Theory and Practice of Science and Technology
2025, VOL. 6, NO. 11, 92-95
DOI: 10.47297/taposatWSP2633-456917.20250611

Research and Engineering Application of Multi-Dimensional Collaborative Anti-Interference Technology for Sensor Interface Circuits

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ABSTRACT

As the core link between sensors and processing units, sensor interface circuits are crucial to information acquisition system reliability. However, in industrial automation, intelligent devices and other scenarios, they suffer from electromagnetic interference (EMI), mechanical vibration, device noise and other interferences, seriously affecting signal quality and measurement accuracy. This study proposes a multi-dimensional collaborative anti-interference system covering physical, circuit and digital layers: physical layer uses composite shielding and hierarchical grounding to block interference (20-80dB shielding for high-frequency EMI); circuit layer adopts low-noise conditioning and isolation to purify signals; digital layer applies Kalman-wavelet fusion filtering and fault-tolerant coding to correct errors (communication success rate up to 99.9%). Engineering applications in pressure sensors, MEMS accelerometers and wireless nodes show that measurement errors are reduced to ±0.1%FS, posture recognition error rate is below 2%, and battery life is extended to 18 months. This research provides an efficient solution for improving anti-interference capability of sensor interface circuits.

KEYWORDS

Sensor interface circuits; Multi-dimensional collaborative anti-interference; Electromagnetic interference (EMI)

1 Introduction

As core components for information collection, sensors are widely used in industrial automation, intelligent devices, and the Internet of Things (IoT) field. The interface circuit, serving as the bridge between sensors and processing units, is responsible for weak signal conditioning, conversion, and transmission, and its performance directly determines system reliability. In practical applications, interface circuits face complex interferences: power frequency and high-frequency Electromagnetic Interference (EMI) generated by motors and transformers in industrial sites invades through coupling, causing signal distortion; mechanical vibration displaces and deforms sensitive components, leading to output fluctuations; temperature and humidity drift changes the material properties of sensors, especially exerting significant impacts on sensitive sensors. Data shows that most measurement errors of sensors in industrial sites stem from interference, which not only reduces precision and affects quality but also may cause system failures and economic losses. Therefore, improving the anti-interference capability of interface circuits is crucial to ensuring system stability and has important research value.

2 Classification and Characteristic Analysis of Interference Sources in Sensor Interface Circuits

Among external interferences, Electromagnetic Interference (EMI) is the most typical: power devices of high-frequency switching power supplies and motor drivers have a switching speed of nanosecond (ns) level, generating strong noise with dV/dt > 100V/μs and dI/dt > 10A/μs. The 30MHz-1GHz frequency band radiates through space via the antenna effect, while the 0.1-30MHz frequency band conducts and couples along power lines and signal lines. Noise amplitude above 500mV is sufficient to overwhelm the millivolt (mV)-level sensor output signal.

In environmental interference, mechanical vibration transmits through structures, causing a strain gauge resistance drift of 0.1%/g. In construction machinery scenarios, vibration acceleration can reach over 10g, directly leading to a measurement error of more than 1%. For every 10% increase in humidity, the insulation resistance of sensor packaging materials decreases by an order of magnitude, causing increased leakage current. The parasitic capacitance variation of capacitive sensors can reach 0.5pF, exceeding the measurement precision range [1].

Internal interferences are mainly device and power supply noise: the 1/f noise of operational amplifiers reaches 10nV/√Hz in the 1kHz frequency band, and the quantization noise of 16-bit ADC is 30μVrms, restricting weak signal resolution. The Low-Dropout Regulator (LDO) ripple is 50μVpp, and the DC-DC switching noise is 10mVpp [2], which couple interference signals through the power supply network.

Device noise in internal interferences is the main bottleneck for weak signal detection: the 1/f noise of operational amplifiers reaches 10nV/√Hz in the 1kHz low-frequency band. For 10μV-level sensor signals, the noise accounts for more than 10% after 100x amplification. The quantization noise of 16-bit ADC is 30μVrms; when the input signal amplitude is lower than 100μV, the Signal-to-Noise Ratio (SNR) is less than 10dB, failing to meet precision measurement requirements. Power supply noise couples through common ground paths: the 50μVpp ripple of LDO transmits through the Power Distribution Network (PDN), generating mV-level interference in analog circuits; the 10mVpp switching noise of DC-DC converters couples to the signal link through parasitic inductance, significantly affecting high-frequency sensors (such as ultrasonic sensors) [3].

