International Journal of GEOMATE, May, 2016, Vol. 10, Issue 21, pp. 1956-1963
Geotec., Const. Mat. & Env., ISSN: 2186-2982(Print), 2186-2990(Online), Japan

DEVELOPMENT OF CAPACITANCE DISPLACEMENT MONITORING SYSTEM AND ITS PERFORMANCE TESTS

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ABSTRACT: Geological disasters caused by slope instability frequently result in great loss to human life and property, and real-time and on-line slope monitoring is a most effective method for mastering the deformation dynamics and early warning of landslide disasters. Considering the numerous landslides and high cost of slope monitoring system, three types of capacitance displacement transducer based on the principle of electrostatic capacitance were designed. Basic performance and long-term stability performance of these capacitors were examined, and the impact of temperature behavior on the capacitance measurement circuit was evaluated. The results showed that, comparing with conventional displacement transducers used for slope monitoring, capacitance type transducers can provide sufficient precision, resolution and measurement range, and applying them in slope monitoring could bring obvious advantages, because of its remarkable economic benefit and effectiveness.

Keywords: Linear Capacitance Displacement Transducer, Landslide, Slope Monitoring, Performance

1. INTRODUCTION

Landslide is a serious geological disaster and widely distributed in the global scope, which frequently causes great loss to human life and property. It is difficult to invest immense economic and technology to manage all the potential landslides. Real-time and on-line monitoring of slope is therefore, a most effective method for mastering the deformation dynamics and early warning of landslide in time [1]. However, current monitoring technology has the defects of time-consumption, costliness and high level technologyd, which result in their poor universal applicability in landslide monitoring. In view of this, it is of great significance to develop a simple, low-cost and easily embedded displacement monitoring instrument.

Starting with this premise, the development of low-cost slope monitoring system for consumers was presented in this paper. Based on the principle of electrostatic capacitances, three types of capacitance displacement transducers, Area-alterable Type Parallel-plate Capacitor (ATPC), Area-alterable Type Cylinder Capacitor (ATCC) and Permittivity-alterable Type Cylinder Capacitor (PTCC), were designed, and performance of these transducers was examined.

2. PRINCIPLE OF THE CAPACITANCE DISPLACEMENT TRANSDUCER

Capacitance displacement transducer is utilized for converting a displacement caused by a change of a physical variable into an electrical signal using electrostatic capacitances [2], [3]. Ignoring edge effects, capacitance between a pair of parallel plates is given by Eq. (1).

$$C = \frac{\varepsilon_0 \varepsilon_r S}{d} \tag{1}$$

Where ε_0 is the permittivity of free space; ε_r is the relative permittivity of the dielectric material, in the air, $\varepsilon_r = 1$; S is the overlap area of the plates (m^2); d is the distance between two plates (m).

As can be seen from Eq. (1), there are three variables, ε_r, S, d, and it is advisable to maintain any two of them as constant and adjust the rest by changing the displacement of a movable part of the capacitance transducer, thereby establishing a linear relationship between the capacitance and the adjustable variable. A measure of the capacitance is, therefore, a measure of the displacement of the movable part of the capacitance transducer. The change in capacitance can be converted into digital signal indicating the linear displacement of the transducer by a matching measuring circuit.

2.1 Area-alterable Type Parallel-Plate Capacitor (ATPC)

The ATPC capacitor is formed by having the first and second parallel electrodes fastened on a stationary assembly to constitute the measured capacitance C_m, and the third parallel electrode 3 fastened on a movable assembly constitutes the electrostatic capacitances C_{13} and C_{32} respectively with the first and second electrodes. The electrode 3, moving with the measured object, is provided as a shield and connected to GND. The structure of ATPC capacitor is shown in Fig.1.

In this case, electrode 1 and 2 are composed of polypropylene material, the lower surface of electrode 1 and the upper surface of electrode 2 are covered with a piece of conductive paper (i.e. aluminizing paper) and electrode 3 is composed of conductive paper. The thickness of these three electrodes are 1 mm, lengths are 330 mm, which suggest that the measurement range of this transducer is 330 mm. Made of relatively simple material, this transducer can be manufactured at significantly reduced cost.

