Investigation into the finger structure capacitor in the micro force measurement device

Li Xu¹, Shuxiang Wang²*, Qian Li¹, Peiliang Zheng¹, Zhenyu Huang¹

¹ Guangdong Provincial Institute of Metrology, Guangdong Provincial Key Laboratory of Modern Geometric and Mechanical Metrology Technology, Guangzhou, 510405, China
² Guangzhou Maritime University, Guangzhou, 510725, China
*Corresponding author’s e-mail: li_xu_scm@163.com

Abstract. The finger structure capacitor in the micro force measurement device was investigated by theory model analysis and comparative analysis with traditional parallel plate capacitor. The relationship between the micro force output and the distance variation between the electrodes was analysed. The micro force output of the finger structure capacitor and the traditional parallel plate capacitor were compared. Results show that the finger structure capacitor could produce stable micro force values when the finger structure parameters satisfied with \( x_0/g > 5 \). The output micro force value changed by less than 2% when the distance changed within 1mm in this range. Compared with traditional flat capacitors, the new finger structure capacitor greatly reduced the influence of the measurement and control uncertainty of the distance on the output micro-force values. The new finger structure capacitor device had little change in the output of micro force within 1mm distance variation and its output value changed with 1.7%, under the conditions of different applied voltages.

1. Introduction
With the rapid development of the science and technology, the ability of humans to understand the world has moved from the macro field to the micro size [1-3]. Measurement of the force with micro Newton level has been important in micro-nano processing technology, micro-force sensor technology, biomechanical measurement, liquid surface tension research, micro-friction phenomena, and attitude adjustment and positioning of micro satellites [4-9]. However, the measurement of the micro force value is still directly traced to the mass, and the gravity of the standard weight has been used. The uniform measurement method for micro force values has not been established [10-11]. At present, most researchers had used capacitive structures force generator as the force sources in the micro force measurement device. Shaw et.al in NIST used the cylindrical capacitors as the micro force sensors to develop an electrostatic balance [12-13]. Leach et.al in NPL had also proposed a micro force sensor device by using the cylindrical capacitors [14]. PTB designed a micro-force measuring device using a differential disc capacitance device [15]. The micro force measurement device mainly include parallel plate capacitors and cylindrical capacitors, but the electrode distance of the capacitor had a great influence on the output result. In order to ensure the accuracy of the output micro force value, the electrode distance must be accurately measured by high-precision measurement device, which made the structure of the device complicated and greatly increased the cost.
A new type of finger structure capacitor in the micro force measurement device had been investigated in this paper. It could minimize the influence of the distance uncertainty on the output result, simplify the micro force measurement device design, and reduce the cost of device.

2. The structure of the capacitor in the micro force measurement device

2.1. The force analysis of traditional capacitor in the micro force measurement device

The micro force measurement device based on electrostatic force mostly generated the micro force by the parallel plate capacitor. According to the principle of the capacitor, the electrostatic force between the two plates of the parallel plate capacitor is [16]:

\[ F = \frac{1}{2} \varepsilon \left( \frac{U}{L} \right)^2 A \]  

(1)

Where \( \varepsilon \) is the permittivity of the air between the two electrode plates of the parallel plate capacitor; \( U \) and \( L \) are the potential difference and distance between the two electrode, respectively; and \( A \) is the area of the capacitor electrode plate.

