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A Semi-Cylindrical Capacitive Sensor with Interface Circuit using for Fluidic Measuring

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Abstract- *In this paper, a semi-cylindrical capacitive sensor with interface circuit using for fluidic measuring is newly proposed. The numerical analysis method to calculate the capacitance of the semi-cylindrical capacitive sensor is analyzed and discussed. Besides, the interface circuit is compact to simplify the circuit complexity, and could be easily implemented for fluidic measuring. The pF-range capacitive variation of the semi-cylindrical capacitive sensor can be detected and converted into voltage variation by the interface circuit. All the functions of the interface circuit are proved successfully through HSPICE simulation. These simulation results have successfully confirmed the correct functions and performance of the semi-cylindrical capacitive sensor with interface circuit using for fluidic measuring.*

Keywords– *Capacitive sensor, interface circuit, fluidic measuring, switched-capacitor, HSPICE.*

I. INTRODUCTION

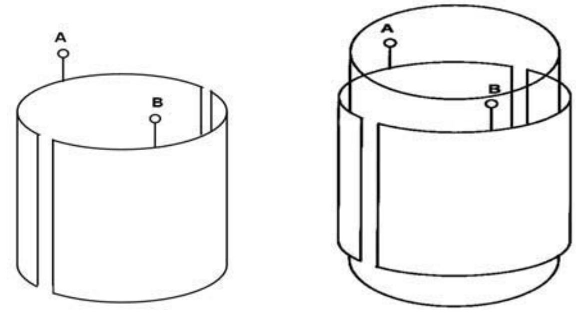
Capacitive sensors have been used in various sensing applications, such as acceleration, force, pressure, dielectric properties, and displacement sensors [1]-[2]. In comparison with the researches of parallel-plate capacitors, the researches of cylindrical capacitive sensors are mainly focused on the analyses of properties, for example, the electrostatic forces of charged coaxial cylindrical capacitor [3]-[4], nonlinear analysis of cylindrical capacitive sensor [5]. Until now, no study is to analyze and discuss semi-cylindrical capacitive sensors used in the fluidic sensing applications. Hence, differing from the structures of cylindrical capacitive sensors, a novel semi-cylindrical capacitive sensor is firstly investigated for fluidic measuring.

In this paper, a semi-cylindrical capacitive sensor with interface circuit using for fluidic measuring is newly proposed. The numerical analysis method to calculate the capacitance of the semi-cylindrical capacitive sensor is analyzed and discussed. Besides, the interface circuit is compact to simplify the circuit complexity, and could be easily implemented for fluidic measuring. In this paper, all the functions of the interface circuit are tested and proved through HSPICE simulation. These simulation results have successfully confirmed the correct functions and performance of the semi-cylindrical capacitive sensor with interface circuit using for fluidic measuring.

In the section II, it describes the capacitive sensing method to calculate the capacitance of the semi-cylindrical capacitive sensor. Section III displays the interface circuit. Section IV presents simulation results of interface circuit. Section V gives conclusions and feature works.

II. CAPACITIVE SENSING METHOD FOR SEMI-CYLINDRICAL CAPACITIVE SENSOR

Fig. 1 (a)-(b) show the architecture of the semi-cylindrical capacitive sensor without and with dielectric fluid. The semi-cylindrical capacitive sensor consists of two metal semi-cylinders, which are separated by a gap distance. The dielectric material in Fig. 1 (a) is air, thus the dielectric constant ε_1 is equal to 1. In Fig. 1 (b), the dielectric constant ε_2 of the specified fluid is more than 2.



(a) (b)

Fig. 1. The architecture of the semi-cylindrical capacitive sensor (a) Without dielectric fluid (b) With dielectric fluid.