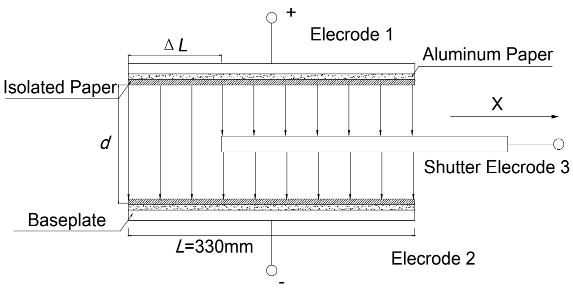

Fig.1 The structure of ATPC capacitor

We are setting permittivity ε_r and distance d remains constant and adjusting the overlap area S by the movable electrode 3 of the transducer, the initial overlap area is $S_0 = a \times L$, here a is the width and L is the length of the parallel electrodes, the initial capacitance is, therefore, given by Eq.(2).

$$C_0 = \frac{\varepsilon_0 \varepsilon_r S}{d} = \frac{\varepsilon_0 \varepsilon_r a L}{d} \tag{2}$$

The change in the overlap area of the relatively fixed electrodes 1 and 2 caused by the linear displacement ΔL of electrode 3 relates to its capacitance directly, and the changed capacitance is given by Eq.(3)

$$C_m = \frac{\varepsilon_0 \varepsilon_r a (L - \Delta L)}{d} = C_0 - \frac{\varepsilon_0 \varepsilon_r a}{d} \Delta L \tag{3}$$

2.2 Area-alterable Type Cylinder Capacitor (ATCC)

This ATCC capacitor is formed by having one hollow cylindrical electrode 1 fastened on a stationary assembly and another solid cylindrical electrode 2 fastened to a moveable assembly. The inner cylinder movably engages within the outer cylinder so that, as the movable electrode is displaced, the overlap area of the measured capacitance changes as a function of linear displacement. Its structure is shown in Fig.2.

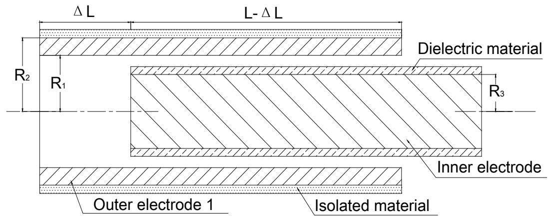

Fig.2 The structure of ATCC capacitor

In this case, both cylinders are composed of metal material. The solid inner cylinder 2 has a dielectric material affixed to its surface. Surrounding the inner cylinder 2 is the hollow cylinder 1 which has an isolated material affixed to its outer surface. The total measurement range of this capacitor is 900 mm.

Capacitance variation formula of ATCC transducer is similar to the ATPC displacement transducer and given by Eq. (4).

$$C = \frac{2\pi \varepsilon_0 \varepsilon_r a (L - \Delta L)}{\ln(R_1 / R_3)} = C_0 - \frac{2\pi \varepsilon_0 \varepsilon_r}{\ln(R_1 / R_3)} \Delta L \tag{4}$$

Where, R_1 is the inner radius of cylinder 1, R_3 is the inner radius of cylinder 2, L is the measurement length and ΔL is the displacement of movable cylinder.

2.3 Permittivity-alterable Type Cylinder Capacitor (PTCC)

The structure of PTCC capacitor is displayed in Fig.3. Two relatively fixed inner and outer capacitor cylinders 1 and 2 are spaced from the inner and outer surfaces of the middle insulating cylinder 3 by a dielectric air gap. The isolating cylinder 3 is fastened to a movable assembly and slidably engaged within the inner and outer cylinders so that, as the insulating cylinder 3 is displaced, the permittivity between these two relatively fixed inner and outer cylinders changes.

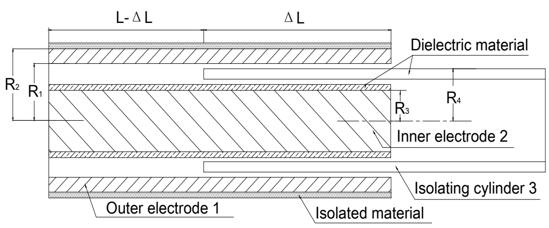

Fig. 3 The structure of PTCC capacitor

In this case, both cylinders 1 and 2 are composed of metal material. The solid inner cylinder 2 has a dielectric material affixed to its surface. Surrounding the inner cylinder 2 is the hollow insulating cylinder 3 which is composed of polyethylene material. The outer cylinder 1 has an isolated material affixed to its outer surface. In addition, the total measured range of this capacitor is 900 mm.

