2024 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)
July 15-19, 2024. Boston, MA, USA

SAW-based Gasket Sensor Design for Bolt Loosening Detection

Licheng Zhang [1,2] , Feida Cai [3,*], Junquan Shen[2], Chin-Yin Chen [2,*], Xingjie Zhang[4], Hakubun Nagaya[4], Xiangjun Tang[4] , Yingang Guo[4] and Junnan Shen[5]

Abstract—**This paper proposes a gasket-type bolt loosening detection sensor based on a surface acoustic wave (SAW) strain-sensitive unit. In order to improve the performance of the sensor, experiments, and simulations analyzed the influence of gel thickness on the strain-sensitive element of the SAW unit. Secondly, the influence of the thickness change of the secondary packaging structure on the packaging structure is studied, and the influence of friction change on the performance of the gasket sensor under different working conditions is discussed through experiments. Experimental and simulation results show that the gasket sensor proposed in this paper can effectively and accurately detect bolt looseness in real-time.**

Keywords—Gasket Sensor, Bolt Loosening Detection, Surface Acoustic Wave

I. Introduction

Bolt connection is the most common and indispensable method for all kinds of equipment. Bolt connection is low cost, easy to dismantle, and widely used in aerospace, wind power, bridges, automotive, etc. [1]. However, bolted connections are prone to loosening under complex working conditions with vibration or impact, which can cause the equipment to fail to operate normally. The equipment can be damaged in severe cases, resulting in significant economic losses and casualties. Therefore, the safety of bolted fasteners must be ensured, and the health diagnosis of the bolted connection is very necessary [2]. Existing methods for bolt health diagnosis include the more traditional methods, such as the knocking method, by knocking the bolt connection part from the sound is abnormal to identify whether the bolt has loosened, or the scribing method, through the observation of the drawing of the two-marking line whether to judge the bolt loosening. The above methods have low recognition accuracy and low efficiency and require manual operation, which has certain risks [3].

[1]Licheng Zhang is with School of Mechanical and Electrical Engineering, Jiangxi University of science and technology, Ganzhou 314000, China (e-mail: zhanglicheng@nimte.ac.cn)

[2]Licheng Zhang, Chin-Yin Chen and Junquan Shen are with Zhejiang Key Laboratory of Robotics and Intelligent Manufacturing Equipment Technology, Ningbo Institute of Materials Technology and Engineering, Ningbo 315201, China. (e-mail: chenchinyin, shenqunjuan@nimte.ac.cn)

[3]Feida Cai is with Institute of Acoustics, Chinese Academy of Sciences, Beijing 100190, China (e-mail: caifeida@mail.ioa.ac.cn)

[4]Xingjie Zhang, Hakubun Nagaya, Xiangjun Tang and Yingang Guo are with Ningbo Minda Automotive Technology Co., Ningbo 315800,China.

[5]Junnan Shen is with TXC (Ningbo) Corporation, Ningbo 315800, China

*Corresponding author: Feida Cai, Chin-Yin Chen (caifeida@mail.ioa.ac.cn, chenchinyin@nimte.ac.cn).

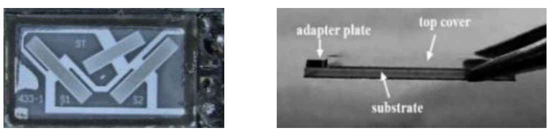
Numerous researchers have investigated detection sensors based on piezoresistive, acoustic wave and other methods for dynamic monitoring of bolted connections. Some scholars have designed strain gauge based for gaskets [4] or piezoresistive gasket sensors [5]. Based on the strain gage gasket sensor stiffness can measure a large force, but the thickness of the larger is not easy to install, and for the wired sensor, cannot be used on a large scale, the practicality of the poor; piezoresistive gasket sensor thickness is thinner, but the piezoresistive material itself is noisy, easy to be affected by the temperature, the use of a limited range. There are also scholars for the bolt itself to design the sensor, the strain gauge will be pasted on the surface of the screw [6] or embedded inside the screw [7]. However, these sensors can damage the structure of the bolt itself, which reduces the strength of the bolt and prevents it from performing its original function of connection. Therefore, there is a need for a sensor that can be made as thin as possible without damaging the structure of the bolt itself, without causing too much impact on the installation, and at the same time can realize more sensitive and stable detection.

