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Industrial feedforward control technology: a review

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Abstract
In the control field, most of the research papers focus on feedback control, but few of them have discussed about feedforward control. Therefore, a review of the most commonly used feedforward control algorithms in industrial processes is necessary to be carried out. In this paper, in order to benefit researchers and engineers with different academic backgrounds, two most representative kinds of feedforward controller design algorithms and some other typical industrial feedforward control benchmarks are presented together with their characteristics, application domains and informative comments for selection. Moreover, some frequently concerned problems of feedforward control are also discussed. An industrial data driven example is presented to show how feedforward controller works to improve system performance and achieve the maximum economic profits.

Keywords Feedforward control · Industrial application · Disturbance rejection · Reference tracking · Temperature control

Introduction

Control actions can be mainly divided into two categories, feedback control and feedforward control. Normally, our attention is concentrated on feedback control because it can stabilize a system and satisfy some robustness requirements as well as saturation limitations in the meantime. However, when a large disturbance appears or a perfect tracking performance is required in a control system, feedforward control is also indispensable, especially in industrial processes. Many research papers and books have shown significant improvements on system control performances after applying feedforward control (Marlin 2000; Fujimoto et al. 2001; Isermann 2013; Zhou et al. 1996; Elliott and Sutton 1996; Seborg et al. 2010; Seidler et al. 2004). But most of the research works have skated over the details of when and how to perform feedforward control. In this paper, the characteristics and application domains of the most representative feedforward control algorithms and some benchmarks in industrial processes are presented in detail, in order to make researchers and engineers with different academic backgrounds get faster and more comprehensive understanding of feedforward control.

The basic concept of feedforward control which was used in the boiler drums' three-element level control loop (Seborg et al. 2010) can be traced back to as early as 1925. But it has not been widely applied in industrial processes until 1960s (Shinskey and Levine 1996). Ever since, feedforward control has become one of the most commonly used control algorithm in industry field (Cori and Maffezzoni 1984; Abukhalifeh et al. 2005; Seborg et al. 2010; Chue and Hugunin 2010; Li et al. 2009). However, feedforward controllers are always designed based on the inverses of transfer functions of the controlled systems, so they are susceptible to have low tolerance on model errors and are easy to be involved in system stability problems (Goodwin et al. 2001). A complete feedforward-driven system should be able to detect disturbance and take action in advance, but it will not be able to adjust the system performance (Johansson 2003). Thus, feedforward control systems usually need the supplement of some certain kinds of feedback control. Therefore, it should be remarked that the feedforward controllers presented in this paper are designed for the systems which have already been stablized by feedback controllers.

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According to different control objectives, there are primarily two kinds of feedforward controllers, which are aiming at disturbance rejection and perfect tracking respectively. The former one which has been frequently used in chemical processes can detect and eliminate disturbance immediately when the disturbance comes into the system (Jinzenji et al. 2001; Elliott 2000; Kempf and Kobayashi 1999; Ghosh and Narayanan 2007; Yan and Shiu 2008; Anibal Valenzuela et al. 2007). Without the disturbance rejection feedforward controller in the control loop, the system will try to eliminate the disturbance influence after it has passed through all the way of the system and generated an error signal. Another typical feedforward controller which is aiming at improving reference tracking performance has also been extensively utilized in different domains (O'Brien and Broussard 1979; Tomizuka 1987; Fujimoto et al. 2001; Song et al. 2005; Fujimoto et al. 2000; Tsao and Tomizuka 1987; Klančar and Škrjanc 2007; Li et al. 2016; Stojanovic and Nedic 2016; Nedic et al. 2015; Marconi and Isidori 2000; Ang et al. 2007). It helps the systems achieve perfect tracking performance without the change of original closed-loop structure. We will review the detailed characteristics of these two kinds of feedforward controllers as well as some benchmarks in the following sections.

The rest of this paper is organized as follows. Feedforward controller design technologies for disturbance rejection and reference tracking as well as their characteristics and application domains are presented in sections "Feedforward controller for disturbance rejection" and "Feedforward controller for reference tracking" respectively; section "Feedforward control for MIMO systems" introduces some feedforward control algorithms for MIMO (Multi-Input-Multi-Output) systems; some other typical feedforward control technologies used in industrial processes are presented in section "Feedforward control in industrial application"; section "Other questions of feedforward control" discusses some frequently encountered problems about feedforward control; section "Example" gives an industrial data driven example to show how to use feedforward control; finally, the conclusions are drawn in section "Conclusion".

Feedforward controller for disturbance rejection

Why and when to use feedforward controller for disturbance rejection

Feedback control is usually necessary in a system control loop, however, feedforward controller is also indispensable when a major disturbance appears in the system. In most ideal cases, feedforward control can completely eliminate the impact caused by measured disturbance on the process output. Even when there are model uncertainties in the controlled system, feedforward control can usually decrease the impact of disturbance more effectively than feedback control (Brosilow and Joseph 2002). Figure 1 gives a graphic understanding of how feedforward controller works to eliminate disturbance impact in a feedforward-feedback control system. Once a disturbance signal enters the system, it will be eliminated immediately by the feedforward controller without any impact on the system output. Otherwise, if there is only feedback controller in the control loop, the disturbance will travel through all the control path to generate an error signal and drive the feedback controller react. Moreover, the long time delay generated in the path of disturbance travelling will cause unnecessary impacts on system output performance which may lead to overcorrections and may even cause oscillations on the controlled variables. These impacts are significant in industry processes and will influence the system economic benefits.

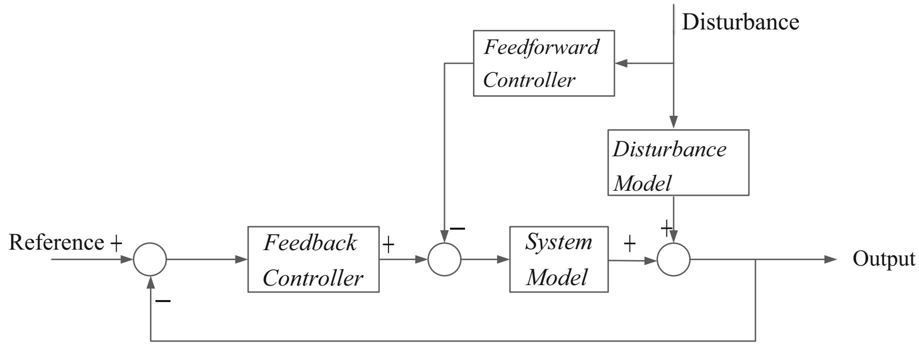
Corripio (2000) has given a criterion to help measure the controllability of feedback controllers, namely the ratio of the system dead time to the process model time constant. When the value of the criterion is equal or greater than one, feedback control usually cannot eliminate the effect caused by measured disturbance. On this condition, feedforward control strategy can achieve the greatest improvement on control performance. Another vital point in the decision process of whether a feedforward controller is necessary or not is the economic benefit, which usually comes first in industry process (Brosilow and Joseph 2002). Therefore, the decision of whether to use feedforward control or not in a control loop also highly depends on the degree of the system performance improvement in the output to the additional cost of the controller implementation and maintenance.

Moreover, the design of an efficient feedforward compensator requires fairly high accuracy on the controlled process model and all possible disturbances dynamic models. These are normally hard to be achieved in a real process. Therefore, a more reasonable method is only adding feedforward controller for those vital disturbances and making the feedback controller deal with other minor disturbances as well as model inaccuracy.

Tuning of feedforward controller for disturbance rejection

A manually tuned feedforward control system example is shown in Fig. 2 (Altmann 2005). When a disturbance enters, it will be detected by the process operator. Then after measuring the disturbance, the operator will make changes of the manipulated variable, such as flow rate, based on his knowledge of the process to minimize the impact of the disturbance on process output. However, this kind of feedforward control operates according to the operator's experience and knowl-

Fig. 1 Block diagram of feedforward-feedback control system



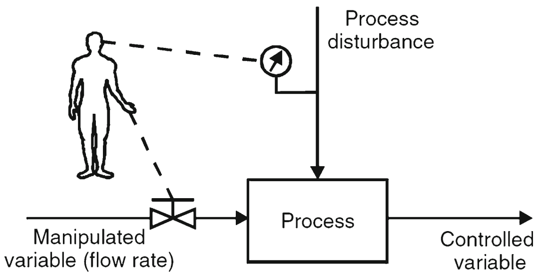


Fig. 2 Manually tuned feedforward control (Altmann 2005)

edge of the process. So it is fragile and uneconomical. These problems blocked the manually tuning method from being widely used in the modern industry processes.

