition and force tracking phase, on the other hand, improving the back-drivability of HD should be taken into account.

In this proposed scheme, appropriate control actions necessary for resisting the existed problems will be generated according to the working conditions of HD. During the normal free motion phase, a classical motor-level PD control is refined by means of load-level acceleration feedback. This intends to attenuate the output ripple and resonance. The load-level torque of the harmonic drive is also monitored through the torque sensor being implemented between the HD and its payload. If an external (expected or unexpected) contact event is detected, torque control is excited in order to improve the back-drivability and force responds of the harmonic drive system.

II. Discontinuous Control Scheme

The proposed discontinuous control scheme is shown in Fig.1, where $\theta_d$, $\dot{\theta}_d$, $r_d$, $r_d$ and $\tau_m$ present respectively, the desired motor shaft position, payload acceleration, desired contact torque, reference torque profile and uncertainty in payload, and $G_m(s)$, $G_s(s)$ and $G_p(s)$ are motor-shaft position, HD output acceleration and
torque control law respectively. This controller is composed of three parts, which are the motor-level PD control refined by load-level acceleration feedback, the torque control with both velocity and acceleration feedback damping, and the condition judgement unit.

![Fig.1 Proposed Control Scheme](image)

A. Motor-Level PD Control with Load-Level Acceleration Feedback Enhancement

The dynamics of a harmonic drive can be simply described as:

$$\gamma (r_m - J_m \dot{\theta}) - \tau_h = \tau_d$$  \hspace{1cm} (1)

and

$$\tau_d = k_h (\theta / \gamma + e_h - q)$$  \hspace{1cm} (2)

in which, $\gamma$: gear ratio, $r_m$: internal disturbance, $k_h$: stiffness coefficient, $e_h$: transmission error, $\tau_d$: generated torque, $\theta$: motor shaft angle, and $q$: payload position. The transmission error, which is caused by the misplacement between the teeth on the flexible spline and the same teeth on the circular spline, can be modelled as:

$$e_h = \xi \sin(2\theta)$$  \hspace{1cm} (3)

where $\xi$ is a constant representing the error amplitude. And the payload dynamics can be modelled as:

$$\tau_a = J_1 \ddot{q} + B_1 \dot{q} + K_1 q + \tau_n$$  \hspace{1cm} (4)

in which $J_1$, $B_1$ and $K_1$ are constants representing the payload inertia, damping coefficient and mass respectively, and $\tau_n$ is the unmodelled disturbance due to payload uncertainties.

As for a current-controlled servo motor, we can reasonably assume:

$$r_m = r_d$$  \hspace{1cm} (5)

within a relatively wide frequency band, where $r_d$ is the set-point torque.

The motor-side PD control refined by integral-type load-level acceleration feedback during normal free motion phase is designed as:

$$\tau_d = (k_p e_m + k_d q_d) \dot{\gamma}^2 + k_a \int_0^\theta (\dot{q}_d - \ddot{q}) dt / \gamma$$

$$e_m = \dot{\theta} - \dot{\theta}$$

$$q_d = \theta_d / \gamma$$  \hspace{1cm} (6)

where $k_p$ and $k_d$ are PD control gains, and $k_a$ is the integral gain of acceleration feedback control, $\theta_d$ and $q_d$ are the set-point motor shaft and payload position respectively, $\xi$ is a positive constant, and,

$$q_d = \theta_d / \gamma$$  \hspace{1cm} (7)

Generally, the PD controller can overcome the internal disturbance $\tau_h$ effectively, and the tracking error between $\theta_d$ and $\dot{\theta}$ is small enough to ensure (3) being rewritten as:

$$e_h = \xi \sin(2\theta_d) = \xi \sin(2\omega t)$$  \hspace{1cm} (8)

Thus, $e_h$ can be seen as an external disturbance inputted to the system instead of a state-dependent one.

By submitting (2)–(4)–(7) into (1) and neglecting the terms containing $J/k_h$, $B/k_h$ and $K/k_h$, we can get the simplified closed-loop dynamics of control law (6) in Laplace form:

$$q = \frac{B(S)q_d / \gamma + C(S)e_h}{A(S)} - r_c$$  \hspace{1cm} (9)

in which

$$A(S) = (\gamma^2 J_m + J_1)S^2 + (k_p + k_a + B_1)S + k_p + K_1 + k_p K_1 / k_h$$  \hspace{1cm} (10)

$$B(S) = (k_d + k_a)S + k_p$$  \hspace{1cm} (11)

$$C(S) = k_p + k_d S + \gamma^2 J_m S^2$$  \hspace{1cm} (12)

$$r_c(S) = \frac{k_p + k_d S + \gamma^2 J_m S^2}{k_h} + B(S) + r_n + r_h$$  \hspace{1cm} (13)

According to equation (9)–(13), the functions of acceleration feedback control can be grouped into the following three aspects.

