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Research Progress of Mechanical Vibration Sensors

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***Abstract*—Mechanical vibration is a very common phenomenon in industrial production, and also an important cause of mechanical equipment failure. Monitoring mechanical vibration signal can know the operation status of mechanical equipment, so as to effectively prevent mechanical failure and sudden accidents. Therefore, the acquisition of vibration signal becomes a necessary link in the condition monitoring of mechanical equipment.**

Mechanical vibration test mainly relies on a variety of vibration sensors, including acceleration sensor and strain sensor. Both of them are widely used and they can accurately collect vibration signals during the operation of mechanical equipment. At present, the research on vibration sensor mainly focuses on the development of materials, the optimization of sensor performance and the introduction of new technology.

Vibration sensors are summarized in this paper, which are divided into acceleration sensors and strain sensors. The former includes piezoelectric acceleration sensors and capacitive acceleration sensors, while the latter includes resistance sensors and fiber Bragg grating strain sensors. Finally, the characteristics of self powered vibration sensors, RFID vibration sensors and other new sensors are discussed, and the research status and development trend of vibration sensors are discussed.

Keywords-State monitoring; Vibration sensor; Acceleration sensor; Strain sensor

I. INTRODUCTION

Vibration, temperature rise and noise are the three main factors affecting the normal operation of mechanical equipment. The source and core of these three elements are vibration. Affected by the damage and aging of parts and components, the equipment often produces vibration in the process of operation. Vibration not only brings temperature rise and noise, but also aggravates the wear of parts and components, thus reducing the operation efficiency of the equipment system. If severe vibration occurs, it will damage the running state of the machine and even shorten its service life. Therefore, the real-time detection of vibration signal is very necessary. It can accurately reflect the structural defects, so as to evaluate the operation status of equipment.

At present, the acquisition of vibration signal mainly depends on a variety of vibration sensors. Its working principle is to reflect the static change and dynamic performance of the structure by measuring the motion of inertia mass[1]. Vibration acceleration sensor and strain sensor are the basic components of the monitoring system, which are used to measure the static change and dynamic performance of the structure. Vibration acceleration sensor is a typical inertial sensor, usually spring mass damping system, which can measure acceleration and obtain vibration displacement, velocity and other parameters. The commonly used acceleration sensors are piezoelectric accelerometer and capacitive accelerometer, which can measure the dynamic and static parameters of structures respectively. The strain sensor is used to measure the mechanical deformation caused by external force. It can measure many parameters such as force, load, strain, displacement, velocity and acceleration. However, the resistance strain sensor is easy to be affected by the environment and cannot be used in the complex environment of strong corrosion and strong electromagnetic interference, while the fiber Bragg grating strain sensor can overcome the above shortcomings and play an important role in marine exploration, structural performance evaluation and condition monitoring of cable equipment[2]. In addition, researchers have also introduced new technologies and new materials into the sensors, and developed a variety of new vibration sensors with new functions.

This paper discusses the application status of piezoelectric acceleration sensor, capacitive acceleration sensor, resistance strain sensor and fiber Bragg grating strain sensor. It also summarizes the research progress of self powered vibration sensor, radio frequency identification vibration sensor and other new vibration sensors, compares and analyzes their advantages and disadvantages, and finally looks forward to the future development trend of vibration sensors.

II. ACCELERATION SENSOR

At present, acceleration sensors have been widely used in structural condition monitoring. Almost all engineering technologies need to be applied to acceleration sensors to monitor the acceleration, displacement, velocity and other parameters produced by equipment in vibration[3]. Generally, there are two kinds of acceleration sensors: piezoelectric and capacitive. Piezoelectric acceleration sensors have good dynamic characteristics, but can't measure static physical quantities; while capacitive acceleration sensors are mostly used for static and quasi-static characteristics measurement [4].

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A. Piezoelectric accelerometer

Figure 1. Piezoelectric acceleration sensor

The sensing element of piezoelectric acceleration vibration sensor is made of piezoelectric material. When the piezoelectric material is under pressure, the surface of the material will generate electric charges. These charges can be detected by peripheral amplification circuit, and then the vibration signal can be described by the amount of charge. Because of its high sensitivity, high signal-to-noise ratio, simple structure, reliable operation and light weight, the sensor is often used in engineering projects to test vibration signals. At present, the research of piezoelectric acceleration sensor mainly focuses on two directions, one is the optimization of sensor performance, the other is the development of piezoelectric materials.

