A Long-term Temperature and Depth Logger for Ocean Mooring System

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***Abstract*—Temperature, depth and conductivity (CTD) are the most essential physical properties of sea water. CTD instrument is one of the most efficient approaches for collecting the accurate ocean information. However, traditional CTD instruments are not best suited for applications that require high resolution data by a large number of sensors because of their large size and high cost. This paper describes the design of a compact, high-accuracy, and low-cost temperature and depth (TD) logger for ocean mooring system. The noise floor of the TD logger was evaluated in lab for determining the logger measurement resolution. A specific calibration method was implemented for pressure transducer calibration to eliminate the thermal affect. The initial temperature accuracy of TD logger is ±0.002°C and the pressure accuracy is ±0.05% of full scale. The effective resolution is 0.0001°C and 0.001% full scale for temperature and pressure measurement, respectively. A 150-day off-shore experiment yielded 0.41 million temperature and pressure measurements that confirmed the stability of TD logger measurement. The correlation analysis revealed a maximum deviation of 0.2°C and 0.8m compared to independent measurements.**

Keywords—Temperature and pressure logger; Mooring systems; Calibration; effective resolution

I. Introduction

Conductivity, Temperature and Depth (CTD) instrument are the primary approach for observing the physical properties of sea water. CTD system usually falls into two categories: mooring measurement and profiling measurement. Generally, temperature and depth measurement for entire water column based on mooring system can meet the requirement of some scientific research purposes [1][2]. However, traditional CTD instruments are usually of large size high cost, and more power consumption [3], which prevent the measurement of mooring system from acquiring high resolution data in long-term temporal or in the vertical spatial efficiently. Therefore, the development of CTDs for mooring system has been focusing on improving accuracy and stability and lowering power consumption.

The objective of this paper is to describe the prototype design and evaluation of a compact, high-accuracy and low-cost temperature and depth (TD) data logger (Fig. 1). The noise floor of the TD logger was evaluated in lab testing for determining the logger's measurement resolution. A specific calibration method was implemented for pressure transducer calibration. The calibration procedure can efficiently eliminate the measurement error of pressure transducer caused by ambient thermal affect. The TD logger was then evaluated in a long term off-shore deployment. Preliminary data analysis and its results are presented in this paper.

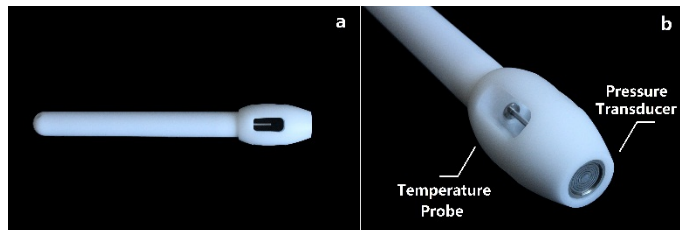

Fig. 1. The TD logger prototype: (a) Top view (b) Details of temperature probe and pressure transducer

II. Instrument Design

The TD logger is 285 mm in length and 25 mm in diameter. Depth rating is 2000 m with polyformaldehyde housing. The TD logger consists of a negative temperature coefficient (NTC) thermistor, a pressure transducer, an ultra-low power microcontroller unit (MCU), flash memory and real-time clock (RTC) (Fig. 2). The entire system is powered by a single 3.6 V AA lithium thinly chloride battery and capacity of flash memory is 128 Mbytes (20 million samples). The RTC chip is operated by a temperature compensation oscillator for providing accurate clock reference and sampling interval. Long-term stability of the RTC is within ±30s per year. Sample interval can be programmed manually from 1 second to 18 hours.

