PSO-based Parameter Tuning for a Two-Degree-of-Freedom IMC Scheme and Its Application to Paper Basis Weight Control

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Abstract: Basis weight is an important indicator for evaluating paper quality and a major factor directly affecting the economic benefits of enterprises. Focusing on the large time-delay, time-varying, and nonlinear characteristics of a basis weight control system, a two-degree-of-freedom (TDF) internal model control (IMC) method based on a particle swarm optimization (PSO) algorithm was proposed. The method took the integral of time multiplied by the absolute error (ITAE) as the objective function, and the PSO algorithm was used to optimize the time constant of the tuning IMC filter. The simulation results for the control system under the proposed TDF-IMC method based on the PSO algorithm demonstrate good set-point tracking performance, strong anti-interference capabilities, and good robustness properties. The application results revealed that the basis weight fluctuation range of the paper was ± 2 g/m^2, which significantly improved both the control quality and the product quality.

Keywords: basis weight control system; large time delay; IMC; two-degree-of freedom control; PSO algorithm

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1 Introduction

Basis weight is an important indicator for evaluating the quality of paper, which directly affects the economic benefits of enterprises; thus, it is the focus of the automatic control of the papermaking process. The basis weight is the weight per unit area of paper (unit: g/m^2). Factors, such as the coupling between the basis weight

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and the moisture content, pulp flow, concentration, papermaking machine itself, and surrounding environment, increase the difficulty of the basis weight control of paper. Moreover, the measurement point of the basis weight is at the curling portion, and the actuator (quantitative valve) is installed on the inlet pipe of the headbox. The large distance between the measurement point and the actuator results in basis weight control characteristics of a large time lag, time variation, and nonlinearity.

The Smith predictor has proven to be an effective controller for large time-delay processes, but it has the following two disadvantages: a) The primary controller (for example, PID controller) of the Smith predictive scheme does not have established parameter tuning rules; and b) the robustness of the closed-loop system is poor. Consequently, numerous modified schemes for the conventional Smith predictor have been proposed. Wang et al[1-2] proposed a two-degree-of-freedom (TDF) Smith predictor control scheme to improve the disturbance rejection; however, its robustness was not significantly improved and the complexity of the parameter tuning for the primary controller was not fully resolved. Gatcia et al[3] converted the Smith structure into an internal model control (IMC) structure, which significantly improved the robustness of the closed-loop system. However, the traditional IMC only has one degree of freedom; thus, the desired control effectiveness for the performance and robustness cannot always be simultaneously achieved under this framework[4]. Fortunately, an IMC with two degrees of freedom (TDF-IMC) can overcome the above deficiencies. Good performance and robustness can be simultaneously obtained with the TDF-IMC through the design of the set-point tracking controller and disturbance attenuation controller, respectively. However, tuning and optimizing the parameters of the TDF-IMC remains a problem, which has attracted a considerable amount of interest from scholars worldwide. For instance, Zhao[5] used the Taylor series expansion to tune the IMC parameters. Kaya[6] tuned the IMC parameters by specifying the robustness of the amplitude and phase margin. Sun et al[7] proposed a method by which the IMC filter time constants are determined by the maximum sensitivity function. However, large calculation costs are unavoidable for the abovementioned methods. Furthermore, the optimum parameters cannot get as empirical knowledge is often necessary to obtain satisfactory closed-loop control effectiveness. As a population-based algorithm, particle swarm optimization (PSO) has many advantages, such as simplicity, fast convergence speed, and high efficiency. Therefore, the PSO algorithm is employed in this study to optimize the filter time constants of the TDF-IMC at one time by taking the ITAE index as the objective function. Simulation results demonstrate that the disadvantages of the abovementioned methods can be overcome by the proposed parameter tuning and optimization method. In addition to the higher speed, better performance, and robustness compared to the traditional method, the TDF-IMC method can also be ensured.