3 Core Anti-Interference Technology System for Sensor Interface Circuits

To effectively address the complex interference environment faced by sensor interface circuits and improve system reliability and stability, a comprehensive and efficient anti-interference technology system needs to be established. This system covers the physical layer, circuit layer, and digital layer, and suppresses interference through collaborative technologies at different levels to ensure the stable operation of sensor interface circuits.

3.1 Physical Layer Interference Suppression Technology

Physical layer anti-interference technology focuses on "source blocking" and reduces interference coupling efficiency through shielding, grounding, layout optimization, and other means. It serves as the first line of defense in the anti-interference system, achieving a suppression effect of 20-60dB on high-frequency EMI.

The Composite Shielding System is designed hierarchically for three types of interference: electric field, magnetic field, and radiation. The inner layer of silver-plated copper foil (conductivity 6.3×10^{7} S/m) generates a reverse electric field through electrostatic induction, achieving a shielding effectiveness of over 80dB for high-frequency electric fields in the 30MHz-1GHz band. The middle layer of Permalloy (permeability 10^{5}) attenuates 99% of power frequency magnetic fields in the 50Hz-1kHz band through magnetic circuit shunting. The outer layer of metal braided mesh (coverage ⩾90%) forms a closed conductive loop and absorbs spatial radiation energy through the eddy current effect. In the application of capacitive liquid level sensors, after adopting this structure for the drive cable, the parasitic capacitance fluctuation is reduced from ±5pF to ±0.2pF, and the measurement precision is improved from 0.5% Full Scale (FS) to 0.1% FS [4].

The Hierarchical Grounding Strategy is designed differently according to signal characteristics: the analog ground (sensor and amplifier circuit) and digital ground (MCU and ADC circuit) are interconnected at a single point through a 0Ω magnetic bead. The magnetic bead has an impedance >1kΩ in the frequency band above 10MHz, blocking digital high-frequency noise coupling. The power ground (motor and heater circuit) is independently wired to the ground stake, with a distance of >3cm from the signal ground to avoid common ground interference [5]. High-frequency circuits (such as radio frequency sensor interfaces) adopt multi-point grounding, with a ground hole spacing ⩽ λ/20 (λ is the signal wavelength) to ensure a grounding impedance <1Ω.

3.2 Circuit Layer Signal Conditioning Technology

Circuit layer anti-interference technology focuses on "signal purification" and improves SNR through low-noise amplification, filtering, isolation, and other means, reducing the interference signal amplitude below the circuit noise threshold. It is suitable for handling interferences that have coupled into the signal chain.

The low-noise amplification system adopts a "front-end attenuation + main amplification" architecture: the front end uses an AD8629 low-noise operational amplifier (1.1nV/√Hz) to construct an instrumentation amplifier circuit, with a Common Mode Rejection Ratio (CMRR) of 140dB@50Hz to suppress common-mode interference. The back end is equipped with a 10kHz second-order Butterworth low-pass filter, which has a passband ripple ⩽0.1dB and a stopband attenuation ⩾60dB per decade, filtering out 99% of high-frequency noise. For 10μV-level biosensor signals, after adding the chopper stabilization technology, the DC drift is reduced from 1μV/℃ to 0.1μV/℃, and the measurement error is < 0.05% FS within the temperature drift range of -40℃ to 85℃ [6].

Isolation technology achieves "electrical disconnection + signal transmission": Optoelectronic isolation uses a 6N137 high-speed optocoupler, with a transmission delay of 50ns to meet the 10MHz signal bandwidth requirement and an isolation voltage of 2.5kVrms to block 220V mains ground interference. After application in power grid monitoring sensors, the common-mode interference suppression effect is improved by 40dB [7]. Transformer isolation uses an ADT1-6 audio transformer, with a bandwidth of 20Hz-20kHz covering AC sensor signals such as vibration and sound. It restores the DC operating point with a ±5V bias circuit, increasing the SNR from 20dB to 45dB in fan vibration monitoring.

