euspen's 17th International Conference &
Exhibition, Hannover, DE, May 2017
www.euspen.eu

Disturbance Compensation by Set-Point Alteration for Improved Tracking Performance

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Abstract
In precision motion control systems, the two degree of freedom (2-DOF) control structure is widely utilized for improving tracking performance. Although ideally the 2-DOF control can yield zero tracking error, the practical performance is often deteriorated due to disturbances. The disturbances can sometimes be measured or estimated and then compensated by modifying the control input. However, in many industrial applications, the control engineers are not allowed to modify the control input directly, as the commercial controllers are often proprietary and have closed architecture. In order to address this practical difficulty, in this paper, we propose a disturbance compensation scheme which alters the set-point instead of the control input. Since we no longer have preview of the altered set-point, the traditional feedforward controller is no longer implementable due to its non-causality. The non-causality problem is then solved by using a predictive feedforward approach, which is based on prediction of the set-point as well as a general offsetting mechanism to compensate for the prediction errors. Real-time experiment is conducted to further illustrate the proposed method and show its practical appeals in industrial applications.

Feedforward control, Tracking, Disturbance rejection

1. Introduction

In industrial control systems, the two degree of freedom (2-DOF) control is commonly used for improved tracking performance. The feedforward controller is included to reduce the inevitable lagging of traditional PID control and it is often designed as the inverse the system model in order to cancel the system dynamics.

In practically situation, perfect tracking is not achievable by using the feedforward controller due to the external disturbances as well as the model mismatches. The disturbances can be measured or estimated and compensated by modifying the control input, but in many practical situations, the control engineers do not have access to the control input, because the commercial controllers are often proprietary and have closed architecture. In this paper, we develop a new disturbance compensation scheme by making modification to the set-point. The proposed approach is different from the well-known input shaping technique. The input shaping technique helps to reduce vibration in the higher frequency band while our approach deals with disturbances in the low frequency band.

The paper is organized as follows. In Section 2, we introduce the approach for disturbance compensation by set-point alteration. The predictive feedforward approach to deal with the altered set-point is illustrated in Section 3. The effectiveness of the proposed approach is demonstrated using a timing-belt actuation system in Section 4. Finally, conclusions are drawn in Section 5.

2. Disturbance compensation by set-point alteration

In this section, the traditional two degree of freedom (2-DOF) control is reviewed and then the proposed disturbance compensation scheme is introduced.

2.1. 2-DOF Control

The typical 2-DOF control structure is shown in Figure. 1, where P(z), C(z), and F(z) are the motion system, the feedback controller and the feedforward controller respectively. The signals r, e, d, u, n, y denote the set-point, tracking error, disturbance, control input, noise and output respectively. The transfer function from r to e is:

$$\frac{e}{r}=\frac{1-P(z)F(z)}{1+P(z)F(z)} \qquad (1)$$

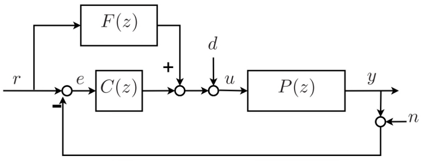

Figure 1. Conventional two degree of freedom control

2.2. Disturbance Compensation

In order to compensate for the external disturbances and model mismatches, a disturbance compensation scheme is proposed in Figure. 2. When the disturbance is not measurable, the disturbance d can be estimated by using a disturbance observer [1] which is composed of the inverse system model

F(z) as well as a low pass filter Q(z). The bandwidth of the low pass filter is used to balance the disturbance rejection performance and robust stability of the system. The estimated disturbance $\hat{d}$ is used for the compensation by only making adjustments to the set-point. In Figure 2, the transfer function from d to y can be derived as

$$H_{yd}(z) = \frac{P(z)(1-Q(z))}{1+P(z)C(z)-Q(z)(1-P(z)F(z))} \qquad (2)$$

In the low frequency band, $Q(s) \approx 1$, and

$$H_{yd}(z) \approx \frac{P(z)\times 0}{P(z)C(z)+P(z)F(z)} = 0 \qquad (3)$$

This indicates that the proposed disturbance compensation scheme is able to compensate the disturbance effectively.