From equation (1), the micro force measurement device could control the electrostatic force value by controlling the area (\( A \)), the distance (\( L \)), or the potential (\( U \)). The distance \( L \) between the plates was squared with the electrostatic force \( F \) of the micro force measurement device. If the distance \( L \) measurement was slightly deviated, there was a very large impact on the output of the micro force value in the micro force measurement device. In addition, a slight error in the distance control would also have a great influence on the test results. So the uncertainty of the distance \( L \) measurement or the slight change in the position of the two electrode plates would lead to significant results deviation. Therefore, many researchers had to use precision equipment such as laser interferometers to measure the distance for reducing the micro force value error. In addition, in order to maintain the accuracy of the electrode position, precise auxiliary equipment must be used. These would be increase the volume and cost of the device. Researchers carried out various methods to overcome the influence of the plates distance uncertainty for the micro force measurement device testing results, such as differential capacitance way, cylindrical capacitor device instead of parallel plate capacitor device, etc. These methods reduced the micro force measurement error caused by the distance uncertainty compared with parallel plate capacitors, but the manufacture difficulty increased.

2.2. The force analysis of finger structure capacitor in the micro force measurement device

The new type finger structure capacitor in the micro force measurement device was shown in Figure 1. \( U \) is the load voltage of the finger structure capacitor; \( 2x_0 \) is the intersecting length of the finger structure capacitor; \( 2g \) is the lateral spacing of the adjacent fingers, and the cross-sectional length and width of a single finger are \( 2c \) and \( 2d \), respectively. The lateral spacing between the adjacent fingers \( 2g \) was determined by the processing and installation accuracy. When the accuracy requirements during processing and installation were guaranteed, it would not cause any other influence on the micro force measurement results. Using the new type of finger structure capacitor force generator in the micro force measurement device, according to the simplified theoretical calculation of the model, the electrostatic force between the two finger structure plates is [17]:

\[ F = 2NeU^2 \left( 1.0245 - \frac{8}{\pi x_0} \right) \]  

(2)

Where \( N \) is the finger number of the finger electrode plate. Other parameters are shown in Figure 1. According to formula (2), when the accuracy during processing and installation was guaranteed, the output micro force value could be controlled by controlling the loading voltage \( U \). Comparison of formula (1) and formula (2), the effect of the distance between the finger structure capacitor electrodes on the output of micro force had been significantly reduced. And the uncertainty of distance measurement impact on the results of micro force measurement device was also reduced by using the finger structure capacitor.
Figure 1. The new type finger structure capacitor

The relationship between the output micro-force value and the related parameters of the new type of finger structure capacitor in the micro force measurement device was shown in Fig. 2. From this figure, the output micro force value can be clearly divided into three regions with the changes of the finger structure capacitor related parameters.

Region I: The intersecting length and the lateral spacing was satisfied with \( x_0/g \leq 1.5 \). In this region, the output micro force value increased rapidly with the increase of the parameter \( x_0/g \), almost linearly rising. If the parameter \( x_0/g \) changed slightly, it would cause a sudden change in the output micro force value. So the parameters in this range were not suitable as the parameters of the micro force measurement device.

Region II: With the increase of parameter \( x_0/g \), the output micro force value changed gradually. In the area of \( 1.5 \leq x_0/g \leq 5 \), the output micro force value still increased with the increase of parameter \( x_0/g \), but its growth had been significantly reduced. For example, when \( x_0/g \) increased from 2.5 to 5 and the increase reached 200\%, the increase of output micro force value was only 6\%.

Region III \((x_0/g > 5)\): When the parameter \( x_0/g \) continued to increase, the output micro force value change curve had become flat, and its slope was also close to 0. For example, when \( x_0/g \) increased from 5 to 15, the output micro-force value changed less than 3\%. It was indicating that the output micro-force value in this area has changed very slowly, and the output micro-force value hardly changed with the variation of the finger structure parameter \( x_0/g \). In region III, even if the finger structure parameter \( x_0/g \) changed slightly, the output micro force value remain almost unchanged.