3.3 Digital Layer Interference Countermeasure Technology

Digital layer anti-interference technology focuses on "error correction" and restores signal authenticity through adaptive algorithms, fault-tolerant coding, and other means for digital signal transmission errors and sampling noise. It serves as the final guarantee in complex interference scenarios.

The Kalman-Wavelet Fusion Filtering Algorithm processes signals in two steps: Kalman Filtering dynamically estimates the signal mean based on state equations and optimizes the noise covariance through Q and R matrix iteration, achieving a 90% suppression rate for Gaussian white noise. Wavelet Transform uses db4 wavelet basis for 5-layer decomposition, extracts high-frequency noise components and sets their thresholds to zero, achieving a 95% elimination rate for impulse interference. In the dynamic test of hydraulic pressure sensors, the reconstruction error is ⩽0.5% at 10dB SNR, and the dynamic response time is reduced from 50ms to 20ms, meeting the real-time monitoring requirement for injection molding machine mold clamping pressure.

The Fault-Tolerant Coding System is designed in the transmission layer and link layer: the transmission layer adopts Cyclic Redundancy Check-16 (CRC-16) verification (generator polynomial 0x8005) combined with Manchester coding. The encoded signal has a 100% transition rate, solving the synchronization loss problem in wireless transmission. The bit error rate in the 433MHz band is reduced from 10^{-3} to 10^{-6}. The link layer designs a "master-slave arbitration + timeout retransmission" mechanism for SPI/I2C buses. The master device detects conflicts through SDA line level and retransmits after a random delay of 1-10μs when a conflict occurs. The communication success rate is increased from 85% to 99.9% in EMI environments [8].

4 Typical Application Scenarios and Engineering Practices

4.1 Industrial Automation Field: High-Precision Pressure Sensor Interface Design

In the industrial automation process, the injection molding machine pressure measurement and control system directly determines the plastic melt filling quality, requiring a pressure measurement precision ⩽0.1% FS. However, in the working environment, the 10-50kHz vibration of the hydraulic pump causes mechanical fatigue of the sensor's sensitive components, resulting in a zero drift of 0.3% FS within 3 months. The 30MHz-1GHz EMI generated by the frequency converter couples through the power line, causing the ADC sampling value to fluctuate by ±5 Least Significant Bits (LSB) (16-bit ADC), with a measurement error exceeding 0.5% FS, failing to meet precision injection molding requirements.

To effectively solve these interference problems, a four-dimensional solution of "mechanical damping + double-layer shielding + differential amplification + digital filtering" is adopted: a rubber damping pad (damping coefficient 0.3) is added to the sensor housing, reducing the vibration acceleration from 10g to 0.5g. Double-shielded twisted pair (distributed capacitance ⩽30pF/m, mutual inductance ⩽8nH/m) is used for signal transmission, with the outer shield grounded at a single point to block radiation interference. The front-end amplification uses an AD620 instrumentation amplifier (gain 100, CMRR=120dB@50Hz) to suppress common-mode interference. The MCU has built-in 5-point median filtering + Kalman filtering to eliminate impulse noise and random noise. Practical measurements show that the pressure measurement error is reduced from ±0.5% FS to ±0.1% FS, the zero drift is <0.05% FS after 6 months of continuous operation, and the product qualification rate is increased from 88% to 99%.

4.2 Intelligent Device Field: MEMS Accelerometer Anti-Vibration Design

In wearable devices such as smart bracelets, Micro-Electro-Mechanical System (MEMS) accelerometers are used for step counting and posture recognition, requiring a posture detection error rate ⩽5%. However, in practical use, the 100Hz-500Hz mechanical vibration generated by human running causes the sensor output noise amplitude to reach 200mg, far exceeding the walking signal (50-100mg). The 2.4GHz WiFi signal of mobile phones couples through PCB parasitic capacitance, generating 10mV-level interference in the sensor interface circuit, resulting in a step counting error of 15% and frequent posture recognition errors.

