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Hardware-in-the-Loop Simulation of Pressure Measurement Modules in While-Drilling Systems

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Abstract

To address the issues of high cost and low efficiency in traditional testing of pressure measurement modules while drilling—which rely on physical sensors and simulated high-temperature environments—a testing system based on hardware-in-the-loop simulation technology is proposed to achieve efficient and low-cost performance verification of the measurement module. The system consists of a PC host computer, a real-time simulator (PXIe platform), and the measurement module. Simulation models of pressure and temperature sensors are built using Simulink and deployed to the real-time simulator via VeriStand software to emulate voltage and resistance signals consistent with those of actual sensors. A host computer interface is developed using C# to enable parameter configuration, data acquisition, and error analysis. The system validates the effectiveness of the temperature drift compensation algorithm through comparative experiments with and without correction. Test results show that the system can effectively simulate downhole sensor outputs, and after correction, the pressure measurement error is controlled within ±108 psi, significantly suppressing the influence of temperature on measurement accuracy. This verifies the feasibility and superiority of the hardware-in-the-loop simulation method in testing measurement-while-drilling modules.

Keywords

Pressure Measurement; While Drilling (MWD); HIL Simulation.

1. INTRODUCTION

Pressure measurement while drilling (MWD) plays a critical role in ensuring wellbore safety and optimizing drilling parameters [1]. Embedded within the bottom hole assembly (BHA), the pressure measurement module captures real-time data on both internal and external drill string pressures. These data support surface engineers in making informed decisions, thereby improving reservoir penetration rates and minimizing drilling expenses [2]. At present, functional testing and performance validation of pressure-while-drilling modules typically rely on field trials or laboratory-based environmental simulations [3]. However, such approaches, which depend entirely on physical sensors, are associated with high costs and limited testing efficiency. As a result, they are inadequate for supporting rapid design iterations and efficient validation workflows, ultimately increasing development overhead and slowing the testing process.

To overcome these limitations—namely, the reliance on physical sensors and simulated downhole thermal environments—this study introduces a hardware-in-the-loop (HIL) simulation system for pressure measurement modules while drilling. By integrating advanced modeling techniques with real-time simulation platforms, the proposed system accurately and dynamically emulates the output signals of downhole pressure and temperature sensors under

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laboratory conditions. This methodology offers a cost-effective and efficient solution for validating pressure measurement modules in MWD applications.

2. MEASUREMENT PRINCIPLE OF THE PRESSURE MEASUREMENT MODULE

2.1. Measurement Principle of the Temperature Sensor

The temperature measurement within the pressure module is realized using a PT1000 resistive thermal device (RTD) fabricated from platinum wire. This sensor exploits the characteristic that its electrical resistance increases with rising temperature, exhibiting strong linearity over the operating range [4]. To achieve high-sensitivity detection of resistance variations caused by minute temperature fluctuations, the PT1000 is typically integrated into a Wheatstone bridge configuration. The resulting weak differential voltage signal from the bridge is subsequently conditioned by an amplification circuit, enabling precise downhole temperature measurement. The corresponding measurement principle is illustrated in Figure 1.

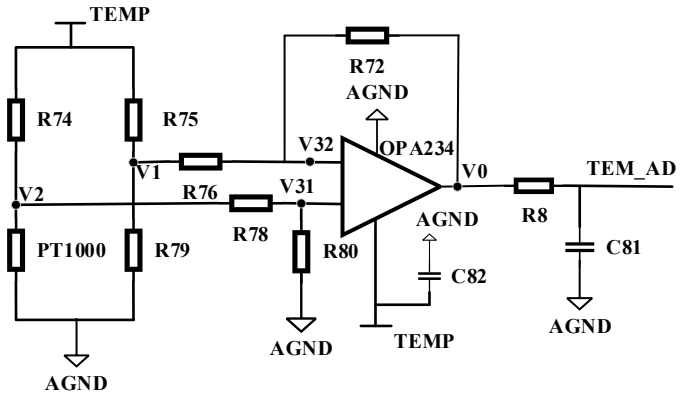


Figure 1. Temperature sensor measurement diagram

The PT1000 is a platinum resistance thermometer with a temperature coefficient of resistance (TCR) of 0.003851. Within the temperature range of 0 °C to 850 °C, the relationship between temperature and resistance is expressed by Equation (1).

$$\begin{cases} R_{PT1000} = R_0\left(1 + AT + BT^2\right) \\ A = 3.9083 \times 10^{-3}\ ^oC^{-1} \\ B = -5.775 \times 10^{-7}\ ^oC^{-2} \end{cases} \tag{1}$$

