

Research on Superconducting Cavity Helium Pressure Tuning System Based on Adaptive Smith Predictive Control

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Date: 2025-04-22T17:09:48+00:00

Abstract

To meet the frequency tuning requirements of superconducting cavities in superconducting linear accelerators, the Institute of Modern Physics, Chinese Academy of Sciences has designed and developed a helium pressure tuning controller that achieves stable superconducting cavity frequency through real-time monitoring of helium gas pressure and motor position, enabling precise control of fast-pulse solenoid valves. The research focuses on the nonlinearity and delay issues inherent in helium pressure regulation. Traditional control methods are inadequate for meeting the high-precision and rapid-response demands of superconducting cavity tuners. Consequently, an optimized solution is proposed: employing adaptive algorithms to dynamically adjust control parameters to address nonlinear characteristics, while integrating Smith predictive control to compensate for system delays and enhance response speed. Experimental results demonstrate that this approach significantly improves the closed-loop control accuracy, robustness, and dynamic performance of superconducting cavity frequency tuning, satisfying the stringent requirements for superconducting cavity frequency synchronization in superconducting linear accelerators, thereby providing an efficient solution for superconducting cavity tuning.

Full Text

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Abstract

To address the frequency tuning requirements of superconducting cavities in linear accelerators, the Institute of Modern Physics, Chinese Academy of Sciences, has developed a helium pressure tuning controller that achieves frequency stability through precise control of fast-pulse solenoid valves based on real-time monitoring of helium pressure and motor position. The study focuses on the nonlinearities and time delays inherent in helium pressure regulation, which pose significant challenges for conventional control methods in meeting the stringent demands for high precision and rapid response in superconducting cavity tuners. We propose an optimized solution that employs an adaptive algorithm to dynamically adjust control parameters for handling nonlinear characteristics, combined with Smith predictor control to compensate for system delays and enhance response speed. Experimental results demonstrate that this approach substantially improves the closed-loop control accuracy, robustness, and dynamic performance of superconducting cavity frequency tuning, satisfying the rigorous synchronization requirements for superconducting cavity frequencies in linear accelerators and providing an efficient solution for cavity tuning.

Keywords: Superconducting cavity; helium pressure tuning; adaptive control; Smith predictor control; frequency stability

CLC number: TL53 **Document code:** A

Received date: 2025-03-11

Revised date: 2025-04-10

Foundation items: Item 1 (2017-000052-75-01-000590); Item 2 (E329851Y)

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Accelerator Driven Subcritical Systems (ADS) represent a cutting-edge technology for nuclear waste transmutation via hard neutron spectra. High-power proton beams in these systems are produced by linear accelerators utilizing superconducting acceleration technology, with superconducting cavities serving as the core components [1]. The extremely narrow bandwidth of superconducting cavities necessitates strict synchronization between their operating frequency and the accelerator reference frequency. However, operational disturbances such as helium pressure fluctuations, Lorentz force detuning, and microphonic effects can induce cavity frequency offsets, directly compromising stable operation [2]. Consequently, real-time frequency control by tuners is essential for ensuring superconducting cavity system stability.

To enhance the mechanical stability of superconducting cavities, the Institute of Modern Physics, Chinese Academy of Sciences, has developed a half-wave resonator (HWR) copper-niobium composite superconducting cavity operating at 162.5 MHz in a 4.2 K liquid helium environment [3]. However, copper-niobium composite cavities exhibit greater stiffness than pure niobium cavities, rendering the original scissor-type tuner ineffective at deforming the cavity. Consequently, a pneumatic tuner is now employed, which adjusts the cavity geometry by regulating internal helium pressure to achieve frequency tuning. This approach offers significant advantages over traditional slow mechanical tuners, including zero backlash, vibration-free operation, and structural simplicity, making it a highly promising tuning method for superconducting cavities. Nevertheless, pneumatic tuners face multiple challenges in practical applications. First, helium pressure regulation exhibits pronounced nonlinear characteristics, with varying response across different pressure ranges [4]. Second, the mechanical system's dynamic response involves substantial time delays, creating significant difficulties for high-frequency real-time control. Additionally, various environmental disturbances necessitate a control system with both high precision and rapid response capabilities.

