Overview of Micro-force Sensing Methods

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Abstract. At present, reliable micro-force sensing is one of the most important research for micromanipulation and micro-assembly. Six kinds of methods to detect micro-force are described in this paper. Analysis of the basic principle and detection accuracy of each sensing method, and applications in micro-assembly and micromanipulation are briefly introduced. The purpose of this paper is to be useful to provide some references for scholars engaging in the micro-force sensing, which in turn promotes automatic processing level of micro-assembly and micromanipulation to reliably manufacture micro devices of high quality.

Introduction

As detecting equipment and the main part of the mechanical assembly systems, force sensors have a wide range of applications in many fields [1], such as industrial production, automotive manufacture and assembly of components. With the deep going research on the microscopic world, traditional force sensors have been unable to meet the needs of MEMS/NEMS and nano-technology for micro-force measurement and control. For example, the main component of optical communication network system is micro-lens [2], which is easily broken when the force during the level of micro-Newton (µN) acts on it. However, existing micro-force sensors are unable to detect the force at µN level reliably. Usually, micromanipulation force in the process of cell injection is during µN level. If the contact force is not reliably detected and controlled, it is likely to damage the operated object. At present, the MEMS/NEMS also needs to detect micro contact force in the assembly process, to avoid the damage of devices caused by uncontrollable micro-force. Therefore, reliable, high-precision micro contact force detection is of great significance for production, assembly and equipment protection. Design and realization of micro contact force sensors is currently one of the most important research objectives of many universities and institutions. Several methods and research situation of micro-force sensing are described, and briefly principle of each method, measurement accuracy and practical applications are also introduced in this paper.

Micro-force Sensing Methods

Strain-gauge Sensors. Strain-gauge sensors are widely used to detect contact force. Strain means deformation of conductor or semiconductor under external mechanical stress. According to Hooke's law, when the force \( F \) acts on the object, in the context of the elastic limit change in length is:

\[
\sigma = \frac{F}{A} = E \varepsilon = E \frac{\Delta I}{I}.
\]

Where \( \sigma \) -- mechanical stress; \( A \) -- cross-sectional area; \( E \) -- Young modulus; \( \varepsilon \) -- strain. As shown in Figure 1 [3], strain \( \varepsilon \) is defined as the ratio of deformation along the length direction and length (\( \varepsilon = \Delta I / I \)).
Object in the elastic region is the elastic strain, as shown in Figure 2. That is, after getting rid of mechanical stress, the stressed object can completely return to its original size and shape. Under such condition, mechanical stress is proportional to strain, \( \sigma = \varepsilon E \). Measurement principle of strain-gauge sensors is based on the above relations.

Based on strain-gauge detecting principle, micro-force detecting sensors have attracted many scholars inland and abroad. For example, Puttlitz et al. designed a wireless RF-MEMS sensor based on strain-gauge [4]. The sensor can measure stress of bones to monitor recovery of the fracture patients. This sensor with high sensitivity can be achieved 5.148kHz \( \mu \varepsilon \) (\( \mu \varepsilon \) is unit symbols of micro-strain. Micro-strain represents the amount of relative change in length). At the same time, it has low nonlinearity error (less than 200\( \mu \varepsilon \)) and other advantages. Sosnowchik et al. designed a piezoresistive sensor on the AFM (atomic force microscope) probe [8], measuring accuracy can achieve 0.1mN. Gnerlich, Perry et al. used silicon micro-cantilever-beam piezoresistive sensor detects the biochemical reaction and converts the reaction into electrical signal that is able to be measured. Finally the pressure on people is detected by potential conversion circuit. Zesch et al. installed piezoresistive sensor on the AFM (atomic force microscope) probe [8], measuring accuracy can achieve 0.1mN. Gnerlich, Perry et al. used silicon material to design a kind of novel piezoresistive sensor to measure lateral force [9]. It is applied for

