Research on wide-range micro force generator based on interdigital capacitor array modules

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Abstract. The micro Newton level standard force generator was important in the micro/nano force measurement and traceability device. How to obtain a stable and wide-range standard micro force at a lower voltage (≤220V) was a important technical problems for improving the measurement accuracy and range. The interdigital capacitor array modules were used to generate the standard micro force at a lower voltage. The research results showed that the device could achieve stable, high-accuracy, wide-range micro force output under a relatively low constant voltage. The device output range would be expanded and the output resolution would be improved without increasing the complexity of the device. The symmetrical arrangement of the micro force generator array modules and the interdigital capacitor structure greatly reduced the influence of the unbalanced load of the device and the deformation of the elastic support structure on the output micro force value. These structures were ensuring the accuracy of the micro force generator. It provided a useful basis for the design and manufacture of low-voltage and wide-range force generator in micro force measurement and value traceability devices.

1. Introduction
With the rapid development of information technology, the application of MEMS devices and micro-nano processing technology in the new generation of information technology equipment is increasingly widespread [1, 2]. In MEMS technology and micro-nano processing, the measurement of micro force was becoming more and more important. The accuracy and reliability of micro force measurement would directly affect the accuracy of micro-nano processing technology and the performance of MEMS devices. And the micro-nano processing technology (such as lithography technology, etc.) had become an important direction in the innovation of new generation information technology equipment. Therefore, the accurate measurement of micro force was of great significance for improving the performance and technological innovation of the new generation of information technology equipment [3, 4]. For example, in the WDM (wavelength-division multiplexing), the micro lens required an assembly force of the micro Newton order in the assembly process. When the micro force exceeds a certain value, the micro lens would be broken. Therefore, ensuring the accuracy and reliability of the applied micro force was the key issue to the progress of the micro-lens assembly process [5]. And the LIGA technology (a MEMS processing technology based on X-ray lithography), involving the manufacture and assembly of a large number of micro-nano components. And most of the manufacture and assembly involved the micro force feedback control process. The accuracy and
reliability of the micro force measurement results were the prerequisite and guarantee for the realization of micro-nano processing technology and the automation of MEMS components [6].

In the micro force measurement device, the core component was the force generator that generates the micro Newton-level standard force. At present, most researchers used capacitive force generator in the micro force measurement and value traceability devices [7~11]. In order to increase the measurement range, the output range of the force generator in the micro force measurement device must be increased. However, high loading voltage (≥2000V) was likely to cause the discharge breakdown of the capacitive micro force generator device, and ensuring the stability and accuracy of the DC high voltage input was also a difficult problem, requiring complex and huge auxiliary equipment, increasing the size and the complexity of the entire measurement system.

The interdigital capacitor array modules were used in this paper. Through the reasonable layout and control of the array modules, the device that could output a wide range of standard micro force values at a certain lower voltage could be designed. It would effectively expand the measurement range of the device and avoid the influence of unstable voltage on the measurement results by high voltage. And it achieved free switching between different ranges.

2. Structure of the micro force generator

2.1. Overall structure of the device

Figure 1 was the schematic structural of the wide-range micro force generator device based on the interdigital capacitor array modules. The device was mainly composed of five parts, including the top substrate, the bottom substrate, the micro force generator array, the elastic support structure, and the output probe. The upper substrate was connected to the lower substrate through the elastic support structure, as the main structure of the device. The upper and lower substrates played the role of arranging the micro force generator array. The elastic support structure was responsible for supporting the entire device and generating elastic deformation when the device was working. The micro force generator array was arranged between the upper substrate and the lower substrate. As the core part of the device, the micro force generator array included several array modules. Each array module was composed of a set of interdigital capacitors. The interdigital capacitor was arranged between the upper substrate and the lower substrate. Each array module was connected to a power source for generating micro-nano force. The output probe was responsible for the force output of micro force generated by the micro force generator array.

2.2. Micro force generator array structure

In the wide range micro force generator device based on the interdigital capacitor array, the micro force generator array was the core part of the entire device. The standard micro force output was achieved through the layout and control of the micro force generator array modules. The structure of the micro force generator array was shown in Figure 2.

The micro force generator array was located on the top and bottom substrates. Each micro force
generator array was composed of several array modules. The micro force generator array module was composed of interdigital capacitors, and each group of interdigital capacitors forms an array module.

![Micro force generator array](image1)

The top substrate and the bottom substrate were both four-layer structure substrates. The four-layer structure substrate was formed by upper insulating layer, circuit layer, lower insulating layer, and the base layer. The upper insulating layer and the lower insulating layer were both used to fix and insulate each of the array modules. The circuit layer was used to connect each array module to an external power source. Each array module was individually powered by wiring or printed circuit on the circuit layer in the top or bottom substrate. So each array module could supply a micro force with a certain value. The circuit layer could be a printed circuit with a very small thickness in order to facilitate the miniaturization and integration of the device.

