

DESIGN AND DEVELOPMENT OF A NOVEL HIGH-PRECISION INTEGRATED MEASUREMENT AND CONTROL GATE

CONCEPTION ET DÉVELOPPEMENT D'UNE NOUVELLE VANNE INTÉGRÉE DE MESURE ET DE RÉGULATION DE HAUTE PRÉCISION

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ABSTRACT

Against the global demand for intelligent water conservancy and refined open-channel management, this paper proposes a novel precision integrated flow measurement and control gate based on ultrasonic layered velocity measurement and dual-mode closed-loop control. The research aims to overcome the common defects of traditional integrated gates, including low accuracy caused by layered data missing, unstable measurement under variable water levels, and single control function. An improved open-channel ultrasonic flow calculation model is established using the travel-time difference method to measure layered velocity, combined with the sectional velocity-area method and embedded sluice orifice flow formula, which ensures high precision across full water-level conditions. To solve the problem of missing layered signals in field applications, the SAITS (Self-Attention-based Imputation for Time Series) model is adopted to reconstruct incomplete velocity data, significantly enhancing the robustness of the measurement system. The gate adopts modular hardware and software design, consisting of a main control unit, multi-layer ultrasonic acquisition, step motor drive, solar power supply, and 4G/LoRa communication. An adaptive PID algorithm is applied to realize autonomous switching and stable operation between constant water level control and constant flow control. The mechanical structure integrates an optimized gate body, sealed frame, actuating mechanism, and dedicated ultrasonic measurement column, featuring compact layout, reliable water stop, corrosion resistance, and easy installation. Experiments are conducted in a rectangular open channel with a length of 5.92m and a width of 1.00m. Results show that the SAITS imputation model achieves a MAPE of 1.77% under missing layers, and the overall flow measurement error is controlled within $\pm 2\%$. This integrated gate effectively improves the accuracy, stability, and flexibility of open-channel measurement and control, providing a practical technical solution for intelligent water resources allocation and smart irrigation construction worldwide.

Keywords: Integrated Measurement and Control Gate, Precision Irrigation, Automatic Control, Water Resources Management, Irrigation District Modernization.

RÉSUMÉ

Face à la demande mondiale en faveur d'une gestion intelligente de l'eau et d'une gestion fine des canaux à surface libre, cet article propose une nouvelle vanne intégrée de mesure et de régulation précise du débit, fondée sur la mesure ultrasonore de la vitesse par couches et sur une commande en boucle fermée à deux modes. La recherche vise à remédier aux défauts courants des vannes intégrées classiques, notamment la faible précision due à l'absence de données pour certaines couches, l'instabilité des mesures lorsque le niveau d'eau varie et la présence d'une seule fonction de commande. Un modèle amélioré de calcul ultrasonore du débit en canal à surface libre est établi : il

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utilise la méthode de la différence des temps de parcours pour mesurer la vitesse par couches, combinée à la méthode vitesse-section et à une formule intégrée d'écoulement par orifice de vanne, ce qui garantit une grande précision sur toute la plage des niveaux d'eau. Pour résoudre le problème des signaux de couches manquants dans les applications de terrain, le modèle SAITS (Self-Attention-based Imputation for Time Series) est utilisé afin de reconstituer les données de vitesse incomplètes, ce qui renforce sensiblement la robustesse du système de mesure. La vanne adopte une conception modulaire du matériel et du logiciel, comprenant une unité de commande principale, un dispositif d'acquisition ultrasonore multicouche, un entraînement par moteur pas à pas, une alimentation solaire et des communications 4G/LoRa. Un algorithme PID adaptatif permet le basculement autonome et le fonctionnement stable entre la régulation à niveau d'eau constant et la régulation à débit constant. La structure mécanique intègre un corps de vanne optimisé, un cadre étanche, un mécanisme d'actionnement et une colonne dédiée à la mesure ultrasonore ; elle se caractérise par une disposition compacte, une étanchéité fiable, une résistance à la corrosion et une installation aisée. Des essais ont été réalisés dans un canal rectangulaire à surface libre de 5,92 m de long et de 1,00 m de large. Les résultats montrent que le modèle d'imputation SAITS atteint une MAPE de 1,77 % lorsque des couches sont manquantes et que l'erreur globale de mesure du débit reste comprise dans une plage de ± 2 %. Cette vanne intégrée améliore efficacement la précision, la stabilité et la souplesse de la mesure et de la régulation en canal à surface libre, et offre ainsi une solution technique pratique pour la répartition intelligente des ressources en eau et le développement de l'irrigation intelligente à l'échelle mondiale.