2.2. Measurement Principle of the Pressure Sensor

As the core sensing element, the pressure sensor is primarily employed to monitor the mud pressure inside the drill string and the fluid pressure in the annulus. By capturing real-time dynamic variations in fluid pressure within both the drill string and annular regions during drilling operations, it converts the physical pressure generated by drilling mud and formation fluids into electrical signals for output. However, when the ambient temperature deviates from the reference value, both the zero-point drift and sensitivity factor exhibit nonlinear variations with temperature, thereby compromising the accuracy of pressure measurements [5]. Consequently, it is necessary to compensate for temperature-induced measurement errors. The output signals of different pressure sensors as a function of temperature are described by Equation (2).

$$P = SF(T) \cdot U + ZB(T) \tag{2}$$

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Here, P denotes the theoretical pressure value during drilling, U represents the measured voltage output of the pressure sensor under different temperature conditions, SF(T) is the sensitivity coefficient of the sensor at a given temperature, and ZB(T) refers to the zero-point drift of the sensor under varying thermal environments.

To characterize the temperature-dependent behavior, the drift and sensitivity coefficients are fitted using polynomial regression based on the least squares method [6]. The polynomial function employed for this fitting is given by Equation (3).

$$f(T) = \beta_0 + \beta_1 T + \beta_2 T^2 + \cdots\cdots + \beta_n T^n = \sum_{j=0}^{n} \beta_j T^j \tag{3}$$

3. DESIGN OF THE HARDWARE-IN-THE-LOOP SIMULATION SYSTEM

3.1. System Composition

The proposed hardware-in-the-loop simulation system for pressure measurement modules while drilling enables real-time emulation of pressure and temperature sensor signals in a laboratory environment. This setup facilitates reliability and accuracy testing of the downhole measurement module while significantly reducing the costs associated with physical sensors and downhole environment simulation, thereby improving overall test efficiency. The system architecture is illustrated in Figure 2. The hardware primarily comprises a host PC, an RS485 communication interface, a real-time simulator, and the measurement module under test. The real-time simulator integrates a PXIe chassis, a PXIe-8861 embedded controller, a PXIe-6738 voltage output module, and a PXIe-2722 resistance output module. On the software side, Simulink is employed for constructing and compiling the online sensor simulation models deployed to the real-time target. VeriStand serves as the configuration software for the real-time simulator, managing model deployment, parameter configuration, and real-time monitoring. The user interface, which communicates with the pressure measurement module via RS485, enables interactive control and data exchange.

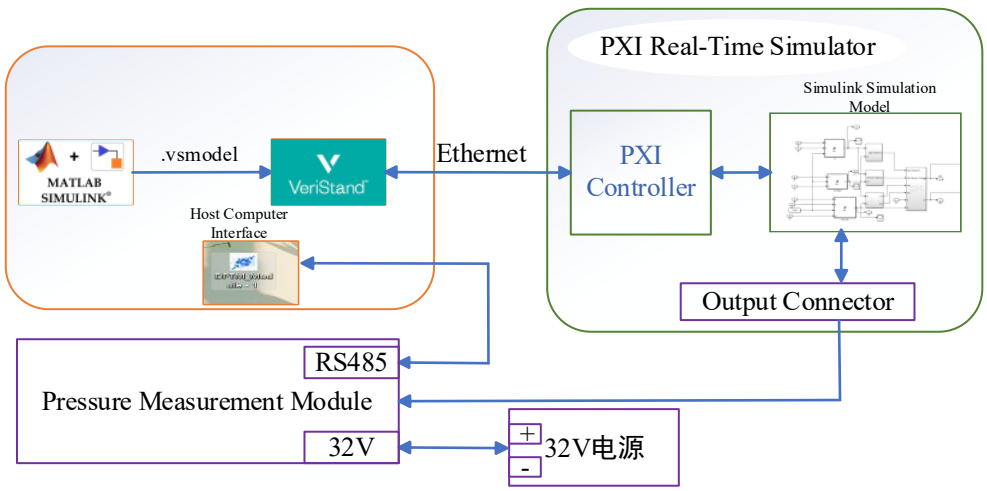


Figure 2. Composition of the Hardware-in-the-Loop Simulation System

3.2. Sensor Simulation Modeling

Based on the theoretical analysis of pressure and temperature measurement principles, simulation models for the internal pressure sensor, external pressure sensor, and temperature sensor were developed using Simulink, as illustrated in Figure 3.