3. Theory of the device working

As the core component of the device, the micro force generator array had multiple rows of the array modules. Each column of the array modules formed a set of array module groups. The output micro force was the same order of magnitude by the same group of array modules. The interdigital capacitance of each array module was shown in Figure 3.

![The interdigital capacitance parameters](image2)

When the interdigital capacitance parameters of the micro force generator array module satisfied certain parameter conditions \((c=d=g)\), the output micro force value could be calculated by the following formula [12]:

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

Where \(N\) is the finger number in the interdigital capacitance; \(\varepsilon\) is the permittivity of the air. \(U\) is the voltage applied in the interdigital capacitance. Other parameters are shown in Figure 3.

| \(x_0\) (mm) | \(N\) | \(F\) (\(\mu\)N) | \(\delta\) (%) |
|----------------|-----|----------------|-----------|
| 4.75~5.15      | 3   | 0.499~0.502    | -0.20~+0.40|
| 4.75~5.15      | 6   | 0.998~1.005    | -0.20~+0.50|
| 4.75~5.15      | 12  | 1.995~2.009    | -0.25~+0.45|
| 4.75~5.15      | 30  | 4.988~5.023    | -0.34~+0.46|
| 4.75~5.15      | 60  | 9.976~10.047   | -0.24~+0.47|
According to formula (1), the requirements of the interdigital capacitance parameters could be deduced, when the output micro-nano force value was an integer (such as 1μN, 2μN, 5μN) at the fixed load voltage. For example, we could get the micro force with integer value at \( U = 100 \text{V} \), when the array module parameters satisfied \( c = d = g = 1.27 \text{mm} \). The output micro force was shown in Table 1. From Table 1, if the loading voltage of the device would to be stabilized at 100V, different micro force value could be achieved by different parameters of the array module. Meanwhile, for using the interdigital capacitor as the array module, even if the distance of the interdigital capacitor changed from 4.75mm to 5.15mm (distance changes by 8.4%), the error of output micro force could still be controlled within ±0.5%.

4. Layout of micro force generator array and device output control method

4.1. Layout of micro force generator array modules
As shown in Figure 4, each micro force generator array module of the same magnitude forms a column. The micro force output in column was the same order of magnitude. The output difference between the adjacent two columns was an order of magnitude. And the output micro force value of each column contained several values of 1, 2, and 5. One or more columns of array modules could be set up according to the requirements of the device output range. The array modules in the same column were arranged in symmetrical positions (Figure 4).

![Figure 4 Layout of micro force generator array modules](image)

4.2. Device output control system
During the use of the device, the specific control principle was as follows: When a certain value micro force output of the micro force measurement device was required, the control system analyzes the required output force value, and split the force value of each magnitude into a combination of 1, 2, and 5. For the value 1, 2 and 5 had corresponding array modules, there was no need to split these 3 values. For other values, the split scheme of the control system was shown in Table 2. In the actual execution process, the values from 1 to 9 could be executed or split according to the scheme in Table 2.

| value | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|
| split scheme | 1 | 2 | 1+2 | 2+2 | 5 | 5+1 | 5+2 | 5+1+2 | 5+2+2 |

After the force value of each magnitude was split according to table 2, the corresponding array modules were connected with the external applied voltage. Then the corresponding micro force value could be output. In order to keep the stability of the output micro force, the symmetrical array modules would be chosen to turn on as the working modules by the control system.

For example, if the output value was 4, the control system would choose two symmetrical 2 value module to turn on in order to eliminate the influence of the unbalanced load on the output micro force. When there was the need for output 13.8μN of the micro force generator, the control system would choose the 10μN module in the 10μN array; the 1μN module and 2μN module in the 1μN array; the 0.5μN module and the 0.2μN module and 0.1μN module in the 0.1μN array. These choose modules would be turn on as the working modules by the control system. At this time, the total force of the micro force output by the micro force generator array modules on the substrate was 13.8μN. This micro force value was output through the output probe.
Because the interdigital capacitor structure was adopted in the array module, the output micro force value of the interdigital capacitor structure was not sensitive to the change of the interdigital intersecting length. During the working process of the device, even if the elastic support structure was slightly deformed and changed the intersecting length of the interdigital capacitor module, the output micro force value still would be stable. This meant the output stability of the device was excellent.

5. Conclusions
Research on the wide range micro force generator based on interdigital capacitor array modules was carried out. The structure, working principle, and control method of the device were analyzed in detail. The following conclusions were obtained:

1. The wide range micro force generator based on interdigital capacitor array modules could achieve high-accuracy micro force values with different magnitudes under a fixed voltage.
2. The device could realize the free increase and decrease of different measurement ranges by setting the micro force generator array. And this greatly expanded the output range of the device.
3. The symmetrical distribution and output control of the micro force generator array module minimized the influence of eccentric load on the output micro force.
4. The interdigital capacitor using in the micro force generator array module greatly reduced the influence of the elastic deformation of the elastic support structure on the accuracy of the micro force output. When the distance change caused by elastic deformation arrived at 8.4%, the micro force output error could still be controlled within ±0.5%.

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