(a) It contributes both damping effect and stable margin to the closed loop tracking system. From equation (10) we can see that the integral gain $k_a$ of acceleration control acts similarly with the payload damping $B_1$ and the differential gain $k_a$ and will help to stabilize the dynamic performance of the closed-loop. Also, equation (11) demonstrates that a smaller zero has been resulted, which can improve the stable margin of the closed-loop control.

(b) The effects of transmission error, namely, the output ripples of harmonic drive, have been reduced by acceleration feedback control. Equation (10) shows that the existence of $k_a$ not only improves the attenuation of the vibration amplitude, but also makes the resonance less significant, even damps out the resonance if it is large enough.

(c) The acceleration feedback control can help to resist both internal and external disturbances, which can been seen from equation (10) and (12).

B. Torque Control Strategy

The above analyses show that the PD controller refined by acceleration feedback control can overcome the problems existed in HD during free motion phase, such as resonance, output ripples and disturbances. However, if the payload of a harmonic drive contacts with external environment, the resulted impact torque on motor shaft will be significantly reduced by the large gear ratio and internal friction. And the harmonic drive is hard to be back-driven even if the motor power has been switched off. This phenomenon of harmonic drive limits its being extensively used in the
cases where force control, hand-by-hand teach or safe impact are needed. By setting \( r_m = 0 \) in (1), we have,

\[
y^2 J_m \ddot{q} - r_h = r_a
\]

where \( r_a \) presents the external torque to back-drive the harmonic drive, and \( q \) is the resulted motion. We can see that both the significantly amplified rotor inertia and internal friction limit the back-drivability.

To improve the back-drivability of HD, active compliance provided by the motor is necessary. In the proposed scheme as Fig.1, the controller will be switched to torque control mode whenever it detects a contact occurring, namely,

\[
\tau_a = k_f f_d - (k_d + k_a) \dot{q} - S + k_f \tau_e
\]

in which \( f_d \) represents desired torque.

Substituting (15) into (1), we have,

\[
\tau_a = k_f \frac{f_d}{S + k_f} - (k_d + k_a) \frac{S}{S + k_f} \dot{q} - \frac{S}{S + k_f} \tau_e
\]

Equation (16) demonstrates that the integral force control ensure the contact force following its set-point value. Also, the low frequency disturbing term \( \tau_e \) will be reduced by this torque control. On the other hand, the motor-side velocity and the load-side acceleration feedback control in (15) damp the force control system and help to suppress high frequency oscillations during contact transition and force tracking phases.

C. Condition Judgement Unit

Besides its motion and torque control modes, this controller has also to be able to switch on/off the appropriate mode according to the external condition automatically. Here we propose the logic for condition judgement, which is based on the sensed payload torque information, i.e.,

\[
\begin{align*}
\text{Motion control mode as long as} & \quad |f_e(t)| < |f_r(t)| + \xi \\
\text{Torque control mode as long as} & \quad |f_e(t)| \geq |f_r(t)| + \xi
\end{align*}
\]

in which \( f_e \) is the measured payload torque, \( f_r \) is a torque reference, and \( \xi \) is a holding margin. \( f_e \) can be obtained by storing the measured torque during the first routine while the harmonic drive is required to execute a repetitive task, and the sampling period can be calculated according to the available memory space and the duration of the task being executed for one time. For those non-repetitive tasks, the result by filtering the actuated torque history in real time can be used as the reference torque. In our experiments presented below, the stored torque is adopted as the reference.

However, the switching logic like (18) is not practicable whenever the actually measured torque includes much noise, because we have to set a relatively high holding margin in such cases to avoid misjudgement. And a large threshold will make the controller insensitive to a real contact. In order to overcome this problem, we add another constrain to the switching condition.

\[
\begin{align*}
\{ & \text{if } t_m > t_c \quad \text{Changing to motion control mode} \\
& \text{else if } t_e > t_c \quad \text{Changing to torque control mode} \\
& \text{else Maintaining current mode}
\end{align*}
\]

in which \( t_m \) is the duration in which \( |f_e(t)| < |f_r(t)| + \xi \) is kept, and \( t_e \) is the duration in which \( |f_e(t)| < |f_r(t)| + \xi \) is maintained, and \( t_c \) is a constant time interval. According to (19), the controller will not change its mode until the sensed torque has satisfied the specified condition as long as a period of time.