Mots-clés : Vanne de mesure et de contrôle intégrée; Irrigation de précision; Contrôle automatique; Gestion des ressources en eau; Modernisation du périmètre irrigué.

INTRODUCTION

Open-channel water conveyance systems are critical infrastructure for agricultural irrigation, urban water supply, ecological water replenishment, and industrial recycled water applications worldwide. High-precision flow measurement and stable gate regulation are essential for refined water resources management, improved water use efficiency, and safe operation of water distribution networks. With the rapid development of smart water conservancy and digital irrigation, integrated measurement and control gates have gradually replaced traditional discrete devices and become the mainstream development direction of open-channel regulation terminals. Among various flow measurement technologies, ultrasonic layered velocity measurement is widely used in integrated gates due to its non-contact, non-pressure-loss, and high-adaptability advantages. However, in field applications, ultrasonic probes are easily blocked by sediment, floating debris, or disturbed by bubbles and turbulence, resulting in layered data missing, which severely reduces the accuracy and reliability of flow calculation. In addition, most existing integrated gates support only a single control mode (fixed opening, constant water level, or constant flow), making it difficult to meet the dual requirements of water level safety and precise water allocation in actual irrigation and water conveyance projects.

To solve the above problems, this paper develops a new precision integrated flow measurement and control gate based on dual closed-loop control: constant water level and constant flow. An improved ultrasonic open-channel flow calculation model is proposed, combining the travel-time difference method for layered velocity measurement and the sectional velocity–area method, with an embedded sluice orifice flow formula to ensure measurement accuracy under extremely low water levels. To address the problem of missing layered data in ultrasonic measurement, the SAITS (Self-Attention-based Imputation for Time Series) model is introduced to achieve high-precision interpolation and reconstruction of missing data, effectively eliminating flow calculation distortion caused by invalid layer signals. Meanwhile, the gate adopts modular hardware–software design and optimized mechanical structure, and realizes autonomous switching and stable operation of dual control modes through an adaptive PID algorithm. Field experiments show that the gate features high flow measurement accuracy, fast response, and strong environmental adaptability, satisfying application requirements in irrigation districts, urban water supply, drainage, and other open-channel scenarios.

Freshwater shortage and supply–demand imbalance have become global constraints to socioeconomic development. Open channels undertake more than 70% of agricultural irrigation water delivery and are also widely used in urban drainage, ecological restoration, and industrial water systems. Traditional open-channel regulation relies on manual gate operation and separate flow meters, which leads to high labor cost, large measurement error, poor real-time performance, and difficulty in refined scheduling. The emergence of integrated measurement and control gates has realized the integration of flow measurement, automatic control, data acquisition, and remote communication, greatly improving the automation level of water conveyance systems.

At present, ultrasonic layered velocity measurement serves as the core flow sensing technology for integrated gates. By arranging ultrasonic probes at different water layers, vertical velocity distribution is obtained, and cross-sectional discharge is calculated using the velocity–area method. Although this method has high theoretical accuracy, in complex field environments, individual probe failure easily causes missing layered velocity data, resulting in a significant increase in flow calculation error. In addition, the single control mode of existing gates cannot balance water level safety and flow allocation accuracy. For example, the upstream main canal usually requires constant water level control to ensure stable water distribution, while branch canals and field outlets require constant flow control to achieve precise water delivery. Therefore, developing an integrated gate with dual-mode constant water level and constant flow control and solving the problem of missing layered measurement data is of great engineering significance and application value for improving the performance of water conveyance systems and promoting the development of smart water conservancy.