To address these challenges, this paper proposes an optimized solution: employing an adaptive algorithm to dynamically adjust proportional-integral (PI) parameters for handling nonlinearities, combined with Smith predictor control to compensate for system delays and improve response speed. Experimental results demonstrate that this scheme significantly enhances superconducting cavity frequency closed-loop precision and system robustness, providing an efficient solution for frequency synchronization in high-intensity accelerators.

1 Helium Pressure Tuner Mechanical Composition and Characteristics

The Institute of Modern Physics, Chinese Academy of Sciences, has designed a novel helium pressure tuner for HWR copper-niobium composite superconducting cavities. The tuner adjusts bellows deformation by regulating helium pressure, which is then transmitted to a tuning plate via steel cables to modify cavity geometry and achieve frequency tuning. This design offers advantages such as zero backlash and structural simplicity, making it suitable for high-precision frequency control.

[Figure 1: see original paper] Superconducting cavity tuner mechanical structure 3D model.

Tuner requirement parameter list HWR010 frequency sensitivity tuner stiffness cavity sensitivity tuning frequency range kHz/kN kN/mm kHz/mm MPa/mm tuning maximum stress.

Additionally, the Facility for Rare Isotope Beams (FRIB) laboratory has designed a similar helium pressure tuner [5]. Their scheme employs a proportional solenoid valve for coarse pressure adjustment, followed by fine pressure tuning

via a stepper motor to stabilize frequency. Although this approach improves tuning control precision to some extent, further optimization of response time under high-disturbance conditions is still needed.

The nonlinear characteristics of superconducting cavity helium pressure tuning systems represent both a distinctive feature and a control challenge. This study tested the pressure regulation frequency characteristics of HWR copper-niobium composite superconducting cavities. [Figure 2: see original paper] demonstrates the nonlinear relationship between helium pressure tuner gas path pressure and cavity frequency variation, along with the impact of system delay on frequency regulation. These factors pose considerable challenges for stable control of superconducting cavity frequency.

[Figure 2: see original paper] Helium pressure tuner nonlinearity test.

2.1 Control Scheme Design

[Figure 3: see original paper] presents the overall control scheme design for the helium pressure tuner. The Low-Level Radio Frequency (LLRF) control system measures the superconducting cavity frequency in real time, issuing control commands to the tuner driver to adjust the pulse solenoid valve status in the helium pressure tuner gas circuit and control the closed-loop stepper motor position, thereby achieving precise regulation of helium pressure. The tuner utilizes bellows deformation to alter cavity geometry, thus stabilizing the superconducting cavity frequency.

LLRF constitutes the core of superconducting cavity control, with key parameters listed in . The LLRF system is used to stabilize the resonant frequency, amplitude, and phase of high-frequency cavities [6]. The LLRF system at the Institute of Modern Physics, Chinese Academy of Sciences (IMPCAS) employs an all-digital quadrature demodulation architecture, supporting multiple frequency points at 162.5 MHz, 325 MHz, and 650 MHz [7,8].

The helium pressure tuner control system monitors cavity frequency detuning in real time by measuring the phase difference between forward and reflected radio frequency (RF) signals via LLRF, using the phase detuning angle as a feedback signal. The target deadband range is set from -5° to 5° . The system employs closed-loop feedback control to regulate the helium pressure tuner, changing helium pressure in the bellows: increased pressure lowers cavity frequency, while decreased pressure raises it.

LLRF key technical parameters

- Frequency: 162.5 MHz
- Architecture: Quadrature demodulation, all-digital closed-loop feedback
- ADC resolution: 16 bits
- Sampling rate: 250 MS/s
- Phase resolution: 0.05°
- Latency: <1.5 s

This scheme combines coarse adjustment (solenoid valve) and fine adjustment (stepper motor) to achieve a balance between rapid response and high-precision control. This design significantly enhances system robustness and dynamic performance, offering substantial practical application value.

2.2 PI Control Scheme

PID control regulates error through proportional (P), integral (I), and derivative (D) terms to achieve stable system control [9]. However, in superconducting cavity tuning systems, the derivative term (D) may amplify system noise due to the high sensitivity and complex dynamic characteristics of superconducting cavities, leading to control instability. Therefore, this paper adopts a PI control scheme to balance system stability and response speed.

The PI controller output $u(t)$ consists of proportional and integral terms, with the mathematical expression as follows: $K_e t$, where $e(t)$ represents the error between the phase detuning angle and the target value; K_p is the proportional gain for rapid error response; K_i is the integral gain for eliminating steady-state error.