Now, the capacitive sensing method for the semi-cylindrical capacitive sensor is analyzed and discussed. In Fig. 2, the capacitance of the two unit metal plates is derived as

$$C = \frac{\varepsilon_0 * \varepsilon_1 * A}{d} * \left[1 - \frac{a\,\theta}{d} \right] \tag{1}$$

where ε_0 is the permittivity of free space of magnitude 8.85 (pF/m), ε_1 dielectric constant, A the area of two unit metal plates, d the minimum gap distance. Therefore, if the cutting number of the semi-cylindrical capacitive sensor is large, d>>aθ, the capacitance in Eq. (1) can be approximated as

$$C \cong [\frac{\varepsilon_0 * \varepsilon_1 * A}{d}] \tag{2}$$

Hence, it can be noticed that the minimum gap distance d of two unit metal plates will be the most important factor in the following numerical analysis of the semi-cylindrical capacitive sensor.

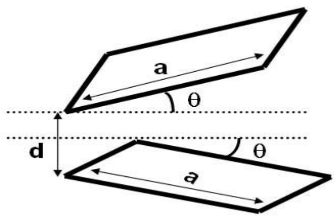
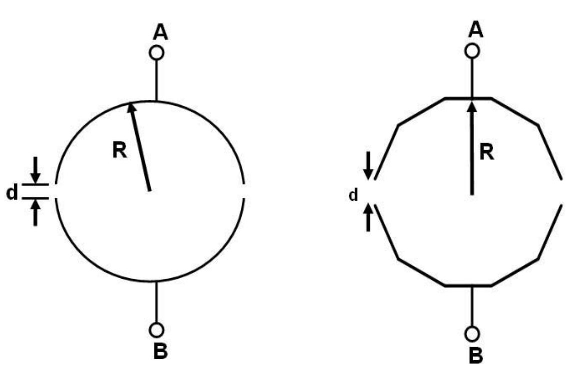


Fig. 2. The capacitive sensing method for the semi-cylindrical capacitive sensor.

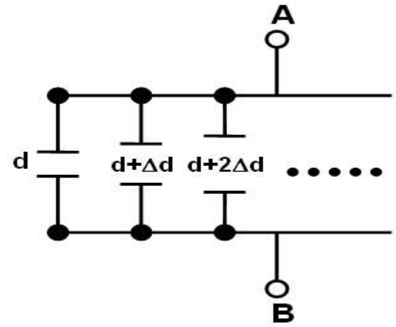
Fig. 3 (a) displays the top view of the semi-cylindrical capacitive sensor without dielectric fluid. The two metal semi-cylinders have the radius R and a minimum gap distance d. The numerical analysis method is applied to approximate the capacitance of the semi-cylindrical capacitive sensor. The structure of the semi-cylindrical capacitive sensor for numerical analysis method is shown in Fig. 3 (b). Based on the structure of Fig. 2, each individual capacitor within two metal semi-cylinders could be modified as each pairs of two unit metal plates with an increment Δd distance. Hence, all the equivalent capacitors could be parallelly structured between A and B terminals as presented in Fig. 3 (c). Following Eq. (2), the capacitance of two metal semi-cylinders without dielectric fluid can be expressed as

$$C_0 = \varepsilon_0 * \varepsilon_1 * 2 * A * \left[\frac{1}{d} + \frac{1}{d+\Delta d} + \frac{1}{d+2\Delta d} + \ldots . + \frac{1}{d+(n-1)\Delta d} \right] + \frac{\varepsilon_0 * \varepsilon_1 * A}{2R} \tag{3}$$

where ε_0 is the permittivity of free space of magnitude 8.85 (pF/m), ε_1 dielectric constant of air, n the cutting number for numerical analysis, A the unit area of metal semi-cylinders, d the minimum gap distance, Δd an increment distance.



(a) (b)



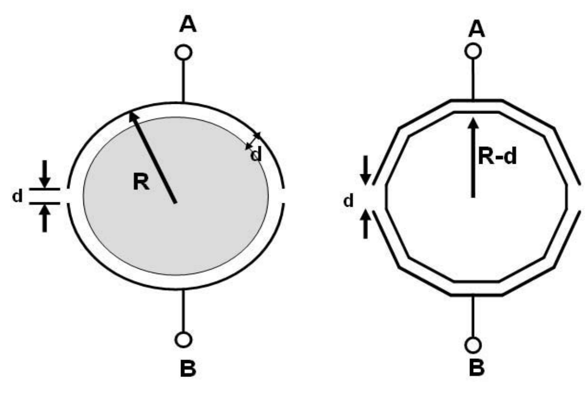
(c)

Fig. 3. (a) The top view of the semi-cylindrical capacitive sensor without dielectric fluid (b) The approximate structure of the semi-cylindrical capacitive sensor for numerical analysis method (c) Equivalent capacitors between A and B terminals.

