Fabrication and Characterization of High Performance Micro Impedance Inclinometer

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Abstract—**In the study, a novel micro impedance inclinometer is presented, consisting of a glass substrate, Cr electrodes and a mercury pendulum. The output signal of the proposed inclinometer is read from the moving metal pendulum based on an LED array measurement scheme. A mercury pendulum mass is used for the inclinometer. The adhesion between the liquid metal and the substrate surface is reduced by etching or sandblasting the substrate surface. Experimental results show the developed inclinometer has a high angle resolution (0.3^o), a rapid time response (385 ms) and a high repeatability (R^2 = 0.9988) with the A280# sandblasted substrate surface and the mercury pendulum of 360 µl. The developed inclinometer provide a simply yet high-performance solution for the inclination measurement.**

Keywords- inclinometer; liquid metal; metal pendulum; sand blasting

I. INTRODUCTION

An inclinometer is a gravity reference device capable of sensing tilt. Inclinometers have been used in a number of applications including the automatic control systems and automobile security systems [1]. With the rapid growing market of the automobile industry, there is an emerging demand on high-performance inclinometers. Therefore, developing a cheap and simple-structured inclinometer is important.

The structures of conventional inclinometers can be classified into three categories, i.e. solid, liquid and gas pendulums [2]. In general, the movement of the pendulum mass corresponding to the rotation is most commonly detected by measuring the resistance or capacitance change. The detection principle of the solid pendulum based inclinometers is simple and straightforward. However, the structure of such inclinometers is relatively complex and bulky. Alternatively, capacitive type of liquid pendulum is the most common type for miniaturizing inclinometers. A certain amount of conductive or dielectric solution is sealed in a chamber for capacitive measurement [3, 4]. Fluidic tilt sensors used several large electrodes for measuring the capacitance or resistance change between the electrodes [3] and provided the advantages of low power consumption, high reproducibility and reliability [4]. However, capacitive type of inclinometer suffers from some drawbacks such as small measurement range, viscous drag lag, non-linear output, damping effect and property change of the dielectric liquids.

Corresponsively, the gas pendulum type of inclinometers is based on the principle of measuring thermal property change of the sealed gas in the inclinometer cavity [5, 6]. Micromachined inclinometer utilizing gas pendulum scheme has been demonstrated to have high sensitivity of 0.003^o and the suspense microstructure could provide a shock survival up to 50,000 g [5, 6]. Nevertheless, the linear range of the gas pendulum design is small ($\pm$ 30^o) and its performance may be sensitive to temperature. Optic fiber cantilevers were reported to be an alternative approach for tilt-angle sensing. A fiber grating (FBG) sensing scheme was used for measuring the wavelength shift during tilting [7].

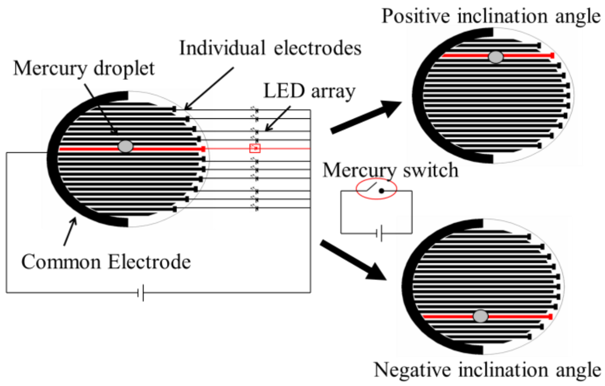
This study employs a straightforward MEMS-based fabrication process to realize a micro impedance inclinometer featuring a glass substrate, Cr interdigitated electrodes (IDEs) and a mercury pendulum. It is found that the angle resolution is 0.3^o, the time response is 385 ms and the repeatability is 0.9988(R^2) with an A280# sandblasted substrate surface and a mercury pendulum of 360 µl. With the optimal roughness of the substrate surface and pendulum size, the experimental results show that the sensor has a high angle resolution, a rapid time response and a high repeatability.

