# Micro-Displacement/Capacitance Measurement and Control System with Phase-Locked Loop

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## 1. Introduction

Phase-locked loop_PLL_is a very popular and cheap tool for pulse generation with almost constant frequency. On the other hand, a user-friendly and cheap tool for micro-displacement/capacitance servo control system still lacks in the market, although it is increasing the need in MEMS (micro-electro-mechanical system) industries. In this article, a cheap_for a micro capacitance/displacement scan movement, without the need of A/D and D/A converters _and stable micro-displacement/capacitance measurement and control system is proposed. Due to the low cost, the high sensitivity between the capacitance of varactor diode and the output pulse frequency [1] and the fast and stable frequency servo capability, PLL is very suitable for us to use its property as controlling micro capacitance/displacement in MEMS or micro-positioning system. In the meantime, as the progress in the microfabrication and micromachining technology, micro capacitance/displacement detection and control system is, more than often, used in many MEMS such as in the micro accelemeter [2], micro pressure sensor [3], and micro flow sensor [4]. In this article, a PLL based micro displacement/capacitance measurement and control system is proposed. For use in a simple scan movement, no A/D and D/A converters are needed and it still can provide capacitance/displacement scan movement with high resolution. And if the properties of the electronic components in the PLL remain close to their nominal values, the scan movement can be achieved with good accuracy. Therefore, this overall system can be made cheaper than a common one. As shown in the simulations and experimental results, the fast and stable servo capability of the proposed system means that it has great potential in MEMS industries.

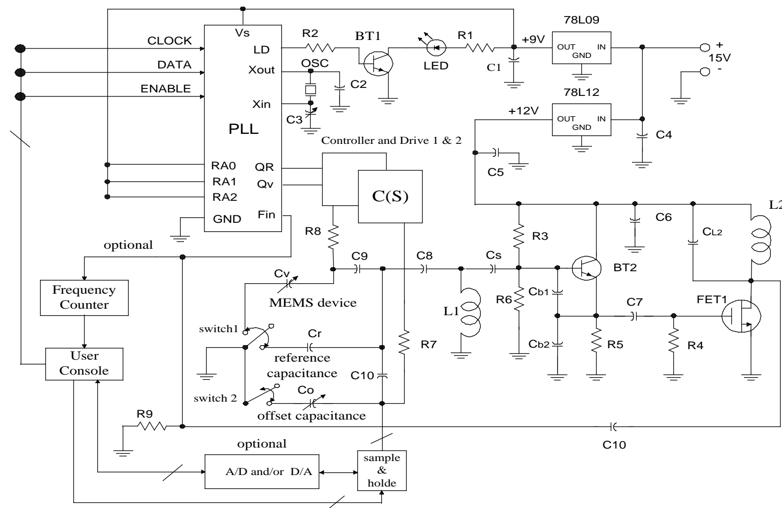


Fig.1 PLL based micro displacement/capacitance measurement and control system.

## 2. System Configuration

The proposed PLL based micro capacitance/displacement control system is shown in Fig.1. A NPC PLL0305A [5] is adopted as the main PLL IC Chip, and it can be operated blow 50 MHz under a normal condition. In the PLL frequency servo loop shown in Fig.1, the Clapp voltage controlled oscillator ( VCO [6] ) is adopted for its good stability against temperature variation. With the proper setting of peripheral electronic components, the oscillation frequency of the Clapp VCO ( when the switch1 is closed to the side of the MEMS and the switch2 is open ) is obtained as follows by neglecting the influences of the other coupling resistors, inductors and capacitors.

$$f = \frac{1}{2\pi}\left[L_1\left(C_v + \frac{1}{1/C_s + 1/C_{b1} + 1/C_{b2}}\right)\right]^{-1/2} \quad \ldots (1)$$

where $f$ is the oscillation frequency, $L_1$ is the inductance value of the coil, $C_v$ is the capacitance value of the MEMS device such as a comb structure [2] or a diaphragm [3-4] in MEMS, and $C_s$ , $C_{b1}$ and $C_{b2}$ are the capacitance values of the matching capacitors.