Refer to Fig. 1, consider the Laplace transforms of reference set-point, process output and disturbance as Y_{sp}, $Y(s)$, $D(s)$, the feedback controller and feedforward controller as $G_c(s)$ and $G_f(s)$, and the process model and disturbance model transfer functions as $G_p(s)$ and $G_d(s)$ respectively. The closed-loop transfer function from disturbance to process output can be derived as:

$$\frac{Y(s)}{D(s)} = \frac{G_d(s) - G_f(s)G_p(s)}{1 + G_c(s)G_p(s)}, \tag{1}$$

Ideally we prefer to achieve perfect control, so the effect of disturbance should be eliminated entirely by setting Eq. (1) into zero. Hence, the feedforward controller $G_f(s)$ is got as:

$$G_f(s) = \frac{G_d(s)}{G_p(s)}. \tag{2}$$

The formulation in Eq. (2) looks quite simple, however, the realizability of it needs a lot of discussion. As we mainly focus on industry processes in this paper, we just take some common used controlled plants into consideration.

Case 1

Consider the following systems

$$G_d(s) = \frac{K_d}{\tau_d s + 1}, \quad G_p(s) = \frac{K_p}{\tau_p s + 1}, \tag{3}$$

where, K_p, K_d are steady states gains, τ_p, τ_d are time constants of these two models respectively. The ideal feedforward controller in this case according to Eq. (2) is

$$G_f(s) = \left(\frac{K_d}{K_p}\right)\left(\frac{\tau_p s + 1}{\tau_d s + 1}\right). \tag{4}$$

Case 2

Now suppose that

$$G_d(s) = \frac{K_d}{\tau_d s + 1}, \quad G_p(s) = \frac{K_p}{\tau_p s + 1} e^{-Ls}, \tag{5}$$

where, L is the time delay of the process model. From Eq. (2), the feedforward controller can be achieved as

$$G_f(s) = \left(\frac{K_d}{K_p}\right)\left(\frac{\tau_p s + 1}{\tau_d s + 1}\right) e^{Ls}. \tag{6}$$

Apparently, the inverse of delay term e^{Ls} is physically unrealizable because it implies the need of predictive information. One solution is making approximation of the e^{Ls} term by integrating the L into the time constant parameter τ_p as $\tau_p + L$ (Seborg et al. 2010). Another possible way is making the feedforward controller design as a single degree of freedom internal model controller (Brosilow and Joseph 2002). Moreover, an additional alternative compromise may be made as just leaving the negative delay term away when it is not significant. But the impacts of this compromise should be taken into consideration first because timing is always an important part in practical control systems. This case is same to the other one which have a longer process model delay than disturbance model delay.

Case 3

Finally, consider that

$$G_d(s) = \frac{K_d}{\tau_d s + 1}, \quad G_p(s) = \frac{K_p}{(\tau_{p_1} s + 1)(\tau_{p_2} s + 1)}. \tag{7}$$

The feedforward controller in this case based on Eq. (2) is

$$G_f(s) = \left(\frac{K_d}{K_p}\right) \frac{(\tau_{p_1} s + 1)(\tau_{p_2} s + 1)}{(\tau_d s + 1)}. \tag{8}$$

Likewise, Eq. (8) is physically unrealizable since the order of its nominator is higher than that of the denominator. The authors in Seborg et al. (2010) used the same way as dealing with the unrealizable delay term above to solve this problem. They made approximation of the nominator in Eq. (8) as one first order polynomial whose time constant is the sum of the two existed ones, namely $\tau_{p_1} + \tau_{p_2}$. Another solution for this problem was also put forward in Brosilow and Joseph (2002). When the relative order of the process model is higher than that of the disturbance model, a filter $ff(s)$ could be added into Eq. (8) to make the controller realizable and limit noise amplification as

$$ff(s) = \frac{1}{(\alpha s + 1)^r}, \tag{9}$$

where, r is the relative order of Eq. (8), and α can be set smaller than the process time constant to limit noise amplification.

Additionally, some remarks on disturbance rejection feedforward control should be put here that:

(1) When a feedforward controller is to be designed, the process disturbance should be pre-measured or measured on-line.
(2) The effectiveness of a feedforward controller highly depends on the accuracy of the controlled process model. If there are some uncertainties in the process model, they should be taken care of mainly by the corresponding feedback controller. However, this will increase the burden of feedback controller.
(3) A desired feedforward control is sometimes physically unrealizable. But some practical approximations can provide effective solutions on this occasion.
(4) The feedforward controller design methods introduced above are also available to other kinds of controlled plants. The control algorithm on eliminating the non-Gaussian noise presented in practical application can be found in Stojanovic and Nedic (2016), Barkefors and Sternad (2014), and Stojanovic and Nedic (2016).

Feedforward controller for reference tracking

Why and when to use feedforward controller for reference tracking

Normally, there are two major requirements on the tuning of control system, namely regulation and trajectory tracking. Some of the control algorithms only concentrate on regulation against disturbance input which have already been discussed in the above section. When trajectory tracking performance is required in control loop, for example, chamber temperature should change along with the predesigned profile in plasma etching process, robots should track a prescribed route to perform tasks, etc, feedforward controller for reference tracking will also be necessary (Tomizuka 1987). In this section, feedforward control algorithms which can help the control objective move along a desired trajectory (Tomizuka 1987; Tsao and Tomizuka 1987; Li et al. 2016; Tomizuka 1993; Fujimoto et al. 2001; Buehner and Young 2015) are introduced.

An effective feedforward tracking controller is always designed based on the inverse model of the closed-loop system transfer function. However, the inverse models of system with cancellable zeros (zeros stand in the stable region) are relatively easy to be achieved, but the other systems with uncancellable zeros (zeros stand right on the stable boundary or in the unstable region) will have problems in the inversion process. Masayoshi proposed a discrete zero phase error tracking control algorithm which can deal with the problem of inversions of systems with uncancellable zeros (Tomizuka 1987). The main idea of these zero phase error feedforward controllers is the cancellation of discrete time zeros (Gross et al. 1994).

Another widely used feedforward tracking control algorithm is called finite optimal preview control which is developed based on the linear quadratic optimal control (Tomizuka 1992). Different from zero phase error tracking control, the feedback controller and feedforward controller parameters are determined simultaneously in this control algorithm by minimizing a quadratic objective performance index. The index includes tracking error term as well as control effort term (Anderson and Moore 2007; Tomizuka 1974). Furthermore, the optimal preview control strategy as well as its continuous version (Peng and Tomizuka 1993) has already been successfully applied to various kinds of motion control systems (Tomizuka and Janczak 1985).

The difference of these two tracking controller design schemes is that zero phase error controller needs only a local period future desired output, but the optimal preview control requires all the future trajectory. However, the optimal preview controller always provides a smoother output action compared with the zero phase error controller. Besides, zero phase error controller depends on the inversion of closed-loop transfer function, namely the feedback controller should be given already. Nevertheless, optimal preview controller can achieve the parameters of both feedforward and feedback controllers. The comparison is made in Table 1. Researchers and Engineers should make wise selection on the choice of feedforward tracking controller according to the controlled system characteristics.

Table 1 Comparison of the discussed tracking algorithms

Different algorithms	Zero phase error tracking control	Optimal preview control
Length of future trajectory needed	A local period	All
Output type provided	Depend on trajectory type	Smooth
Predesigned feedback controller	Necessary	Not necessary
System model inversion	Necessary	Not necessary

Tuning of feedforward controller for reference tracking control

Tuning of zero phase error tracking controller

As mentioned above, zero phase error tracking control (ZPETC) is an effective digital feedforward tracking control scheme which can help track a set-point time varying signal accurately (Tomizuka 1987). The main idea of this control algorithm is the cancellation of all the closed-loop poles as well as the cancellable closed-loop zeros. The so-called cancellable zeros are those who will not cause unstable problem after inversion, because the closed-loop zeros will turn into poles in the inversed model. For those zeros which cannot be inverted directly, Tomizuka (1987) has also proposed a method to cancel the phase shift caused by them. The difference of the frequency response between the actual output and set-point trajectory will become zero after the phase cancellation, and then the system can achieve a perfect tracking performance theoretically.

Consider a discrete time system with a closed-loop transfer function as:

$$\begin{aligned} G_{closed}(z^{-1}) &= \frac{N(z^{-1})}{D(z^{-1})} z^{-L} \\ &= \frac{n_0 + n_1 z^{-1} + \cdots + n_i z^{-m}}{d_0 + d_1 z^{-1} + \cdots + d_j z^{-q}} z^{-L}, \end{aligned} \tag{10}$$

where, $N(z^{-1})$, $D(z^{-1})$ represent the discrete time numerator and denominator polynomials respectively, m, q $(m < q)$ are the largest orders of the numerator and denominator polynomials, and L is the delay length.