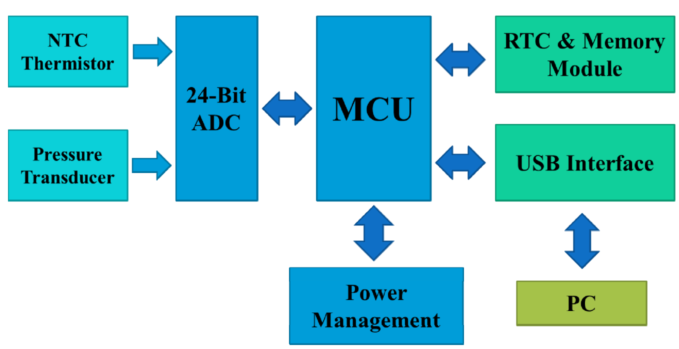

Fig. 2. Functional block diagram of TD logger

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With a low-power management strategy controlled by the MCU, the system can switch between activity mode and low power mode automatically. System power consumption is about 7 mW in activity mode and less than 40 μW in low power mode, and the TD logger can be deployed for more than 6 months with 1s sampling interval. The TD logger utilizes Universal Serial Bus (USB) 2.0 full-speed communication interface for data retrieval with a communication speed of about 2 Mbps. Therefore, all the sampling data can be downloaded within 15 minutes.

A. Temperature Measurement Design

The temperature probe in the TD logger includes a fast response NTC thermistor for sensing temperature variation. The thermistor (Model MF5W,Technical Institute of Physics and Chemistry, Chinese Academic of Sciences, Xinjiang, China) is selected because of its small size, low time constant and high sensitivity. Thermistor was sealed into a 2 mm diameter titanium protection housing for enduing external pressure in deep water. With flexible thermally conductive silicone padded into the housing, the response time of temperature probe can be down to 1s to accommodate maximum sampling frequency.

NTC thermistors usually possess nonlinear resistance-temperature characteristic, which can be modeled as exponential function. This property causes measurement inaccuracy within targeted temperature range. To resolve this, a simple voltage divider circuit is utilized to obtain a desired linear relation between the output signal and temperature variation. The complete measurement circuit consists of constant voltage source, thermistor, fixed resistor, conditioning circuit and Analog-to-digital converter (ADC). The constant driving voltage is generated by a 3VDC low noise low dropout regulator (LDO). The fixed resistor is utilized to adjust linearity and sensitivity of output signal to optimal level over measured temperature range (from -5°C to 35°C). Voltage signal of the linear output is transferred into a zero-drift low-noise amplifier performing as voltage buffer to achieve signal impedance match. The output signal of the amplifier is connected to a 24-bit sigma delta ADC (Model LTC2410, Linear Technology Corporation, Milpitas, CA) to quantize the accuracy and high-resolution signal. Digital output of ADC is sent to the MCU with 3-wires serial peripheral interface(SPI).

B. Pressure Measurement Design

An off-the-shelf piezoresistive pressure transducer (Model PA-10L, KELLER, Switzerland) is used for measuring water pressure. Response time of the pressure transducer is approximately 10 ms. The transducer is a sealed absolute pressure gauge and comprises of silicon chip and stainless steel housing, which is filled with silicone oil for enabling measurement stability.

For general application, the pressure transducer is driven by a constant current and its driving current should be limited small than 1 mA. Pressure measurement circuit consists of compensation resistors network, constant current source, conditioning circuit and ADC. With external series and parallel resistors network, the transducer can be compensated to eliminate zero-drift of output signal. Also, in order to reduce the power consumption and PCB layout area, constant current-drive circuit is employed and consists of a low-noise amplifier, a fixed high-accuracy resistor and 2.5 VDC LDO. These components are combined with four semi-conductor resistors sealed in transducer performing as a negative feedback amplifier circuit. Then, the actual value of constant current is determined to 0.5mA by $I=\frac{V_S}{R}$. Where, V_S is driving voltage of pressure transducer deriving from 2.5V LDO, R is resistance of fixed resistor selected with 5kohm. The differential signal of the transducer output is connected to a precision instrumentation amplifier converted to single ended signal. The final output signal is also fed into the 24-bit ADC to quantize the measured voltage signal.

C. Circuit Performance Analysis

Under ideal conditions, the 24-bit ADC can provide sufficient resolution for the ambient temperature and pressure measurement. However, the noise property of the actual conditioning circuit (PCB layout or electronic components) will affect the final resolution. Because the intrinsic noise appears in the whole measurement system and affects the resolution of measured voltage signal, an effective statistical method should be considered for evaluating final noise floor in temperature and pressure measurement respectively [4].