Most of the existing bolt inspection methods are based on the axial force of the bolt [8]. The tightening torque of the bolt mainly consists of the bolt axial force [9], bolt end face friction, and thread friction. However, existing studies have shown that only 10% of the torque applied to the bolt during tightening is converted into axial force, and 50% is converted into end face friction. Unlike other methods, the SAW force-sensitive unit used in this paper can detect the change of shear force. The gasket sensor designed based on surface acoustic wave (SAW) detects the change of shear force converted from the friction on the end face of the bolt and the gasket, which is more sensitive than the sensor that detects the axial force.

Because of the problems existing in the above detection methods, this paper proposes a bolt health detection sensor based on SAW force sensitive unit, SAW sensitive unit can be realized without destroying the original structure of the bolt under the premise of detection, SAW is a high-frequency measurement element, the use of low energy, can realize the wireless passive detection, and the SAW for the strain is more sensitive and stable, SAW sensitive unit itself small size and thin thickness can be combined into the standard parts gasket as a gasket sensor to achieve a smaller thickness and volume sensor under the health detection of the bolt. At the same time, this paper from the package on the development of the boundary conditions for the SAW sensitive unit of strain sensitivity of the research and discussion, simulation and experiments to verify the feasibility of the proposed sensor.

II. SAW Wafer Structure and Package Structure

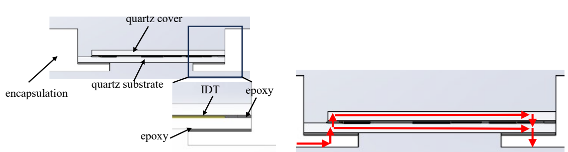
The SAW sensitive unit used in this paper is SAW chip with aluminum electrodes in an all-crystal package [10]. The structure of the chip as shown in Fig 1, the fully crystalline SAW chip consists of a quartz substrate, three SAW resonators, and a quartz cover plate, of which the SAW resonators are made of interdigital transducers (IDTs) and reflector grids. The working principle of SAW is that the antenna receives the external high-frequency sinusoidal signals, which are loaded on the IDT, which converts the electromagnetic signals into acoustic surface waves and propagates along the substrate, which are reflected and strengthened by the reflector grids, and finally return to the IDT, which then converts the SAW signal with substrate information into electromagnetic waves and returns to the receiving end through the antenna [11]. Therefore, SAW can realize wireless passive detection and can be used as a detection sensor in a variety of complex workplaces due to its stable operating characteristics.



(a) (b)

Fig 1 (a) 433MHz SAW unit;(b) Saw unit composition

SAW sensitive unit as a detection sensor, usually need to be milled in the package body on a test plane, and then through the gel bonded to the milled plane, the type of adhesive and the thickness of the gel, the gel internal bubbles and other factors on the characteristics of the sensitive unit will also have a greater impact. In this paper, the colloid material used for LOCTITE® EA 9514 Epoxy, the type of Epoxy adhesive with good shear strength and plasticity, in the use of the process needs to be baked Epoxy, at 175 ℃ to keep more than 30min, the colloid within the organic solvents completely evaporated until the solidification of the colloid in the above temperatures and time baked colloid in the baking process of the colloid mechanical properties Optimal, high shear strength. Thermal expansion and contraction will cause deformation of the connection state of the force-sensitive unit, and due to the high shear strength of Epoxy, too thick a layer of gel will produce a large contraction stress during curing, so it is necessary to control the thickness of the gel in order to minimize the effect of changes in the boundary conditions on the sensitivity of the sensor.



(a) (b)

Fig 2 (a) SAW wafer package structure;(b) SAW encapsulated force transmission direction

