Journal of Engineering Mechanics and Machinery (2026)
Clausius Scientific Press, Canada

DOI: 10.23977/jemm.2026.110211
ISSN 2371-9133 Vol. 11 Num. 2

Research and Development of High-Precision Industrial Flow Meters and Strategies for Improving Accuracy

Chen Xingzhu

Fix Instruments (Shenzhen) Co., Ltd., Shenzhen, Guangdong, China

Keywords: Industrial flowmeter; Accuracy improvement; Flow field shaping; Multi-parameter compensation

Abstract: The continuous pursuit of measurement accuracy in industrial applications has driven flow meters to evolve from single-sensor structures into sophisticated multi-parameter coupled measurement systems. Measurement precision is influenced by numerous interrelated factors, including flow field distortion, sensor nonlinearity, temperature and pressure drift, and signal noise; improvements in any single component alone cannot achieve breakthroughs in system-level accuracy. This paper presents a design approach for high-precision industrial flow meters from three perspectives—system architecture, sensing units, and flow channel structure—and analyzes the root causes of four main error sources: flow field disturbances, sensor characteristics, temperature-pressure coupling, and signal processing. Based on this analysis, an integrated method for enhancing accuracy is proposed, combining flow field shaping with structural matching, multi-parameter compensation with segmented calibration, digital filtering with feature extraction, and full-scale calibration with operational condition adaptability. This provides a systematic reference for high-precision design and performance optimization of industrial flow meters.

1. Introduction

Flow rate is one of the most critical measurement parameters in industrial process control, and the accuracy of flow measurement directly affects the stability of production processes, fairness of energy metering, and controllability of product quality. Industrial field conditions are complex, with pipeline layouts constrained by space, fluctuating fluid properties, and variations in ambient temperature and pressure. These factors combined make it difficult to reproduce the accuracy achieved under laboratory calibration conditions in actual installation environments. Traditional design approaches have focused primarily on improving the performance of sensing elements themselves, while insufficient attention has been given to system-level factors such as flow field distortion, signal transmission loss, and multi-physical field coupling, resulting in significant degradation of overall instrument accuracy in practical engineering applications.[1]

2. System Development and Key Structural Design of High-Precision Industrial Flow Meters

2.1 Flow Measurement Principles and Overall Technical Architecture Design

The essence of flow measurement lies in converting the motion state of a fluid into observable physical signals and then inferring the flow rate. Different principles—such as Coriolis, electromagnetic, and ultrasonic—each have their own limitations regarding medium compatibility and accuracy, requiring careful selection based on specific operating conditions. The overall architecture adopts a layered design comprising sensor perception, signal conditioning, data processing, and communication/output layers. Standard interfaces decouple these layers, clearly defining boundaries for error traceability and module upgrades.[2]

2.2 Flow Sensing Unit and Signal Acquisition Circuit Design

The design objective of the sensing unit is to ensure a stable correspondence between signal output and flow rate under wide operating conditions. The geometric parameters and installation orientation of the sensitive element affect the signal conversion efficiency, and a multi-path cross-arrangement provides better robustness in flow velocity sampling compared to a single-path configuration. The signal acquisition circuit must balance noise suppression with dynamic response; factors such as front-end amplification matching with sensor output impedance, analog-to-digital conversion sampling rate and resolution settings, and isolation between analog and digital grounds all influence the upper limit of the signal chain's signal-to-noise ratio.

2.3 Optimal Design of Flow Channel Structure and Measurement Sensitive Areas

The flow channel structure affects the flow field condition when fluid reaches sensitive areas. In industrial settings, disturbances such as elbows and valves cause the velocity profile to deviate from calibrated assumptions, necessitating internal shaping structures to accelerate flow field homogenization. The design of sensitive regions must balance signal strength and flow interference; excessive component penetration can cause local velocity distortion, while proximity to the pipe wall may place the region within the boundary layer effect zone. By using computational fluid dynamics simulations to modify the component's shape and installation position, the sensitive area can be positioned in a location with stable and representative flow conditions.[3]

3. Mechanisms Affecting Measurement Accuracy of Industrial Flowmeters and Error Analysis

3.1 Measurement Deviations Caused by Flow Field Disturbances and Installation Conditions

Flow field disturbances are the most common source of error in industrial settings, primarily resulting from unavoidable non-ideal installation conditions in piping systems. Secondary flows caused by bends, turbulent wake generated by valves, and velocity redistribution due to diameter changes can all cause the velocity profile reaching the flowmeter to deviate from the calibration assumptions. Different measurement principles vary in their sensitivity to flow field distortions: single-point or single-path sampling methods are more susceptible to interference, whereas principles capable of area integration or multi-path sampling inherently offer better resistance to disturbances.