Electronic noise of a measurement system is normally assumed as random occurrence and histogram should be complied with Gaussian distribution. A large number of data collected from an ADC can be used to describe final noise floor of measured physical parameters. Specifically, when the thermistor used in temperature measurement circuit is replaced with high-precision resistor, the digital output of the ADC is fluctuated around an order of magnitude. These counts are considered as possible resistance of measured fixed resistor resulting from measurement noise. Similarly, when input of the amplifier used in pressure measurement circuit is shorted, the counts of ADC output are interpreted as measured value relative to ground.

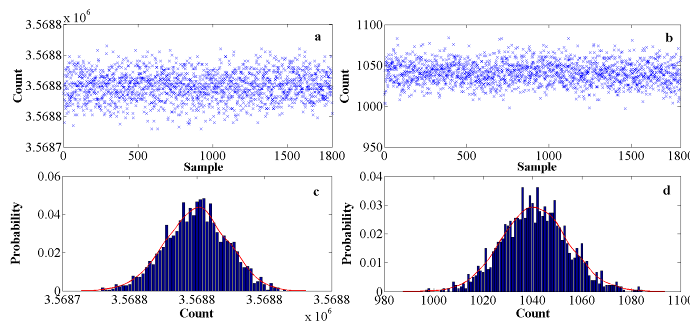

Fig. 3. Noise analysis of measurement circuit: (a) digital output signal of temperature measurement circuit (b) digital output signal of pressure measurement circuit (c) histogram of temperature measurement PDF (d) histogram of pressure measurement PDF

According to mathematics model of Gaussian, the term of mean (μ) is bias level of the ADC input and the term of standard deviation (σ) is used to calculate root mean square (RMS) noise of measurement system by $V_{noise}=\sigma\times\frac{U_{ref}}{2^{24}}$. Where, U_{ref} is voltage reference of the ADC, 3V in temperature measurement and 2.5V in pressure measurement, respectively. The bias level is much trivial to noise evaluation and it is only used by calibration procedure. The value of V_{noise} and sensitivity of transducer can be used for estimating the effective resolution by Noise floor= $\frac{V_{noise}}{Sensitivity \times Gain}$ .Where, sensitivity slightly varies due to various transducers, and gain is magnification of the amplifier.

For actual evaluation, the TD Logger is immersed into a constant temperature water bath with a stability of ±0.005°C to eliminate the effect of thermal drift of electronic components. Finally, the logger collected about 1800 samples (around 30 minutes) with 1 second interval (Fig. 3) and the calculated effective resolution of temperature and pressure is less than 0.0001°C and 0.001% full scale respectively.

III. EXPERIMENT RESULT

The TD logger was calibrated to desired accuracy, and evaluated in a long term off-shore.

A. *Instrument Calibration*

The temperature calibration of TD logger was conducted at a calibration lab located in National Center of Ocean Standards And Metrology (NCOSM). The calibration bath is 1500 mm in diameter and 900 mm in depth, stability and uniform are less than 0.001°C in 30 minutes. TD logger was fully immersed in the bath with the same horizontal position against with a standard platinum resistance thermometer (SPRT). The SPRT provides standard temperature during the entire calibration procedure. Eight temperatures were selected for calibration with 5°C step from 0 to 35°C. TD logger was logging for 10 minutes at each temperature points at 1 second interval. The 600 temperature readings of TD logger were averaged as R_T. Then, the Steinhart-Hart equation [6] was applied to fit R_T and standard temperature T. The formula can be expressed by:

$$\frac{1}{T}=E+F\ln R_T+G\ln^2 R_T+H\ln^3 R_T \quad (1)$$

Where, E to H is calibration coefficients. The calibrated temperature probe has accuracy of ±0.002°C and used to provide temperature reference for pressure calibration procedure.