Extensive research has been conducted on ultrasonic flow measurement, integrated gate design, and missing data imputation worldwide. Yoosefdoost & Lubitz (2022) analyzed the hydraulic characteristics of sluice gates and established a flow calculation model based on gate opening and water level, providing a theoretical basis for gate flow measurement but without involving ultrasonic layered measurement. Liu et al. (2025) studied the hydraulic performance of integrated measurement and control gates under subcritical flow conditions, focusing on the influence of gate structure on flow patterns, but did not optimize the measurement algorithm. Hou & Niu (2023) used an optimized BP neural network to predict the flow of measurement and control gates, improving the accuracy of flow estimation under variable working conditions, but did not solve the problem of missing measurement data. Cao et al. (2025) tested the hydraulic and flow measurement performance of integrated gates in U-shaped channels with different slopes, verifying structural adaptability to various channels, but control functions remained single. Gao et al. (2020) developed an integrated measurement and control gate for irrigation districts, realizing remote automatic control and dynamic water regulation through a self-learning PID algorithm, but without dual-mode constant water level / constant flow control. Du et al. (2023) proposed the SAITS model based on a self-attention mechanism, achieving high-precision interpolation of multivariate time-series missing data and showing excellent performance in processing continuous missing data, providing a new method for solving layered ultrasonic data missing. Umar and Gray (2023) compared multiple missing data imputation methods for water level data, pointing out that machine learning methods have higher accuracy than traditional statistical methods. Jager et al. (2025) reviewed the application of machine learning in sensor data quality control and imputation for water resources management, indicating that self-attention models have obvious advantages in capturing long-term time-series dependence. In terms of control strategies, PID control is widely used in gate water level and flow regulation. Ma et al. (2024) designed a gain-scheduled PID controller for open-channel water level control, improving adaptability to different flow conditions, but without dual-mode switching control. Commercial integrated gate products support constant water level and constant flow control, but rely on imported sensors and are costly, limiting large-scale promotion in developing regions.

Combined with the actual demands of open-channel water conveyance systems and existing technical deficiencies, the research contents of this paper are as follows: (1) Propose an improved ultrasonic open-channel flow calculation model, establish a layered velocity calculation formula based on the travel-time difference method, and realize high-precision flow calculation by combining the sectional velocity–area method and orifice flow formula; (2) Introduce the SAITS imputation model to solve the problem of missing layered data in ultrasonic measurement, realize the reconstruction of missing

velocity data, and improve the robustness of the measurement system; (3) Design the hardware and software control system of the integrated gate, adopt a modular circuit design, and realize dual-mode closed-loop control of constant water level and constant flow based on an adaptive PID algorithm; (4) Optimize the mechanical structure of the gate, integrate the ultrasonic measurement column, and design a compact and reliable structure suitable for field installation; (5) Carry out field experiments to verify the flow measurement accuracy, control effect, and data interpolation performance of the gate, and summarize the application effect.

ULTRASONIC FLOW CALCULATION MODEL

When soundwave propagates in fluid, its speed increases in the downstream direction and decreases in the upstream direction. Over the same propagation distance, the differences of velocity will lead to different travel times. The method of calculating flow velocity using the relationship between the soundwave travel-time difference and the measured fluid velocity is called the travel-time difference method. The average flow velocity V_i of each measurement layer can be calculated as follows.