## 3. Frequency Servo Control of PLL for MEMS

As revealed in [2]~[4], the mechanisms in MEMS such as a comb drive or a diaphragm have the same property as a varactor diode that the capacitance value between the electrodes varies with the voltage difference of the electrodes. Therefore, a MEMS with the same property as the varactor diode can be used in a frequency servo PLL instead of a varactor diode. That is, as shown in equation (1), the frequency servo capability of a PLL can be regarded as the capacitance servo capability of a MEMS device if the electrical properties of all the electronic components used in the PLL remain constant. Therefore, by changing the reference frequency of the PLL, the capacitance/displacement of a MEMS device can be controlled near to its destination value. However, the controller used in the proposed PLL with a MEMS device as the capacitance tuning component is not the same as the controller for the PLL with a varactor diode inside [7], because the dynamics in a MEMS device is different from a varactor diode. As shown in Fig.2, we use a common electrostatic force driven diaphragm structure as an example of the MEMS device in the PLL based servo system. Because for the electrostatic force driven devices the capacitance value between electrodes varies as the voltage difference as a varactor diode as depicted in [8-9].

The linearized frequency servo system with PLL for MEMS device deflection control at its equilibrium point_ $X,V$ _=_ $0,V_o$ _is as shown in Fig. 3. To avoid noise excitation due to on-off nonlinearity of PLL, we adopt an PI ( proportional and integral ) controller with negative gain as in C(S), i.e.,

$$C(S) = -\frac{k_p S + k_i}{S} \quad \ldots (2)$$

And we denote $k_1$ as

$$k_1 = k_o \, \varepsilon_a \, A \, X_o^{-2} \, \frac{L_1}{4\pi}\left[L_1\left(C_{vo} + \frac{1}{1/C_s + 1/C_{b1} + 1/C_{b2}}\right)\right]^{-3/2} \quad \ldots (3)$$

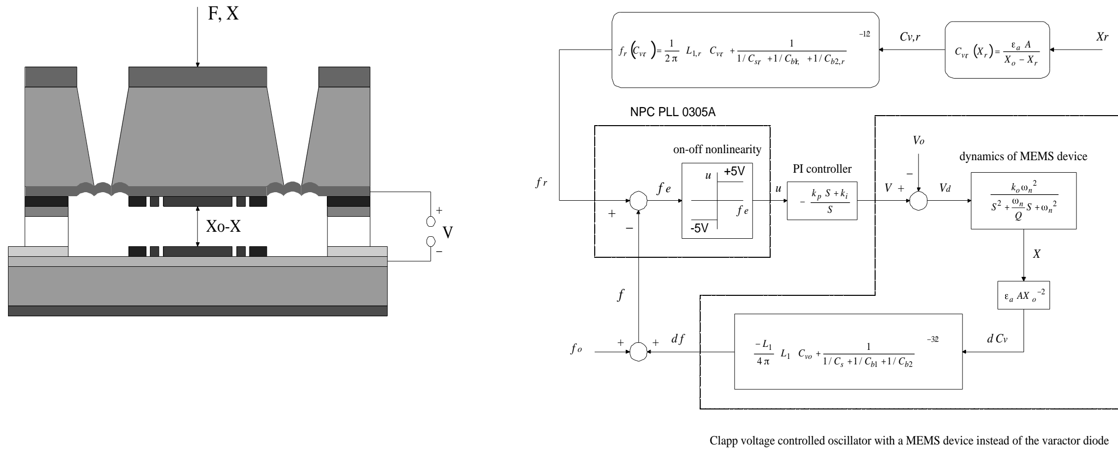


Fig. 2 A diaphragm structure used as a MEMS device. Fig.3 Block diagram of a capacitance control system for a MEMS device with PPL.

The describing function of the on-off element [10] is

$$N = \frac{4\,V_M}{\pi\,F_e} \quad \ldots (4)$$

where $F_e$ is the amplitude of input sinusoidal signal _ in our case it is the amplitude of frequency error $f_e$ _and $V_M$ is the on-off output signal level and $V_M$ is 5 Volt for PLL0305A.