Piezoresistive Sensors. When metal or semiconductor material is under stress, its resistance will change. This phenomenon is called piezoresistive effect. The relative change of resistance \( \Delta R / R = \pi_{\rho} \varepsilon / \rho \) (\( \rho \) -- resistivity; \( \pi_{\rho} \) -- piezoresistive coefficients of the materials; \( \varepsilon \) -- acting force). Piezoresistive sensors are based on piezoresistive effect and integrated circuit technology. The working principle is consistent to that of strain-gauge sensors. More specifically, \( \Delta R \) and \( R \) ratio is:

\[
\frac{\Delta R}{R} = (1 + 2\gamma)\varepsilon + \frac{\Delta \rho}{\rho}.
\]

Where, \( \gamma \) is Poisson's ratio; \( \varepsilon \) is strain (\( \varepsilon = \Delta I / I \)). Because \( \Delta \rho \) of metal is equal to 0, \( \Delta R / R \) is \( (1 + 2\gamma)\varepsilon \).

Figure 3 is a schematic diagram of a piezoresistive sensor's structure [6]. Where, part 1 is piezoresistive sensitive components; part 2 is the upward force; part 3 is the downward force; and part 4 is silicon element. Resistance of sensitive components changes with the force varying.

In MEMS, piezoresistive sensors are widely used. For example, based on MEMS, Abdullah et al. designed a kind of biological piezoresistive sensor [7], which consists of a biological sensor and a micro-cantilever-beam piezoresistive sensor. Biological sensor produces biochemical reaction, while micro-cantilever-beam piezoresistive sensor detects the biochemical reaction and converts the reaction into electrical signal that is able to be measured. Finally the pressure on people is detected by potential conversion circuit. Zesch et al. installed piezoresistive sensor on the AFM (atomic force microscope) probe [8], measuring accuracy can achieve 0.1mN. Gnerlich, Perry et al. used silicon material to design a kind of novel piezoresistive sensor to measure lateral force [9]. It is applied for
the cell biomechanics experiment to measure mechanical properties of a single cell. The smallest micro-force the sensor can detect is less than 100nN (nano-newton) and there is a high signal-to-noise ratio. But the detection accuracy is not mentioned. Generally, the resistance variation is not easily to be directly detected and is delicate to the variation of temperature. To get a higher voltage sensitivity and lower temperature sensitivity, Whiston-bridge is often used. The detecting accuracy of piezoresistive sensor is on the level of mN or sub-mN in general.

**Capacitive Sensors.** Generally, capacitive sensors consist of a fixed electrode and a circular metal film or metallic coating thin film electrode, as shown in figure 4 [10].

Based on capacitance calculation formula $C=\varepsilon_0\varepsilon A/\delta_0$ ($\varepsilon_0$ -- vacuum permittivity; $\varepsilon$ -- relative permittivity; $A$ -- plate area; $\delta_0$ -- distance between the plates), when there is one or more variables changing among $\varepsilon$, $A$ and $\delta_0$, capacitance $C$ changes. Usually, the way to change the capacitance $C$ is by changing the distance $\delta_0$ between the plates. That is, when there is force in thin film electrode, variation in distance between two electrodes will lead to the change of capacitance. Relationship between the relative variation of the capacitance $\Delta C/C$ and force $F$ is:

$$\frac{\Delta C}{C} = \left(1 - g^2 + \frac{1}{3} g^4 \right) \frac{3(1 - \gamma^2)a^4}{16Eh^3\delta_0} F. \quad (3)$$

Where, $g=h/a$; $\gamma$ is Poisson's ratio of silicon; $h$ is electrode thickness; $\delta_0$ is the distance between the fixed electrode and the thin film electrode; $E$ is Young's modulus of thin film electrode. Therefore, by measuring the change of the capacitance ($\Delta C$), the magnitude of the force $F$ can be calculated indirectly.

Compared with piezoresistive sensors, capacitive sensors have low energy consumption, good stability and higher sensitivity, are not sensitive to the changes of environment etc. For the above reasons, capacitive sensors attract scholars' attention. For example, Howver et al. designed ultra-thin MEMS capacitive pressure sensor [11], and the size of the sensor is 1mm$\times$1mm$\times$60µm. It has a wide measuring range from -3.5mN-3.5mN. Resolution can be up to 1.75µN, which is 0.025% of full scale.