The SAW wafers used in this paper were encapsulated once during production, with the IDT layer encapsulated in two quartz wafers of uniform thickness by means of Epoxy. The SAW wafers are used as the force-sensitive units of the sensors, which need to be bonded to the sensor structure using a general-purpose adhesive, the encapsulation structure is as follows Fig 2(a).And Fig 2(b) shows the force transfer diagram of the wafer, the encapsulation body is subjected to the force from the outside world, the force is transferred to the quartz substrate through the Epoxy between the encapsulation body and the quartz substrate, and then transferred to the top cover through the Epoxy adhesive between the quartz substrate and the top cover. Due to the loss of force due to the characteristics of the gel, the force transferred to the quartz cover will be much smaller than the external force on the package, from the SAW stiffness estimation experimental diagrams Fig 3 (a), it can be seen that the damage of the SAW after the force is applied only occurs on the lower quartz substrate and IDT, and the quartz cover is not damaged. Fig 3(b) shows half of the lower substrate and IDT bonded underneath the whole upper cover. Fig 3 (c) shows the remaining half of the lower substrate and IDT. Therefore, when the SAW wafer is loaded, most of the load is applied to the lower substrate, and due to the presence of the Epoxy between the lower substrate and the upper cover, which makes the force transferred to the upper cover smaller, it can be concluded that the Epoxy will limit the force transfer.

(a) (b) (c)

Fig 3 (a) SAW lower fragmentation figure; (b) SAW upper cover adhesive aart lower substrate;(c) SAW section lower substrate

From the quartz cover plate is not damaged can be inferred that the quartz substrate carries most of the force on the SAW wafer; the quartz cover plate is not subjected to a huge load, but the quartz cover plate will limit the deformation of the quartz substrate and the IDT, different thicknesses of the quartz cover plate of the quartz substrate deformation limitations will also be different, the SAW wafer torsion damage experiments, the experimental data as shown in Fig 4, the red waveform is the frequency variation curve of the SAW unit without top cover, the black waveform is the frequency variation curve of the SAW unit with top cover . The force sensitivity coefficient of the quartz wafer with a cover is 8930 Hz/Nm and that of the quartz wafer without a cover is 12614.3 Hz/N.m. This result reflects that the force sensitivity coefficient of the wafer without a cover is much larger than that of the wafer with a cover and that the cover limits the SAW sensors' performance to a certain extent.

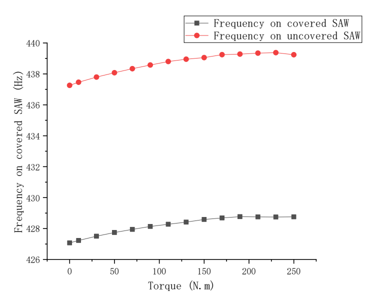


Fig 4 Comparison of frequency changes between covered SAW and SAW

However, IDTs are more vulnerable to damage and failure, and quartz top cover is needed to protect IDTs. The top cover is an indispensable part of SAW wafers, but since the top cover restricts the deformation of the substrate, experiments and discussions are needed to investigate the effect of the thickness of the quartz top cover on the strain of the wafers, but in this paper, due to the limitation of the conditions, experimental studies were not carried out to investigate the effect of the top cover, but discussions are needed to investigate the effect of the other boundary conditions, in order to verify the effect of changing boundary conditions on the strain sensitivity of SAW wafers. Therefore, according to the results of the above discussion, it is necessary to discuss the colloid and other boundary conditions to verify the effect of colloid thickness and other factors on the wafer force and sensor sensitivity, and at the same time, it is necessary to reasonably design the structure of the encapsulation body, so as to maximize the load transferred to the sensitive unit.

III. Effect of Package Structure Variation on SAW Sensitivity

A. *Influence of encapsulating colloids*

This section focuses on the effect of boundary conditions on SAW strain sensitivity in the second encapsulation. In this section, the influence of the change of boundary conditions on the SAW sensitivity is reflected by changing the thickness of the Epoxy. Firstly, the colloidal model of the encapsulant is established, and then the preliminary verification is carried out by finite element analysis (FEA). The mechanical properties of the simulated materials are as follows: TABLE I. The simulation constrains the bottom surface of the gasket and the base as a friction connection. According to the GB97.1-85 standard, the tightening torque applied to the M10 gasket when the bolt is tightened is 30 N.m. According to the torque application formula, the axial force can be calculated to be 11 kN, so a torque of 30 Nm and a force of 11 kN is applied to the contact surface of the bolt and the gasket, and the load applied is shown in Fig 5 .