Generally, ambient temperature variation will significantly affect the accuracy of pressure measurement because of the semiconductor characteristic of the pressure transducer. Therefore, an advanced pressure calibration method is necessary for compensation in realistic environment. Pressure transducer of the TD logger was calibrated in a 200-bar scale pressure chamber. The pressure chamber is immersed in a constant temperature bath with accuracy of ±0.005°C to regulate ambient temperature of TD logger to desired value. A dead weight tester with accuracy of 0.005% full scale is connected to the pressure chamber for providing the standard pressure value. Four temperature points and eight pressure points were selected to calibrate TD logger for temperature compensation. The temperature points included 5, 15, 25 and 35°C and the pressures points was from 0 to 200 bar with 25 bar increments. The TD logger sampled 600 pressure data at each temperature and pressure point. After averaging the reading of the temperature and pressure, a polynomial formula was used to calculate calibration coefficients [6]. The formula can be expressed by:

$$P=A(T)+B(T)R_P+C(T)R_P^2+D(T)R_P^3 \quad (2)$$

$$A(T)=A_0+A_1T+A_2T^2+A_3T^3 \quad (3)$$

$$B(T)=B_0+B_1T+B_2T^2+B_3T^3 \quad (4)$$

$$C(T)=C_0+C_1T+C_2T^2+C_3T^3 \quad (5)$$

$$D(T)=D_0+D_1T+D_2T^2+D_3T^3 \quad (6)$$

Where, P is the standard pressure, R_P is the reading value of pressure measurement in temperature T, A_0 to D_3 is pressure calibration coefficients. With the fitting formula applied, temperature compensation is only achieved by mathematics method without additional circuit design [7]. With temperature compensation method used, calibrated pressure transducer has an accuracy of ±0.05% full scale over the whole temperature measurement range.

B. *Off-shore Experiment*

Two TD loggers were deployed in a short range subsurface mooring system (about 13 m long) located at of JiaoZhou bay in Qingdao to evaluate the stability of the instrument. Additionally, a temperature logger (Model SBE-56, Sea-Bird Electronics, Inc., Bellevue, WA) and pressure logger (Model DR-1060, RBR Ltd., Canada) were deployed with same sample interval to compare measurement data with the TD loggers. All the loggers start sampling on November 10th 2014 and stopped sampling in April 2015 with a 30-s sampling interval. Each of the TD loggers collects about 0.41 million samples during the 150 days of deployment. The entire data of one of the TD loggers are presented in Fig. 4. The correlation analysis shows that the TD logger has a maximum deviation of 0.2°C comparing to SBE-56 and a deviation of 0.8m comparing to DR-1060 (Fig. 5).

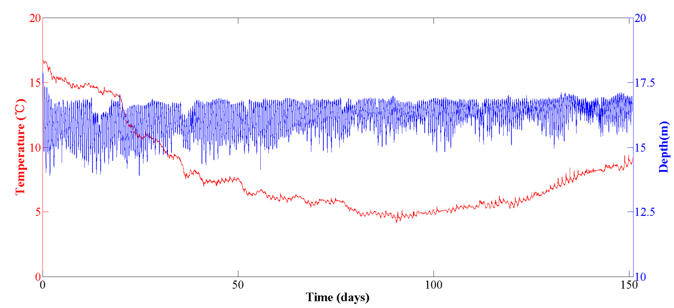

Fig. 4. Off-shore experiment data of TD logger

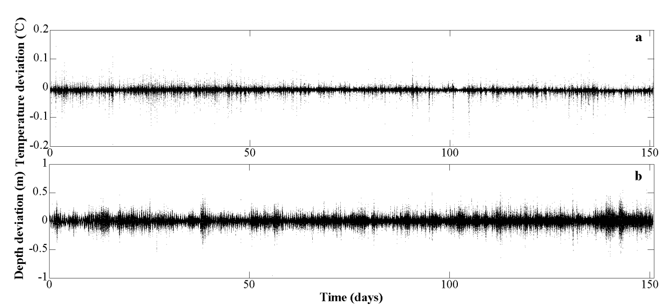

Fig. 5. Correlation analysis: (a) Temperature measurement deviation (b) Pressure measurement deviation

IV. CONCLUTION

The TD logger implemented in this study has a robust physical structure and can be integrated on the ocean mooring system for long-term deployment. Based on the circuit design and lab test, the effective resolution of the TD logger is less than 0.0001°C and 0.001% full scale for temperature and pressure measurement, respectively. The initial temperature accuracy is ±0.002°C and the pressure accuracy is ±0.05% of full scale. The performance of the TD loggers was confirmed in a 150-day off-shore experiment. Sea trials will be conducted in the winter of 2015 to further evacuate the long-term stability of the TD logger under deeper sea conditions.

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