The feedforward tracking control algorithm diagram is shown in Fig. 3, where $G(z^{-1})$, $C(z^{-1})$, $F(z^{-1})$ are discrete time plant model, feedback controller and feedforward controller, $y_{sp}(k+L)$, $y(k)$, $r(k)$ are set-point signal, actual output signal, and feedback system reference signal in time domain respectively. Theoretically, perfect tracking means the actual output can reproduce the set-point trajectory accurately, namely the overall transfer function of the system is 1. Therefore, if the feedback system reference signal $r(k)$ in Fig. 4 is given as

$$r(k) = \frac{D(z^{-1})}{N(z^{-1})} y_{sp}(k+L), \tag{11}$$

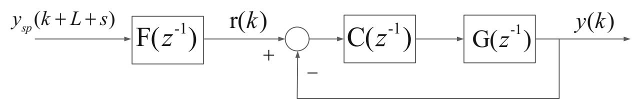


Fig. 3 Feedforward/feedback tracking control system iagram

then, perfect tracking can be achieved in the system. Notice that we use the time domain form of $r(k)$ and $y_{sp}(k)$ in equation (11) for simplicity as the same as Tomizuka (1987).

As it can be seen from Eq. (11), the original closed-loop system zeros turn into poles of the designed feedforward controller. This will have impact on the system stability. Those zeros outside or right on the unit circle are called uncancellable or zeros, because they cannot be cancelled directly, or they will bring unstable or oscillatory performance to the system. Therefore, for systems with uncancellable zeros, the feedforward controller $F(z^{-1})$ cannot be designed referring to Eq. (11). Under this circumstance, we can factorize the numerator $N(z^{-1})$ of Eq. (10) into two parts as:

$$N(z^{-1}) = N^c(z^{-1}) N^{uc}(z^{-1}), \tag{12}$$

where, $N^c(z^{-1})$ includes all the cancellable zeros in Eq. (10) and $N^{uc}(z^{-1})$ includes those uncancellable ones. Then, the feedback system reference signal $r(k)$ in this condition will be designed as:

$$r(k) = \frac{D(z^{-1}) N^{uc}(z)}{N^c(z^{-1})[N^{uc}(1)]^2} y_{sp}(k+L+a), \tag{13}$$

where, a is the number of the uncancellable zeors, $N^{uc}(z)$ is used to cancel the shift phase induced by the the feedback closed-loop system, and $[N^{uc}(1)]^2$ is used as a scaler.

The reason of the induced shift phase cancellation is shown in frequency domain as:

$$\begin{aligned} &\left[\frac{N^{uc}(e^{-j\omega T})}{N^{uc}(1)}\right] \cdot \left[\frac{N^{uc}(e^{j\omega T})}{N^{uc}(1)}\right] \\ &= [\mathrm{Re}(\omega) - j\mathrm{Im}(\omega)] \cdot [\mathrm{Re}(\omega) + j\mathrm{Im}(\omega)] \\ &= [\mathrm{Re}(\omega)]^2 + [\mathrm{Im}(\omega)]^2. \end{aligned} \tag{14}$$

As we can see, there is no imaginary part in Eq. (14), hence, there will not be any phase different between set-point input and actual output.

There are also some modifications of the ZPETC. A continuous version ZPETC tracking controller was proposed in Park et al. (1999), in which the control performance was also enhanced by a gain error compensation. An adaptive digital ZPETC scheme was put forward in Tsao and Tomizuka (1987) and has been used in Ismail et al. (2012). Another generalized optimal ZPETC design method was illustrated in Yamada et al. (1999) which gave an explicit form of the optimal ZPETC. Meanwhile, a ZPETC algorithm with arbitrarily specified gain characteristics and an extended bandwidth ZPETC have been prensented in Yamada et al. (1997) and Torfs et al. (1992) respectively, and so on forth (Lee and Tomizuka 1996; Zhou and Wang 2002).

Though ZPETC feedforward tracking control algorithm is an effective way of trajectory tracking, there are still some remarks should be pointed out here:

(1) Future information, at least $L + s$ steps ahead of the desired trajectory has to be used in the controller design process. However, this is not a big problem because in many mechanical industry processes, the desired output is set in advance.
(2) Some zeros which stand closely to the unit circle may also have impact on the stability of the controlled system. Therefore, they may have to be put into consideration as well.
(3) The tracking performance after adding ZPETC also depends on the accuracy of the original closed-loop system. That means the controlled plant model should be accurate and the feedback controller should be tuned in advance. In other words, ZPETC is sensitive to model uncertainties (Tomizuka 1993).

Tuning of optimal preview tracking controller

Different from the ZPETC algorithm introduced in the above section, the optimal preview tracking control algorithm is an extension of the linear quadratic regulator (LQR) problem (Anderson and Moore 2007), which requires all the future information of the set-point reference. Here, we introduce a general case of a discrete time optimal preview tracking problem. The state space model of the controlled system is considered as Tomizuka (1992):

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k), \\ y(k) &= Cx(k), \end{aligned} \tag{15}$$

where, $x(k),\ u(k),\ y(k)$ are n-dimensional state vector, m-dimensional input state vector and q-dimensional output state vector respectively, and $A,\ B,\ C$ are appropriate dimensional matrices.

Suppose the desired output is $\left\{y_{sp}(k)|0 \leq k \leq N\right\}$ with the specified duration N. The objective optimal quadratic performance index J is given as:

$$J = \sum_{i=0}^{N-1} \left\{e^T(i)Qe(i) + u^T(i)Ru(i)\right\} + e^T(N)Qe(N), \tag{16}$$

where $e(k) = y_{sp}(k) - y(k)$, R is positive definite and $S,\ Q$ are positive semi-definite. It can be seen from Eq. (16) that the objective performance index includes both the tracking error and the control input incremental effort.

Then, the optimal solution to this tracking problem is:

$$\begin{aligned} u(k) = &-\left[B^T G(k+1)B + R\right]^{-1} B^T \left[G(k+1)Ax(k)\right. \\ &\left.+ f(k+1)\right], \end{aligned} \tag{17}$$

where $G(k)$ is the solution of the following Riccati equation:

$$\begin{aligned} G(k) = S = A^T &\left\{G(k+1) - G(k+1)B\left[B^T G(k+1)B\right.\right. \\ &\left.\left.+R\right]^{-1} B^T G(k+1)\right\} A + C^T QCG(N), \end{aligned} \tag{18}$$

and

$$\begin{aligned} f(k) = &\left\{A - B\left[B^T G(k+1)B\right.\right. \\ &\left.\left.+R\right]^{-1} B^T G(k+1)A\right\}^T f(k+1) \\ &-C^T Q y_{sp}(k) f(N), \\ f(N) = &-C^T S y_{sp}(N). \end{aligned} \tag{19}$$

There are also some remarks of optimal preview tracking algorithm:

(1) The optimal preview tracking algorithm designs feedforward and feedback controllers at the same time.
(2) The objective performance index can also include other quantities according to specific control requirements (Tomizuka et al. 1980).

Also notice that the controlled systems of both ZPETC algorithm and optimal preview tracking algorithm should be time-invariant linear systems, otherwise, some linearization methods should be used before controller design.

Feedforward control for MIMO systems

The feedforward control algorithms discussed above concentrate on SISO (Single-Input-Single-Output) systems. Feedforward control algorithms for MIMO (Multi-Inputs-Multi-

Outputs) control systems are also needed to be explored because they are widely used in industrial processes. Most of the time, the only difference between SISO system and MIMO system is coupling. The coupling problem between different inputs and outputs may cause serious problems in system control stage. The most frequently and effectively applied method is making MIMO system decoupled first and treating the decoupled system as several SISO systems (Gagnon et al. 1998; Shinskey et al. 1990), so that all the feedforword control algorithms discussed above can be used accordingly.

Similar to SISO systems, the main applications of the feedforward control algorithms used in MIMO systems are trajectory tracking and disturbance rejection (xin and Hou peng 2011). Moreover, feedforward control may also be used to make the MIMO systems decoupled directly at times (Jiang et al. 2015). An optimal disturbance rejection feedforward control algorithm for MIMO was proposed in xin and Hou peng (2011). The method seems to be straightforward and easy to be implemented, but the presentation and simulation of the paper are relatively simple and cannot fully express the effectiveness of the proposed algorithm. Ref. Piccagli and Visioli (2009), Malchow and Sawodny (2012), and Jain et al. (2010) present some examples of feedforward algorithms used in improving the MIMO system reference tracking performance. Most of them are designed on top of the system inverse model as well. An analytical set-point following control scheme for MIMO processes was proposed in Piccagli and Visioli (2009). The proposed control strategy seems to be useful, but the complexity of the analytical processes should be taken into account. So the application domain of this kind of MIMO feedforward control algorithms still needs to be further explored. Some industrial MIMO feedforward control processes are shown in Malchow and Sawodny (2012) and Jain et al. (2010). Their design processes are straightforward, but the improvements on the MIMO system tracking performance are impressive. Besides, there are some feedforward control algorithms for MIMO systems based on intelligent control methods, namely fuzzy control or neural network control and etc, presented in Rong et al. (2015), Abilov et al. (2002), Chiu (2006), Karer et al. (2011), and Ali et al. (2010).

Feedforward control in industrial application

In this section, some benchmarks of feedforward control algorithms used in industry processes are presented.