III. Experimental Investigations

The proposed control scheme has been extensively investigated on a single link set-up actuated by an AC-servo motor and a harmonic drive (See Fig.2). Current sensor, encoder, torque sensor and accelerometer have been implemented, and a PC-based controller, with its open architecture and friendly human interface, has been adopted to make this device a suitable test-bed for various sensor-based control schemes.

A. Performance During Free-Motion Phase

The joint is first controlled under normal PD law to track a desired trajectory with its link as the only payload. Their curves in Fig.3(a) demonstrates the actual position, velocity, position tracking error, controller output and the measured torque respectively (from upper to lower). Then, a time-varying disturbing torque is added on the link-tip, and Fig. 3 (b) shows the tracking performance, from which we can see that the maximum value of the disturbance is about 35Nm, ten times larger than the link itself. Comparison between Fig.3 (a) and (b) demonstrates that the PD control has successfully overcome the disturbing torque and there exists no significant difference between the tracking errors. This result proves that the harmonic drive acts as a good isolator between the motor and its payload, and for the circumstances where cross coupling disturbances exist, a multi-DOF manipulator for example, the classic independent PD control can be continuously used and achieve relatively high motor-side tracking accuracy.

![Fig.2 Experimental Set-up](image)

Indeed, the output ripple is the critical problem of a harmonic drive during free motion phase, especially when its frequency, which is determined by the rotational input speed, comes into the resonance. Fig.4 shows the ripples
actually measured by the load-side accelerometer when the motor is controlled under normal PD law to track a constant speed of 12rpm, 18rpm and 37rpm respectively. The ripples in Fig.4 (b) are much larger than those in (a) and (c). This is because that the rotation speed of 18rpm results the ripple frequency coinciding with the resonance of this harmonic transmission.

Comparatively, Fig.5 demonstrates the ripples when there exists acceleration feedback enhancement. We can see the ripples have been reduced to half of those in Fig.4 after acceleration feedback enhancement is adopted.

B. Torque Control to Improve Back-Drivability

In this section, we use the slope of $\dot{\theta}/\tau_a$ to measure the back-drivability of a harmonic drive, where $\tau_a$ and $\dot{\theta}$ are the torque externally exerted and its resulted motor speed respectively. Fig.6 (a) shows the curve $\dot{\theta}/\tau_a$ when there is not any active closed loop, namely, the motor power is switched off. And Fig.6 (b) is the curve of $\dot{\theta}/\tau_a$ when the torque control law as (15) is active. Comparison between them demonstrates two improvements after torque closed-loop being adopted: one is that the torque necessary to start the back motion has been reduced from 20Nm to about 7Nm, another is the slope of the curve, has been increased from 45' to 80'. This means that the back-drivability has been improved, namely, much less torque is needed when we try to back drive the harmonic drive.
C. Event-Based Switching Between these Two Control Laws

In our experiments, switching logic (19) is adopted and the reference \( f_e \) is selected as the torque stored during the first routine while the harmonic drive is executing a repetitive motion. If the controller detects a contact, torque control will be excited automatically to avoid significant impact occurring.

Fig. 7(a) demonstrates how the joint responds to an unexpected contact occurring during normal tracking routine, when there exists only the refined PD control. The controller was unconscious to the occurrence of a relatively large contact torque (as much as 47Nm was measured) and still executed its desired trajectory. Comparatively, Fig. 7(b) shows the results under the proposed event-based discontinuous control scheme, from which we can see that the controller reacted to the unexpected contact quickly and stopped the motor shaft compliantly, and no significant impact occurred.

IV. Conclusion

Two control strategies, which are output torque control and refined motion control, have been combined together by the sensor-based switching logic. This is intend to apply appropriate control actions to overcome the different problems of a harmonic drive in different work conditions. During the free motion phase, motor-side PD control is refined by load-side acceleration feedback to damp the resonance and output ripples of HD. Switching logic is established based on the sensed payload information. Whenever an external contact is detected, torque control with both acceleration and velocity feedback damping will be active to improve the back-drivability and compliance of the harmonic drive. Experimental results on a single-link set-up demonstrate the effectiveness of this proposed scheme.

V. References