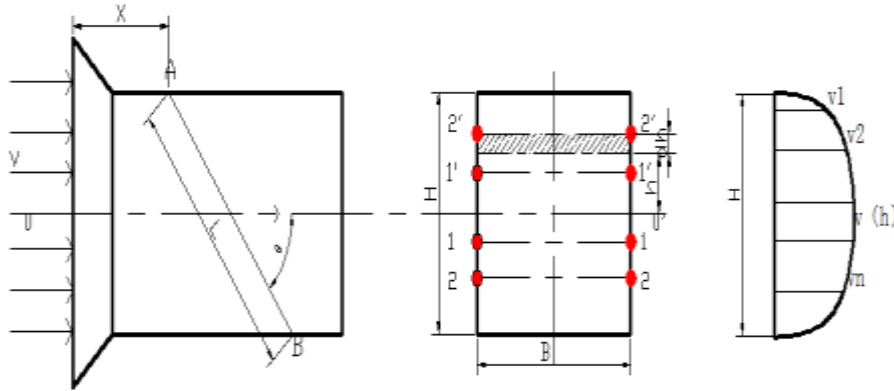


Figure 1. Schematic diagram of ultrasonic flow measurement channel

As shown in Figure 1, water enters from the left side. Ultrasonic probe group consists of A and B are installed in layers at a stable flow section on the outlet side, with a horizontal distance L and an inclined angle θ to the horizontal direction. Assume that the propagation time of the soundwave from A to B in the downstream direction is denoted by t_1 , the propagation time of the soundwave from B to A in the upstream direction is denoted by t_2 . It can be expressed as follows.

$$\frac{L}{t_1} = c - V_i \cos \theta \quad (1)$$

$$\frac{L}{t_2} = c + V_i \cos \theta \quad (2)$$

By defining that $\Delta T = t_2 - t_1$ and $\bar{T} = \frac{t_2 + t_1}{2}$, it can be obtained

$$V_i = \frac{2L}{\cos \theta} \frac{\Delta T}{4\bar{T}^2 - \Delta T^2} \quad (3)$$

This formula reduces the number of velocity-related parameters from five to four and eliminates the need to involve the speed of soundwave. Since flow velocity varies with water layer and water level, the formula is extended to each layer i :

$$V_i = \frac{2L_i}{\cos \theta} \frac{\Delta T_i}{4\bar{T}_i^2 - \Delta T_i^2} \quad (4)$$

When the gate opening equals to 0, the channel flow is 0. When the gate opening greater than 0, according to the actual operation of irrigation district, the water level should at least 10 cm. Therefore, the first probe is installed 10 cm above the channel bottom. To ensure accuracy under extreme low-water conditions, the algorithm integrates the sluice orifice flow formula to maintain precision at low water levels.

Assume $N=[h_d/10]$, when $h_d < 10\text{cm}$, the flow is calculated as

$$Q = \mu b e \sqrt{2g(h_d - h_u)} \quad (5)$$

Where Q is cross-sectional discharge flow, μ is flow coefficient, b is the width of channel, e is gate opening, g is gravitational acceleration, h_d is upstream water level, h_u is downstream water level.

When $h_d > 10\text{cm}$, the flow is calculated by the sectional velocity-area method, as shown in Figure 2.

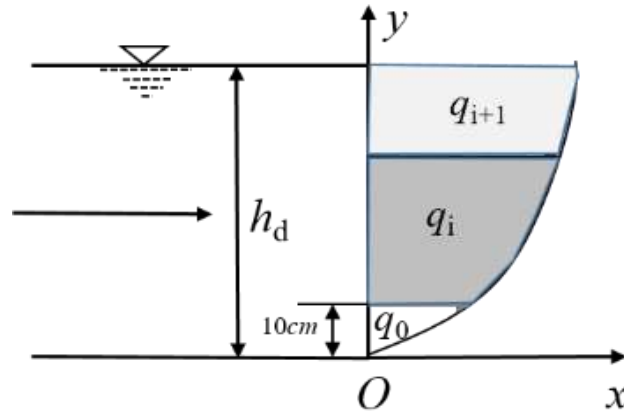


Figure 2. Schematic diagram of sectional velocity-area method

The total discharge flow is divided into three parts, q_0 , q_i and q_{i+1} , it can be expressed as