Ratio control

Ratio control which has been widely applied in industry processes is a special kind of feedforward control (Powell et al. 1998; Brosilow and Joseph 2002; Hori et al. 1999; Bartroli et al. 2010; Skogestad and Morari 1987; Kaibel 1987; Dang et al. 2017). It is essentially one of the simplest types of feedforward control. The objective of ratio control is maintaining a specified ratio of two process variables. Most of the time, the two process variables are flow rates. For example, if there is a disturbance variable d in the controlled system, a manipulated variable u will be needed, so the specific ratio will be $R = u/d$. The ratio R is usually kept as a constant, and the manipulated variable value will change together with the change of the disturbance variable. There are some representative applications of ratio control including applications in blending operations (Gonzalez 1995), reactors (Bartroli et al. 2010), distillation columns (Skogestad and Morari 1987; Kaibel 1987), furnace (Kusama et al. 1986) and etc.

There are two typical kinds of ratio control implementations as shown in Fig. 4 (Seborg et al. 2010). In Fig 4a, flow rates of both disturbance and manipulated stream are measured, and the ratio R_m is calculated by $R_m = u_m/d_m$. Then the calculated R_m will be sent to a ratio controller (RC) and compared to the ratio set point value R_d. At last, the manipulated flow u_m will be adjusted according to the comparison result of R_m versus R_d. This can also be treated as a feedback system, therefore, its reaction to the disturbance change will be slow. Besides, another significant disadvantage of this control scheme is the divider in the control loop may lead to nonlinear behavior of the process gain. An alternative implementation scheme is illustrated in Fig. 4b. When a disturbance stream d comes into the controlled system, it will be measured and sent to the ratio station (RS) first, and then multiplied by the set point ratio R_s. Hence, the output signal of RS is the set point stream u_{sp} which can be used to modify the flow rate of manipulated stream value u. In this scheme, the process gain is a constant during control process, so it is more preferred by control engineers. Ref. Hägglund (2001) presents a modified version of this ratio control scheme aimming at the transient mismatch between disturbance stream and manipulated stream.

Learning feedforward control

Conventional feedforward controller design is normally based on analytical calculation which requires fairly accurate process model. However, these accurate model may not always be available before running the process, and sometimes the process disturbance may change overtime. Aiming at this problem, the learning feedforward control algorithm which only requires the on-site measured feedback loop characteristic was proposed by Tao et al. (1994a). This control scheme has been widely applied in a lot of industry manufacture processes ever since, especially in semiconductor fabrication (Tao et al. 1994b; Choi and Do 2001). It makes the tuning of feedforward controller easier because it can learn

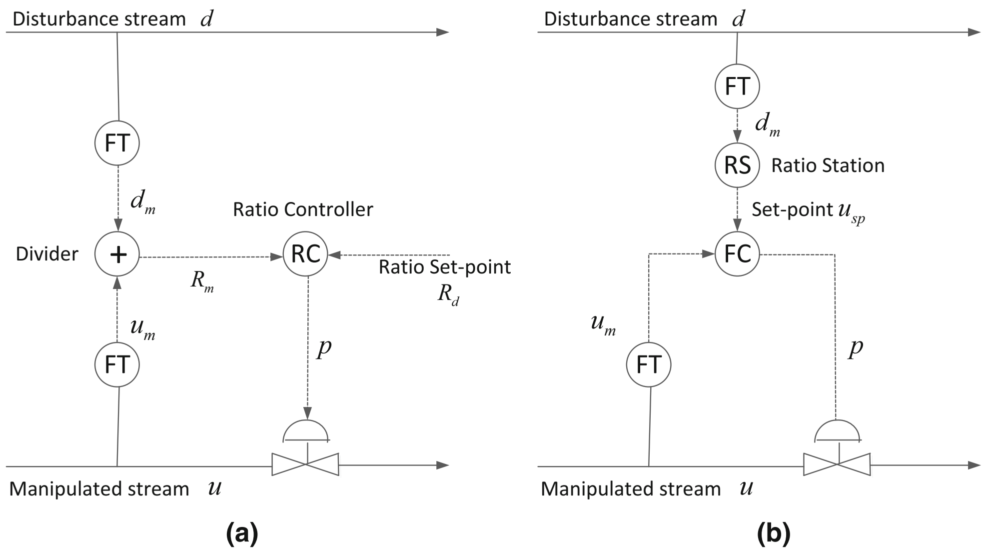


Fig. 4 Ratio control configurations

from the past on-site control circulation. Since a lot of manufacturing tasks are repetitive target-oriented, the learning algorithm is comparatively suitable for the tasks (Tao et al. 1994a). An example of applying the learning feedforward control scheme to the rapid thermal processing stage of semiconductor wafer manufactory process has been presented in Tao et al. (1994a). It is shown that one processing step time has been reduced by more than 20 seconds which is quite significant to this rapid thermal processing by this approach. Another implementation dynamic feedforward filter which is driven by appropriate feedforward signals was proposed in Tao et al. (1994b). The extension of this scheme has been applied to nonlinear systems and has received quite satisfactory results (Tao et al. 1994c). Besides, a frequency domain adaptive learning feedforward control algorithm which was also proved to be applicable to industry processes with nonlinearities was presented in Chen and Moore (2001) with only two tuning knobs.

Intelligent feedforward control

Classical feedforward control algorithm has some limitations. For example, it is hard to deal with the system nonlinearities, plant model uncertainties and time delay term. Therefore, except from the traditional feedforward control algorithms, there are some advanced control schemes which combines feedforward concept with some intelligent control methods. A hybrid intelligent control strategy which includes feedforward neural network and fuzzy logic control algorithms was proposed in Chen (1992) for semiconductor manufacturing process. It is shown that this innovative intelligent control scheme could achieve several improvements like higher yield, enhanced processing uniformity, efficient fabrication and so on, and it is also applicable to other chemical processes. A similar work applied on rapid thermal process temperature control which combined iterative learning control with feedforward neural network algorithm can be found in Choi and Do (2001). The controller could adapt itself to the dynamic changes in on-site environments and it was proved that it could get fast convergence. Another effort on quick wafer alignment which used feedforward neural networks has also proved to be more effective than conventional methods (Kim et al. 2010). Moreover, a criteria decision making method which was achieved by feedforward neural network model was presented in Wang and Malakooti (1992). The effectiveness of this method was supported by theoretical analysis as well as illustrative simulation results. However, most of the papers which proposed intelligent feedforward control algorithms have not discussed about the implementation of the method. Hence, the implementation problem and economical benefits of these novel control schemes still need to be verified by researchers and engineers.

Some other efforts of feedforward controller applied in industry manufactory processes can be found in Ho et al. (2007), Schaper et al. (1992), Wagner et al. (1999), Ruegsegger et al. (1999), Stoddard et al. (1994) and Wu et al. (2007).

Other questions of feedforward control

Stability of feedforward control system

There are usually three vital points in control systems, namely dynamic performance, stability and robustness. We have focused on the dynamic performance of the systems with feedforward controller in the above sections, in this section, we will discuss the stability of these systems.

For the feedforward controllers which are designed for disturbance elimination, the signals always travel forward and will not go through a feedback loop. Under this circumstances, the feedforward controllers will not impact the stability of the original system. But they are also not able to prevent instability in the system response (Corripio 2000).

However, there is another scenario when the feedforward controller is designed for perfect tracking. In this situation, the signals will also travel forward, but they will go through a loop, so the feedforward term itself should be stable to guarantee that the system is stable after adding the feedforward term. Besides, we have already introduced how to design a stable feedforward tracking controller in section "Feedforward controller for reference tracking".

Robustness design of feedforward control system

As mentioned in the above sections, both feedforward controllers for disturbance rejection and perfect tracking are based on accurate disturbance model or closed-loop system model, and they are sensitive to the model uncertainties. There have already been some papers discussing about the robustness issue in feedforward controller design. Ref. Adam and Marchetti (2004) stressed that a robust feedforward controller should not be tuned independently from the feedback loop, and there were two examples in this paper presenting the satisfactory results of the proposed robust tuning method. However, this may be not enough to fully support the point in the paper. So it is suggested to be treated as a sufficient but not necessary condition in solving robust feedforward controller tuning problem. Another efficient convex feedforward controller design which was a practical method based on frequency gridding was proposed in Ferreres and Roos (2005). Nevertheless, the application domain of this method has not been illustrated accordingly. Moreover, some robust tracking design algorithms have been discussed in Miyazaki et al. (2004), Tan et al. (2006), and Ko et al. (2013).

Feedforward control or feedback control ?

It was emphasized in the beginning of this paper that all the systems discussed are feedforward-feedback combined systems. But could a system be driven only by a feedforward controller? An entirely feedforward-driven system always cannot adjust itself to meet the set-point reference, though it can take action in advance when a disturbance enters the system. On the other hand, a feedback-driven system can detect the error between set-point signal and actual output and then correct the error, but it cannot eliminate a significant disturbance immediately and may cause other troubles in the actual output. Therefore, an ideal control system will be a well tuned feedback-driven system with an 'add on' feedforward term which takes care of significant disturbance elimination or perfect tracking.