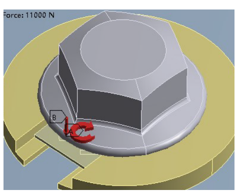


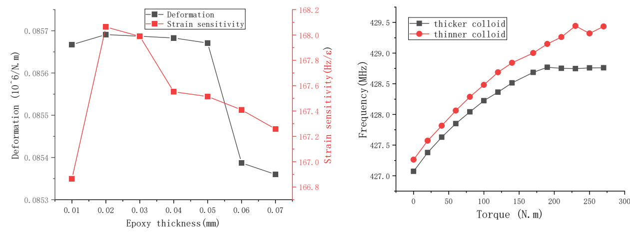
Fig 5 Load application

TABLE I Simulation of me chanical properties of materials

Material	Poisson's ratio	Young's modulus (GPa)	Densities (kg/m)3
Epoxy	0.38	0.129	1300
Quartz	0.16	73.1	2650

The results are shown in Fig 6(a) , black curve shows the deformation of the SAW wafer and the red curve shows the strain sensitivity of the SAW when subjected to torque .The colloid thickness is between 0.01mm-0.02mm, the deformation and strain sensitivity of the SAW force-sensitive unit increases with the thickness of the colloid, but after the colloid thickness is greater than 0.02mm, the deformation and strain sensitivity of the SAW force-sensitive unit decreases with the increase of the colloid thickness.

Thus, thicker colloids reduce the force-sensitive unit sensitivity, presumably because the creep effect of thicker colloids allows less force to be transferred from the encapsulant to the SAW force-sensitive unit, and because thicker colloids may produce more air bubbles during curing. Air bubbles can cause the bonded force-sensitive unit to be displaced. The increase in the thickness of the adhesive will shift the wafer position away from the location where the strain is most concentrated, resulting in a decrease in the strain applied to the wafer.



(a) (b)

Fig 6 (a) Effect of colloid thickness variation on wafer deformation and strain sensitivity;(b) Comparison of SAW frequency changes for thinner and thicker colloids

Because the adhesive needs to be manually applied to the test axis plane, it is not easy to control the amount of adhesive and thickness precisely. Zhou's experiment [12] also mentions that the air bubbles in the adhesive will cause the wafer to be displaced, which will affect the sensing characteristics. Assuming that the strain sensitivity of the sensitive units used in the experiments is the same, during the experiments, the sensitive units are pasted after uniformly applying Epoxy on the plane of the test axes without additional processing of the adhesive; a smaller amount of adhesive is applied on the other set of test axes, and at the same time, more significant pressure is exerted on the top of the wafers during the baking process, to make the thickness of the adhesive thinner and to exclude the bubbles as much as possible, which may reduce the force transmission performance. The optimum mounting position of the wafer relative to the carrier may be shifted, reducing the strain performance of the transducer.

As can be seen from Figure 6(b) of the experimental results, the red curve is the experimental result of colloidal treatment, and the black curve is the experimental result of no colloidal treatment. From the results, it can be seen that the frequency coefficient of the sensitive unit force of colloidal adhesion is higher (9990 Hz/Nm) after treatment, and the frequency coefficient of the unit force of the treatment without colloidal adhesion sensitive unit force is 8930 Hz/Nm. The force-frequency coefficient of the adhesive is increased by about 10.6% compared to the force-frequency coefficient treatment without the adhesive. In addition, it can be seen from the figure that the gel thickness of the force-sensitive unit of about 0.02 mm in the nonlinear region is late so that it can be measured in a broader range, and the strain response is faster and more sensitive.

As mentioned above, simulation and experimental results can verify that the strain sensitivity of the force-sensitive unit is somewhat improved when the thickness of the colloid is thinner and the internal gas content is less. The possible reason for this is that the thinner colloid has a better force transfer performance, the colloid produces less creep, and the force of the carrier is transferred to more parts of the wafer. Therefore, in the later stages of the actual application of the sensor installation, after the completion of the adhesive in the baking should be certain treatment of the colloid, can make the sensor sensitivity is higher, the measurement range is wider.

B. Structure thickness effect

Since quartz is a susceptible material, a slight dust can cause frequency to drift. Therefore, to guarantee the sensor's performance and protect the quartz wafer, a quartz force sensitive unit package is required. However, the packaging structure can alter the boundary conditions of the quartz wafer, which can affect the sensitivity of the sensor strain. According to the stiffness equivalence principle [12], the equivalence relationship between the stiffness and the force-frequency coefficient of the quartz wafer and the stiffness of the package and the force-frequency coefficient are established, as shown in Eq. (1).