**Piezoelectric Sensors.** Some material under stress will produce a reversible electrode phenomena. This phenomenon is called piezoelectric effect. Piezoelectric effect is divided into direct piezoelectric effect and the inverse piezoelectric effect. The direct piezoelectric effect is that some of the dielectric will deform when the external force along a certain direction acts on the material, and the internal produces polarization phenomena. At the same time, positive and negative charges appear on two opposing surfaces. When the force is removed, the dielectric will return to neutral state. Charge of dielectric is proportional to the magnitude of the force. Principles are shown in figure 5. Most of piezoelectric sensors are designed based on the direct piezoelectric effect and achieve mutual conversion between mechanical energy and electrical energy.
Piezoelectric material Polyvinylidene-fluoride (referred to as PVDF) is a new type of polymer-type material. Because of wide frequency response, dynamic range, excellent wear resistance, flexibility, high and mechanical strength, PVDF has been widely applied in many areas, such as health care and measurement. For example, Edward Chen et al. designed a low-cost PVDF pressure sensor for sensing the motion of a robot fish [12]. Kotian et al. designed a PVDF sensor for measuring in-plane sinusoidal and impact induced by stresses [13]. Kon et al. designed a piezoelectric sensor to detect vibrations of mechanical structure [14]. It has high resolution, which can reach 0.043\(\mu\)e. Figure 6 is a PVDF sensor designed by Yiyang Liu [15,16,17,18] an associate fellow of Shenyang Institute of Automation, Chinese Academy of Sciences. This sensor can reliably measure micro contact force in the range of sub-micro-newton (sub-\(\mu\)N). The device is mainly used in micro-assembly and micromanipulation, and the detection accuracy can achieve 0.1\(\mu\)N.

**Piezomagnetic Sensors.** The piezomagnetic sensor (also known as the magnetoelastic sensor) is a relatively new type of sensor. Its working principle is based on magnetoelastic effect. When ferromagnetic material subjects to mechanical stress, its internal strain leads to changes in permeability. By detecting the magnetic permeability changes, mechanical stress can be measured. Figure 7 shows a typical structure diagram of piezomagnetic sensor [19].

The relationship between relative permeability change of ferromagnetic material and mechanical stress is:

\[
\frac{\Delta\mu}{\mu} = \frac{2\lambda_m}{B_m^2} \sigma \mu.
\]

Piezomagnetic sensors have a lot of advantages. Compared with strain-gauge sensors, this kind of sensors does not have to be pasted and is able to be installed simply. Compared with piezoelectric sensors, piezomagnetic sensors can measure a dynamic force, also apply to the static force measurement. The signal amplification circuit is simple, without charge amplifier. Piezomagnetic sensors have very good ability to resist overload and strong anti-interference ability. For example, Jinhui Lan et al. designed a sensor to recognize vehicles by detecting magnetic interference produced by vehicles and applied appropriate signal processing and recognition algorithm [20].
magnetoelastic effect, Kaniusas et al. designed a skin curvature sensor applying to biomedicine. This sensor can monitor many human physiological parameters, such as cardiac activity on the neck, respiration on the chest, eye movements below the eyelids and so on.

In theory, the resolution of force sensors based on magnetoelastic effect can reach nano-newton (nN). As the technology is very sensitive to electromagnetic environment, the accuracy decreases to µN or even below sub-µN.

**Sensors Based on Optical Technology.** Sensors based on optical technology can also be used to detect micro-force. At present, there are four main methods to detect the micro-force using optical technology. In recent years, many scholars in universities and institutions have done a lot of research in this area.

First of all, Arai et al. developed a set of micro-force measuring device using laser Raman spectrometer method to detect micro-force [21]. Theoretical accuracy of this method is up to 6.94µN and the sensor is mainly used to realize non-contact measurement. However, there are some disadvantages in this method, such as the slow detection speed, poor real-time and general capacity of measuring multidimensional information.

Second, the precision using Laser Interferometer to detect micro-force is 66µN. This method is primarily used for non-contact measurement, accesses to micro-force information and the relative position information in the meantime. But it is hard to measure the force of multidimensional information.