II. SENSOR DESIGN

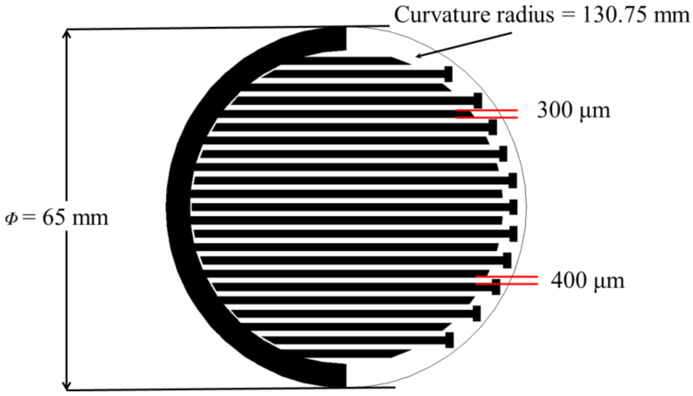
As shown in Figure 1, the micro impedance inclinometer developed in this study comprises a concave glass substrate, Cr IDEs and a mercury pendulum. The IDEs facilitate the direct electrical measurement of the change in conductivity induced by the contact of the mercury pendulum as it is moved with the different tilt angles. The droplet size of the mercury pendulum and the roughness of the substrate surface should be optimized, and therefore both the resolution and the response time of the device can be enhanced due to the increase of the contact angle between the substrate surface and the mercury droplet.

III. FABRICATION

Figure 2 shows a simplified fabrication process of the micro impedance inclinometer. The substrate used in the study is a concave glass with a curvature radius of 103 mm and a diameter of 65 mm. Five kinds of the substrate surface roughness were prepared and compared in the study: (a) bare glass substrate, (b) BOE etching (20 min), (c) A30# sandblasting (granule ϕ: 600 -710 µm), (d) A60# sandblasting (ϕ: 250 - 300 µm), (e) A120# sandblasting (ϕ: 105 - 125 µm) and (f) A280# sandblasting (ϕ: 40 -50 µm), respectively. The



(a)



(b)

Figure 1. (a) Schematic illustration and (b) dimensions of micro impedance inclinometer.

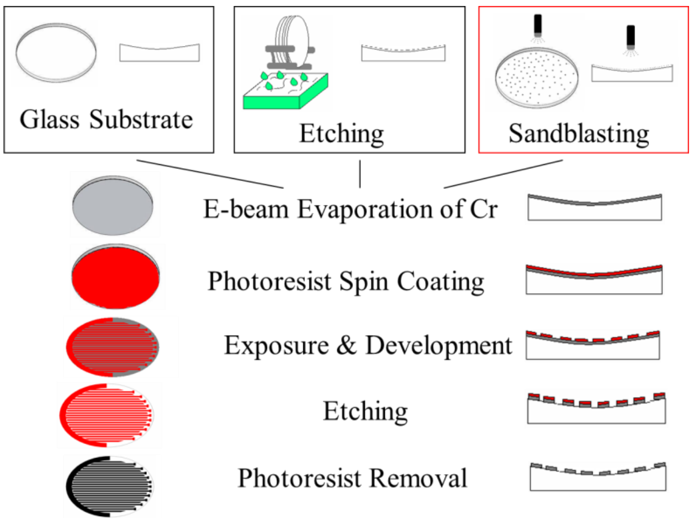
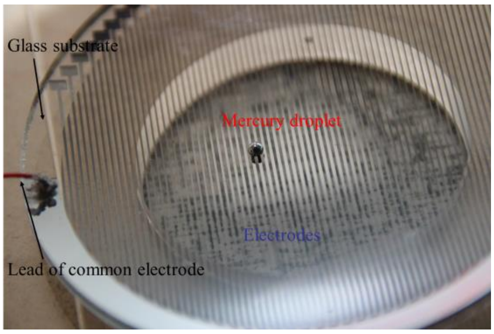


Figure 2. Overview of fabrication process for micro impedance inclinometer.

Cr film was prepared using an E-beam evaporator with 0.2 µm. A standard photographic and etching technique was then employed to pattern the Cr IDEs by Cr-7t etchant.



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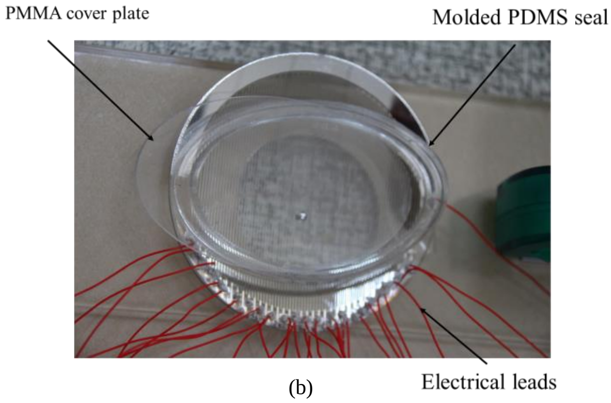


(b)

Figure 3. (a) Photograph of fabricated bottom plate and (b) assembly of micro impedance inclinometer

Figures 3 show photographs of the fabricated micro impedance inclinometer. There are 38 pairs of Cr IDEs with 300 µm of width and 400 µm of spacing (figure 3(a)). After the fabrication of the bottom plate of the sensor, it is assembled with a molded PDMS seal and a PMMA cover plate with UV glue (figure 3(b). Every pair of Cr IDEs is connected with an individual LED, respectively, in an external electrical circuit.