From the analysis in Fig. 2, when the new type finger structure capacitor had been used and the finger structure parameter could be ensured in region II or region III, the uncertainty of the measurement of the finger structure electrode position had little effect on the measurement output micro-force value.
3. Results and discussion

3.1. The influence of the distance variation between the electrodes on the output micro-force value

The relationship between the output micro-force value and the distance variation between the electrodes was shown in Fig. 3. It can be clearly seen from Figure 3 that when the traditional parallel plate capacitor was used, its output micro force value decreased rapidly with the increase of the plate electrodes distance. For example, when the distance between the parallel plate capacitor electrodes changed from 5mm to 7mm, the output tiny force value had been reduced to 51% of the original value ($F_0$). The variation of the plate electrodes distance by 40% could lead to the reduction of output micro force value by 49%. When the plate electrodes distance reached at 10mm, the output micro force value was only 1/4 of the original value ($F_0$). Doubling the distance between the plate electrodes would lead to the output micro force value reduced to 1/4. If the distance produced 1 mm variation, the error of the output micro force value will exceed 20%. The distance between the plate electrodes must be accurately measured and controlled, otherwise the measurement results accuracy of micro force couldn’t be guaranteed. However, high-precision position measuring devices and control devices were relatively expensive, which would greatly increase the cost of the micro force measurement device. And the size of the additional measuring and control auxiliary devices were relatively large, which was not conducive to installation and carrying.

![Figure 3. Relationship between the output micro force value and the distance variation between the electrodes](image)

After adopting the new type of finger structure capacitor, the decrease of the output micro force value with the distance variation would have significantly reduced. Especially at the position close to the initial value (d=5mm), the output micro force value changes very slowly with the distance. When the distance between the electrodes increased from 5mm to 7mm (40% increased of distance), the output micro force value changed by less than 2%. Even when the distance between the electrodes doubled to 10mm, the output micro force value changes within 10%. When the distance changed within 1mm, the error of the output micro force value was within 2%. The position measurement and position control with 1mm accuracy could be easily achieved by using general instruments and mechanical structures. Thus it could be seen that the influence of the distance between the electrodes on the output micro force value was greatly reduced by using the new finger structure capacitor. The output micro force value was almost unchanged by the slightly distance variation between the electrodes.

3.2. The influence of the loading voltage on the output micro-force value

Figure 4 showed the output micro force value varies with the distance of the fingers under different voltages. From figure 4, the output micro force value increased with the applied voltage growth. Set $A_0$, $B_0$, $C_0$ ($2x_0=5mm$) as the standard state output micro-force value at the loading voltage 500V, 600V and 700V, respectively. The actual distance would be shifted due to the error of distance measurement or position control during the using of the finger structure capacitor micro force measurement device. When the actual distance changed from the standard state (5mm) to the state "1" ($2x_0=4mm$, namely $A_1$,
B₁, C₁, respectively), the error of the output micro force value was only -1.7% in the finger structure capacitor micro force measurement device. And the actual distance changed from the standard state (5mm) to the state "2" (2x₀=6mm, namely A₂, B₂, C₂, respectively), the error of the output micro force value was only +1.1%. Because the state "1" was in the region II, and the state "2" was in the region III, the output micro force value error of state "2" was smaller than the error of state "1".

Figure 4. Micro-force output under different loading voltages with finger structure capacitor

Under different voltage conditions, when the finger structure capacitor parameters were in the regions II and III, even if the actual distance deviates from the standard state due to measurement errors or position control errors, it has little effect on the output micro-force value.

Figure 4 also showed that the new finger structure capacitor device was not only suitable for a specific loading voltage, but within the effective voltage loading range (the electrodes didn’t break down), its output micro force value was little affected by the distance measurement error and position control error.

The finger structure capacitor greatly reduced the effect of distance measurement or control uncertainty on the output of micro force values. This feature of the new finger structure capacitor was of great significance for simplifying the structure of micro force measurement device and reducing the cost of corresponding devices.

4. Conclusions
Investigation into the finger structure capacitor in the micro force measurement device was carried out. Through theoretical analysis and comparative research with traditional plate capacitors, the following conclusions were obtained:

(1) The new finger structure capacitor could produce stable micro force values in space when the finger structure parameters satisfied with x₀/g >5, and the output micro force value changed by less than 2% when the distance changed within 1mm in this range.