In the helium pressure tuning system, PI control adjusts the solenoid valve opening in real time based on phase detuning angle error to regulate helium pressure. Specifically, the proportional term K_p enables rapid response to error changes, while the integral term K_i eliminates steady-state error by accumulating historical error values, ensuring long-term stability of superconducting cavity frequency. In experiments, PI control parameters K_p and K_i are optimized through scanning tests, with specific parameter selection and results detailed in Section 3.3.

Compared with full PID control, the PI control scheme avoids noise amplification from the derivative term, making it more suitable for high-precision, low-noise superconducting cavity tuning control scenarios. This design enhances system robustness and stability while maintaining control precision.

2.3 Adaptive PI Control

In superconducting cavity helium pressure tuning systems, helium pressure regulation exhibits significant nonlinear characteristics, making it difficult for traditional PI control methods to maintain optimal performance across different operating points. To address this issue, this paper proposes an adaptive PI control scheme that introduces Fuzzy Logic Control (FLC) to dynamically adjust PI controller parameters, adapting to system nonlinearities and thereby improving control precision and response speed [10].

The core of the adaptive PI controller lies in real-time adjustment of proportional gain K_p and integral gain K_i based on system error $e(t)$ and error change rate $\Delta e(t)$. The implementation proceeds as follows: first, error $e(t)$ and error change rate $\Delta e(t)$ are mapped into fuzzy sets as fuzzy variables; next, fuzzy inference

rules are designed based on experience and system characteristics to determine K_p and K_i adjustment strategies; finally, fuzzy inference results are converted into specific K_p and K_i values and applied to the PI controller.

In superconducting cavity tuning systems, the adaptive PI controller demonstrates several advantages: (1) Nonlinear adaptability: through fuzzy logic, the controller can dynamically adjust parameters based on error magnitude and trend. For example, increasing K_p when errors are large to accelerate response, while decreasing K_p and increasing K_i when errors are small to eliminate steady-state error and reduce oscillation and overshoot. (2) Dynamic response: real-time parameter adjustment maintains optimal response characteristics across different operational phases, enhancing tuning efficiency.

Experiments show that adaptive PI control significantly optimizes control performance through piecewise parameter adjustment. Specifically: during initial tuning stages, rapid response capability shortens adjustment time; when approaching target frequency, reduced adjustment amplitude decreases overshoot; compared with traditional fixed-parameter PI control, the adaptive PI controller exhibits stronger stability and anti-interference capability during long-term operation (detailed data in Section 3.4).

By combining fuzzy logic with PI control, the adaptive PI control scheme can effectively address the nonlinear characteristics of helium pressure in superconducting cavity tuning systems, improving overall system control performance. This method provides a valuable reference for similar nonlinear control scenarios.

2.3 Smith Predictor Combined with PI Control

The superconducting cavity helium pressure tuning system is used to precisely control cavity resonant frequency, with the key being helium pressure control. However, the mechanical system of the helium pressure tuner exhibits significant time delays (approximately 18.5 ms), causing traditional PI controllers to perform poorly in control precision and response speed. To overcome this challenge, this paper proposes combining Smith Predictor Control with PI control to compensate for system delays and improve overall performance [11].

Smith predictor control is an optimization method for time-delay systems that uses a predictive model to estimate future system outputs, thereby counteracting delay effects [12]. Its core principles include: (1) System modeling: based on system dynamic characteristics, establish a delay-free transfer function model $GB(s)$ and accurately identify the actual system delay time t ($t = 18.5$ ms in this system). (2) Prediction mechanism: the Smith predictor uses the delay-free model $GB(s)$ to predict system output after delay time t . By applying the controller output signal to the system t time units in advance, the lag effect caused by delay is effectively compensated. (3) The closed-loop transfer function can be expressed as:

where $D(s)$ is the PI controller transfer function, $GB(s)$ is the delay-free model, and e^{-ts} represents the delay term. Through this design, the delay term is moved outside the closed-loop control loop, no longer directly affecting system stability [13].