Piezoelectric acceleration sensor is mainly used to monitor vibration signal to prevent machine failure. It is the most widely used acceleration sensor. Therefore, people pay more attention to its measurement accuracy, sensitivity and other performance. Some researchers have found that the measurement accuracy of the sensor can be effectively improved by selecting the appropriate damping ratio from the angle of sensor structure design; in addition, the high-frequency accuracy calibration can also be achieved by increasing the installation stiffness of the sensor.

The measurement accuracy of sensor is an important factor to evaluate the quality of sensor, and the sensitivity is also the embodiment of its measurement performance. Because of the anisotropy of piezoelectric crystal, its cutting form will affect the electrical properties of the crystal, and then affect the sensitivity of the sensor. Based on this principle, many scholars improve the sensitivity of the sensor from the perspective of improving material properties. In addition, some researchers use intelligent algorithms such as piecewise interpolation method and BP neural network to compensate the nonlinear characteristics of the output voltage sensitivity of the piezoelectric acceleration sensor to improve the sensitivity of the sensor[5]. The accuracy and sensitivity of the sensor are important characteristics of piezoelectric acceleration sensor, which means whether the vibration signal can be accurately captured in monitoring, and then affect the judgment of structural damage. Therefore, it is very important to improve the accuracy and sensitivity of the sensor. However, too high sensitivity will also affect the stability of the sensor, so the sensitivity characteristics of the sensor should be selected according to the application situation [4].

Lead zirconate titanate is the most widely used piezoelectric material in piezoelectric acceleration sensors due to its high electromechanical coupling coefficient and good temperature stability[6]. Lead zirconate titanate was modified by adding Nb, La, Sb and other trace elements to produce piezoelectric ceramics with different uses. In addition, lead zirconate titanate and polyvinylidene fluoride (PVDF), epoxy resin and other polymers can be used as composite materials to make piezoelectric ceramics not only have electrical properties, but also have the flexibility of polymer materials, so that the sensor has high sensitivity.

At present, scholars continue to study how to carry out lightweight and miniaturized packaging of sensors to reduce the mass to test vibration of small components; for sensitive component materials, the development of many high-temperature sensitive materials has broadened the temperature range of sensors [7]. How to ensure the stability of high-temperature piezoelectric properties of components and improve the service life of high-temperature piezoelectric sensors are also the problems to be solved in future research. Although piezoelectric acceleration sensor has the characteristics of low noise output, wide dynamic range and wide frequency range, its application range is limited, and it can't measure static and quasi-static vibration information. The capacitive accelerometer can be used to measure the static parameters accurately.

B. Capacitive acceleration sensor

Capacitive acceleration sensor is a kind of parametric sensor, which takes all kinds of capacitors as sensor sensitive elements and transforms external parameters into internal capacitance changes of sensors[8]. Because of its high sensitivity and accuracy, good stability, small temperature drift and low power consumption, it is widely used in many precision mechanical fields such as navigation, automotive electronics and so on.

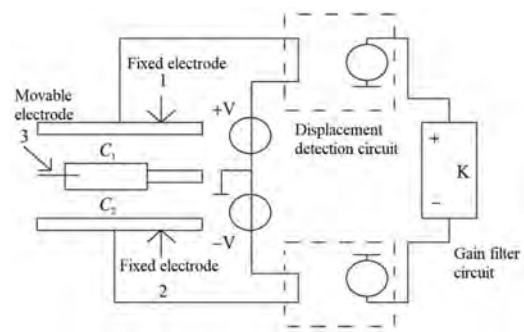

Figure 2. Basic structure of capacitive accelerometer

The development of capacitive accelerometer depends on the progress of micromachining technology. The capacitive accelerometer can realize the change from simple single axis measurement to accurate multi axis measurement, and realize the change from independent multi mass block integration to single mass block structure.