Lacking elements and future research trends of feedforward control

As we have discussed in the previous sections, there are still some drawbacks and limitations in the existing feedforward control technologies. The lacking elements and future research trends are briefly summarized as following:

(1) As it was discussed in subsection "Robustness design of feedforward control system", most of the existing feedforward controller are model-based, so the controlled systems are sensitive to model uncertainties. This will limit the industrial application domain of feedforward controller because completely accurate models may not easy to be achieved. Therefore, feedforward control algorithm which is robust to model uncertainties is needed to be explored.
(2) Several feedforward control algorithms used on industrial applications have been presented by researchers and engineers. However, most of them focused only on dynamic control performance improvement. The implementation methods, limitations and economic cost which are equally important as dynamic control performance in this field are ignored. These aspects should be discussed to improve the practicability of the future work.
(3) The feedforward tracking controller presented in subsection "Tuning of zero phase error tracking controller" may have an improper expression, and the controlled system may be sensitive to high frequency disturbance. The related research on these problems will be useful to enlarge the application domain of the feedforward tracking control algorithms.
(4) More industrial application examples are needed to demonstrate the effectiveness of feedforword controllers used in various fields.
(5) Most existing feedforward control strategies are applied on linear time invariant systems. The corresponding control algorithms used on nonlinear systems need to be further studied.

Example

In this section, an industrial application example of feedforward disturbance rejection controller is presented, so that readers can get an authentic understanding of how feedforward controllers design and work. All the on-site data used in this section has been scaled to protect the supplier privacy and also to make the results easy to be understood.

Fig. 5 The internal structure of a plasma etching chamber

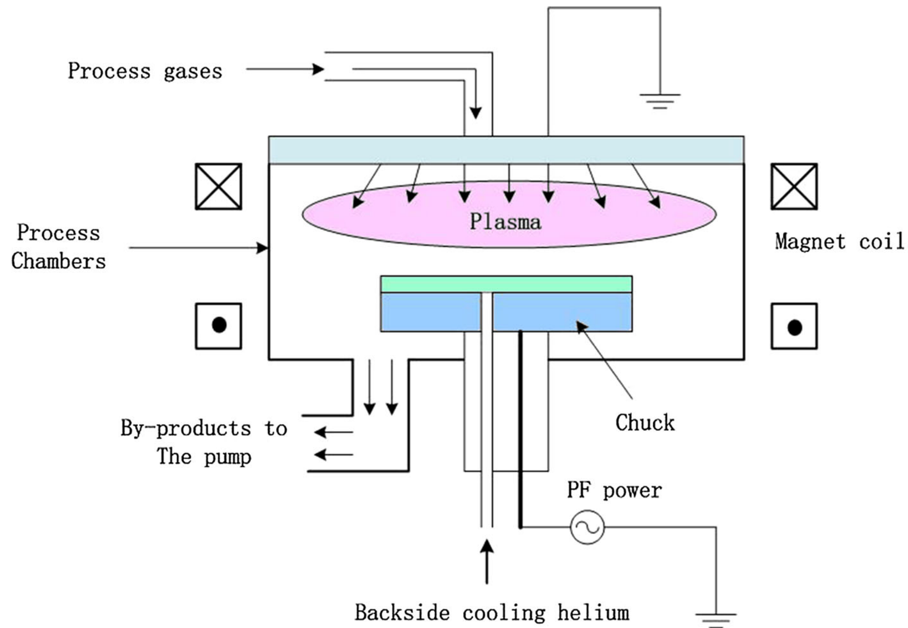


Fig. 6 The cross section of a plasma etching chamber

The system we are working on is a plasma etching chamber of a semiconductor manufactor. The configuration of the chamber is quite complicated as shown in Figs. 5 and 6, but it can be considered as a four zones heater abstractly. Hence, the controlled plant is essentially a four-input-four-output system. Since we have already added some decouplers in the corresponding zones, so each of the four zones can be treated as a SISO system. Moreover, because the disturbance forms of each zone are similar, we just take one zone as our control objective for simplicity.

Every time when plasma is placed on the heater, it will cause some fluctuation on the chamber temperature. This is a common and inevitable phenomenon in plasma etching process, and the etching quality will degenerative if the fluctuation is bigger than the tolerance interval. Before we put the disturbance rejection feedforward controller into the control loop, the fluctuation amplitude was $\pm\, 0.15\,^{\circ}C$ when a $10\,^{\circ}C$ set-point was applied. It was not too big but still quite significant in plasma etching process, thus we decided to reduce the fluctuation amplitude into $\pm\, 0.05\,^{\circ}C$ to improve etching quality.

There are mainly five steps in the disturbance rejection feedforward controller design process. Firstly, we should collect on-site disturbance data and make analysis of the composition of the disturbance caused by plasma involvement. Secondly, disturbance model identification should be done based on the collected on-site data. Then, the corresponding feedforward controller can be designed according to the tuning method presented in section “Tuning of feedforward controller for disturbance rejection” and Fig. 1. After we get both the plasma disturbance and feedforward controller models, we simulate the whole process in Matlab/Simulink to verify the control performance and may retune the controller. Finally, after all the above steps are accomplished, the disturbance rejection feedforward controller will be integrated into the real tool, and tests will be conducted to verify the effectiveness of the designed controller. However, some compromises may have to be made during the implementation process of the controller according to the implementation and maintenance cost.

Disturbance analysis and on-site data collect

Since the heating chamber is quite complicated, many factors may contribute to the disturbance caused by plasma involvement. For example, RF (Radio Frequency) bias power impact which comes from chamber bottom, TCP (Temperature Control Power) impact which comes from chamber top, isolation gas (argon, oxygen or mixture gas) impact, chamber pressure impact, set-point temperature impact, and etc. After the disturbance elements are clear, different sets of data under

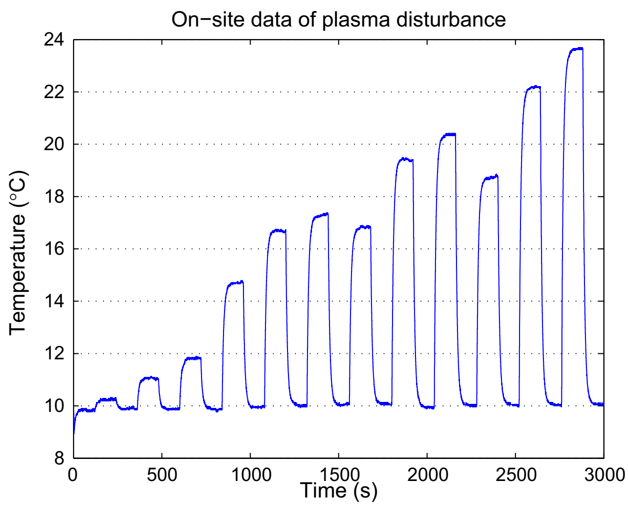


Fig. 7 On-site data of plasma disturbance

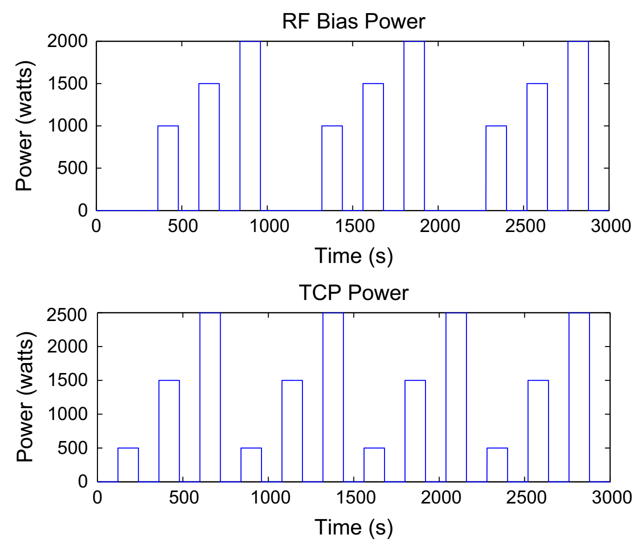


Fig. 8 RF bias and TCP disturbance inputs

different disturbance conditions, namely under different RF bias power and TCP, are collected. One example of the data sets which has 12 steps with different power combination is shown in Fig. 7.

Disturbance model identification

The on-site data sets got as Fig. 7 are quite long and complicated with 12 steps. We cut each set of the data into 12 steps and normalize them to make the fitting process simpler. The two impacts, namely RF bias power impact and TCP impact are chosen as inputs, and the on-site disturbance data is treated as output in the model fitting process. In industrial control systems, a lot of processes can be modeled or approximated in the following form:

$$G(s) = \frac{K}{Ts+1}e^{-Ls}. \tag{20}$$

So we also use this model to fit the data as:

$$G_{rf}(s) = \frac{0.018}{22s+1}e^{-2s}, \tag{21}$$

$$G_{tcp}(s) = \frac{0.0019}{22s+1}e^{-2.1s}, \tag{22}$$

where, $G_{rf}(s)$ and $G_{tcp}(s)$ are RF bias power disturbance model and TCP power disturbance model respectively.