2 Basis weight control system

A simplified diagram of an ordinary fourdrinier is illustrated in Fig.1. The mixed pulp is pumped into the machine chest, diluted with water and white water to a specified concentration of pulp, and then mixed with alum and other fillers. The pulp is fed through the high box, wire pit, pressure screen, and headbox, and then onto a wire screen[8]. Then, the stock was formed into a sheet, pressed, dried, and reeled up onto a reeling drum[9]. Quantitative control of the paper quality faces

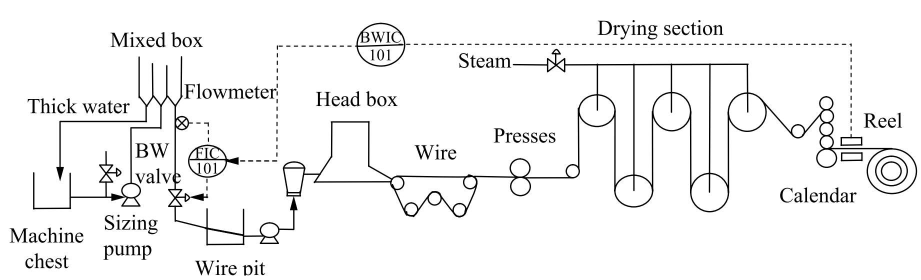


Fig.1 Schematic diagram of fourdrinier papermaking process

the following difficulties:

(1) There is an extremely long distance between the basis weight (BW) detection point (at the point where the sheet is reeled up onto the reeling drum) and the actuator (on the thick stock pipe of the stuff box outlet). Hence, papermaking is a large time-delay process.

(2) The papermaking process has time-varying nonlinear characteristics, which makes it difficult to establish an accurate mathematical model of the process.

(3) When the paper type is changed, the pulping, vehicle speed, etc. must be adjusted accordingly, which implies that the mathematical model will change. Consequently, the control system needs to have strong robustness.

To mitigate the abovementioned limitations and improve the quality of the papermaking process control, it is necessary to find an effective control algorithm that is suitable for large time-delay processes, does not rely on accurate mathematical models, and ensures control performance with strong robustness. Therefore, this study proposes the application of the PSO-TDF-IMC method to the basis weight control system of the papermaking machine.

3 IMC and TDF-IMC

Consider the traditional IMC control system depicted in Fig.2. The system output is the sum of the set-point tracking response and the load disturbance response. The IMC controller is usually designed in two steps as described below.

Step 1: Factorize the process model into the following:

$$G_m(s)=G_{m+}(s)G_{m-}(s) \tag{1}$$

Where, $G_{m+}(s)$ and $G_{m-}(s)$ denote the non-minimum phase and the minimum phase part, respectively. $G_{m+}(s)$ usually contains all the right-half plane zeros and the time delay in $G_{m-}(s)$.

Step 2: Design $C_1(s)$ as the inverse of $G_{m-}(s)$. To ensure the physical realization of the primary controller, a low-pass filter, $F(s)$, is often adopted. Then, we have the following:

$$C_1(s)=G_{m-}(s)^{-1}F(s) \tag{2}$$

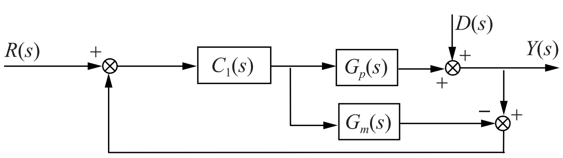
Where, $F(s)=\frac{K_f}{(\tau s+1)^r}$, r is specified as the minimum positive integer that can ensure that C_1 is physically realizable, τ is the filter time constant by which the performance and robustness of the closed-loop system can be adjusted easily and arbitrarily, and K_f must satisfy $G_{m+}(0)F(0)=1$.

The above IMC scheme has a single degree of freedom, which means that a trade-off must be made between the set-point and the disturbance control performance. A two-degrees-of-freedom control scheme can cater to both separately and achieve a better performance. The TDF-IMC controller is shown in Fig.3. If the model matches the process exactly, i.e., $G_p(s)=G_m(s)$, the two controllers can be designed separately.

$$C_1(s)=G_{m-}^{-1}F_1(s) \tag{3}$$

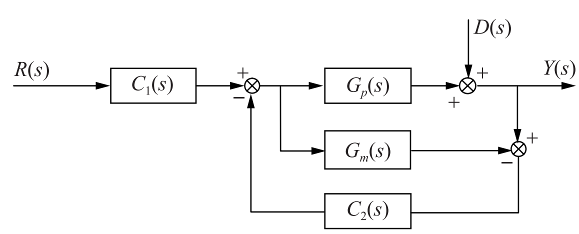
$$C_2(s)=G_{m-}^{-1}F_2(s) \tag{4}$$

Where, $F_1(s)=\frac{K_f}{(\tau_1 s+1)^r}$, $F_2(s)=\frac{K_f}{(\tau_2 s+1)^r}$, in which τ_1 and τ_2 are the filter time constants. Usually, parameteris τ_1 tuned for the set-point response speed and the robustness, while τ_2 is tuned for the disturbance rejection speed and the robustness. Such tunings are time-consuming and rely mainly on trial and error or experience.