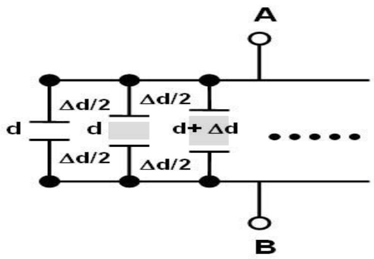
Similarly, Fig. 4 displays the structure of the semi-cylindrical capacitive sensor with dielectric fluid for numerical analysis method. Based on (3), the capacitance of two metal semi-cylinders with dielectric fluid can be written as

$$C = \varepsilon_0 * 2 * A * \left[\frac{1}{\frac{d}{\varepsilon_1}} + \frac{1}{\frac{\Delta d}{\varepsilon_1} + \frac{d}{\varepsilon_2}} + \frac{1}{\frac{\Delta d}{\varepsilon_1} + \frac{d+\Delta d}{\varepsilon_2}} + \ldots . + \frac{1}{\frac{\Delta d}{\varepsilon_1} + \frac{d+(n-1)\Delta d}{\varepsilon_2}} \right] + \frac{\varepsilon_0 * A}{\frac{\Delta d}{\varepsilon_1} + \frac{2R-2d}{\varepsilon_2}} \tag{4}$$

where ε_2 is dielectric constant of the specified fluid. Therefore, as analyzed in (3) and (4), the capacitance of the semi-cylindrical capacitive sensor is varied when the dielectric fluid flows through these two metal semi-cylinders. The capacitive variation will be detected and converted into voltage variation by the interface circuit.



(a) (b)



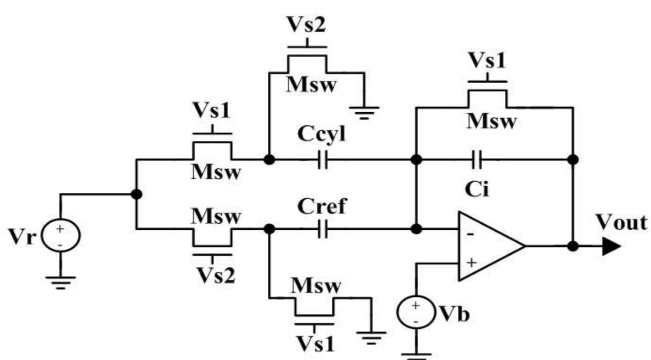
(c)

Fig. 4. (a) The top view of the semi-cylindrical capacitive sensor with dielectric fluid (b) The approximate structure of the semi-cylindrical capacitive sensor for numerical analysis method (c) Equivalent capacitors between A and B terminals.

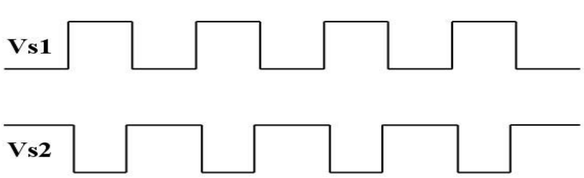
III. THE INTERFACE CIRCUIT

Following the switched-capacitor techniques, the compact interface circuit and timing diagram are shown in Fig. 5 (a)-(b). This circuit applies the charge redistribution method. The signals Vs1 and Vs2 are non-overlapping two phase clock cycles. When Vs1 signal is logic high, the total charge is stored on the semi-cylindrical capacitor Ccyl. The output voltage of operational amplifier is fixed at controlling voltage Vb. In another phase, the same reference dc voltage Vr charges the reference capacitor Cref. Besides, the difference in charge between two phases will be stored on the capacitor Ci. Hence the capacitor ratio $\frac{Ccyl - Cref}{Ci}$ is derived as

$$\frac{Ccyl - Cref}{Ci} = \frac{Vout - Vb}{Vr - Vb} \tag{5}$$



(a)



(b)

Fig. 5. (a) The interface circuit (b) Timing diagram of Vs1 and Vs2 non-overlapping two phase clock cycles.