Here, the overlap area S_0 and distance d remain constant and the permittivity between cylinder 1 and 2 is adjusted by the displacement of the movable isolating cylinder 3, the initial capacitance is given by Eq.(5).

$$C_0 = \frac{2\pi\varepsilon_0\varepsilon_r L}{\ln(R_1/R_3)} \tag{5}$$

If the isolating cylinder 3 moves through the fixed inner and outer cylinders 1 and 2, a capacitance C_m will be formed by two sections. The first contribution on the total capacitance C_m will be the capacitance between the inner and outer cylinder for the area in which both cylinders are not overlapped by the movable isolating cylinder 3. The length corresponding to this area is designated as ΔL. The second contribution to the total capacitance C_m will be the capacitance between the inner and outer cylinders for the area in which both cylinders are overlapped by the movable isolating cylinder 3 and the length corresponding to this area is designated as $L-\Delta L$. The total capacitance C_m is given by Eq. (6).

$$C_m = C_0 - \frac{2\pi\varepsilon_0(\varepsilon_r - 1)}{\ln(R_1/R_3)}\Delta L \tag{6}$$

The above equation demonstrated that as the movable isolating cylinder is displaced, the measured capacitance changes as a linear function of the displacement ΔL.

3. MEASUREMENT CIRCUIT OF THE CAPACITANCE DISPLACEMENT MONITORING SYSTEM

Figure 4 showed the measurement system. The variation of capacitance is induced by the displacement of the measured object. Measurement unit composed of embedded microcomputer and sensing amplifier [4]-[6] is utilized to realize real-time data transmission, processing and conversion, and finally display the result to PC to accomplish real-time monitoring the displacement of measured object.

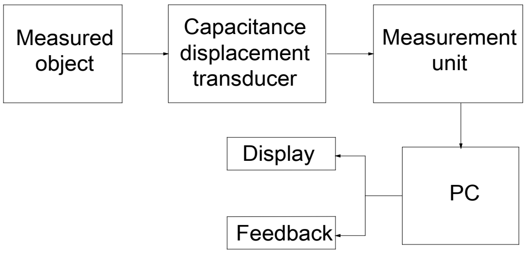

Fig.4 Measurement system of the capacitance displacement monitoring system

3. BASIC PERFORMANECE TEST AND ITS EVALUATION

The basic performance, including linearity, resolution, measurement range and the relative error of slope of transducers, were examined. The change of capacitance caused by the displacement of movable part was directly measured by the measurement circuit and characterized in terms of count value. Here 1 count is roughly equivalent to 3 fF capacitance. The relationship between displacement and count was drawn (see Fig.5~7) and the results were summarized in Table 1.