Again, some scholars use AFM to measure micro-force. For example, Faucher et al. used AFM to measure micro-force [22], and detecting accuracy can be achieved with 0.2nN. The probes of commercial AFM setups are mostly based on microsized oscillating cantilevers. In a vacuum, they are able to provide pico-newton (pN) resolution. This requires that the silicon resonant converter has high resonance frequency and high quality.

Finally, optical tweezers can be used to measure micro-force. Optical tweezers is also called the single particle beam trap. It is a tool that is based on the mechanical effect of the laser, and captures particles by three-dimensional trap formed by the interaction between a bunch of strong converging laser and tiny particles. Optical tweezers is not just a tool to manipulate the position of particles, also serves as a "probe" measuring the micro-force. This is because the particle in optical trap deviates from the trap center and moves to a new position. Optical trap force $F$ that points to the trap center will act on it. When the particle influences by other external force $F'$, in the new position optical trap force and external force balance. Within range of the trap center, particle offset $x$ from the trap centre is proportional to the optical trap force:

$$\vec{F} = -k_x \cdot \vec{x}. \quad (5)$$

In the equation (5), $k_x$ is optical trap stiffness. Knowing the relationship between the optical trap force $F$ and offset $x$, external force can be calculated in the equation (6). The nature of optical trap liking a spring makes it be a probe to measure micro-force.

$$\vec{F}' = -\vec{F}(x). \quad (6)$$

Resolution of optical tweezers can reach nN or sub-nN level. Yinmei Li, a professor from laser Biology Laboratory of China University of science and technology, and others developed a "Nano-Optical tweezers System". According to experiments by Gong and others, the measuring accuracy of this system can reach sub-pico-newton (sub-pN). Compared with microprobe of traditional operations on micron particles or other devices such as AFM, the use of optical tweezers that can capture exercise machine longitudinal sample has advantages of non-contact, no mechanical damage etc. So to measure micro-force using optical tweezers has important status and outstanding advantages in the study of dynamical system of tiny particles, which is mainly reflected in the field of biology. Since optical tweezers manipulate micro-objects and also measure micro-forces that are during the level of nN, which MEMS is unable to do, it does not apply to MEMS at the moment.
Conclusions

To sum up, each method of micro-force sensing has its own advantages and shortcomings. In the design of sensors and micro-sensor systems using these methods, designers should make full use of the characteristics of each method, while enabling to meet the requirements and to save costs. For example, measuring principle of strain-gauge sensors and piezoresistive sensors is basically same, and measurement accuracy is on milli-newton or sub-milli-newton level. These measurement methods are mature, simple and with wide measuring range. So they can apply for the systems which do not need high accuracy. Capacitance sensor detection accuracy can be achieved micro-newton or sub-micro-newton. It is not sensitive to the variation of the environment and little affected by temperature, so this kind of sensors can be used in the occasions where environment or temperature changes a lot. Also, piezoelectric sensor detection accuracy can be achieved micro-newton or sub-micro-newton. Because of excellent resistance, flexibility, high mechanical strength, good plasticity, impact resistant and anti-aging, it is more suitable for installation in the occasions of relatively high detection accuracy. Detection accuracy of piezomagnetic sensors is high with the theoretical resolution of nano-newton. But it is susceptible to electromagnetic interference, which leads to lower detection accuracy. Micro-force sensors using optical technology can reach nano-newton theoretically. These sensors mainly use non-contact measurement, and can access to location information associated with force, but manufacturing costs are higher. They are more suitable for structural analysis of institutions.

Six kinds of methods to detect micro-force are described in this paper. The basic principles of each sensing method, the detection accuracy and range of applications (micro-assembly and micromanipulation) are simply analyzed and introduced in the paper. Field of micro-force sensing still needs more scholars to conduct an in-depth research, so the purpose of this paper is to provide some references for scholars engaging in the field of micro contact force sensing research, which in turn promotes automatic processing level of micro-assembly and micromanipulation to reliably manufacture micro devices of high quality.

References