The schematic of operational amplifier is displayed in Fig. 6. This two-stage operational amplifier consists of the biasing circuits (transistors M8-M13 and a resistor Rbias), the first stage amplifier (transistors M1-M5), the second stage amplifier (transistors M6-M7), and compensation circuits (transistor M14 used as a nulling resistor and a Miller compensation capacitor Cc). All the simulations of the operational amplifier and the interface circuit are analyzed in section IV.

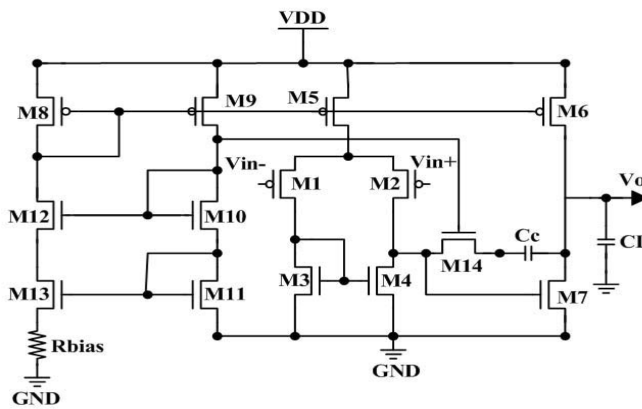
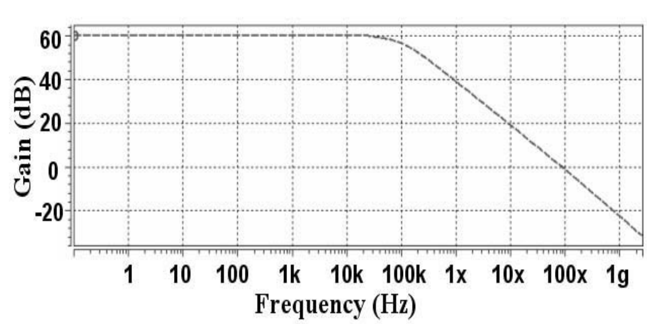


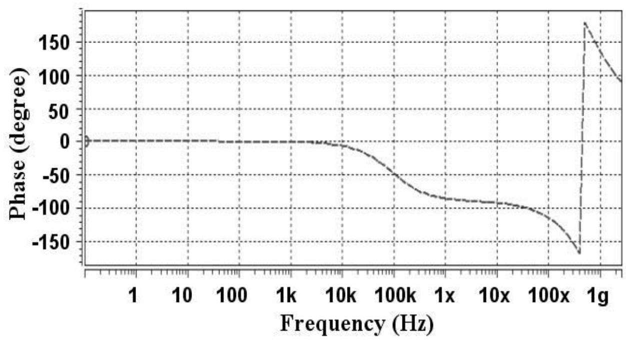
Fig. 6. The schematic of the operational amplifier.

IV. SIMULATION RESULTS

All simulation results are based upon the device parameters of 0.35 μm 2P4M CMOS technology with 3 V power supply. The simulated device dimensions are listed in Table I. Firstly, the operational amplifier under the sweeping frequency range from 0.1 Hz to 2 GHz is verified as shown in Fig. 7. The unit gain bandwidth is 100 MHz and phase margin is 66°. Then, two phase clock cycles Vs1 and Vs2 are both operated at 50 kHz to perform the functions of interface circuit. The output of the interface circuit is used to calculate the capacitor ratio. Fig. 8 (a)-(c) show this interface circuit has good performances to convert pF-range capacitive variation into voltage variation. The output voltage in Fig. 8 (a)-(c) are 1.5, 1.53, and 1.67V, respectively. All the calculated results are plotted in Fig. 9 by performing Eq. (5).