$$Q = q_0 + q_i + q_{i+1} \quad (6)$$

Where q_0 is the discharge flow of bottom layer, q_i is the discharge flow of middle layer and q_{i+1} is the discharge flow of upper layer, and expressed as

$$q_0 = ((V_i - V_{i-1})/2) \times b \times h_c \quad (7)$$

$$q_i = \sum_{j=1}^{i-1} ((V_j + V_{j-1})/2) \times b \times h_c \quad (8)$$

$$q_{i+1} = ((V_i + V_{i-1})/2) \times b \times (h_d - N \times h_c) \quad (9)$$

The discharge flow can be obtained by $Q = Q_i \times K$, where K is comprehensive flow coefficient.

DESIGN OF HIGH-PRECISION INTEGRATED MEASUREMENT AND CONTROL GATE

Hardware and Software Design of Control Circuit

The core of the automated operation of the integrated measurement and control gate is the design of the main control circuit board. To facilitate the high-precision measurement and control, the circuit is

developed in a modular design, includes power supply unit, main control unit, remote control unit, communication interface unit, storage unit, data acquisition unit, motor drive unit and ultrasonic flow measurement unit. Embedded software algorithms are programmed in the microcontroller to enable coordinated operation among these units. The designed PCB and physical circuit are shown in Figure 3.



Figure 3. The designed PCB and physical circuit

The gate is equipped with a touch-enabled human-machine interface(HMI), supporting real-time system condition monitoring, operation data acquisition and display, equipment status update, remote software upgrade, and system information configuration and management. The HMI includes five interfaces as system condition, operation data, equipment status, remote upgrade, and system settings.

System condition can real-time display the upstream/downstream water level, water head, gate opening, instantaneous flow, total water volume and so on. It supports manual control by setting gate opening or automatic control by selecting gate opening, water level, or flow mode. Operation data can store and display the real-time data at fixed intervals, it also supports historical data query. Equipment status can monitor the electrical state and anomalies, including water level sensing, ultrasonic transducer excitation and reception, 4G communication, solar charging, power voltage, motor, and limit switches. Remote upgrade can display the software version and the time of historical MCU firmware updates. System settings can configure production information, channel parameters, and the user permission management.



Figure 4. The human-machine interface

Structure Design of Gate

As shown in Figure 5, the gate consists of two parts: the main gate structure and the ultrasonic flow measurement column. The main gate is powered by the solar. A vertical bar installed on top of the gate supports the solar panel. A protective cover is using to protect the installed components, such as the rechargeable battery, stepper motor, reducer, control circuit, and others. The gate supports 4G, LoRa, and other wireless communication methods. It can form a network with other gates and connect to a remote control center for information interaction. A touch panel is provided for user to operate and control the gate. A hand crank is available for emergency manual operation. The ultrasonic transducers for flow measurement are integrated at both left and right sides. They are working in the mode of transmit to receive. The number of transducers is related with the water level. The discharge flow is calculated with the ultrasonic flow measurement channel as discussed above.

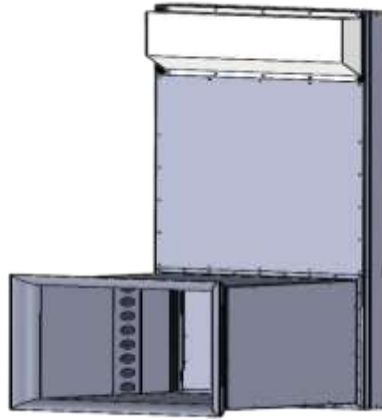


Figure 5. Structural diagram of the integrated measurement and control gate

Autonomous Feedback Regulation: Constant Water Level and Constant Flow

The gate uses the PID control algorithm to achieve dual-mode regulation: constant water level and constant flow. Constant water level control is preferred for ensuring water level safety and stability. Constant flow control is directly influenced by the gate opening, thus it offers faster response, but requires much more high-precision flow measurement. This control method is preferred for accurate water allocation. But in reality, layered data missing often occurs due to the transducer sheltered by clutters or sensor failure. It requires data interpolation to maintain stable flow measurement. This part introduces the SAITS generative imputation model to solve this problem.