(2) Compared with traditional flat capacitors, the output micro-force values of the new finger structure capacitor changed slowly with the distance variation, which greatly reduced the influence of the measurement and control uncertainty of the distance on the output micro-force values.

(3) Under the conditions of different applied voltages, the new finger structure capacitor device had little change in the output of micro force with distance variation within 1mm and its output value changed with 1.7%, appearing good stability.

Acknowledgments
The authors thank for the financial support by the National Natural Science Foundation of China with the contract numbers of 51806041, the Guangdong Science and Technology Project (2014A040401044, 2018A0303130013) and the State Administration for Market Regulation Science and Technology Project (2016QK028).
References

[1] Kim M, Pratt J R. SI traceability: Current status and future trends for forces below 10 MicroNewtons [J]. Measurement, 2010, 43(2): 169–182.

[2] Lay A, Wang D S, Wisser M D, et al. Upconverting nanoparticles as optical sensors of nano to micro Newton forces[J]. Nano letters, 2017, 17(7): 4172-4177.

[3] Wei Y, Xu Q. An overview of micro-force sensing techniques[J]. Sensors and Actuators A: Physical, 2015, 234: 359-374.

[4] GUELPA, Valérian, et al. 3D-printed vision-based micro-force sensor dedicated to in situ SEM measurements. In: 2017 IEEE international conference on advanced intelligent mechatronics (AIM). IEEE, 2017. p. 424-429.

[5] GAO, Yuyu, et al. Microchannel - Confined MXene Based Flexible Piezoresistive Multifunctional Micro - Force Sensor. Advanced Functional Materials, 2020, 30.11: 1909603.

[6] GARCÉS-SCHRÖDER, Mayra, et al. Characterization of skeletal muscle passive mechanical properties by novel micro-force sensor and tissue micro-dissection by femtosecond laser ablation. Microelectronic Engineering, 2018, 192: 70-76.

[7] ZANG, Haoyan, et al. Recent advances in non-contact force sensors used for micro/nano manipulation. Sensors and Actuators A: Physical, 2019, 296: 155-177.

[8] CHEN, Hai-chao, et al. Design and construction of a novel instrument for high-frequency micro-force electrical sliding friction testing. Review of Scientific Instruments, 2019, 90.9: 095103.

[9] RANJAN, Ravi, et al. Cold gas micro propulsion development for satellite application. Energy Procedia, 2017, 143: 754-761.

[10] LIANG, Qiaokang, et al. Multi-dimensional MEMS/micro sensor for force and moment sensing: A review. IEEE Sensors Journal, 2014, 14.8: 2643-2657.

[11] MARTI, K., et al. Micro-force measurements: a new instrument at METAS. Measurement Science and Technology, 2020, 31.7: 075007.

[12] Shaw G A, Stirling J, Kramar J A, et al. Milligram mass metrology using an electrostatic force balance[J]. Metrologia, 2016, 53(5): A86.

[13] Shaw G A. Current state of the art in small mass and force metrology within the international system of units[J]. Measurement Science and Technology, 2018, 29(7): 072001.

[14] Leach R, Chetwynd D, Blunt L, et al. Recent advances in traceable nanoscale dimension and force metrology in the UK[J]. Measurement Science and Technology, 2006, 17(3): 467.

[15] DAI, Gaoliang, et al. Overview of 3D micro-and nanocoordinate metrology at PTB. Applied Sciences, 2016, 6.9: 257.

[16] Karadag B, Cho S, Funaki I. Note: Precision balance for sub-miliNewton resolution direct thrust measurement[J]. Review of Scientific Instruments, 2018, 89(8): 086108.

[17] Johnson W A, Warne L K. Electrophysics of micromechanical comb actuators[J]. Microelectromechanical Systems, Journal of, 1995, 4(1): 49-59.