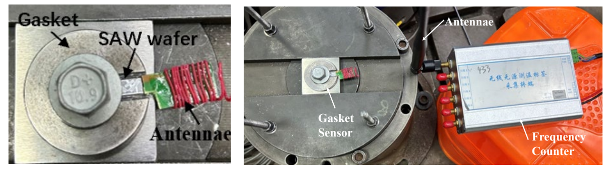
$$\delta_r \times S_r = \delta_m \times S_m \quad (1)$$

Where: δ_r is the stiffness of the quartz wafer, S_r is the force-frequency coefficient of the quartz wafer, δ_m is the stiffness of the encapsulation body, and S_m is the force-frequency coefficient of the encapsulation body, which needs to satisfy the condition $\delta_m \geq \delta_s$. This principle can be equated to the force frequency coefficient of the sensitive unit by the stiffness of the encapsulation body, because the product of the stiffness of the quartz and encapsulation body and the force frequency coefficient is equal, that is, when the stiffness of the encapsulation body decreases, the force frequency coefficient of the quartz wafer will increase, so when designing the structure of the encapsulation body, it is possible to appropriately reduce the structural stiffness of the encapsulation body to enhance the sensitivity of the force-sensitive unit, and this paper also designs the structure of the sensor according to this principle.

Since the SAW force-sensitive unit can detect shear force, it is possible to make the gasket detection sensor thin, mainly detecting the shear force converted from the friction torque of the bolt head acting on the gasket. At the same time, due to the high stiffness characteristics of the SAW chip, the SAW chip as part of the gasket sensor structure, as a structural load-bearing element, the gasket structure as a secondary encapsulation of the chip, maximize the strain of the sensitive unit, in order to improve the sensitivity of the chip strain at the same time, but also reduces the encapsulation of the body structure rigidity, so the design of the sensor from the structure of the thickness of the thinner, and the thickness of the standard parts of the gasket. The thickness of the resulting sensor is thin and comparable to that of a standard gasket. SAW paste in the processed gasket baking needs to be done on the adhesive pressure treatment, as far as possible to discharge the adhesive internal air bubbles and reduce the thickness of the adhesive, and finally in the SAW wafer electrode soldering antenna and antenna around the PCB board fixed, in kind, such as Fig.7 (a) shown.

Mount the fabricated gasket sensor on the bolt torque tester. Fig. 7 (b) shown, the instrument can detect the axial force and friction of the bolt, respectively, in the actual experiment, first apply 30Nm to the bolt until completely tightened, completely tightened and held for a period of time, and then completely loosened the bolt to stop the test.

From the figure, the change trend of the sensor frequency is closer to that of the axial force and torque, and in the torque application stage, the slope of the frequency change is steeper, and the frequency signal changes at the moment of torque application, when the torque application is stopped, the frequency signal is relatively stable and approximately straight, when the load is unloaded, the frequency signal is delayed, the response speed is still available, and the sensor sensitivity is general when the load is unloaded,. Therefore, the following is done to improve this phenomenon.



(a) (b)

Fig 7 (a) Sensor's structure & Antennas; (b) Experimental equipment and connectivity

In order to further verify the influence of the shim structure, i.e., the secondary encapsulation structure, on the sensitivity of the SAW strain unit, the thickness of the shim and the width of the gouge for mounting the force-sensitive unit are discussed. First of all, we discuss the effect of shim thickness on the strain cell, according to the M10 bolt shim thickness of 2 mm, the simulation is set up in the range of 2mm-3mm ten groups of different thickness of the shim, apply the same boundary conditions, the simulation results are as follows Fig.8. In this figure, the red waveform shows the deformation of the SAW wafer, and the black waveform shows the strain received by the SAW wafer at different shim thicknesses.