A collaborative solution of "mechanical vibration isolation + electromagnetic shielding + circuit filtering + algorithm threshold" is adopted: a silica gel damping structure (natural frequency >2kHz) is built into the sensor package, attenuating 80% of 100Hz-500Hz vibration through resonance suppression. In PCB design, a copper shield is laid in the sensor area and grounded at a single point to form a Faraday cage, reducing the WiFi interference coupling from 10mV to 0.5mV. A 10μH/100nF LC π-type filter is used at the power supply end to filter out high-frequency noise. The algorithm layer adopts adaptive threshold detection, dynamically adjusting the step determination threshold according to the vibration amplitude, and combining 3-axis data fusion to eliminate false signals. After optimization, the posture detection error rate is reduced from 15% to below 2%, the step counting error is ⩽3%, and the user experience is significantly improved.

4.3 Wireless Sensor Network: Low-Power Anti-Interference Node Design

In the Industrial Internet of Things (IIoT), 433MHz band wireless sensor nodes are used for remote monitoring of parameters such as temperature, humidity, and pressure, requiring a data transmission success rate ⩾95% and a battery life ⩾12 months. However, in industrial sites such as chemical and iron and steel plants, multiple devices operating in the same frequency band cause co-channel interference, reducing the receiving sensitivity from -100dBm to -85dBm, with a data transmission success rate of only 70%. Traditional nodes have a continuous operating current of 10mA, and a 2000mAh battery lasts only 2 months, failing to meet long-term monitoring requirements.

A low-power anti-interference solution of "Frequency-Hopping Spread Spectrum (FHSS) + channel detection + sleep-wake" is adopted: the RF module uses FHSS technology, setting 16 frequency points in the 433MHz±10MHz band and hopping 50 times per second to avoid fixed-frequency interference. Before transmission, Energy Detection (ED) is used to judge the channel power, and transmission is only performed when the power is <-105dBm, reducing the collision rate by 90%. The node adopts a "sampling-transmission-sleep" cycle mode: sampling time 10ms (current 5mA), transmission time 5ms (current 30mA), and sleep time 985ms (current <1μA). Practical measurements show that the receiving sensitivity is improved to -110dBm, the data transmission success rate is increased from 70% to 98%, and the 2000mAh battery life is extended to 18 months, meeting the 1-year maintenance-free requirement in chemical parks.

5 Challenges and Prospects

5.1 Existing Technical Bottlenecks

Although significant progress has been made in the anti-interference technology of sensor interface circuits, there are still many technical bottlenecks in practical applications, restricting the further improvement of performance and expansion of application scope.

The coupling mechanism of multi-source interference is complex, and there is a lack of unified modeling tools, which is another major problem currently faced. In practical sensor application scenarios, there are often multiple interference sources, such as EMI, mechanical vibration, and temperature-humidity changes. These interference sources act on the sensor interface circuit through different coupling paths, and their coupling mechanisms are extremely complex. Taking industrial sites as an example, multiple interference sources such as EMI generated by motors, mechanical vibration, and environmental temperature-humidity changes exist simultaneously, interacting with each other and making the interference coupling situation more complex. Currently, there are many modeling methods for different interference sources and coupling paths, but there is a lack of a unified modeling tool that can comprehensively consider various interference factors. This results in the need to analyze and model different interference sources and coupling paths separately during anti-interference design, leading to a long design cycle (typically 4-6 weeks). Moreover, due to the lack of unified modeling tools, it is difficult to accurately evaluate the comprehensive effect of various anti-interference measures, increasing the difficulty and uncertainty of anti-interference design.

5.2 Future Research Directions

Intelligent anti-interference technology will become one of the key research directions in the future. By integrating machine learning algorithms to build an interference pattern recognition and adaptive adjustment system, dynamic optimization of anti-interference strategies can be achieved. Deep learning algorithms are used to learn and train a large amount of interference signal data to establish an interference pattern recognition model. This model can real-time analyze the signals received by the sensor interface circuit and accurately identify the type, intensity, frequency, and other characteristics of the interference. Then, according to the recognition results, the anti-interference strategy is adaptively adjusted, such as automatically switching filter parameters and adjusting amplifier gain, to achieve the best anti-interference effect. In practical applications, when the frequency of the interference signal is detected to change, the system can automatically adjust the cutoff frequency of the filter to effectively filter out the interference signal. This intelligent anti-interference technology enables the sensor interface circuit to real-time adjust the anti-interference strategy according to different interference environments, improving its adaptability and reliability in complex electromagnetic environments.

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