$Y(s)$ is the system output; $R(s)$ is the set-point; $D(s)$ is the load disturbance; $G_p(s)$ is a stable process; $G_m(s)$ denotes the mathematical model of $G_p(s)$; $C_1(s)$ is the primary controller of the IMC.

Fig.2 Structure of the traditional IMC



$C_1(s)$ is the set-point tracking controller; $C_2(s)$ is the disturbance attenuation controller.

Fig.3 Structure of the TDF-IMC controller

Table 1 TDF–IMC for low–order processes

$G_M(s)$	$C_1(s)$	$C_2(s)$
$G_M(s)=\frac{K}{Ts+1}e^{-\tau s}$	$C_1(s)=\frac{Ts+1}{K(\tau_1 s+1)}$	$C_2(s)=\frac{Ts+1}{K(\tau_2 s+1)}$
$G_M(s)=\frac{K}{(T_1 s+1)(T_2 s+1)}e^{-\tau s}$	$C_1(s)=\frac{(T_1 s+1)(T_2 s+1)}{K(\tau_1 s+1)^2}$	$C_2(s)=\frac{(T_1 s+1)(T_2 s+1)}{K(\tau_2 s+1)^2}$

4 Proposed PSO tuning for TDF–IMC

To facilitate the tuning of the TDF-IMC with better performance, PSO is adopted to make the optimal selection of the two filter parameters, as shown in Fig.4. The ITAE index is taken as the objective function for optimization. Each particle has its position and speed updated in terms of social and individual cognition during the optimization search procedure until the optimality condition is reached. The proposed method is expected to simultaneously yield both satisfactory performance and robustness of the system.

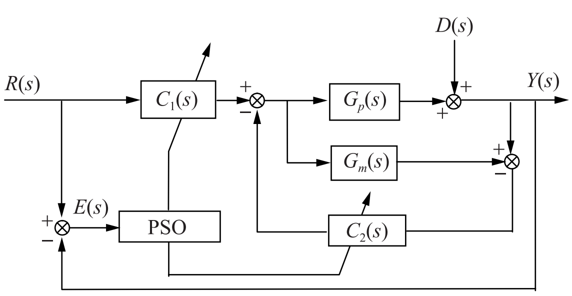


Fig.4 Control scheme of PSO-TDF-IMC

The PSO algorithm is a swarm intelligence optimization algorithm proposed by Eberhart and Kennedy in 1995[10]. Because of its simple structure and fast searching speed, the PSO algorithm has been successfully applied in a wide range of fields. A flowchart of the algorithm is depicted in Fig.5.

During the optimization process, a particle tracks its own best experience (the $pbset_{ij}^{k}$) and the whole population's best memory (the $gbest_j^k$), updates its velocity, adjusts its position, and finally reaches a position regarded as the so-far best solution for optimizing the filter time constants[11]. Regarding the information obtained by each particle and the swarm, the i-th particle's velocity and position at the k-th iteration are updated by Eq. (5).

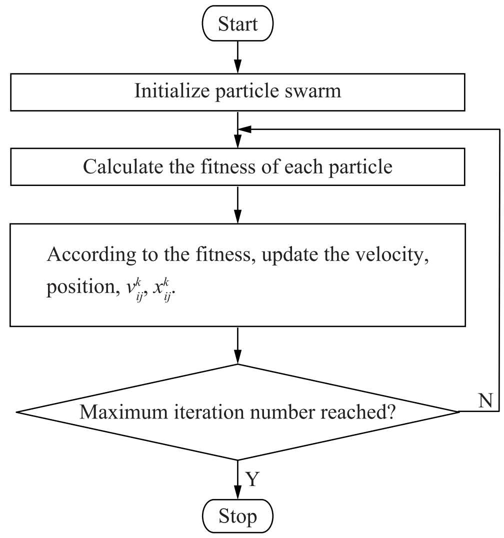


Fig.5 Flowchart of the PSO algorithm

$$\begin{cases} v_{ij}^{k+1}=wv_{ij}^{k}+c_1(pbest_{ij}^{k}-x_{ij}^{k})rand_1()+c_2(gbest_j^k-x_{ij}^{k})rand_2() \\ x_{ij}^{k+1}=x_{ij}^{k}+v_{ij}^{k} \quad i=1,2,3\cdots,N; j=1,2,\cdots,D \end{cases} \tag{5}$$

Where, v_{ij}^k, $x_{ij}^k \in R^n$ are the i-th particle's velocity and position vectors at the k-th iteration; ω is a number in [0,1] called the inertia weight; c_1, c_2 are the learning coefficients; $rand_1$, $rand_2$ are random numbers in [0,1]; $pbest_{ij}^k$, $gbest_j^k$ different from each other; are the individual best and the global best particles in the j-th dimension at the k-th iteration.

