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Bolt loosening detection method based on double-layer slotted circular patch antenna

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Abstract

An innovative bolt loosening detection method based on double-layer slotted circular patch antenna is proposed. By integrating the patch antenna with the bolt, the longitudinal length variation of the bolt can be transformed into a change in the air gap thickness of the antenna and cause the resonant frequency to vary. Thus, we can detect the bolt loosening through the resonant frequency shift of the double-layer circular patch antenna. Furthermore, the circular radiation patch of the antenna is slotted to increase the effective length of current flow, thus achieving the miniaturization of the antenna sensor for bolt loosening detection. The proposed double-layer slotted circular patch antenna sensor can be as small as a coin with a high sensing sensitivity of 626.57 MHz/mm, and it can be interrogated either wired or wirelessly. A series of simulations and experimental tests demonstrate the feasibility and effectiveness of the proposed antenna sensor for bolt loosening detection. The experimental results show that the relationship between the bolt preload and the antenna resonant frequency is relatively linear, and the resonant frequency of the antenna shifts 18 MHz for an M24 bolt from completely loosened to fully fastened.

Keywords

Structural health monitoring, bolt loosening detection, patch antenna, double-layer substrate, resonant frequency

Introduction

Bolted construction is a common form of connection, typically involving a nut, a shaft, and two components to be joined. Bolts have many advantages, such as simple structure, easy disassembly and assembly, and low cost. Thus, bolts are widely used in various fields such as aviation, machinery, and engineering fields.[1,2]

Bolts are designed to tightly connect two components by utilizing tension and friction. However, they are susceptible to loosening or detaching as a result of factors such as vibrations, shocks, and temperature fluctuations.[3] This can potentially jeopardize the safety and overall performance of the structure, and sometimes even lead to the failure of the entire structure. For example, during the flight of British Airways Flight 5390 in 1990, a piece of the cockpit windshield suddenly flew off,[4] causing the captain of the plane to be injured. The main reason for the accident is that some bolts in the cockpit failed. Coincidentally, in 2010, an escalator at the International Trade Station of Shenzhen Metro Line 1 suddenly reversed upward, injuring 25 passengers.[5] The accident was also caused by the loosening of fixed bolts on the main machine of the escalator. The lessons of these accidents tell us that although the bolt is a small part, its role cannot be ignored, and we should pay sufficient attention to the issue of bolt loosening.[6]

Considering the crucial significance of bolt loosening detection, numerous scholars have embarked on research in this area to explore various bolt loosening detection methods. Some proposed methods for detecting bolt looseness mainly include vibration-based methods,[7] piezoelectric impedance-based methods,[8–10] acoustic wave-based methods,[11,12] vision-based

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methods,[13,14] and some strain or angle sensors-based bolt loosening detection methods.[15–17] The vibration-based bolt loosening detection methods mainly detect bolt looseness based on the frequency and modal variation of structural vibration. However, sometimes local bolt looseness may not result in significant alterations in the overall dynamic characteristics of the structure, which limits its practical use. When using piezoelectric impedance technology for bolt loosening detection, the impedance changes in a piezoelectric material can indirectly indicate the changes in bolt preload and the degree of looseness. Piezoelectric impedance technology has good potential in detecting bolt looseness, but the accuracy can be affected by many factors, such as the material properties and size of the piezoelectric element, and the sensitive frequency band is limited. The acoustic wave monitoring technology can also be used in bolt loosening detection. This method mainly takes the transmitted wave energy of the acoustic wave as the bolt tightening index. However, when the bolt preload reaches a certain level and the real contact area between the bolted connection surfaces reaches a saturation value, the transmitted acoustic wave energy no longer changes as the preload increases, causing a significant decrease in bolt loosening detection sensitivity. The vision-based bolt loosening detection method usually combines deep learning technology and image processing technology to estimate the rotation angle or axial elongation of bolts from bolt connection images. The method performs well and can integrate with drones; however, when there is a cover around the bolt, the vision-based method will no longer work. The strain or angle sensors-based methods rely on the sensors to measure the longitudinal elongation or rotation angle of the bolt, and then analyze the bolt loosening status. In addition, these sensors typically require cables for signal transmission and power supply, resulting in complex installation and numerous wires.[18]