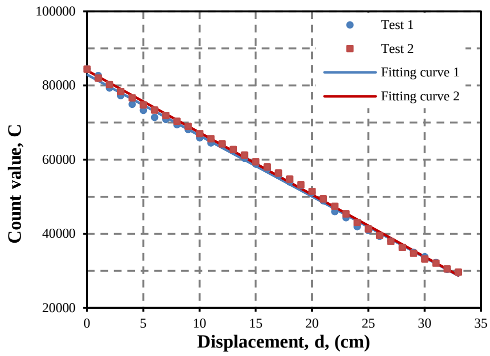

Fig.5 Basic performance test results of ATPC

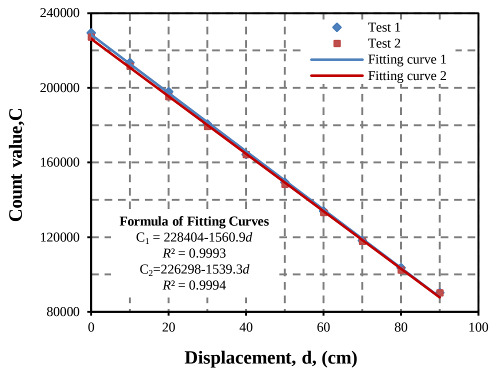

Fig.6 Basic performance test results of ATCC

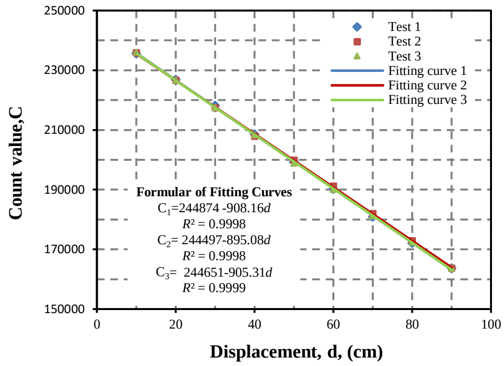

Fig.7 Basic performance test results of PTCC

Table 1 Basic performance test results of three types of capacitance transducers

Evaluation Item	ATPC	ATCC	PTCC
Type	Parallel-plate	cylindrical	cylindrical
Test Times	2	2	3
Measurement Range （mm）	330	900	900
R	0.9989	0.9997	0.9999
Sensitivity	166	153	80
Resolution （mm）	0.0060	0.0064	0.0125
Relative errors of the slope	0.899%	0.697%	0.620%
Structure	Simple manufacture	Complex wiring	Simple wiring

The test results in Figure 5~7 & Table 1 showed that the correlation coefficient (R) are all higher than 0.99. Measurement ranges of cylindrical capacitors (ATCC& PTCC) are 900mm, which is larger than parallel-plate capacitor (ATPC). The resolution of ATPC and ATCC (i.e. 0.0060 and 0.0064 respectively) are better than PTCC (i.e. 0.0125). The structure of ATPC and PTCC are simpler than ATCC. The results suggested that capacitance type transducers can provide sufficient precision, resolution and measurement range, comparing with conventional displace transducers used for slope monitoring. Therefore, displacement monitoring approaches such as that developed in the present study, basing on the principle of capacitance, is feasible to provide an alternative means for slope monitoring.

5. STABILITY PERFORMANECE TEST AND ITS EVALUATION

5.1 Stable Performance of Capacitance Transducers

The long-term stability of data acquisition is required in slope monitoring. For this sake, count value of parallel-plate type and coaxial type capacitors were recorded under indoor environment for 15 hours to advance understanding of stable performance of capacitance transducers. According to Eq. (7), the variation rate of count value can be calculated, and the relationship between variation rate of count value and measured time was indicated in Fig.8.

$$C_{ROC} = \frac{C_t - C_0}{C_0} \tag{7}$$

Where, C_0 is the initial capacitance; C_t is the capacitance measured in different time.

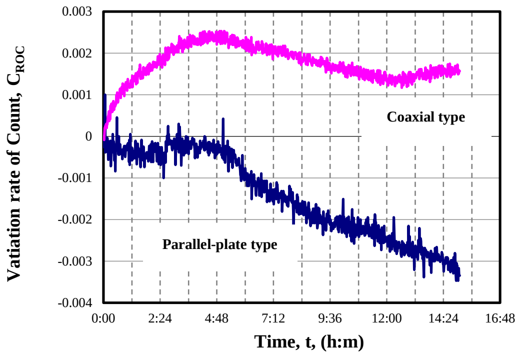

Fig.8 Long-term stability performance of parallel-plate type and coaxial type transducers

Figure 8 illustrated that, in the first 5 hours, the count variation rate of the parallel-plate type is basically stable, and gradually decreases with time. Its variation rate is -3.03×10^{-03}~1.00×10^{-03} within 15 hours, which is equivalent to about 0.33mm displacement. In contrast, the count variation rate of coaxial type capacitor is increased with time in the first 5 hours, and then gradually turns to be stable. Its variation rate is 10^{-3}, which is equivalent to about 0.2 mm displacement and the error is smaller.

Based on the test result, we can see that the stability performance of the cylindrical type capacitor is more satisfied than the parallel-plate type one, while a minor change on the electrode structure of this type of displacement transducer can be expected to further improving its stable performance. Furthermore, shielding system for both types of capacitors still remains improvement as well.

5.2 Stable Performance of Measurement Circuit

Further tests in evaluating the stability of the measurement system under the condition of long time at different temperatures were conducted as well. Measurement circuit of this capacitance displacement monitoring system is composed of sensing amplifier, microcomputer and coaxial cables.

5.2.1 Temperature characteristic test of the sensing amplifier

The sensing amplifier selected in this paper is used for amplifying the measured signals obtained from the capacitor. Five types of sensing amplifier were selected for temperature characteristic test, their difference depends on their constituent elements, including IC model, silicon diodes, supply voltage and resistance (see Table 2).