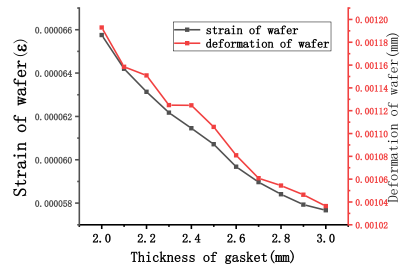


Fig 8 Simulation of the effect of shim thickness on wafer deformation and strain

From the simulation results, it can be seen that as the thickness of the gasket structure becomes thicker, the strain on the wafer gradually decreases, and the strain sensitivity of the sensor decreases, but as the deformation of the wafer after the force is applied also decreases, the sensitive unit in the thin gasket is closer to the bolt surface. Because of the limited experimental conditions, only the loading and unloading experiments of 2 mm and 3 mm shims were done, as shown in Fig.11,the frequency change and force frequency coefficient of the 2 mm gasket are close to twice that of the 3mm gasket under the same load, but according to the simulation, the maximum shear stress on the wafer of the 2 mm gasket is about 48 MPa, but the maximum shear strength of the quartz is 70 MPa, which will easily cause the wafer to be broken during the process of load application, therefore, in the subsequent experiments, all the experiments are conducted with the 3mm gasket. gaskets were used in the subsequent experiments.

Under the same load conditions, the SAW strain cell in a thinner gasket is subjected to more strain and is more likely to break. Therefore, reduce the thickness of the gasket structure will improve the sensitivity of the sensor, but at the same time will make the wafer subjected to greater strain, but also because in the bolt tightening will produce a large torque and axial force, which will lead to the wafer cracking caused by the failure of the sensor. Therefore, it is not advisable to design the thickness of the gasket sensor too thin in order to improve the safety and measuring range of the sensor.

In addition to the impact of the thickness of the gasket structure on the strain sensitivity of the SAW wafer, the width of the gasket sensor slots will also have a greater impact on the strain sensitivity of the wafer, and at the same time, changes in the width of the gasket slots will also have an impact on the overall stiffness of the sensor, in this paper the design of the gasket sensors, there are two different slotting widths, and there is a large difference in the two cases of the size of the gasket slots, respectively, 6mm and 10mm, one is to place the gasket horizontally and the other is to place the SAW wafer vertically, the placement is as follows Fig.9 (a) and (b), and the physical object is shown in Fig.9 (c). The simulation and experimental comparisons of these two cases were performed to verify the effect of the shim slot size on the wafer sensitivity, wafer stiffness and overall stiffness. The simulation results are shown in Table II.

(a) (b) (c)

Fig 9 (a) Schematic of 6mm slotted spacer sensor;(b) Schematic of 10mm slotted spacer sensor;(c) 10mm slotted gasket with antenna

TABLE II EFFECT OF DIFFERENT SLOTTING WIDTHS ON WAFERS AND SHIMS

Slot width(mm)	**Wafer strain(me)**	**Wafer deformation(mm)**	**Gasket deformation(mm)**
10	47.42	3.91*10^-4	0.0037864
6	143.94	2.88*10^-3	0.0027867

From the simulation results, under the condition of the same thickness, the overall deformation generated by the gasket sensor with larger opening is larger. However, the strain transferred to the wafer is less, and the deformation of the wafer is also smaller, and most of the torque and axial force are applied to the gasket structure, while the part transferred to the wafer is smaller. And the strain sensitivity of comparing the large and small opening shim in loading and unloading phases is verified experimentally. Compared with the small slotted shims, the frequency of the large slotted shims is more consistent with the trend of the bolt axial force and torque, and the strain sensitivity of the large slotted shims is higher.

The frequency variation curve of the gasket sensor is compared with the bolt torque application curve as shown in Fig10. In this figure, the orange dashed line indicates the frequency change of the sensor; the red curve shows the variation of the thread torque; the blue curve shows the total applied torque; the gray curve indicates the axial force. In the loading stage, the strain sensitivities of the large slotted gasket and small slotted gasket are 1233 Hz/Nm and 646 Hz/Nm in the loading stage, and 946 Hz/Nm and 902 Hz/Nm in the unloading stage, respectively. The experimental results are consistent with the simulation results, and the large slotted gasket has a higher strain sensitivity in the case of small strains in the actual experiments, the probability of damage is smaller for small strains, and the deformation of large slotted gasket does not increase much compared with small slotted gasket, which is more practical. The probability of damage is also smaller, and the deformation of the large slotted shim does not increase much compared with that of the small slotted shim, so it is more practical. In the torque unloading stage, when the torque produces changes in the frequency signal also begins to change, almost no hysteresis, as the reliability and practicality of the sensor compared to the small openings of the gasket is better, and can be more real-time detection of the changes in the connection of connecting parts connection.