IV. Results and Discussion

Undesirable adhesion of the metal to the substrate surface is one of the important factors of the inclinometer performance (e.g. angle resolution, time response, repeatability...). The bigger the contact angle is, the less the adhesion of the metal to the surface is. Figures 4 show the measured contact angles for the mercury droplet on different substrate surfaces. The contact angles are 131.52°, 131.04°, 140.86°, 141.25°, 142.05° and 145.29° on bare, etched and sandblasted (A30#, A60#, A120# and A280#) substrate surfaces, respectively. It can be found the highest contact angle (145.29°) is measured as the substrate surface is sandblasted by A280# granules before Cr evaporation. The kind of substrate surface was selected to be the standard bottom of the inclinometer in the following experiments.

Figure 5 presents a simplified schematic of the experimental setup in the study. The testing platform is constructed by a fabricated inclinometer, a plate (280 X 200 X 6 mm^3), a regulation screw (75 mm L), a power supply (gpd-

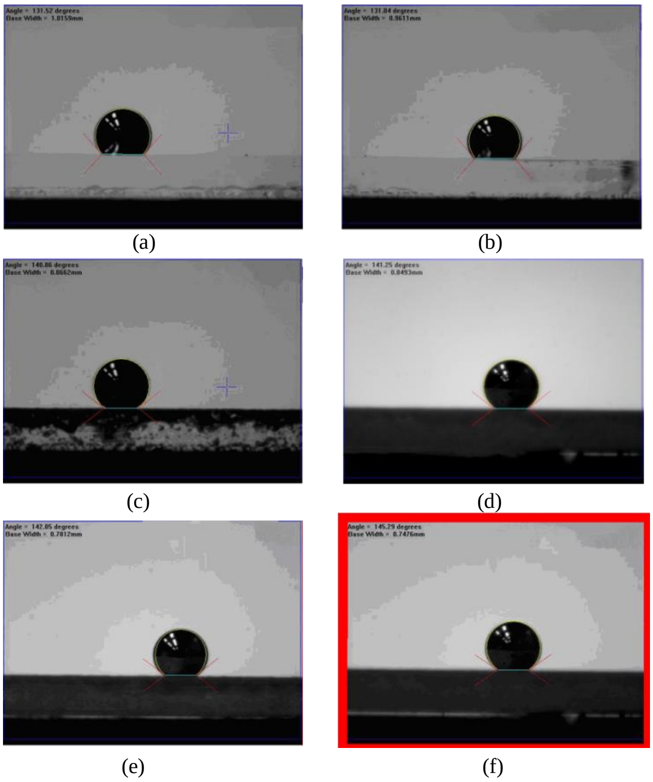
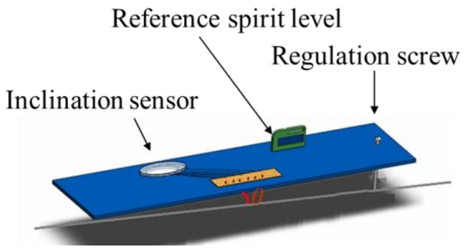
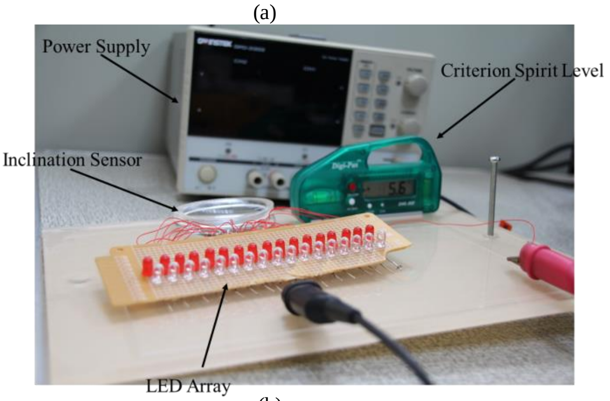


Figure 4. Contact angle measurement for mercury ball on (a) bare, (b) etched, (c) A30#, (d) A60#, (e) A120# and (f) A280# sandblasted substrate surfaces, respectively.



(a)



(b)

Figure 5. (a) Schematic and (b) photograph of experimental setup for inclinometer performance testing.