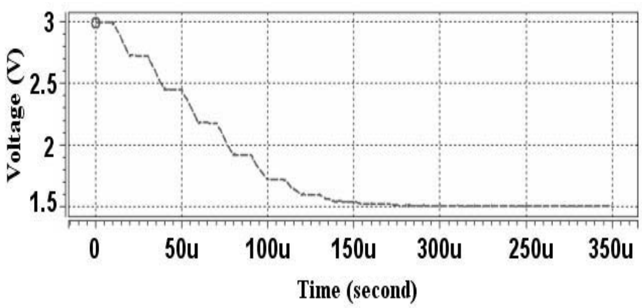


(a)

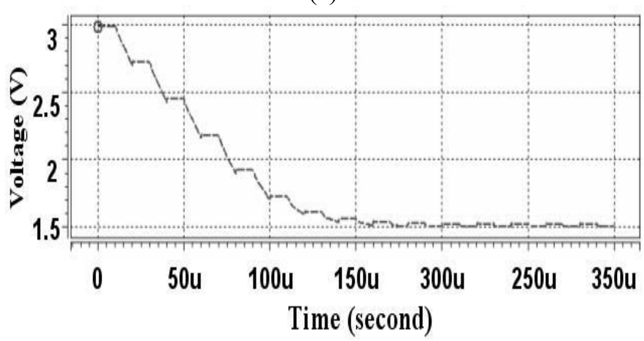


(b)

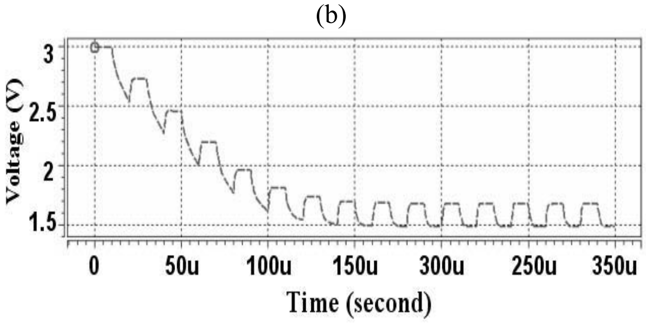
Fig. 7. Simulation results of the operational amplifier under the sweeping frequency range from 0.1 Hz to 2 GHz (a) Gain response (b) Phase response.



(a)



(b)



(c)

Fig. 8. (a) Capacitor ratio $\frac{Ccyl-Cref}{Ci}=0$ (b) Capacitor ratio $\frac{Ccyl-Cref}{Ci}=0.01$ (c) Capacitor ratio $\frac{Ccyl-Cref}{Ci}=0.1$ under Ci=1000 pF, Cref=20 pF, Ccyl =20 pF, 30 pF , 120 pF, respectively.

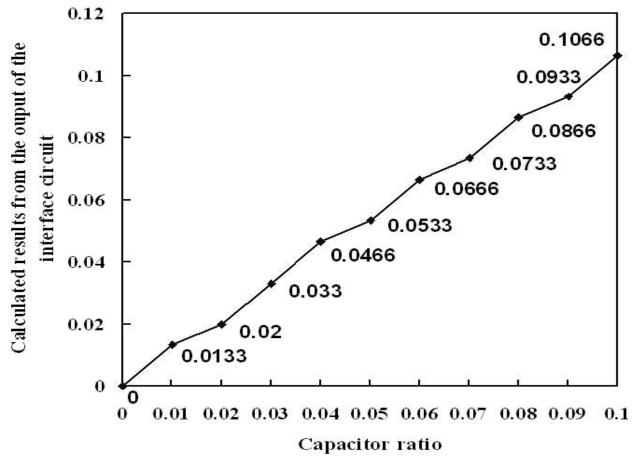


Fig. 9. Simulation results of the interface circuit by performing Eq. (5) under Ci=1000 pF, Cref=20 pF, Ccyl sweeping from 20 pF to 120 pF.