The deviations caused by installation conditions are directional and structural, not random noise. Elbows generate swirls that systematically shift the ultrasonic signal travel time, while increased

turbulence intensity downstream of valves leads to greater signal fluctuations. These deviations cannot be eliminated by simple averaging; they require mitigation through either flow field shaping or algorithmic compensation.[4]

3.2 Sensor Nonlinearity, Zero Drift, and Repeatability Error

The input-output relationship of the sensor is not strictly linear across the entire measurement range, with nonlinearity being more pronounced at both ends of the range. In the low-signal region, output sensitivity decreases due to base noise and threshold effects; in the high-signal region, output compression occurs due to physical limitations of components and circuit saturation.

Zero drift refers to the phenomenon where the sensor output slowly changes over time under zero flow conditions. Its causes include material stress relaxation, temperature-induced variations in circuit parameters, and gradual changes in environmental electromagnetic fields. Zero drift directly superimposes onto the measurement signal, resulting in significant relative errors under low-flow conditions and potentially causing incorrect judgments about flow direction. Repeatability error reflects the dispersion among multiple measurements taken under identical conditions, influenced by mechanical structural hysteresis, unstable electrical contacts, and minor fluctuations in fluid conditions. It is a fundamental indicator for evaluating the reliability of measurement results.

3.3 Coupled Effects of Temperature and Pressure Changes on Flow Measurement Results

Temperature and pressure are among the most common process variables subject to fluctuations in industrial environments, and both influence flow measurement results through various mechanisms. Temperature changes cause physical parameter drift in sensing elements; variations in material elastic modulus, thermal expansion or contraction of geometric dimensions, and temperature-induced drift in circuit component parameters all affect the gain and zero point of signal conversion.

Pressure variations primarily affect measurement results through changes in medium density and compressibility, with a more significant impact on gaseous media. As pressure increases, gas density rises, altering the total mass flow corresponding to the same volumetric flow rate. If the flowmeter provides volumetric flow data but the user requires mass flow, pressure compensation is essential. The combined effect of temperature and pressure is not simply additive; under certain conditions, temperature and pressure may change in opposite directions, requiring the compensation algorithm to account for the interaction terms between both parameters.

3.4 Signal Noise, Parameter Calibration, and Error Propagation in Data Processing

Signal noise exists throughout the entire measurement chain, including intrinsic noise from sensing elements, thermal and quantization noise from circuits, and electromagnetic interference from industrial environments. Various types of noise superimpose onto the useful signal in different ways. The spectral distribution of noise determines the appropriate filtering method: white noise-like disturbances can be suppressed using smoothing techniques, while power-line interference and its harmonics require notch filtering. Noise not only affects measurement repeatability but also, under low-signal conditions, can mask the true flow signal, thereby raising the lower limit of measurement.

Parameter calibration is a crucial step in converting raw signals into engineering flow values, and errors inevitably occur during the calibration process. The uncertainty of the calibration device, the coverage range of calibration points, and differences between the calibration medium and the actual medium can all contribute to final measurement errors. In data processing, error propagation

requires attention to the numerical stability of algorithms—some compensation algorithms may become ill-conditioned under certain parameter combinations, causing minor input deviations to result in significant output errors. The purpose of error propagation analysis is to identify the links within the entire chain that have the greatest impact on final accuracy, allowing optimization resources to be focused on these critical nodes rather than distributed evenly across all components.