Table 2 List of constituent elements of the sensing amplifier

Type	IC Model	Supply Voltage	Silicon Diodes	Resistance (Ω)
N2	74HC4538	5V	Have	1M
N4	MC14538	3.3V	Have	1M
N5	MC14538	3.3V	None	1M
N6	MC14538	5V	None	1M
N15	MC14538	3.3V	None	100k

1) Impact of silicon diodes and different IC models

Three types of sensing amplifier, N2, N4, N5, were selected for conducting the temperature characteristic test to evaluate the impact of silicon diodes and different IC models. The relationship between their variation rate of count value and temperature were drawn in Fig.9.

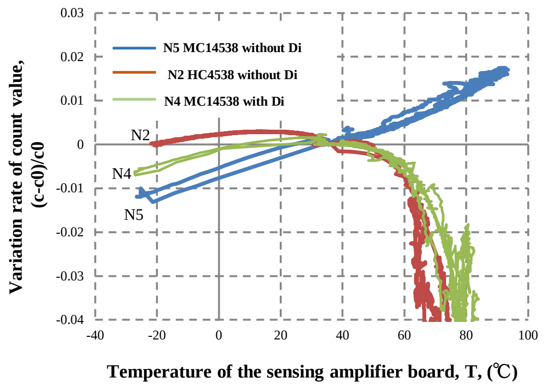

Fig.9 Temperature characteristics test result of different IC models

Figure 9 suggests that:

(1) The count variation rate of N5 shows a linear growth with the increasing temperature. As the temperature increases from -30 ℃ to 90 ℃, its variation rate of count value C_{ROC} increases by 0.032 from -0.014 to 0.018. Its calculated temperature coefficient is about 2×10^{-4} /℃, which is small and can be neglected if the requirement of measurement accuracy is not high.

(2) The variation law of N2 and N4 sensing amplifiers are very similar. With the increase of temperature, both of their variation rates of count value are changed slightly when the temperature is below 50 ℃, while they all fell sharply with increasing temperature when the temperature is higher than 60℃.

(3) Both of the N2 and N4 sensing amplifiers are installed with a silicon diode. Although silicon diodes have good stability at elevated temperatures, a phenomenon of reverse leakage current which increased with temperature, still exist. When the temperature is higher than 50℃ or 60℃, reverse current will increase multiply for every 10℃increase, and decrease its capacitance accordingly. This is why the measured count value of N2 and N4 sensing amplifiers drop dramatically as the temperature rises up to 50 ℃.

(4) In reality, when the sensing amplifier is embedded inside the slope, the environment temperature would not be higher than 50 ℃. As the temperature ranges from 0℃ to 40℃, the variation rates of count value of N2 and N4 sensing amplifiers are quite smaller. When the sensing amplifier is embedded in a measurement box placed on the ground, its environment temperature would be higher in summer, and N5 sensing amplifier is more satisfactory. However, proper amount of temperature compensation is necessary for improving the measurement accuracy.

2) Impact of different resistances of RC integrating circuit

Two types of sensing amplifiers with different resistance, N5 (1MΩ) and N15 (100kΩ), were selected to understand the impact of different resistances. The relationship between the count variation rate and temperature was drawn in Figure.10.

As can be seen in Figure10, the variation rates of N5 and N15 both linearly increase with the increase of temperature, and the variation rate of N15 is nearly five times larger than N5. Their calculated temperature coefficients are 14×10^{-4}/ ℃ and 2×10^{-4}/℃, respectively. It seems quite apparent that sensing amplifiers with a 1MΩ resistance would be more suitable for improving the measurement accuracy.

In RC integrating circuit, the charging time of a capacitor is proportional to its resistance. The smaller resistance provides the shorter output pulse of the sensing amplifier. During the IC operation process, a certain time for rising and falling the pulse signal of the sensing amplifier is needed and depends on the IC speed correlated with temperature, significantly, i.e. the pulse rise and fall time will be affected by the temperature. As for smaller resistance, when temperature rises up, the output pulse signal of the sensing amplifier will be smaller correspondingly, resulting in the increase of rise and fall time of pulse signal, thereby increasing the variation rate of count value.

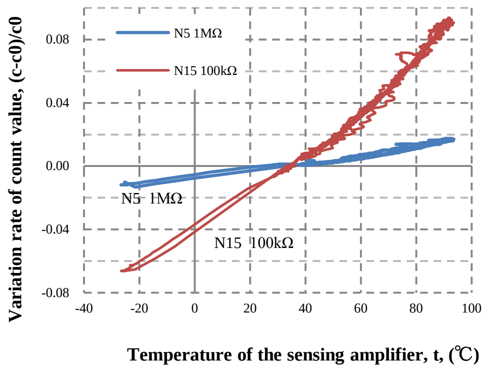

Fig.10 Test results of different resistances R

3) Impact of different supply voltage

Two types of sensing amplifiers with different supply voltages, N5 (3.3V) and N6 (5V), were selected to evaluate the impact of different supply voltages. The relationship between the count variation rate and temperature was indicated in Fig.11.