Finally, MATLAB software is performed to calculate the capacitors of Eq. (3) and (4) for fluidic measuring. The calculated capacitors C_0 and C_1 are 13.7382 pF and 24.256 pF, respectively. Hence, these two values are simulated through HSPICE software. Capacitor C_0 and C_1 are replaced as capacitor Cref and Ccyl, respectively. After simulation, the output voltage of the interface circuit is 1.52V. The calculated result by performing Eq. (5) is 0.0133 and the capacitor ratio is 0.01051. Hence, the pF-range capacitive variation of the semi-cylindrical capacitive sensor can be detected and converted into voltage variation by the interface circuit. These simulation results above have successfully confirmed the correct functions and performance of the semi-cylindrical capacitive sensor with interface circuit using for fluidic measuring. After circuit fabrication, this interface circuit will be used in the fluidic measuring of the semi-cylindrical capacitive sensor as shown in Fig. 10.

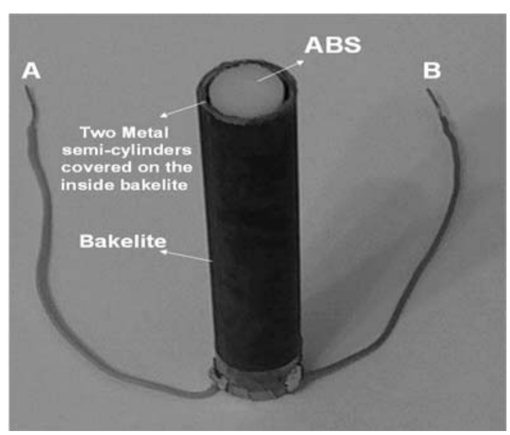


Fig. 10. The prototype of the semi-cylindrical capacitive sensor. The

material of fluid is acrylonitrile, butadiene, styrene (ABS). Two metal semi-cylinders are covered on the inside bakelite. The maximum radius of the fluid is 5 mm and the minimum gap distance of two metal semi-cylinders is 0.2 mm.

Table 1. Simulated device dimensions

Technology	0.35μm Polyside CMOS (2P4M)	
M_{sw} (W/L)	1.0μm / 1.0μm	(M=1)
M_1-M_2 (W/L)	112.2μm / 0.5μm	(M=2)
M_3-M_4 (W/L)	63.92μm / 0.35μm	(M=1)
M_5 (W/L)	156.86μm / 0.35μm	(M=1)
M_6-M_7 (W/L)	112.2μm / 0.5μm	(M=2)
M_8-M_{12}(W/L)	13.07μm / 0.35μm	(M=1)
M_{13} (W/L)	58.28μm / 0.35μm	(M=1)
M_{14} (W/L)	138.87μm / 0.35μm	(M=2)
C_C	5 pF	
R_{bias}	1.724 kΩ	

V. CONCLUSION

A semi-cylindrical capacitive sensor with interface circuit using for fluidic measuring is newly proposed. The numerical analysis method to calculate the capacitance of the semi-cylindrical capacitive sensor is analyzed and discussed. Besides, the interface circuit is compact to simplify the circuit complexity, and could be easily implemented for fluidic measuring. All the functions of the semi-cylindrical capacitive sensor with interface circuit are proved successfully through HSPICE simulation. In the future research, this fabricated interface circuit will work with the semi-cylindrical capacitive sensor in the fluidic measuring.

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REFERENCES

[1] T. N. Toth and G. C. M. Meijer, "A low-cost smart capacitive position sensor," *IEEE Trans. Instrum. Meas.*, vol. 41, no. 6, pp. 1041-1044, Dec. 1992.
[2] L. K. Baxter, *Capacitive Sensors Design and Applications*. New York: IEEE Press, 1997.
[3] Y. S. Ku, "Developing an axisymmetric parametric model for an electrostatic force balance," *Meas. Sci. Technol.*, vol. 15, no. 1, pp. 267-270, Jan. 2004.
[4] Y. S. Ku, "Optimization of axisymmetric parametric model for electrostatic force balance," *Meas. Sci. Technol.*, vol. 15, no. 10, pp. 2108-2112, Oct. 2004.
[5] H. J. Ahn, I. H. Kim, and D. C. Han, "Nonlinear analysis of cylindrical capacitive sensor," *Meas. Sci. Technol.*, vol. 16, no. 3, pp. 699-706, March 2005.