Assume the ultrasonic flow measurement data matrix is $V = (v_1, \dots, v_i^j, \dots, v_T)$, the observation data matrix is $v_i^j = (v_i^1, \dots, v_i^N)$, where N is the number of vertical layers, T is the number of time steps. A mask matrix M indicates missing values

$$M = \begin{Bmatrix} m_1^1 & m_2^1 & \dots & m_T^1 \\ m_1^2 & m_2^2 & \dots & m_T^2 \\ \dots & \dots & \dots & \dots \\ m_1^N & m_2^N & \dots & m_T^N \end{Bmatrix} \quad (10)$$

When $m_i^j=0$, it represents data of v_i^j is missing; When $m_i^j=1$, it represents data of v_i^j is valid. The goal is to recover the complete data matrix based on the observation data. It should be as close as the real data.

The Self-Attention-based Imputation for Time Series(SAITS) model is a time series missing value imputation model based on self-attention mechanism, primarily used for handling multivariate time series data with missing values. By focusing on specific time points within the sequence via the self-attention mechanism, the model is essentially a Transformer encoder stacked with multiple identical layers. As illustrated in Figure 6, each layer leverages two parallel attention mechanisms for learning: conventional self-attention computes attention across all time steps in the sequence, primarily capturing long-term temporal dependencies, whereas masked self-attention only calculates attention between positions free of missing values. The outputs of these two attention mechanisms are concatenated and fed into a feed-forward neural network to generate the final output of the layer. This process can be formally formulated as

$$H^{(l)} = \text{TransformerLayer}^{(l)}(H^{(l-1)}) \quad (11)$$

In the equation, the TransformerLayer contains the combined operation of the aforementioned dual attention mechanisms, where $H^{(l)}$ represents the hidden state of the output at layer l .

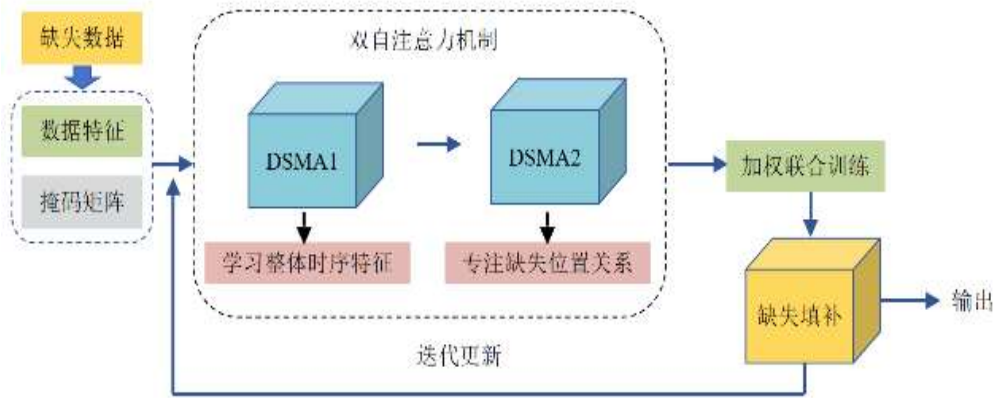


Figure 6. Flow chart of SAITS model

An indicator of Mean Absolute Percentage Error(MAPE) is used to evaluate the imputation accuracy.It is listed in following

$$MAPE = \frac{1}{n} \sum_{t=1}^N \left| \frac{y_t - \hat{y}_t}{y_t} \right| \times 100\% \quad (12)$$

EXPERIMENT

Experimental Setup

The experimental system is shown in Figure 7. The test channel is a horizontal rectangular open channel with length 5.92m, width 1.00m and depth 1.29m. Its roughness is 0.014. The gate is installed 1.5m from the head of channel. A data acquisition system records 1000 groups of velocities.