In the superconducting cavity helium pressure tuning system, the combined application of Smith predictor control and PI control includes the following steps: first, introduce the Smith predictor into the control system based on the measured delay time of 18.5 ms, using the predictive model to calculate system response in advance and eliminate delay effects. Then, the PI controller dynamically adjusts the solenoid valve opening based on the prediction error signal provided by the Smith predictor, thereby achieving precise control of helium pressure. Experimental results show that after adopting Smith predictor combined with PI control, the system can adjust the phase detuning angle from 35° to the target deadband range (-5° to 5°) in only 8.3 seconds. In contrast, traditional adaptive PI control requires 13 seconds, representing a reduction in adjustment time of approximately 36.2% (detailed in Section 3.5).

Smith predictor control significantly improves the response speed and control precision of superconducting cavity tuning systems by effectively compensating for system delays. Compared with traditional PI control, this method demonstrates superior performance in handling time-delay systems, providing an efficient and reliable solution for high-precision pressure regulation. The successful application of this method validates its practical value in complex industrial control scenarios.

3.1 Horizontal Test Bench Setup

As shown in [Figure 4: see original paper], the horizontal test platform is a comprehensive experimental system integrating a radio frequency superconducting cavity, cryostat, power coupler, frequency tuner, and vacuum and cryogenic equipment. Its primary purpose is to evaluate tuner performance and superconducting cavity operating characteristics by applying high-frequency electromagnetic fields to the RF superconducting cavity in the superconducting state and performing frequency tuning.

[Figure 4: see original paper] Test platform 3D diagram (left) and site photo (right). During testing, the superconducting cavity is placed in a cryostat and cooled to 4 K to achieve superconductivity. High-frequency power is then introduced through a capacitive coupler to establish an electromagnetic field. The tuner uses helium-driven actuation to adjust cavity frequency, and by measuring the deviation between resonant frequency and theoretical values, the tuner's tuning range, precision, and superconducting cavity operational performance are verified.

3.2 Frequency Closed-Loop Testing

To evaluate the closed-loop control performance of the helium pressure tuning system, this experiment employs the superconducting cavity frequency detuning angle as a feedback signal to test frequency regulation capability under various operating conditions. The objective is to maintain the phase detuning angle within the deadband range (-5° to 5°) to ensure superconducting cavity frequency stability. Test results are shown in [Figure 5: see original paper].

[Figure 5: see original paper] On/Off control closed-loop test. The control system regulates helium pressure in real time based on phase detuning angle changes, with the following specific strategy: when the phase detuning angle exceeds 5° , the intake valve is closed and the exhaust valve opened to reduce helium pressure and increase frequency; when the phase detuning angle falls below -5° , the exhaust valve is closed and the intake valve opened to increase helium pressure and decrease frequency; when the phase detuning angle enters the deadband range, valve adjustment stops and fine-tuning is performed by the stepper motor.

In the experiment, On/Off logic control is adopted for frequency regulation. Results show that the system can gradually adjust cavity frequency to the target range, but significant overshoot occurs during regulation, with maximum overshoot amplitude of approximately 33.6° . When approaching the target frequency, noticeable frequency fluctuations occur and rapid stabilization is not achieved, indicating insufficient dynamic performance.

[Figure 5: see original paper] illustrates the phase detuning angle variation curve in the frequency closed-loop test. Test results demonstrate that On/Off logic control has limitations in regulation speed and precision, necessitating the introduction of optimized algorithms such as PI control in subsequent work to improve system stability and regulation performance.

3.3 PI Control Testing

To optimize the closed-loop performance of the superconducting cavity helium pressure tuning system, this experiment tested PI control effectiveness and determined optimal control parameters through parameter scanning. Experimental results are shown in [Figure 6: see original paper] and [Figure 7: see original paper].

The experiment initially manually adjusted the phase detuning angle to -80° , then activated the PI control program with the goal of regulating the phase detuning angle to the deadband range (-5° to 5°). The PI controller adjusts solenoid valve opening in real time based on error $e(t)$ to control helium pressure. Parameter scanning tests recorded regulation effects under different K_p and K_i combinations, with specific data provided in .

[Figure 6: see original paper] PI control closed-loop test. [Figure 7: see original paper] PI control parameter scanning test. PI control parameter scanning phase

detuning angle.

[Figure 6: see original paper] shows that compared with On/Off logic control, PI control significantly reduces overshoot, smoothly adjusting the phase detuning angle from -80° to the deadband range with overshoot less than 5° , markedly improving closed-loop stability. [Figure 7: see original paper] and present parameter scanning results, indicating that most parameter combinations exhibit some overshoot and deviate significantly from the deadband range. When $K_p = 0.7$ and $K_i = 0.0012$, the system performs optimally, with the phase detuning angle entering the deadband range first (final value of 1.86°) and a smooth regulation process consistent with design expectations.