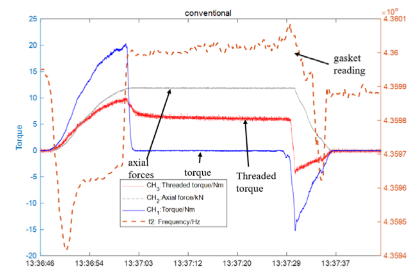
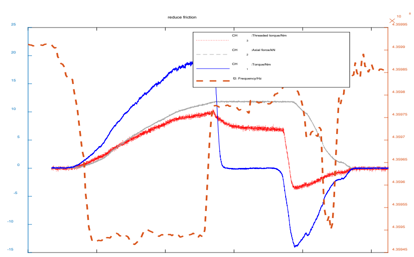


Fig 10 Comparison of Torque Detection Results and Frequency Signals for Large Opening Shims

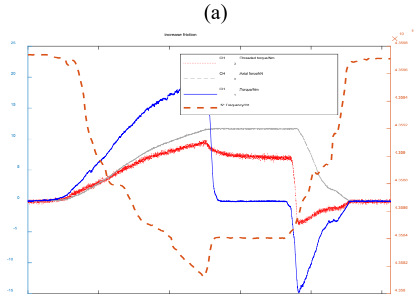
C. Various working conditions

In order to verify whether the designed gasket sensor is more sensitive to the friction of the end face, different working conditions of the gasket sensor are discussed, and this paper verifies the effect of the end face friction by changing the friction coefficient of the contact surface between the bottom surface of the gasket and the workpiece. The first working condition is to reduce the friction at the bottom of the gasket by applying oil on the bottom of the gasket; the second working condition is to glue the bottom surface of the gasket to the upper surface of the workpiece with the purpose of increasing the friction between the gasket and the workpiece as a means of comparing the effect of friction on the bottom surface of the gasket.

The experimental results shown in Fig.11 (a) that the sensitive cell with reduced bottom friction has a minor frequency change of 28579 Hz under the same torque and axial force applied, and the SAW sensitive cell is subjected to less strain under such boundary conditions; Fig.11 (b) For the case of increasing bottom friction, the frequency variation of the sensitive unit is more significant, 156310 Hz, and the strain on the sensitive unit is larger under the condition of increasing bottom friction; Fig.10 for the conventional installation, conventional installation of the working conditions, the frequency change amount is 58468 Hz. This can be proved because the bottom surface of the friction coefficient of the change for the SAW gasket strain sensor is more sensitivity; the preliminary inference is that because the bottom surface of the gasket and the contact area of the workpiece is larger compared with the upper surface of the contact area of the gasket, the bottom surface of the gasket to withstand the bolt face friction is larger, therefore, when changing the bottom friction of the gasket and the workpiece contact area is larger, the gasket bottom surface to bear the bolt face friction. Therefore, when changing the coefficient of friction of the bottom surface of the gasket, the friction force transmitted to the gasket will produce a large change, and the bolt force change itself is nonlinear; the frequency of the strain transducer will produce large and irregular changes. Bottom surface friction is small; the sensor only in the bolt application moment and unloading moment has a short change; in the force application stage, sensor frequency remains static, which may be due to the friction coefficient of the reduction caused by the bottom surface friction reduction, the friction force applied to the sensor is greatly reduced, the sensor is insensitive to very small changes, so only in the change of the moment of the larger fluctuations in the frequency; and bottom surface friction coefficient is large, the When the bottom surface friction coefficient is large, the end surface friction force is almost all applied to the bottom surface of the bolt sensor, the sensor is more sensitive to the change of friction force. Therefore, it can be seen in the figure in the torque application stage that the rate of change of the frequency is slow, the amplitude is larger, and the torque unloading stage also has a larger change of the frequency. This proves that the SAW bolt gasket detection sensor designed in this paper can detect changes in the friction of the bolt end face and can quickly reflect the frequency at the moment of friction change. The trend of the frequency change is consistent with the trend of the bolt torque application, thus realizing the detection of the healthy connection of the bolt.