4. Precision Enhancement and Performance Optimization Strategies for High-Precision Industrial Flowmeters

4.1 Improving Measurement Stability through Flow Field Conditioning and Structural Parameter Matching

Flow field conditioning involves installing flow-guiding structures inside or upstream of the flowmeter to restore turbulent flow to a fully developed state, thereby reducing dependence on upstream straight pipe sections. When designing flow conditioners, it is essential to balance rectification effectiveness with additional pressure loss. Although densely arranged guide vanes may offer superior rectification, they increase flow resistance and can generate new wake regions. By conducting computational fluid dynamics (CFD) simulations to analyze rectification efficiency and pressure loss characteristics under various structural parameters, an optimal balance between rectification performance and pressure drop can be achieved. For installations with spatial constraints, integrating the flow conditioner directly into the flowmeter body allows improvement of the flow field without requiring additional upstream straight piping.

Structural parameter matching refers to the coordination between the geometric parameters of the sensing element and the pipeline dimensions and operating conditions. Parameters such as transducer installation angle, acoustic path coverage, and sensor insertion depth must be determined based on specific pipe diameter and flow velocity ranges, and cannot rely on a single standardized design. For small-diameter flow meters, special attention should be paid to the proportion of flow field disturbance caused by the sensing element, while for large-diameter flow meters, the key issue is ensuring that the acoustic path or sampling points are representative of the cross-sectional flow velocity. By combining parametric simulation with experimental methods, a mapping relationship between structural parameters and measurement stability can be established, providing a basis for designing products of different specifications.

4.2 Systematic Error Correction Based on Multi-parameter Compensation and Piecewise Calibration

Multi-parameter compensation involves incorporating operational parameters such as temperature, pressure, and medium density into the flow calculation model to perform real-time correction of sensor output. Establishing a compensation model requires extensive experimental data, measuring the sensor's output characteristics under various combinations of temperature and pressure to determine the influence coefficients of each parameter on measurement results. The order and complexity of the compensation model must match the actual operating range—too simple a model cannot account for nonlinear variations across wide conditions, while an overly complex model may lead to overfitting, resulting in greater prediction errors in unrepresented operating ranges.

Segmented calibration divides the full measurement range into several intervals, using different calibration parameters within each interval to approximate the sensor's nonlinear characteristics. The number of segments should balance calibration workload and fitting accuracy: too many segments increase calibration cost and may cause discontinuities at the boundaries, while too few

fail to adequately correct nonlinearity. Segment points should be selected based on the sensor's nonlinear behavior—increasing segment density in regions with high curvature and merging segments where linearity is good. By combining compensation with calibration, system errors can be controlled within an acceptable range while maintaining consistent accuracy across the entire measurement range.

4.3 Optimization of Weak Signal Processing Based on Digital Filtering and Feature Extraction

Digital filtering employs different methods based on the characteristics of noise. Random noise can be reduced using time-domain techniques such as moving average and exponential smoothing, but these may introduce phase lag. Frequency-domain filtering suppresses out-of-band noise by designing appropriate passbands and stopbands to preserve the frequency components of useful signals. For common industrial power-line interference and harmonics, adaptive notch filters can track slow frequency drifts of the interference, providing better suppression than fixed-frequency notch filters. The selection of filter parameters must balance noise suppression with response speed; although transitional filtering produces smooth output, it may lose dynamic flow information, resulting in lag errors under rapidly changing operating conditions.[5]

Feature extraction involves extracting flow-related features from noisy signals to improve measurement signal-to-noise ratio and stability. For ultrasonic measurements, accurately determining the arrival time of echo signals is critical. Traditional threshold-based methods are prone to misjudgment under low signal-to-noise ratios, whereas feature extraction techniques based on cross-correlation or wavelet transforms can more reliably identify signal characteristics. For flow signals containing pulsating components, spectral analysis enables separation of steady-state and pulsating components, thereby enhancing both steady-state measurement accuracy and dynamic response capability. The computational complexity of the feature extraction algorithm must match the performance of embedded processors to ensure real-time processing within sampling intervals.