The water level is maintained by the constant water level autonomous feedback regulation system, it keeps the water depth at 40cm. Layered velocities are obtained by the ultrasonic transducers. The mean velocity and standard deviation (SD) are calculated and plotted in Figure 8. The horizontal line represents the mean velocity at different depths. It shows that the velocity of top layer is the largest and the bottom layer is the smallest. The SD value reflects the degree of dispersion of velocity. The value at 40cm is the largest (SD = 0.024). This phenomenon conforms to the velocity distribution pattern of open channel cross-section flow.

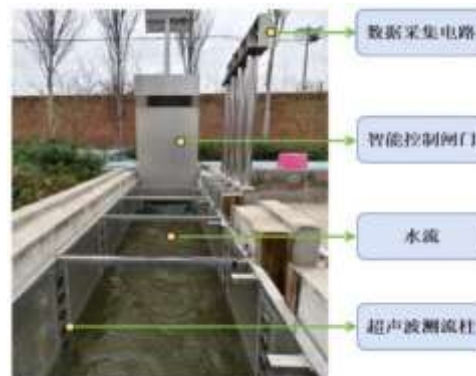


Figure 7. Experimental system setup

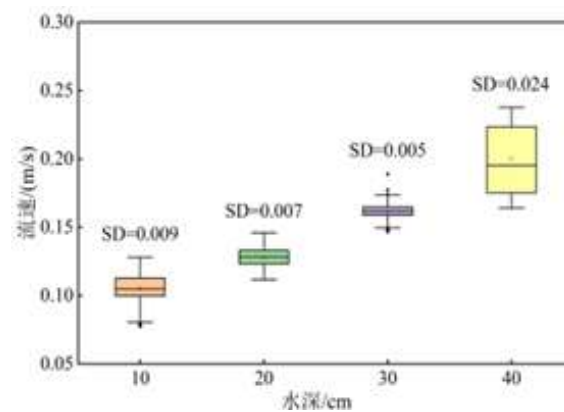


Figure 8. The box plot of ultrasonic layered velocity measurement results

Figure 9 shows the predicted data and measured data. Assume the number of missing layers $N_m=2$. Under this water level condition, the MAPE of SAITS model achieves 1.77%.

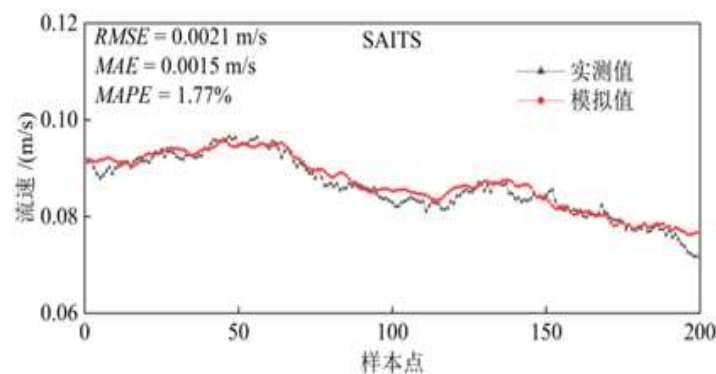


Figure 9. Imputation result: predicted vs. measured values

CONCLUSION AND DISCUSSION

A new precision integrated flow measurement and control gate based on dual-mode control is developed for smart irrigation in open-channel water distribution systems. A data imputation method is proposed to address layered data missing in ultrasonic layered flow measurement. Results show that the SAITS self-attention mechanism can dynamically and non-uniformly weight valid observations across the time series, effectively learning complex long-term and short-term temporal dependencies in

flow data, with strong performance for continuous and large-gap missing data. For random single-layer missing conditions, the mean error of the SAITS model is below 2%, fully meeting post-processing requirements of flow measurement data. The gate achieves high measurement accuracy, stable dual-mode regulation, and strong field adaptability, providing a reliable solution for intelligent open-channel management.

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