According to the research on the PSO-TDF-IMC scheme, the problem of optimizing the TDF-IMC controller parameters can actually be converted into an optimization problem in n-dimensional space. Therefore, this problem is based on how to find the optimal parameters of τ_1 and τ_2 within (0~3)T, which can be directly encoded with the real-code PSO algorithm; thus, X=[τ_1, τ_2]. It is necessary for the system to have a short settling time, small overshoot, and zero steady-state error.

It is supposed that the population size is N=30 and the particle position can be determined by the previous two controller parameters in the PSO-TDF-IMC scheme; thus, j=2, and we have the following:

$$P=(2,30)=\begin{bmatrix} \tau_{11} & \tau_{21} \\ \cdots & \cdots \\ \tau_{1N} & \tau_{2N} \end{bmatrix} \tag{6}$$

The results of numerous simulation experiments demonstrated that the ITAE could be used as an objective function and no further constraints were needed for a large time-delay. Therefore, the following fitness value function is chosen:

$$J = \frac{1}{\int_0^t t|e(t)|\mathrm{d}t} \tag{7}$$

According to the PSO flowchart, the detailed procedures for this system are as follows:

Step 1: The following PSO parameters are used to obtain the optimal performance of the control strategy:

ω_{max}=0.9, ω_{min}=0.4, c_1=c_2=2.

Several experiments are performed with different values for the population size N and the maximum number of iterations. The following values are considered to be acceptable:

N=30, iter_max=40.

For the optimization of the filter time constants, let $0 \leqslant \tau_1 \leqslant 3T$, $0 \leqslant \tau_2 \leqslant 3T$, to initialize the velocity and position of the particles.

Step 2: Now the initial values of the velocity and position of particles are plug into Eq. (5).

Then, the new velocity and position of the particle is given. The fitness function, J, is tested during this course. If the current particle's performance is better than that of its $pbest_{ij}^k$ and $gbest_j^k$, the better one will be saved and used as the new $pbest_{ij}^k$ or $gbest_j^k$ until the maximum iterations (here, iter_max=40) have been completed.

5 Simulation studies

The performance of the proposed method was first evaluated through the simulation study on the Simulink platform for the first order plus time delay system (FOPTD) and the second order plus time delay system (SOPTD).

Consider the FOPTD with the following transfer function:

$$G_{p1}(s) = \frac{1}{s+1}e^{-3s} \tag{8}$$

And consider the SOPTD described by the following transfer function:

$$G_{p2}(s) = \frac{1}{(10s+1)(5s+1)}e^{-s} \tag{9}$$

To demonstrate the performance and robustness of the PSO-TDF-IMC, some simulation comparisons based on the representation of Eq.(8) and Eq.(9) are performed via four methods: empirical method (EM-TDF-IMC), TDF-IMC method for which the controller parameters are tuned based on the maximum sensitivity (Ms-TDF-IMC), and the proposed method presented in this study (PSO-TDF-IMC). The results are listed in Table 2. The controller parameters of the double-controller Smith scheme (EM-TDF-Smith) from Ref. 3 are C_1=1+1/s and C_2=(0.9502s^2+1.95s+1)/(0.4s+1)^2.

Table 2 PSO–tuned TDF–IMC parameters

Methods \ Filter time constant	FOPTD		SOPTD	
	τ_1	τ_2	τ_1	τ_2
EM-TDF-IMC	1.468	2.975	1.952	4.576
Ms-TDF-IMC	1.657	2.0729	1.4142	3.4364
PSO-TDF-IMC	1.3042	1.8203	0.85717	0.82264

Herein, the set-point signal and disturbance signal are considered simultaneously due to the many measurable or non-measurable disturbance factors typically related to the industrial field. In the FOPTD system, the set-point input is a unit step signal and the load disturbance input is brought in at t = 25 s with an amplitude of 60% of the unit step. The simulation curves are shown in Fig.6. It is indicated that the PSO algorithm plays a significant role in the parameter optimization. Under normal conditions, the proposed method is more reliable and can provide a shorter settling time and higher anti-interference capabilities compared to the traditional method. At the same time, the control system has a slightly stronger robustness, but the Smith predictor also has the best performance, as shown in Fig.6(a). Therefore, in the practical control implementation, model mismatch is inevitable, namely parameter perturbation. Here, the robustness of the PSO-TDF-IMC system is also considered. The simulation results in Fig.6(b), Fig.6(c) and Fig.6(d) show that the controllers designed by the proposed method are still able to demonstrate good control performance even if the time-delay constants (τ) and time constants (T, T_1, T_2) are disturbed at random. Compared with the EM-TDF-Smith controller, the proposed method has a strong robustness.