4.4 Comprehensive Accuracy Improvement Based on Full-Range Calibration and Operating Condition Adaptation

Full-scale calibration covers the entire range from the lower to upper measurement limits, ensuring that every flow point is verified through actual calibration rather than relying on interpolation or extrapolation based on a few reference points. In addition to verifying accuracy at nominal flow rates, the calibration process must also test resolution in low-flow regions, dynamic response under rapidly changing conditions, and long-term stability during extended operation. Calibration data are used to adjust the parameters of the compensation model, minimizing prediction errors across the actual operating range. The accuracy class of the calibration equipment should be higher than that of the meter being calibrated; otherwise, the uncertainty of the calibration results may obscure the true performance of the device under test.

Working parameter adaptation means that the flowmeter can automatically adjust its working parameters and compensation models according to real-time operating conditions, rather than relying on fixed factory settings. When medium properties change or installation conditions deviate, the system detects operational drift through internal diagnostic logic, then switches to the corresponding compensation parameter set or adjusts algorithm thresholds accordingly. Working parameter adaptation requires multi-parameter monitoring, pattern recognition algorithms, and sufficient computational power. The overall improvement in accuracy results from a combination of structural optimization, compensation correction, signal processing, and adaptive calibration—no single strategy alone can achieve high precision across all operating conditions Table 1. Therefore,

integration and coordination among these strategies must be carefully considered during the system design phase.

Table 1 Comparison of characteristic dimensions for different flow measurement principles

Specific dimension	Coriolis-type	Electromagnetic	Ultrasonic
Type of measurement quantity	Mass flow rate	Volumetric flow rate	Volumetric flow rate
Dielectric conductivity requirements	No requirements	Must be conductive	No requirements
Pressure drop characteristics	There is pressure loss in the pipeline section.	Low pressure drop with no flow obstruction	Local pressure loss occurs during insertion.
Flow field sensitivity	Sensitive to vibration	Moderately sensitive to flow field uniformity	Sensitive to the representativeness of velocity profiles
Typical application scenarios	Precision Measurement and Trade Handover	Conductive liquids such as water and wastewater	Large diameter and difficult-to-isolate installation scenarios
Maintenance concerns	Installation stress and zero-point stability	Electrode Contamination and Liner Integrity	Transducer Coupling and Acoustic Path Attenuation

5. Conclusion

The development of high-precision industrial flow meters is a process that integrates multiple technologies, including sensing principles, machinery design, circuitry, and algorithm processing. Improving accuracy cannot rely solely on enhancements in any single aspect; instead, it requires a systematic analysis of error mechanisms throughout the measurement chain, followed by targeted corrections. Mechanical improvements such as flow field shaping and structural parameter matching enhance the fundamental conditions for measurement, while multi-parameter compensation and segmented calibration correct system errors through modeling. Digital filtering and feature extraction improve signal quality, and full-scale calibration along with operational adaptability ensure long-term precision during operation. These four-dimensional strategies work in concert to form a comprehensive accuracy assurance system covering the entire lifecycle from design and manufacturing to operation. With advances in sensor materials and computational power, achieving higher accuracy increasingly depends on the deep integration of multiphysics coupled modeling and intelligent algorithms, enabling superior measurement performance across a wider range of operating conditions.

References

[1] Wang Tao, He Xiuru, Yang Hong, et al. Research and Application of On-site Calibration for Ultrasonic Flowmeters in Hydropower Stations [J]. Water Resources and Hydropower Engineering (Chinese and English), 2025, 56(S2): 486-490.

[2] Li Tianhao. Research on Prediction and Multi-Objective Optimization of High-Power Laser Bevel Cutting Quality Based on IWOA-LSSVM and NSGA-II [D]. Qilu University of Technology, 2025.

[3] Li Ji, Zhang Jigang, Wang Zhiyuan, et al. Optimal Design of Ultrasonic Flow Meter Rectifier [J]. Industrial Instrumentation and Automation Equipment, 2024, (1): 38-41+56.

[4] Jiang Rui, Qi Weijun, Yang Yiren, et al. Analysis and Correction of Gas Measurement Errors in Vortex Flowmeters [J]. Chemical Industry and Instrumentation Automation, 2023, 50(6): 791-795.
[5] Chen Wenlin, Wu Jianjun, Ding Zhao. Effect of Local Flow Disturbance on Probe on Ultrasonic Flow Meter Measurement Results [J]. China Testing, 2023, 49(1): 126-130.