3303, GW, China), a LED array and a reference spirit level (DWL-80E, Digi-Pas, Singapore). The common electrode of the inclinometer is connected with the positive electrode of the power supply and the individual electrodes are connected with

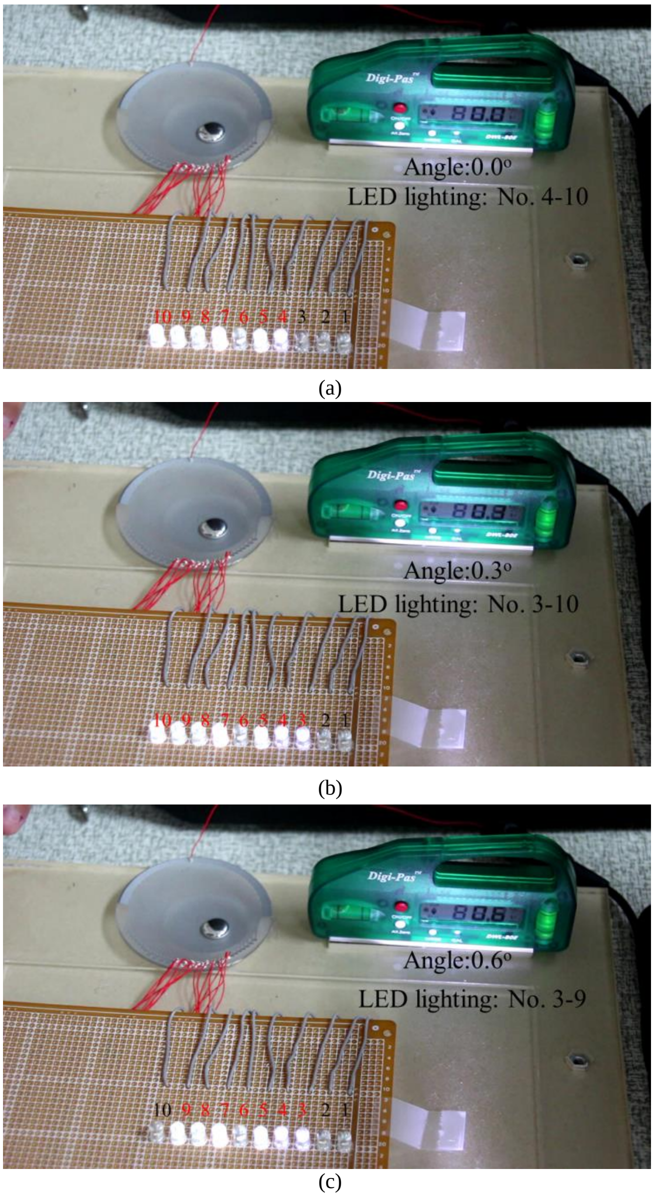


Figure 6. LED state of the inclinometer at (a) 0.0°, (b) 0.3° and (c) 0.6°.

the negative electrode of the power supply via LEDs, respectively, for measurement of the mercury droplet positions. The voltage of the power supply is 20 V and the inclination angle can be controlled by regulating the relative position of the screw and the plate. As the position of the mercury droplet changes with the change of the inclination angle, the lighting state of the LED array changes due to the changed electrode contacts caused by any specific inclination.

A. Sensitivity

Figures 6 show the different lighting states of LED array as the inclination angles of the testing platform are 0.0°, 0.3° and 0.6°, respectively. It is found that the LED No. 4-10, 3-10 and 4-9 are lighted on as the inclination angles are 0.0°, 0.3° and 0.6°, respectively, because the mercury droplet moves rightward as the left side of the platform is lifted with specific angles and conducts different LED as it moves. It is clear that the resolution of the developed inclinometer is 0.3°.