The capacitance element of capacitive sensor is easy to be affected by temperature change and electrothermal property, which leads to the decrease of measurement accuracy. Therefore, reducing the temperature coefficient of the sensor and reducing the influence of thermal deformation on capacitance is very important for high-end application of acceleration sensor. To solve this problem, many teams have made great efforts in circuit design, sensor structure optimization and so on. However, most researchers are from the acceleration sensor circuit design, sensor structure to reduce the impact of temperature on the accuracy of the sensor, little research on the parasitic capacitance of capacitive accelerometer. In the sensor detection circuit, the existence of parasitic capacitance makes the charge between the detection capacitors unable to transfer completely to the feedback capacitor, which leads to the decrease of the output voltage of the charge amplifier circuit, thus reducing the amplitude of the output voltage[9], And the parasitic capacitance will change with the change of temperature. The parasitic capacitance change caused by temperature change has a great influence on the bias capacitance value, which will affect the performance of capacitive acceleration sensor. When analyzing the influence of temperature on the measurement performance of acceleration sensor, considering the existence of parasitic capacitance and temperature compensation will effectively increase the measurement accuracy of the sensor when the temperature changes.

With the continuous development of materials and technology, the performance of capacitive acceleration sensor has been continuously improved and optimized, and gradually developed into a high sensitivity, high precision micro vibration measurement sensor. It is not only applied in industrial dynamic detection, but also has potential applications in low voltage and some special measurement. Piezoelectric acceleration sensor and capacitive acceleration sensor can complement each other in application function. The dynamic and static characteristics of the measurement system composed of the two sensors can provide reliable vibration information for structural health monitoring.

III. STRAIN SENSOR

In the monitoring method, the measurement of dynamic strain can improve the sensitivity of structural damage [10], In particular, the strain sensor has higher sensitivity than other sensors when testing the structural properties under microcracks and disconnectors[11]. Resistance strain sensor and fiber Bragg grating strain sensor are often used in structural condition monitoring. The resistance type strain sensor is simple in structure and easy to be measured. Its principle is that the strain of the object under test changes the resistance of the sensitive gate in the sensor, which affects the output voltage or current of the bridge. The fiber Bragg grating sensor uses the photosensitive characteristics of the fiber to realize the external strain measurement by modulating the light wavelength. Because the optical wavelength in the fiber is generally stable, it has a strong anti-interference ability [12].

A. Resistance strain sensor

Resistance strain sensor is widely used in vibration measurement. The earliest developed resistance strain sensor is adhesive metal resistance strain gauge. The development of semiconductor materials with piezoresistive effect provides more choices for the sensitive gate materials of semiconductor strain gauges, which promotes the improvement of the performance of resistance strain sensors. However, the metal foil and semiconductor plate can't adapt to large deformation, and can't achieve good synergistic deformation effect with the specimen surface. Although many strain gauges made of composite materials and polymers with piezoresistive effect have been introduced into strain sensors, due to the limitations of sensor manufacturing methods, the sensor package is still rigid, which makes the application of strain sensors not flexible enough[13], The cost is also high, which limits its development space and use environment.

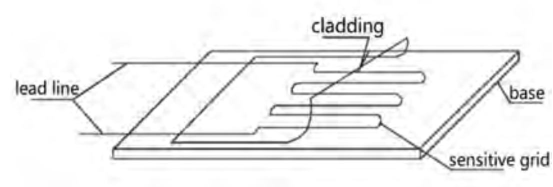

Figure 3. Structure of strain gauge

Because of its high sensitivity to structural strain sensing, strain gauges are widely used in structural dynamic measurement. With the development of monitoring technology, strain gauge can be used to monitor dynamic parameters in real time, evaluate the quality of structure and predict its life. In addition, strain sensors are also used in the monitoring of civil structures such as buildings, but uncontrollable factors such as temperature will affect the measurement results. The resistance of the sensitive gate material in the resistance strain gauge is affected not only by the stress and strain, but also by the temperature. Therefore, accurately distinguishing the influence of temperature and strain on resistance will greatly improve the measurement accuracy of strain sensor. The simplest method is to introduce a reference sensor to measure temperature in the measurement system. In fact, the temperature compensation method of strain gauge is limited, which can only rely on material properties or measurement layout for multi strain gauge comparative measurement. This method can make up part of the measurement error caused by temperature, but still can't completely eliminate its influence.

Resistance strain sensors are widely used in aerospace, medical, civil construction, industrial equipment and other fields. The sensor has the advantages of simple operation, high sensitivity and good frequency response characteristics. However, because the sensitive gate materials are mostly organic materials which are easy to be corroded, and the sensor circuit is vulnerable to electromagnetic interference, its measurement environment is relatively limited. The working principle of fiber Bragg grating strain sensor is to change the wavelength of grating light caused by strain. The fiber is composed of dielectric, and the frequency of electromagnetic radiation is much lower than that of light. Therefore, fiber Bragg grating strain sensor has the characteristics of anti electromagnetic interference and can be used in harsh environment.