Thus, this will cause a steady state error as

$$f_{e,\,ss} \quad f_{e,\max} \quad \ldots (5)$$

$$\text{where} \quad f_{e,\,\max} = \frac{4\,V_M\;k_1\;k_i\;Q}{\pi\;\omega_n}$$

## 4. Experiments and Simulations

The electric components with their default values as $L_1$ =0.8μH, $C_s$ =5pF, $C_{b1}$ =47pF, and $C_{b2}$ =68pF are used in our experiments. And when we use reference capacitor $C_{r1}$ =8pF, the reference frequency $f_{r1}$ measured by the frequency counter is 45.721MHz. Similarly, with the reference capacitor $C_{r2}$ =16pF, the reference frequency $f_{r2}$ measured by the frequency counter is 37.009MHz. Therefore, the value of $1/(1/C_s + 1/C_{b1} + 1/C_{b2})$ is 7.2028pF and the inductance of $L_1$ is about 0.7971μH. The default value of $1/(1/C_s + 1/C_{b1} + 1/C_{b2})$ is about 4.2376pF. Therefore, the frequency to capacitance sensitivity of the Clapp VCO is about 1.5037MHz/pF. And then when a varactor diode is used in the PLL instead of the reference capacitor and close the PLL with reference frequency set as around 45 MHz, the output frequency servos at steady state error within 1 kHz. That is 1fF measurement and control resolution is achieved if the properties of the electric components remain constant during operation. And thus we measure many reference capacitors with capacitive value as 5~20pF and tolerances within 5 %, the measurement error remains within 1pF. It shows good measurement accuracy is achieved when the capacitive value of the measured element is very small. The simulation results with reference displacement as 100 nm of the PLL based micro displacement servo control of MEMS device as a diaphragm structure shown in Fig.3 are shown in the

following figures Fig.4a~d.

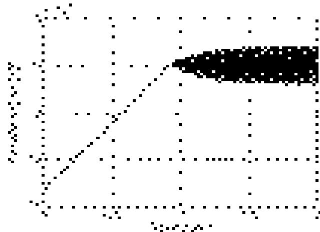

Fig.4a Frequency error v.s. time

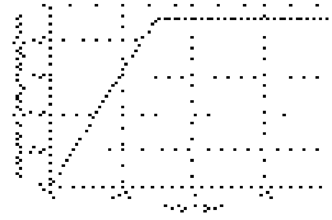

Fig.4b Perturbation driving voltage v.s. time

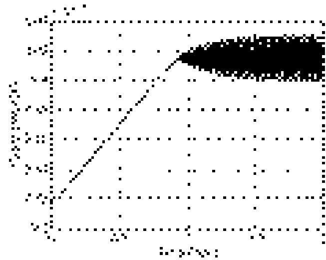

Fig.4c Capacitance between electrodes v.s.time

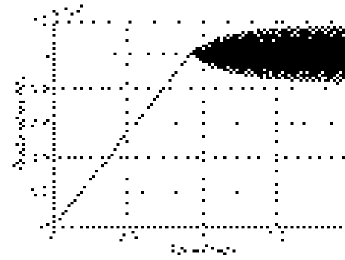

Fig.4d Displacement v.s. time

## 5. Application and Conclusions

The proposed PLL based micro capacitance/displacement measurement and control system can be used in many MEMS device such as in micro pressure sensor, micro flow sensor, micro accelerometer and micro spectrometer system. Due to its low cost nature _no any A/D and D/A converters are needed for a simple scan movement _, it has great potential in MEMS industries for batch production. And the measurement resolution can be raised with more higher oscillation frequency of VCO. In our experiments the oscillation frequency of around 45MHz is used and capacitance measurement resolution of 1fF can be achieved if properties of all the electric components used in Clapp VCO remains constant. And the simulation results of displacement servo control for a diaphragm structure shows the proposed PLL can provide 20 nm positioning accuracy. It shows a cheap and accurate displacement servo control system can be made with the proposed PLL based system. However, to assure the electric components used in the PLL have almost constant properties, environment conditions such as temperature should be controlled near constant during operation. Based on the proposed servo system, we are now developing low cost MEMS devices such as micro pressure sensors and micro spectrometers.

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