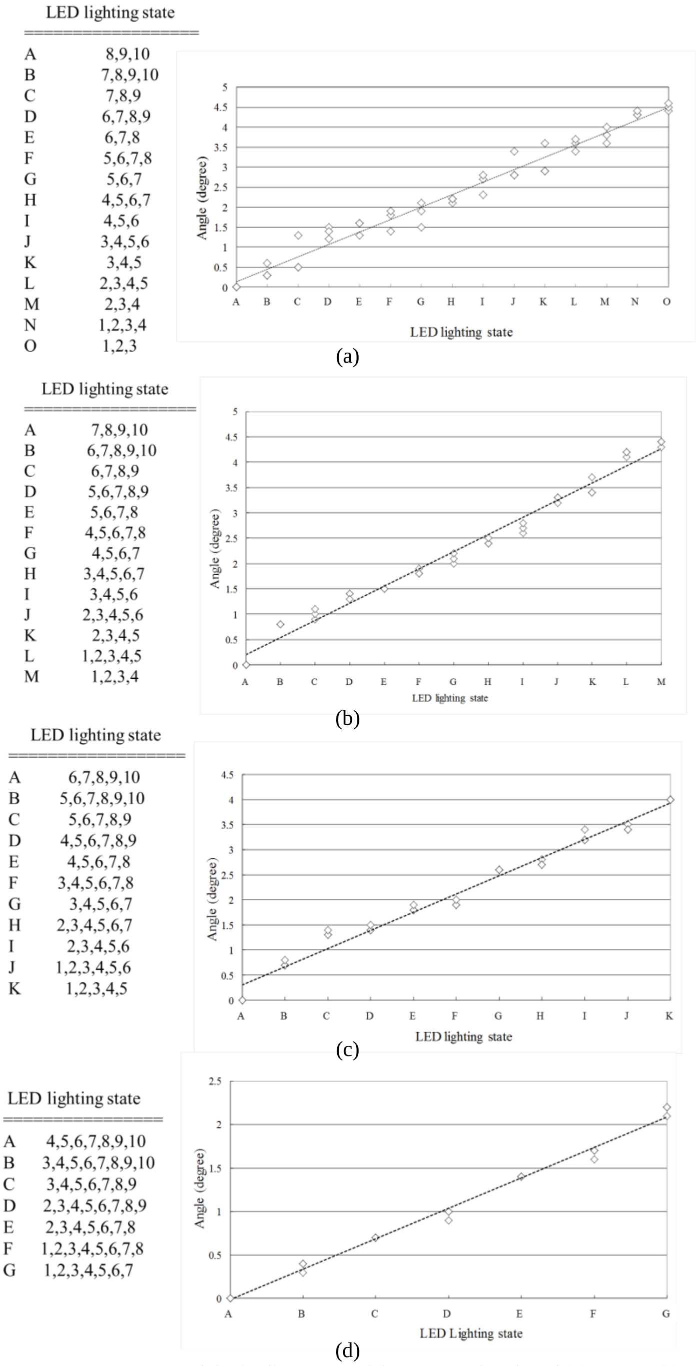


Figure 7. LED state of the inclinometer with mercury deoplet of (a) 60 μL, (b) 120 μL, (c) 180 μL and (d) 360 μL at diffetent inclination angles.

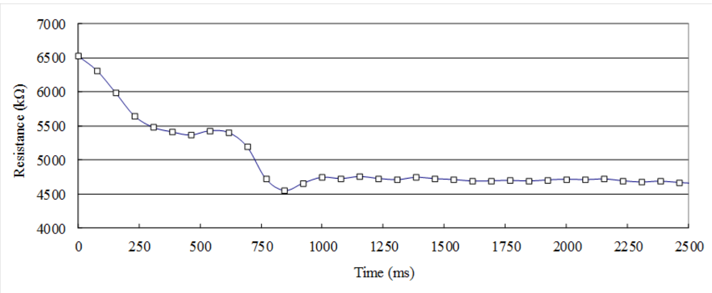


Figure 8. Time response of inclinometer when inclination angle is increased from 0^o to 3^o.

B. Repeatability

To prevent adhesion problem of the metal droplet on the chamber bottom and improve repeatability of the inclinometer, different volume of mercury droplets is tested to compare its effect on the inclinometer performance. Figures 7 present the repeatability results obtained by utilizing the volume of the mercury droplet with 60, 120, 180 and 360 μl, respectively. It is found the calculated R^2 values of the test results are 0.9709, 9.9830, 0.9792 and 0.9923 with 60, 120, 180 and 360 μl of mercury droplets, respectively. The R^2 value of the mercury droplet with 360 μl shows a better repeatability, which means a 360 μl of mercury droplet is the optimized size of the metal pendulum in the current study.

C. Time Response

Figures 8 present the test results of time response of the inclinometer as the inclination angle is increased from 0^o to 3^o by abruptly lifting one side of the testing platform. From inspection, the average time constant (T_{50}) of the inclinometer is found to be 385 ms.

V. Conclusions

This study has demonstrated a simple and reliable method to fabricate impedance type of inclinometers with a concave glass substrate, Cr IDEs and a mercury pendulum. It was found that the friction between the liquid metal and substrate surface can be reduced by sandblasting the substrate surface (A280#), the repeatabilioty can be improved with a mercury pendulum of 360 μl (R^2 = 0.9923) and the response time (T_{50}) of the developed inclinometer is 385 ms. The proposed sensor has a high degree of sensitivity, a rapid response time , and a high resolution (0.3^o). The inclinometer developed in the study provides a low-cost yet high-performance mthod for inclination measurement.

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