Feedforward controller design

The original process plant model is

$$G(s) = \frac{1.1877}{20s+1}e^{-s}. \tag{23}$$

According to Eqs. (6), (21)–(23) and the control structure diagram in Fig. 1, the following feedforward controllers are obtained aiming at the corresponding disturbance:

$$G_{frf}(s) = \frac{0.0152(20s+1)}{22s+1}e^{-s}, \tag{24}$$

$$G_{ftcp}(s) = \frac{0.0016(20s+1)}{22s+1}e^{-1.1s}, \tag{25}$$

where, $G_{frf}(s)$ and $G_{ftcp}(s)$ are RF bias power disturbance and TCP disturbance rejection feedforward controllers respectively.

Simulation

After all the parameters of models and controllers are achieved, we first test the control algorithm by simulation instead of on-site tool test in order to reduce the tuning time and implementation cost. The simulation diagram is generated based on the block diagram shown in Fig. 1. The system set-point input temperature is 10 $°C$, and the disturbance inputs are RF bias power and TCP respectively which are generated as shown in Fig. 8. If we do not put the designed feedforward disturbance rejection controllers in the control loop, the system output will be impacted by RF bias power and TCP as Fig. 9 illustrates. It can be seen from Fig. 9 that the disturbances impact the output with a fluctuation around ± 0.15 $°C$ when the input temperature is fixed as 10 $°C$. Then, the above two designed feedforward disturbance rejection controller are integrated into the feedforward loops respectively, and the control performance is shown in Fig. 10. The stable temperature trajectory in Fig. 10 shows that the disturbance impacts are completely eliminated by the feedforward controllers.

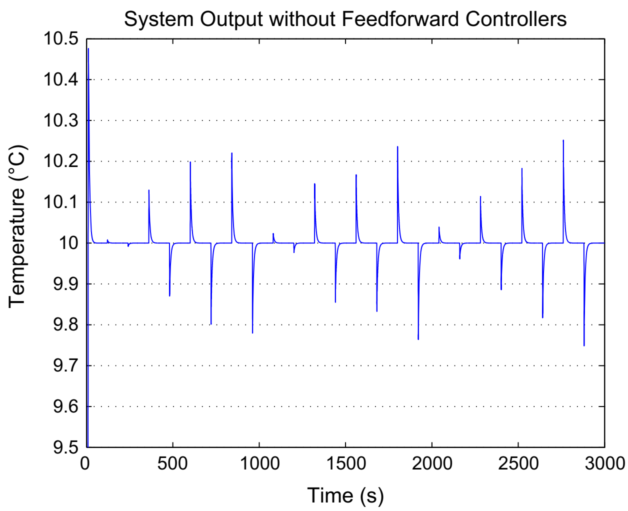


Fig. 9 System output without feedforward controllers

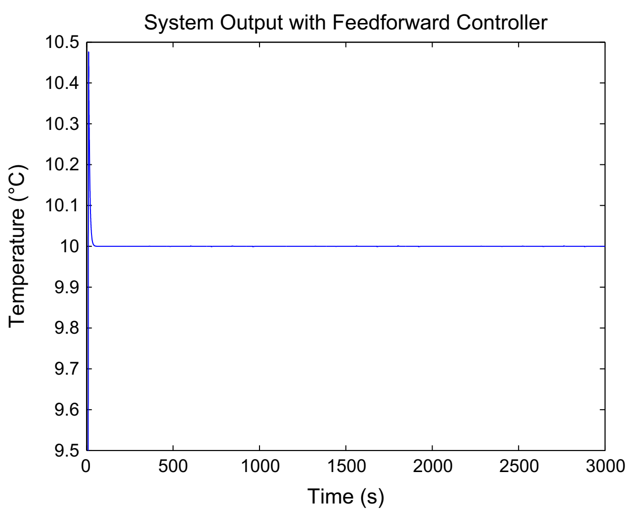


Fig. 10 System output with feedforward controllers

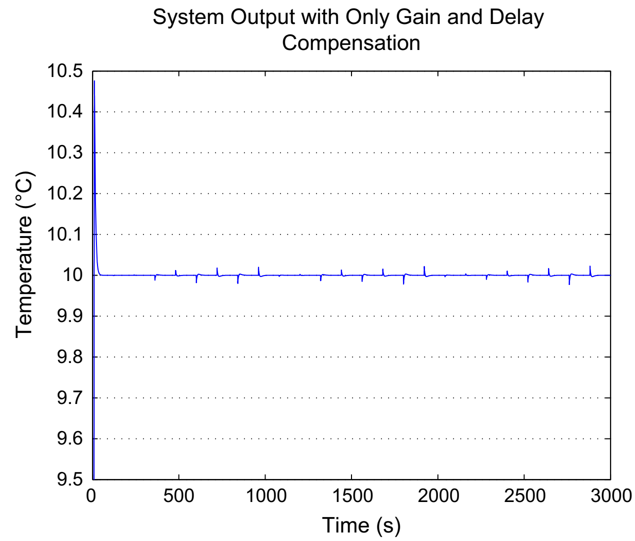


Fig. 11 System output only with gain and delay compensation

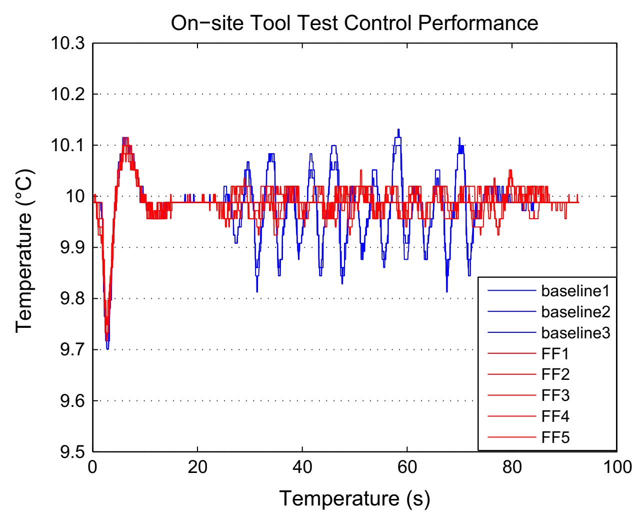


Fig. 12 On-site tool test control performance

Furthermore, different from pure research, added cost of implementation and maintenance is also one of the most important factors which affect the success degree of our control algorithm. The real semiconductor manufactory chamber is quite complicated, the added cost of a dynamic model will be much more than a static one. Besides, it is also shown in Eqs. (24) and (25) that both of the dynamic models of these two controllers are close to 1. Therefore, a more economical way is removing the dynamic parts and only applying two static gains with corresponding delay. The system output with only gain and delay compensation can be found in Fig. 11. It is shown in Fig. 11 that the disturbance inputs only cause $\pm\, 0.02\,^{\circ}C$ output fluctuations with only gain and delay compensation. Since our target is reducing the fluctuations into $\pm\, 0.05\,^{\circ}C$, only static feedforward controller is enough to satisfy both control performance and economic requirements.

On-site tool test

After all the design and verification stages are accomplished, the feedforward controllers are implemented into the real tool chamber to conduct the final tool test stage. The temperature set-point input and disturbance inputs are the same as we used in the above simulation. The feedforward control performance is shown in Fig. 12, in which the three blue lines are the original outputs without static feedforward compensation, the five red lines are outputs with disturbance compensation. The first 20 seconds period is the initialization process which can be ignored. It is clearly illustrated by Fig. 12 that the disturbance impacts have been significantly reduced by the added feedforward controllers. The on-site tool test result is exactly accorded with the theoretical derivation and simulation results.

Conclusion

In this paper, a comprehensive review of feedforward control algorithms in industrial application has been presented. Two major categories, i.e. aiming at disturbance rejection and reference tracking are introduced together with their own usage and application fields. Feedforward control algorithms for MIMO systems, some other commonly used industrial controller design methods and some frequently occurred problems have also been discussed. Comments on when and how to implement different kinds of feedforward controllers are given, therefore, researchers and engineers with various academic backgrounds can get easily involved in this field. A detailed industrial data based example is presented to give readers an authentic feeling of how to design feeforward controller for performance improvement as well as reducing economic expense.

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References

Abilov, A. G., Zeybek, Z., Tuzunalp, O., & Telatar, Z. (2002). Fuzzy temperature control of industrial refineries furnaces through combined feedforward/feedback multivariable cascade systems. *Chemical Engineering and Processing*, *41*(1), 87–98.

Abukhalifeh, H., Dhib, R., & Fayed, M. (2005). Model predictive control of an infrared-convective dryer. *Drying Technology*, *23*(3), 497–511.