For the SOPTD system, the set-point input is also set as a unit step signal and the load disturbance signal is brought in at t = 60 s with an amplitude of 60% of the unit step input. The simulation curves are shown in Fig.7. A similar conclusion can also be drawn from Fig.7. The EM-TDF-Smith controller clearly shows a weak robustness. Therefore, the proposed method indicates an acceptable performance. The simulation results demonstrate that the control strategy can maintain a shorter settling time than the EM-TDF-IMC and Ms-TDF-IMC except for a small overshoot in the case of parameter perturbation. For these reasons, the proposed method can be applied for low overshoot requirements, such as paper basis weight control.

6 Application to paper basis weight control

In this study, the FOPTD transfer function model is used to represent the controlled object, i.e., the paper basis weight in the papermaking process. The identified FOPTD model of the process is represented as follows[12]:

$$G(s) = \frac{Y(s)}{R(s)} = \frac{1.7}{30s+1} e^{-80s} \tag{10}$$

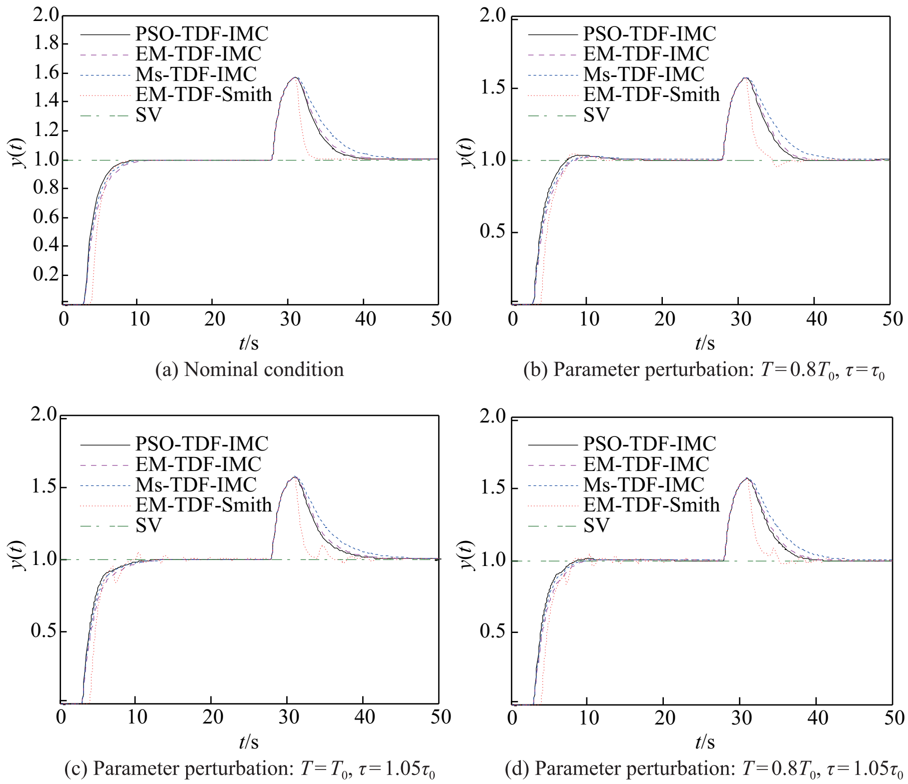


Fig.6 Simulation curve of FOPTD

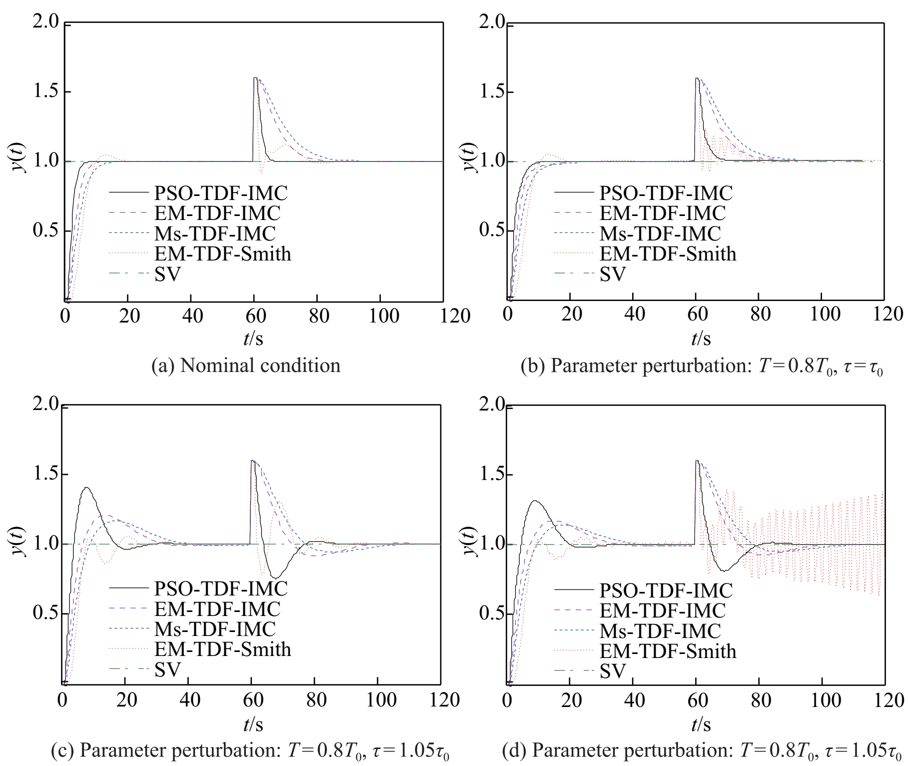


Fig.7 Simulation curve of SOPTD