3.4 Adaptive PI Control Testing

To further enhance the superconducting cavity helium pressure tuning system's adaptability to nonlinear characteristics, this experiment tested adaptive PI control performance. Experimental results are shown in [Figure 8: see original paper]. The experiment lasted 30 minutes, initially manually adjusting the phase detuning angle to -40° , then activating adaptive PI control. The adaptive algorithm dynamically adjusts K_p and K_i based on error $e(t)$ and error change rate $\Delta e(t)$ through fuzzy logic: initial stage—when error is large, larger K_p and moderate K_i are used to rapidly reduce phase detuning; intermediate stage—when error decreases, parameters switch to medium values to slow adjustment speed; approaching target—smaller K_p and larger K_i are used for fine-tuning to avoid overshoot. The goal is to stabilize the phase detuning angle within the deadband range (-5° to 5°).

[Figure 8: see original paper] illustrates the adaptive PI control regulation process: (1) Rapid response: during the initial stage, the phase detuning angle quickly approaches the target from -40° in approximately 13 seconds, outperforming fixed-parameter PI control; (2) Stability: after entering the deadband, the system maintains stability for 30 minutes, and despite helium pressure fluctuation disturbances, the control system adjusts promptly to keep the phase within the deadband range; (3) Oscillation issues: multiple oscillations occur during regulation, especially when approaching the target, with oscillation amplitude of approximately $\pm 3^\circ$, indicating that anti-interference capability needs optimization.

Delay tests show that system delay has some influence on oscillation phenomena. Adaptive PI control demonstrates superior performance compared with traditional PI control in terms of rapid response and long-term stability, particularly for nonlinear operating conditions. However, the oscillation issue suggests that further optimization of delay compensation strategies is needed.

[Figure 8: see original paper] Adaptive algorithm combined with PID control closed-loop test for half an hour.

3.5 Smith Predictor PI Control Testing

To address delay issues in the superconducting cavity helium pressure tuning system, this experiment tested Smith predictor combined with PI control performance. Experimental results are shown in [Figure 9: see original paper]. Based on the previously measured system delay time (18.5 ms), the Smith predictor delay constant is set to 0.0185 s in the control program. The test initially manually adjusted the phase detuning angle to 35° , with the goal of regulating the phase to the deadband range (-5° to 5°). The Smith predictor adjusts the PI controller output signal in advance by predicting future system output, driving the solenoid valve to regulate helium pressure.

[Figure 9: see original paper] illustrates the Smith predictor combined with PI control regulation process: (1) Regulation speed: the system stabilizes the phase detuning angle from 35° to the deadband range in two adjustments (totaling approximately 8.3 seconds), representing a reduction of about 36.2% compared with adaptive PI control (13 seconds); (2) Stability: after entering the deadband, the phase detuning angle can be maintained within the target range for extended periods (fluctuation amplitude less than $\pm 2^\circ$) without significant overshoot, demonstrating good closed-loop stability; (3) Delay compensation effect: the Smith predictor effectively counteracts system delay effects, making control responses more timely.

Additionally, during the test process shown in [Figure 9: see original paper], both superconducting cavity amplitude and phase are simultaneously closed-loop and maintained stable for long durations. Compared with traditional PI control and adaptive PI control, Smith predictor combined with PI control shows significant improvements in both response speed and precision, particularly exhibiting the best performance in handling time-delay systems. This result validates the applicability of the Smith predictor in superconducting cavity tuning. Smith predictor combined with PI control significantly improves system dynamic performance and stability, representing the optimal control scheme among those tested.

[Figure 9: see original paper] Smith predictor combined with PID control closed-loop test.

4 Summary and Outlook

For superconducting cavity helium pressure tuners, this study has developed an efficient control scheme that achieves closed-loop stable regulation of copper-niobium composite superconducting cavity frequency through direct control of fast-pulse solenoid valves, combined with adaptive algorithms and Smith predictor control to optimize the PI controller. Experiments demonstrate that Smith predictor combined with PI control substantially reduces superconducting cavity frequency closed-loop regulation time, significantly outperforming both traditional PI control and adaptive PI control. This scheme effectively improves

system dynamic performance and robustness, meeting the stringent frequency synchronization requirements of high-intensity accelerators.