B. *Fiber Bragg grating strain sensor*

Figure 4. Fiber Bragg grating strain sensor

Compared with the previous electrical sensors, FBG strain sensors have the advantages of anti electromagnetic interference, high temperature resistance, corrosion resistance and long-distance transmission of signals. Since its birth, FBG strain sensor has become an important kind of fiber sensor. With the development of fiber Bragg grating (FBG), fiber Bragg grating sensor (FBG) has become the most widely used fiber sensor. FBG can directly monitor the change of strain and temperature through the drift of its central wavelength.

Fiber Bragg grating (FBG) strain sensors can be installed on the surface of components or embedded in the structure to realize the distributed measurement of the whole structure[14]. Although the wavelength drift of FBG is linear with the change of strain and temperature, the sensitivity of FBG strain sensor to temperature changes at low temperature. Some researchers have pointed out that with the decrease of temperature, the thermal sensitivity of FBG strain gauge changes nonlinearly, and can maintain good stability and reliability in low temperature environment.

Fiber Bragg grating strain sensor overcomes the problems of electrical sensor, such as easy to be affected by electromagnetic interference and difficult to use in harsh environment. It provides an opportunity for equipment condition monitoring in complex environment, and plays an important role in condition monitoring[15]. The basic parameters of fiber Bragg grating strain sensor are strain and temperature. In the process of measurement, cross sensitivity is inevitable. Therefore, it is the key to solve the problem effectively.

Acceleration sensor and strain sensor are the two most commonly used sensors to detect vibration signal in structural health detection. They can measure acceleration, displacement, velocity, strain and other vibration parameters, and provide reliable vibration data for structural condition monitoring. However, most of the traditional vibration sensors are contact measurement, some even the structure surface will be damaged while measuring. Therefore, in some special applications, acoustic emission sensor, infrared vibration meter and digital image correlation technology can be used for nondestructive testing of structures. However, the cost of these instruments is high, and some of them are time-consuming. At present, people's research on vibration sensor has gradually turned to digital and intelligent direction, in which the new sensor circuit structure used in non-contact monitoring and self powered monitoring has been simplified, the production cost has also been greatly reduced, and low-cost nondestructive testing has been realized.

IV. NEW TYPES OF VIBRATION SENSOR

Acceleration sensors and strain sensors are commonly used vibration sensors. In addition, researchers have developed self powered vibration sensors, radio frequency identification vibration sensors, and low-cost, contactless and intelligent vibration sensors with the help of high integration manufacturing technology and advanced emerging technologies.

Friction can produce energy. If the energy is collected and reused effectively, self powered technology can be realized[16]. Although it is more simple to make sensor circuit by using self powered principle, the output of self powered vibration sensor is unstable due to the random distribution of charge and uncontrollable factors such as environment, which needs to be improved continuously.

Radio frequency identification(RFID) is a communication technology based on backscattering theory, which has the characteristics of wireless, passive and low cost. In recent years, with the rapid development of radio frequency identification (RFID), many scholars have tried to introduce RFID chips into vibration sensors to realize passive, wireless and low-cost non-contact measurement [17]. They also explored the factors affecting the measurement accuracy of sensors from various angles. The performance of RFID vibration sensors has gradually reached the expected goal, which can't only detect metal junctions It can also monitor the growth of cracks, provide long-distance communication for low-cost users, and realize remote non-contact measurement[18].

Compared with the traditional vibration sensor, the new sensor has the characteristics of miniaturization, digitization and intelligence, which makes up for the defects of traditional vibration sensor, such as inflexible use and non-contact measurement. It also simplifies the operation.

V. CONCLUSION AND PROSPECT

In this paper, the development status of piezoelectric acceleration sensor, capacitive acceleration sensor, resistance strain sensor, fiber Bragg grating strain sensor, and the development of new vibration sensors with new technology, such as self powered vibration sensor and radio frequency identification vibration sensor, are summarized.

In the era of intelligent information, the monitoring of vibration signals of large-scale equipment and mechanical structures is becoming more and more complex, which promotes the development of vibration sensors in the direction of miniaturization, digitization, intellectualization and flexibility.

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