Adam, E., & Marchetti, J. L. (2004). Designing and tuning robust feedforward controllers. *Computers & Chemical Engineering*, *28*(9), 1899–1911.

Ali, S. S. A., Al Sunni, F. M., Shafiq, M., & Bakhashwain, J. M. (2010). U-model based learning feedforward control of MIMO nonlinear systems. *Electrical Engineering*, *91*(8), 405–415.

Altmann, W. (2005). *Practical process control for engineers and technicians*. Newnes.

Anderson, B. D., & Moore, J. B. (2007). *Optimal control: Linear quadratic methods*. Courier Corporation.

Ang, W. T., Khosla, P. K., & Riviere, C. N. (2007). Feedforward controller with inverse rate-dependent model for piezoelectric actuators in trajectory-tracking applications. *IEEE/ASME Transactions on Mechatronics*, *12*(2), 134–142.

Anibal Valenzuela, M., Bentley, J. M., Aguilera, P. C., & Lorenz, R. D. (2007). Improved coordinated response and disturbance rejection in the critical sections of paper machines. *IEEE Transactions on Industry Applications*, *43*(3), 857–869.

Barkefors, A., & Sternad, M. (2014). *Design and analysis of linear quadratic Gaussian feedforward controllers for active noise control*. IEEE Press, pp. 1777–1791.

Bartroli, A., Perez, J., & Carrera, J. (2010). Applying ratio control in a continuous granular reactor to achieve full nitritation under stable operating conditions. *Environmental Science & Technology*, *44*(23), 8930–8935.

Brosilow, C., & Joseph, B. (2002). *Techniques of model-based control*. Englewood cliffs: Prentice Hall.

Buehner, M. R., & Young, P. M. (2015). Robust adaptive feedforward control and achievable tracking for systems with time delays. *International Journal of Control*, *88*(4), 768–782.

Chen, S. S. (1992). Intelligent control of semiconductor manufacturing processes. In *Proceedings of IEEE international conference on fuzzy systems*. IEEE, pp. 101–108.

Chen, Y., & Moore, K. L. (2001). Frequency domain adaptive learning feedforward control. In *Proceedings of 2001 IEEE international symposium on computational intelligence in robotics and automation*. IEEE, pp. 396–401.

Chiu, C. S. (2006). Mixed feedforward/feedback based adaptive fuzzy control for a class of MIMO nonlinear systems. *IEEE Transactions on Fuzzy Systems*, *14*(6), 716–727.

Choi, J. Y., & Do, H. M. (2001). A learning approach of wafer temperature control in a rapid thermal processing system. *IEEE Transactions on Semiconductor Manufacturing*, *14*(1), 1–10.

Chue, J. M., & Hugunin, T. D. (2010). Feedforward compensation for fly height control in a disk drive, Nov. 23 US Patent 7,839,595.

Cori, R., & Maffezzoni, C. (1984). Practical-optimal control of a drum boiler power plant. *Automatica*, *20*(2), 163–173.

Corripio, A. B. (2000). *Tuning of industrial control systems*. Instrument Society of America.

Dang, C., Tong, X., Huang, J., Wang, Q., & Zhang, H. (2017). Qpr and duty ratio feedforward control for vienna rectifier of HVDC supply system. *IEEE Transactions on Electrical and Electronic Engineering*.

De xin, G., & Hou peng, D. (2011). Optimal disturbance rejection via feedforward-PD for MIMO systems with external sinusoidal disturbances. *Procedia Engineering*, *15*, 459–463.

Elliott, S. J. (2000). Optimal controllers and adaptive controllers for multichannel feedforward control of stochastic disturbances. *IEEE Transactions on Signal Processing*, *48*(4), 1053–1060.

Elliott, S. J., & Sutton, T. J. (1996). Performance of feedforward and feedback systems for active control. *IEEE Transactions on Speech and Audio Processing*, *4*(3), 214–223.

Ferreres, G., & Roos, C. (2005). Efficient convex design of robust feedforward controllers. In *Proceedings of the 44th IEEE conference on decision and control*. IEEE, pp. 6460–6465.

Fujimoto, H., Hori, Y., Yamaguchi, T., & Nakagawa, S. (2000). Proposal of seeking control of hard disk drives based on perfect tracking control using multirate feedforward control. In *Proceedings of the 6th international workshop on advanced motion control*. IEEE, pp. 74–79.

Fujimoto, H., Hori, Y., & Kawamura, A. (2001). Perfect tracking control based on multirate feedforward control with generalized sampling periods. *IEEE Transactions on Industrial Electronics*, *48*(3), 636–644.

Gagnon, E., Pomerleau, A., & Desbiens, A. (1998). Simplified, ideal or inverted decoupling? *ISA Transactions*, *37*(4), 265–276.

Ghosh, R., & Narayanan, G. (2007). Generalized feedforward control of single-phase pwm rectifiers using disturbance observers. *IEEE Transactions on Industrial Electronics*, *54*(2), 984–993.

Gonzalez, C. (1995). Fuel blending system method and apparatus. Nov. 28, US Patent 5,469,830.

Goodwin, G. C., Graebe, S. F., & Salgado, M. E. (2001). *Control system design* (Vol. 240). New Jersey: Prentice Hall.

Gross, E., Tomizuka, M., & Messner, W. (1994). Cancellation of discrete time unstable zeros by feedforward control. *Journal of Dynamic Systems, Measurement, and Control*, *116*(1), 33–38.

Hägglund, T. (2001). The blend stationa new ratio control structure. *Control Engineering Practice*, *9*(11), 1215–1220.

Hori, Y., Sawada, H., & Chun, Y. (1999). Slow resonance ratio control for vibration suppression and disturbance rejection in torsional system. *IEEE Transactions on Industrial Electronics*, *46*(1), 162–168.

Ho, W. K., Tay, A., Chen, M., & Kiew, C. M. (2007). Optimal feed-forward control for multizone baking in microlithography. *Industrial & Engineering Chemistry Research*, *46*(11), 3623–3628.

Isermann, R. (2013). *Digital control systems*. Berlin: Springer.

Ismail, H., Ishak, N., Tajjudin, M., Rahiman, M. H. F., & Adnan, R. (2012). Adaptive feedforward zero phase error tracking control with model reference for high precision xy table, In *Proceedings of the 4th international conference on intelligent and advanced systems (ICIAS), vol. 2*. IEEE, pp. 526–530.

Jain, N., Otten, R. J., & Alleyne, A. G. (2010). Decoupled feedforward control for an air-conditioning and refrigeration system. In *Proceedings of American control conference*, pp. 5904–5909.

Jiang, Y., Zhu, Y., Yang, K., Hu, C., & Yu, D. (2015). A data-driven iterative decoupling feedforward control strategy with application to an ultraprecision motion stage. *IEEE Transactions on Industrial Electronics*, *62*(1), 620–627.

Jinzenji, A., Sasamoto, T., Aikawa, K., Yoshida, S., & Aruga, K. (2001). Acceleration feedforward control against rotational disturbance in hard disk drives. *IEEE Transactions on Magnetics*, *37*(2), 888–893.

Johansson, B. (2003). Feedforward control in dynamic situations, Ph.D. dissertation, Linköping University.

Kaibel, G. (1987). Distillation columns with vertical partitions. *Chemical Engineering & Technology*, *10*(1), 92–98.

Karer, G., Mui, G., krjanc, I., & Zupani, B. (2011). Feedforward control of a class of hybrid systems using an inverse model. *Mathematics and Computers in Simulation*, *82*(3), 414–427.

Kempf, C. J., & Kobayashi, S. (1999). Disturbance observer and feedforward design for a high-speed direct-drive positioning table. *IEEE Transactions on Control Systems Technology*, *7*(5), 513–526.

Kim, H., Lee, K., Jeon, B., & Song, C. (2010). Quick wafer alignment using feedforward neural networks. *IEEE Transactions on Automation Science and Engineering*, *7*(2), 377–382.

Klančar, G., & Škrjanc, I. (2007). Tracking-error model-based predictive control for mobile robots in real time. *Robotics and Autonomous Systems*, *55*(6), 460–469.

Ko, P. J., Wang, Y. P., & Tien, S. C. (2013). Inverse-feedforward and robust-feedback control for high-speed operation on piezo-stages. *International Journal of Control*, *86*(2), 197–209.

Kusama, A., Nakamachi, I., Shigihara, K., Amemori, H., Miyata, Y., & Iwamoto, T. (1986). Air fuel ratio control system for furnace. Apr. 29, US Patent 4,585,161.

Lee, H. S., & Tomizuka, M. (1996). Robust motion controller design for high-accuracy positioning systems. *IEEE Transactions on Industrial Electronics*, *43*(1), 48–55.

Li, M., Zhu, Y., Yang, K., Hu, C., & Mu. H. (2016). An integrated model-data based zero phase error tracking feedforward control strategy with application to an ultra-precision wafer stage. *IEEE Transactions on Industrial Electronics*, pp. 1–1.