This research provides new insights for frequency tuning of copper-niobium composite superconducting cavities and validates the feasibility of pulse-width modulation (PWM) solenoid valve control and novel LLRF control algorithms. Compared with the helium pressure tuner control scheme at the FRIB laboratory, this system achieves high-precision control without requiring stepper motor fine-tuning, simplifying the structure and reducing delays, thus providing an important reference for the design of high-performance accelerators such as ADS.

References

- [1] ZHAN Wenlong, XU Hushan. Advanced Fission Energy Program-ADS Transmutation System [J]. Bulletin of Chinese Academy of Sciences, 2012, (3): 375-381. (in Chinese). (詹文龙, 徐瑚珊. 未来先进核裂变能——ADS 嬗变系统 [J]. 中国科学院院刊, 2012, 27(03): 375-381. doi: 10.3969/j.issn.1000-3045.2012.03.017)
- [2] LI Tao, ZHANG Bin, LIU Lubei, et al. Design and test of the helium pneumatic tuner based on 162.5 MHz superconducting cavity [J]. Nuclear Techniques, 2015, 38(10): 22-26. (in Chinese) (李涛, 张斌, 刘鲁北, 等. 基于 162.5 MHz HWR 超导腔的氦压调谐器的设计与测试 [J]. 核技术, 2015, 38(10): 22-26. DOI: 10.11889/j.0253-3219.2015.hjs.38.100201)
- [3] 中国科学院近代物理研究所. 我国首套铜铌复合腔高稳定超导加速单元研制成功 [EB/OL]. [2025-2-18]. https://www.imp.cas.cn/kyjz2017/202412/t20241231_7512356.html
- [4] HE Shoubo, HE Yuan, YUE Weiming, et al. Study on the frequency tuning of the half-wave resonator at IMP [J]. Chinese Physics C, 2014, 38(06): 113-117. doi: 10.1088/1674-1137/38/6/067
- [5] Chang W, Hartung W, Kim S, et al. Enhanced Pneumatic Tuner Control for FRIB Half-Wave Resonators [C] // 20th International Conference on RF Superconductivity (SRF' 21), Geneva, Switzerland: JACOW 2022: 829.
- [6] Chen Q, Gao Z, Zhu Z L, et al. Multi-frequency point supported LLRF front-end for CiADS wide-bandwidth application [J]. Nuclear Science and Techniques, 2020, 31(3): 29. doi:org/10.1007/s41365-020-0733-9
- [7] Zhu Z, Wang X, Wen L, et al. The Test of LLRF control system on superconducting cavity [J]. arXiv preprint, 2014. doi:org/10.48550/arXiv.1406.1266
- [8] Geng Z. Superconducting cavity control and model identification based on active disturbance rejection control [J]. IEEE Transactions on Nuclear Science, 2017, 64(3): 951. doi: 10.1109/TNS.2017.2663660
- [9] Knospe C. PID control [J]. IEEE Control Systems Magazine, 2006, 26(1): 30-31. doi: 10.1109/MCS.2006.1580151.

- [10] Fischle K, Schroder D. An improved stable adaptive fuzzy control method[J]. IEEE transactions on fuzzy systems, 1999, 7(1): 27-40.doi: 10.1109/91.746301
- [11] Grimholt C, Skogestad S. Should we forget the Smith Predictor?[J]. Elsevier IFAC Publications / IFAC Proceedings series. 2019, 51 (4), 769.doi: org/10.1016/j.ifacol.2018.06.203
- [12] ZHANG Qi, XI Aimin, LI Li. A Fuzzy Controller with Smith Compensation[J]. Industry Control and Applications,2008,(05):39-42. (in Chinese). 张琦, 席爱民, 李莉. 基于施密斯补偿原理的模糊 PID 控制器设计 [J]. 自动化技术与应用,2008,(05):39-42.doi: 1003-7241 (2008) 05-0039-04
- [13] Xiong Zhenkai. Smith For eor daining Estimated Implement Ar ithmetic Research[J]. MECHANICAL MANAGEMENT AND DEVELOPMENT,2007,(06):7-8. (in Chinese). 熊珍凯. 施密斯 (Smith) 预估器算法研究 [J]. 机械管理开发,2007,(06):7-8.doi:10.16525/j.cnk i.cn14-1134/th.2007.06.052.

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