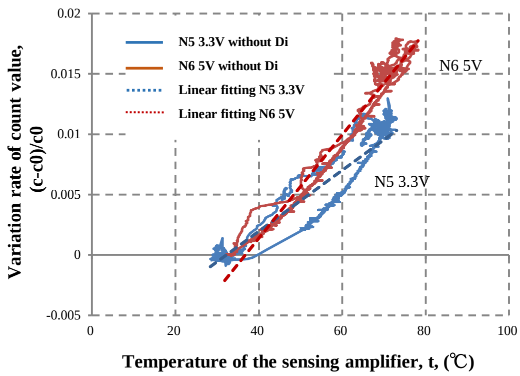

Fig.11 Temperature characteristics test results of different supply voltage

It can be seen from Figure11, the temperature increases from 30 ℃ to 80 ℃, the variation rate of count value of N5 increases from 0 to 1.3×10^{-2} with a calculated temperature coefficient of 2.5×10^{-4}/℃. While the variation rate of N6 increases from 0 to 1.8×10^{-2}, and its calculated temperature coefficient is 4.3×10^{-4}/℃, which is larger than N5. However, both of their variation rates are quite small, which means that temperature has very little impact on different supply voltages.

Based on the comprehensive consideration of energy consumption, noise interference, and temperature characteristic, the sensing amplifier with 3.3V supply voltage can meet the requirements of this measuring system.

5.2.2 Temperature characteristic test of the microcomputer

Microcomputer is utilized for transforming the measured capacitance from the sensing amplifier into count value by the on-chip clock generator which is composed of an external crystal and a built-in phase lock loop (PLL) circuit. The change of temperature on the crystal and the PLL circuit will change the frequency of the clock generator, which dominants the measurement accuracy. Therefore, it is necessary to examine the temperature characteristic of the microcomputer.

Sensing amplifier has three output channels recorded as ch1, ch2 and ch4, measured data from these three channels were transformed to the microcomputer. Heating the microprocessor up to 100℃ with a dryer, the author measured the count values of these three channels. Temperature of microcomputer was also measured using LM61 temperature sensor installed on the microcomputer board. The relationship between the temperature and variation rate of count value can be drawn (see Figure 12).

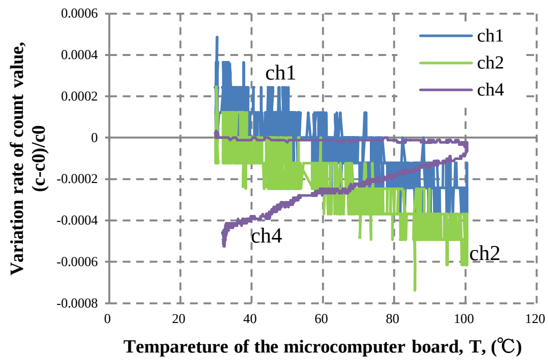

Fig.12 Temperature characteristic test results of the microcomputer

Figure 12 illustrated that the variation amount of count value is about 1×10^{-4} and its calculated temperature coefficient is about 1×10^{-6}/℃ with the temperature increasing from 30 ℃ to 100 ℃, which is very small. We can draw the conclusion that temperature has very little impact on the measurement accuracy of the microcomputer and can be neglected.

5.2.3 Stable performance test of coaxial cable

Cables between sensors and sensing amplifiers have also certain values of capacitance, which affects objective measurements, such as displacements. The temperature characteristics of 5D2V coaxial cable, having a capacitance of 100pF/m, widely used as a high quality shield cable, were examined at indoor temperature for 24 hours. Temperature was measured by LM61 temperature sensor on both sensing amplifier and microcomputer boards, and capacitance was measured and recorded by Teraterm software. Test results were organized in Fig.13. Curve 1 and curve 2 are the measured temperatures of sensing amplifier and microcomputer respectively, while curve 3 is the variation amount of count value of coaxial cable whose initial value is 33,992.