(a)



(b)

Fig 11 (a) reduced friction on the bottom surface of the gasket (b) increase friction on the bottom surface of the gasket

IV. CONCLUSION

In this paper, a gasket bolt loosening detection sensor with SAW as the strain-sensitive element is proposed, and the influence of boundary conditions changes on the strain sensitivity of the SAW-sensitive element is discussed. Through simulation and experiment, the relationship between the process parameters and the sensor performance of the SAW secondary packaging process is verified, and the force sensitivity coefficient can reach 9990 Hz/Nm after the optimization of the process parameters, which is 10.6% higher than that of the untreated sensitive unit. In addition, this study further studied the influence of gasket thickness and notch width on the sensitivity of the SAW force-sensitive unit; from the experimental results, it can be seen that the thickness of the gasket thickens, the strain of the force-sensitive unit gradually decreases, and the overall stiffness of the gasket sensor increases, at the same time, the size of the gasket groove will also have a more significant impact on the sensitivity and stiffness, although the larger groove reduces the stiffness of the structure, the strain of the force-sensitive unit is smaller than that of the small groove gasket, and the strain sensitivity of the gasket is higher, which can reach 1233Hz/ Nm, which is 190% higher than the gasket with a smaller opening.

Finally, the performance of the gasket sensor is verified by different bolting forms, and the measured value of the gasket sensor can be equivalent to the torque of the bolt under the condition of a large contact area, which is used to detect whether the bolt is loose.

ACKNOWLEDGEMENT

This paper was supported by the Ningbo Science and Technology Innovation 2025 Major Project (2022Z067), the Key R&D Program of Ningbo (2023Z012).

REFERENCES

[1] Z. Yuan. Research on the loosening detection of thin-plate connection bolts based on electromechanical impedance[D]. Dalian University of Technology,2022(02). (In Chinese)

[2] K. Xing, Q.H. Liu, C.T. Tang , Z.Wang, Z.Y. Geng, X. Yi A preload measurement method of bolt group connection based on gasket type force sensor. Aviation Manufacturing Technology,2015 (16):90-95. (In Chinese)

[3] C.C. Song, L.Y. Xie, S.T.Xue. Experimental research on bolt loosening monitoring based on piezoelectric impedance technology. Highway Transportation Science and Technology,2016,33(04):113-119. (In Chinese)

[4] T. Schotzko, W. Lang ,Embedded Strain Gauges for Condition Monitoring of Silicone Gaskets. Sensors. 2014; 14(7):12387-12398. https://doi.org/10.3390/s140712387

[5] X. Liu. Research on a bolt loosening monitoring device and its identification method based on piezoresistive sensing effect . Lanzhou University of Science and Technology,2021(01).(In Chinese)

[6] Y. Liu, S.X. Li, J.N. Cai, Q.X. Zhang. A new method for wireless measurement of tensile force and pressure on bolted parts. Electromechanical Engineering,2014,31(07):860-864. (In Chinese)

[7] Z.W. Zhang, J.Q. Wang, X. F. Shi, K.L. Liu & Q.N. Zhang. Research and application of implanted strain gauge type intelligent bolt preload measurement system. Quality and Reliability,2020, No.207(03):31-34. (In Chinese)

[8] P. C. B. sLuyt, N. J. Theron, and F. Pietra. "Non-linear finite element modelling and analysis of the effect of gasket creep-relaxation on circular bolted flange connections." International Journal of Pressure Vessels and Piping 150 (2017): 52-61.

[9] M. B.Karamiş, , and S. Burhan . "Analysis of the friction behaviour of bolted joints." Wear 166.1 (1993): 73-83.

[10] P.X. Li, "Thesis: Research on Acoustic Surface Wave Strain Sensor Based on All-Crystal Package," M.S. thesis, University of Chinese Academy of Sciences., Sichuan, China, 2020.(In Chinese)

[11] C. Fu, K. Lee, S. S. Yang, & W. Wang. A stable and highly sensitive strain sensor based on a surface acoustic wave oscillator. Sensors and Actuators A: Physical, (2014),:218, 80-87.

[12] Y. Zhou , C. Y. Chen, L.C. Zhang , J. Chen, Q. Zhou, M. C. Chao, & Y. Wang, "Research on Force-Frequency Coefficient of Square Quartz Crystal With Encapsulation Body," in IEEE Sensors Journal, vol. 23, no. 12, pp. 13469-13477, 15 June 15, 2023, doi: 10.1109/JSEN.2023.3268074.