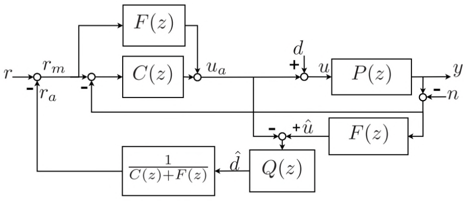

Figure 2. Proposed disturbance compensation scheme for unmeasurable disturbances.

3. Predictive feedforward approach for the altered set-point

In order to implement the non-causal feedforward controller F(z), the set-point information has to be known beforehand [2]. However, the approach proposed in Section 2 makes changes to the set-point and set-point preview is no longer available. In this section, we make use of a predictive feedforward approach [3] to solve this problem.

Suppose the motion system under control is

$$P(z) = \frac{p_n z^n + \cdots + p_1 z + p_0}{z^m + q_{m-1} z^{m-1} + \cdots + q_0} \qquad (4)$$

The feedforward controller is

$$F(z) = \frac{z^m + q_{m-1} z^{m-1} + \cdots + q_0}{p_n z^n + \cdots + p_1 z + p_0}, \qquad (5)$$

and can be separated into its causal and non-causal part as

$$F(z) = \sum_{i=1}^{m-n} f_i z^i + F_p(z) \qquad (6)$$

The causal part can be implemented without any trouble, but for the non-causal part, the set-point prediction is needed. In our approach, we make use of a polynomial extrapolation approach to estimate the future set-point. Consider a q-order polynomial function

$$r(k) = a_0 + a_1 k + \cdots + a_q k^q + \epsilon, k \geq q+1 \qquad (7)$$

where ϵ is the fitting error. Its parameter vector is obtained by available data points using the least square method and this polynomial function is then used to predict the future set-point

$$\hat{r}(k+1) = a_0 + a_1(k+1) + \cdots + a_q(k+1)^q \qquad (8)$$

To compensate for the prediction error, an additional offsetting signal can be introduced. Consider a general second order plant

$$P(z) = \frac{p_1 z + p_0}{z^2 + q_1 z + q_0} \qquad (9)$$

The additional offsetting signal can be expressed as

$$f_c(k) = \frac{q_1}{p_1} e_p(k) + \frac{q_0}{p_1} z^{-1} e_p(k). \qquad (10)$$

where $e_p(k)$ is the prediction error. This offsetting signal forms a deadbeat control for the prediction error and is able to further improve the tracking performance.

4. Experiment result

In this section, the proposed disturbance compensation scheme is applied to a timing-belt actuation system to further improve its tracking accuracy. The plant under control is simplified to be a simple second order system

$$P(z) = \frac{3.737\times 10^{-5} z + 3.737\times 10^{-5}}{z^2 - 1.992z + 0.992} \qquad (11)$$

Due to its low cost, severe disturbance such as fiction and backlash deteriorates the tracking performance. With the proposed disturbance compensation scheme by set-point alteration, the tracking error can be reduced significantly as shown in Figure. 3. Further reduction of the tracking error to nm scale is not easy due to the mechanical limitation, e.g. no air bearing to eliminate the friction effect.

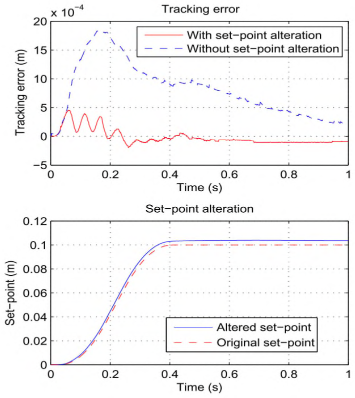

Figure 3. Tracking error comparison in real-time experiment and the corresponding set-point alteration.

5. Conclusion

In this paper, we propose a disturbance compensation scheme by set-point alteration. It is applicable to commercial controllers which has closed architecture, as only the set-point is modified without any changes to the existing control structure. The proposed approach is validated using a timing-belt actuation system.

References

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