The proposed control scheme is used for the basis weight control of a papermaking plant. The simulation

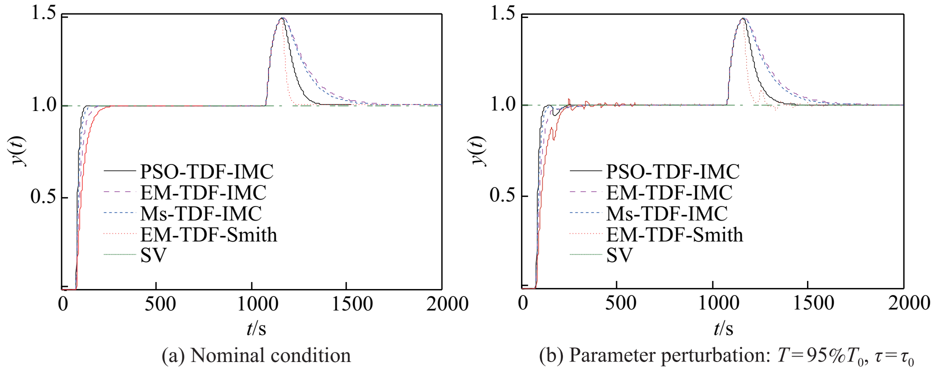


Fig.8 Simulation curve of paper basis weight control

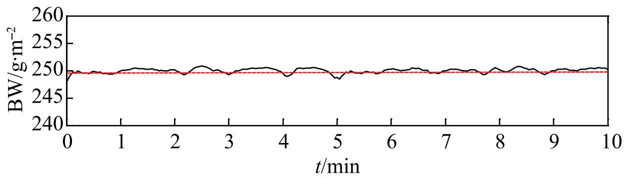


Fig.9 Curves of quantitative longitudinal change under stable condition

results are shown in Fig.8, and the actual results are shown in Fig.9.

The fluctuation range of the basis weight was controlled within the range of −2.5 g/m^2 to +2.5 g/m^2. However, according to the national standard, the quality specification of the basis weight fluctuation range is −7 g/m^2 to +6 g/m^2. Hence, the product quality is greatly improved, resulting in notable economic benefits.

7 Conclusions

In this study, the optimal parameter tuning based on the PSO algorithm for the TDF-IMC was proposed for the basis weight control system. The simulation results demonstrated that the proposed method is practical and effective. The performance and robustness of the closed-loop system tuned by the proposed method was also analyzed. The real-time application to paper basis weight control indicated the feasibility and effectiveness of the proposed tuning method for the TDF-IMC structure.

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