Li, H., Jeong, S. K., & You, S. S. (2009). Feedforward control of capacity and superheat for a variable speed refrigeration system. *Applied Thermal Engineering*, *29*(5), 1067–1074.

Malchow, F., & Sawodny, O. (2012). Model based feedforward control of an industrial glass feeder. *Control Engineering Practice*, *20*(20), 6268.

Marconi, L., & Isidori, A. (2000). Mixed internal model-based and feedforward control for robust tracking in nonlinear systems. *Automatica*, *36*(7), 993–1000.

Marlin, T. E. (2000). *Process control*. New York: McGraw-Hill.

Miyazaki, T., Ohishi, K., Inomata, K., Kuramochi, K., Koide, D., & Tokumaru, D. (2004). Robust feedforward tracking control based on sudden disturbance observer and zpet control for optical disk recording system. In *Proceedings of the 8th IEEE international workshop on advanced motion control*. IEEE, pp. 353–358.

Nedic, N., Stojanovic, V., & Djordjevic, V. (2015). Optimal control of hydraulically driven parallel robot platform based on firefly algorithm. *Nonlinear Dynamics*, *82*(3), 1–17.

O'Brien, M. J., & Broussard, J. R. (1979). Feedforward control to track the output of a forced model. In *Proceedings of the 17th IEEE conference on symposium on adaptive processes*. IEEE, pp. 1149–1155.

Park, H. S., Chang, P. H., & Lee, D. Y. (1999). Continuous zero phase error tracking controller with gain error compensation. In *Proceedings of the 1999 American control conference, vol. 5*. IEEE, pp. 3554–3558.

Peng, H., & Tomizuka, M. (1993). Preview control for vehicle lateral guidance in highway automation. *Journal of Dynamic Systems, Measurement, and Control*, *115*(4), 679–686.

Piccagli, S., & Visioli, A. (2009). An optimal feedforward control design for the set-point following of MIMO processes. *Journal of Process Control*, *19*(6), 978–984.

Powell, J. D., Fekete, N., & Chang, C.-F. (1998). Observer-based air fuel ratio control. *IEEE Control Systems*, *18*(5), 72–83.

Rong, H. J., Wei, J. T., Bai, J. M., Zhao, G. S., & Liang, Y. Q. (2015). Adaptive neural control for a class of MIMO nonlinear systems with extreme learning machine. *Neurocomputing*, *149*, 405–414.

Ruegsegger, S., Wagner, A., Freudenberg, J. S., & Grimard, D. S. (1999). Feedforward control for reduced run-to-run variation in microelectronics manufacturing. *IEEE Transactions on Semiconductor Manufacturing*, *12*(4), 493–502.

Schaper, C. D., Cho, Y. M., Park, P., Norman, S. A., Gyugyi, P., Hoffmann, G., Balemi, S., Boyd, S. P., Franklin, G., Kailath, T. et al. (1992). Modeling and control of rapid thermal processing. In *Proceedings of rapid thermal and integrated processing*. International Society for Optics and Photonics, pp. 2–17.

Seborg, D. E., Mellichamp, D. A., Edgar, T. F., & Doyle, F. J. (2010). *Process dynamics and control*. London: Wiley.

Seidler, R., Noll, D., & Thiers, G. (2004). Feedforward and feedback processes in motor control. *Neuroimage*, *22*(4), 1775–1783.

Shinskey, F. G., & Levine, W. (1996). *The control handbook*. CRC Press and IEEE Press.

Shinskey, F. G. (1990). *Process control systems: Application, design and tuning*. NY: McGraw-Hill.

Skogestad, S., & Morari, M. (1987). Control configuration selection for distillation columns. *AIChE Journal*, *33*(10), 1620–1635.

Song, G., Zhao, J., Zhou, X., & De Abreu-García, J. A. (2005). Tracking control of a piezoceramic actuator with hysteresis compensation using inverse preisach model. *IEEE/ASME Transactions on Mechatronics*, *10*(2), 198–209.

Stoddard, K., Crouch, P., Kozicki, M., & Tsakalis, K. (1994). Application of feedforward and adaptive feedback control to semiconductor device manufacturing. In: *Proceedings of the 1994 American control conference, vol. 1*. IEEE, pp. 892–896.

Stojanovic, V., & Nedic, N. (2016). A nature inspired parameter tuning approach to cascade control for hydraulically driven parallel robot platform. *Journal of Optimization Theory & Applications*, *168*(1), 332–347.

Stojanovic, V., & Nedic, N. (2016). Identification of time-varying OE models in presence of non-Gaussian noise: Application to pneumatic servo drives. *International Journal of Robust & Nonlinear Control*, *26*(18), 3974–3995.

Stojanovic, V., & Nedic, N. (2016). Joint state and parameter robust estimation of stochastic nonlinear systems. *International Journal of Robust & Nonlinear Control*, *26*(14), 3058–3074.

Tan, S. C., Lai, Y., Tse, C. K., & Cheung, M. K. (2006). Adaptive feedforward and feedback control schemes for sliding mode controlled power converters. *IEEE Transactions on Power Electronics*, *21*(1), 182–192.

Tao, K. M., Kosut, R. L., & Aral, G. (1994). Learning feedforward control. In *Proceedings of the 1994 American control conference, vol. 3*. IEEE, pp. 2575–2579.

Tao, K. M., Kosut, R. L., & Ekblad, M. (1994). Feedforward learning-nonlinear processes and adaptation. In *Proceedings of the 33rd IEEE conference on decision and control, vol. 2*. IEEE, pp. 1060–1065.

Tao, K. M., Kosut, R. L., Ekblad, M., & Aral, G. (1994). Feedforward learning applied to rtp of semiconductor wafers. In *Proceedings of the 33rd IEEE conference on decision and control, vol. 1*. IEEE, pp. 67–72.

Tomizuka, M. (1974). The optimal finite preview problem and its application to man-machine systems. Ph.D. dissertation, Massachusetts Institute of Technology.

Tomizuka, M. (1987). Zero phase error tracking algorithm for digital control. *Journal of Dynamic Systems, Measurement, and Control*, *109*(1), 65–68.

Tomizuka, M. (1992). Feedforward digital tracking controllers for motion control applications. *Advanced Robotics*, *7*(6), 575–586.

Tomizuka, M. (1993). On the design of digital tracking controllers. *Journal of Dynamic Systems, Measurement, and Control*, *115*(2B), 412–418.

Tomizuka, M., Dornfeld, D., & Purcell, M. (1980). Application of microcomputers to automatic weld quality control. *Journal of Dynamic Systems, Measurement, and Control*, *102*(2), 62–68.

Tomizuka, M., & Janczak, D. (1985). Linear quadratic design of decoupled preview controllers for robotic arms. *International Journal of Robotics Research*, *4*(1), 67–74.

Torfs, D., De Schutter, J., & Swevers, J. (1992). Extended bandwidth zero phase error tracking control of nonminimal phase systems. *Journal of Dynamic Systems, Measurement, and Control*, *114*(3), 347–351.

Tsao, T. C., & Tomizuka, M. (1987). Adaptive zero phase error tracking algorithm for digital control. *Journal of Dynamic Systems, Measurement, and Control*, *109*(4), 349–354.

Wagner, A. B., Ruegsegger, S. M., Freudenberg, J. S., & Grimard, D. S. (1999). Interprocess run-to-run feedforward control for wafer patterning. In *Proceedings of the 1999 IEEE international conference on control applications, vol. 1*. IEEE, pp. 789–795.

Wang, J., & Malakooti, B. (1992). A feedforward neural network for multiple criteria decision making. *Computers & Operations Research*, *19*(2), 151–167.

Wu, M. F., Lin, W. K., Ho, C.-L., Wong, D. S. H., Jang, S. S., Zheng, Y., et al. (2007). A feed-forward/feedback run-to-run control of a mixed product process: Simulation and experimental studies. *Industrial & Engineering Chemistry Research*, *46*(21), 6963–6970.

Yamada, M., Funahashi, Y., & Fujiwara, Si. (1997). Zero phase error tracking system with arbitrarily specified gain characteristics. *Journal of Dynamic Systems, Measurement, and Control*, *119*(2), 260–264.

Yamada, M., Funahashi, Y., & Riadh, Z. (1999). Generalized optimal zero phase error tracking controller design. *Journal of Dynamic Systems, Measurement, and Control*, *121*(2), 165–170.

Yan, M. T., & Shiu, Y. J. (2008). Theory and application of a combined feedback-feedforward control and disturbance observer in linear motor drive wire-edm machines. *International Journal of Machine Tools and Manufacture*, *48*(3), 388–401.

Zhou, K., Doyle, J. C., Glover, K., et al. (1996). *Robust and optimal control* (Vol. 40). New Jersey: Prentice hall.

Zhou, K., & Wang, D. (2002). Unified robust zero-error tracking control of CVCF PWM converters. *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, *49*(4), 492–501.