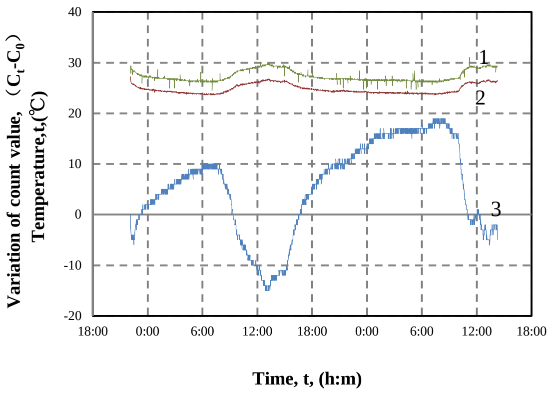

Fig.13 Temperature characteristics test result of 5D-2V coaxial cable

It can be seen from Figure13, at the beginning (from 22:30 to 6:00), as the temperature drops by 3.14℃, the variation of count value shows a trend of increase and increases by 15. Then as the temperature rise up, the count value appears a decreasing phenomenon. The test result suggested that the variation of count value is small and appears a negative increase with the increasing temperature. In order to further understand the relationship between variation rate of count value and temperature, the test data was further processed and the test curve was shown in Fig.14.

Figure 14 shows the variation rate of count value at different environmental temperatures. As a whole, the variation rate of count value presents a linear negative relationship with the temperature. Its calculated temperature coefficient is about 0.1deg/℃/m=2.8×10-4/℃/m per electrical length, its order of magnitude is reasonable, while a proper amount of temperature compensation is necessary for improving the measurement accuracy.

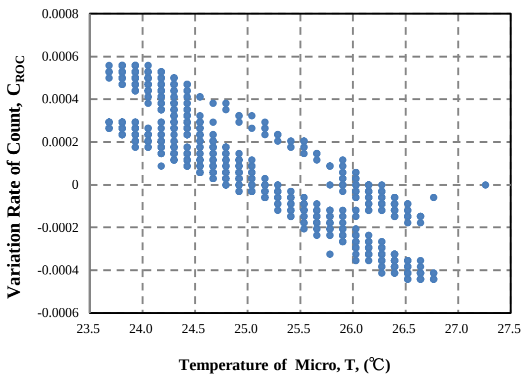

Fig.14 Temperature characteristic of coaxial cable

6. CONCLUSION

(1) Based on the principle of capacitance, three types of capacitance displacement transducers were designed, they are Area-alterable Type Parallel-plate Capacitor (ATPC), Area-alterable Type Cylinder Capacitor (ATCC) and Permittivity-alterable Type Cylinder Capacitor (PTCC).

(2) Basic performance of these three transducers was examined. The result indicates that capacitance type transducers can provide sufficient precision, resolution, measurement range and stable performance, comparing with conventional displace transducers used for slope monitoring.

(3) Stability test of capacitance displacement transducers was conducted. The result indicates that the stability performance of the cylindrical type capacitor is more satisfied than the parallel-plate type one, while a minor change on the electrode structure of this type of displacement transducer can be expected to further improving its stable performance.

(4) Temperature characteristics of capacitance measurement circuit were investigated, and results suggest that:

a) As for the sensing amplifier, it tends to be significantly different depending on its internal constitute elements, thus the measurement accuracy can be increased by selecting suitable internal elements of the sensing amplifier;

b) As for the microcomputer, temperature has little impact on it and the error can be basically neglected;

c) As for the coaxial cables used to connect transducers to sensing amplifiers, the count variation rate shows a linear negative relationship with the increasing temperature and a proper amount of temperature compensation is necessary for improving the measurement accuracy.

Further detailed studies in field application of capacitance displacement monitoring system would be expected to provide a cost-effective method for slope monitoring based on the principle of capacitance.

7. ACKOWLEGEMENTS

Development of capacitance sensors was supported by JSPS KAKENHI Grant Number 25420506. The authors are deeply grateful to the financial support from Japan Society for the Promotion of Science. This research was also supported and encourage by the grant from Awa Bank Foundation for the Promotion of Academism and Culture.

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International Journal of GEOMATE, May, 2016, Vol. 10, Issue 21, pp. 1956-1963.
MS No. 5349 received on June 30, 2015 and reviewed under GEOMATE publication policies.

Pertinent discussion including authors' closure, if any, will be published in Jan 2017 if the discussion is received by July 2016.
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