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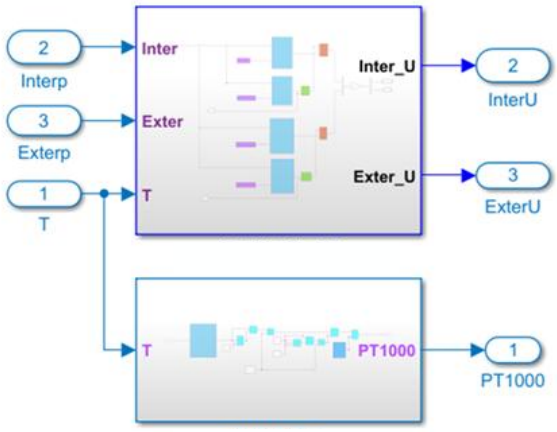


Figure 3. Simulation Model of the Sensor

In the model, the input parameters—denoted as Inter, Exter, and T—represent the internal pressure, external pressure, and ambient temperature acting on the downhole drilling assembly, respectively. The corresponding outputs include InterU and ExterU, which represent the signal outputs from the internal and external pressure sensors, while PT1000 denotes the output signal from the temperature sensor.

4. SYSTEM TEST AND VALIDATION

The pressure measurement module acquires real-time internal and external pressure parameters while drilling through its integrated internal and external pressure sensors. To comprehensively assess its computational accuracy and the effectiveness of the temperature drift correction algorithm, simulation models of the internal pressure sensor, external pressure sensor, and their corresponding temperature sensors were deployed in the real-time simulator for hardware-in-the-loop testing.

4.1. Testing without Compensation

The uncorrected test aims to evaluate the basic computation functionality of the pressure measurement module under ideal signal input conditions. During the test, both the internal and external pressure sensor models were configured as ideal models without any introduced errors, and the correction algorithm within the measurement module remained disabled. Based on the measurement ranges of internal and external pressures, five representative sets of parameters were randomly selected for functional verification. For each parameter set, 100 computed values of internal and external pressure were collected in real time via the host computer interface and saved to an Excel file. The absolute maximum error between the input pressures and the computed values under each test condition was recorded. The results are presented in Table 1.

Table 1. Results of Uncorrected Testing

Numble	Internal Press (psi)	External Press (psi)	|△InterP|(psi)|	|△ExterP|(psi)
1	2600	4230	90	45
2	6710	7670	91	80
3	12000	13380	90	80
4	16125	15095	87	25
5	20000	19000	98	63

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4.2. Testing with Temperature Compensation

To validate the reliability of the temperature drift correction algorithm, error models for the internal and external pressure sensors, along with their corresponding temperature sensor models, were deployed in the real-time simulator to simulate the interference of downhole temperature variations on pressure measurements. A comparative experimental design was adopted, with tests conducted under both disabled and enabled correction algorithms to quantify the improvement in computational accuracy. The internal and external pressures were fixed at 8000 psi, while the temperature was increased from 30 °C to 150 °C in increments of 30 °C. At each temperature step, 100 consecutive pressure data points were collected, and the maximum absolute error was recorded. The results are presented in Table 2.

Table 2. Results of Corrected Testing

Temperature (℃)	Uncorrected Borehole and Annular Pressure Computational Errors		Corrected Borehole and Annular Pressure Computational Errors	
	|△InterP|(psi)	|△ExterP|(psi)	|△InterP|(psi)	|△ExterP|(psi)
30	303	210	108	74
60	460	313	106	76
90	502	398	102	72
120	596	456	97	97
150	678	518	103	101

Before correction, the measurement errors increased significantly with rising temperature. At 150 °C, the internal pressure error reached 678 psi and the external pressure error reached 518 psi, both exceeding the design specifications. This degradation is primarily attributed to temperature-induced sensitivity drift of the sensor, thermal stress within the structure, and imbalance in the Wheatstone bridge, all of which introduce additional errors. After enabling the correction algorithm, the errors at all temperature points were confined to within ±108 psi, satisfying the design requirements, with no observable increase in error as temperature rose. The residual errors after correction, though slightly higher than those under ideal uncorrected conditions, mainly stem from the fitting residuals of the temperature compensation model and the propagated measurement inaccuracies of the temperature sensor itself. Overall, the results demonstrate that the correction algorithm effectively eliminates temperature-induced interference and significantly enhances the measurement accuracy of the module across a wide temperature range.

5. CONCLUSION

This paper investigates a hardware-in-the-loop simulation system to address the high cost and low efficiency of traditional testing methods for pressure measurement modules while drilling. A temperature drift error model was established based on sensor measurement principles, and the least squares method was used to determine the model parameters. The system is built around a PXIe real-time simulator, utilizing Simulink for modeling and VeriStand for deployment to achieve high-precision real-time simulation of sensor signals. A user interface was also developed using C#. Test results show that uncorrected pressure errors increase significantly with temperature, reaching up to 678 psi at 150°C. After enabling the compensation algorithm, the error across the entire temperature range is controlled within ±108 psi, confirming the accuracy of the model and the reliability of the correction algorithm. The proposed system effectively replaces physical sensors and high-temperature environments,

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offering an efficient and low-cost solution for testing pressure measurement modules while drilling.

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