The above bolt loosening detection methods have already demonstrated their effectiveness, but still have some limitations in practical use, such as dependence on cables and power supply. Therefore, more practical and reliable methods for bolt loosening detection are needed. In this regard, the antenna-based sensing technology which has the advantages of passive and wireless sensing can be used as a sensor to detect bolt loosening.[19] The sensing principle of the antenna sensor is that the variation in monitored physical parameters induces changes in the electromagnetic characteristics of the antenna, and the antenna itself has the dual function of sensing and signal transmission.[20–24] Since the antenna sensor is a type of passive sensor that does not require a power supply and allows for wireless interrogation, it can avoid the defects of some traditional sensors.

In recent years, a lot of antenna-based sensors have been developed. For example, some antenna sensors have been proposed for strain sensing,[25,26] displacement sensing,[27,28] crack sensing,[29,30] temperature sensing,[31,32] concrete humidity sensing[33,34] and so on. The wireless and dynamic interrogation technologies of antenna sensors are also attracting research from relevant scholars.[35] However, the antenna sensors based on monolithic patch antenna usually need to be attached to the structure's surface, resulting in incomplete strain transfer. This limitation restricts the utilization of antenna sensors for structural health monitoring.[36] Recently, to overcome the problem of current monolithic antenna sensors, some unstressed patch antenna sensors that can sense the strain or crack by the relative movement between two antenna components came into being.[37,38] The authors also proposed some unstressed antenna sensors and explored their application in bolt loosening detection.[39,40] However, the size of the developed antenna sensor for bolt loosening detection is still large, making it difficult to be used in practice.[41] Therefore, developing a miniaturized antenna sensor for bolt loosening detection has great practical significance.

In this study, the innovative bolt loosening detection method based on a double-layer slotted circular patch antenna sensor is proposed. The double-layer antenna sensor has two dielectric substrates, which create an air gap between the two layers. The thickness of the air gap plays a significant role in determining the resonant frequency of the antenna. When the double-layer circular patch antenna is installed on the bolt, the longitudinal length changes of the bolt can be converted into variation in the air gap thickness. Consequently, we can detect the bolt loosening by the resonant frequency shift of the antenna. The double-layer patch antenna sensor realizes sensing based on the relative movement of two components of the antenna, and its unstressed structure makes it suitable for bolt loosening detection. Furthermore, the slotted surface of the circular radiation patch antenna enables the antenna size to be significantly reduced since it increases the effective length of current flow. The proposed double-layer slotted circular patch antenna has the characteristics of simple installation, high sensitivity, small size, and can be interrogated wirelessly. The feasibility and effectiveness of the proposed antenna sensor for bolt loosening detection are demonstrated through a series of simulations and experiments.

Methodology and theoretical analysis

Bolt preload is a crucial factor in detecting bolt loosening, and any reduction in bolt preload results in a decrease in the bolt's longitudinal length. Thus, the bolt preload variation can be determined by measuring the bolt's longitudinal length alteration. This study presents a novel bolt loosening detection method using a double-layer slotted circular patch antenna, which can detect the changes in the bolt's longitudinal length. The double-layer slotted circular patch antenna has an air gap between the two layers of substrate, and the variation in the bolt's longitudinal length induces the change of the air gap thickness. The change of the air gap thickness leads to a shift of the antenna resonant frequency, and the resonant frequency shift of the antenna can be measured by the antenna reader, such as vector network analyzer (VNA). Therefore, by the resonant frequency shift of the antenna, the bolt loosening can be detected quantitatively. The concepts of the bolt loosening detection method based on the double-layer slotted circular patch antenna are shown as Figure 1.

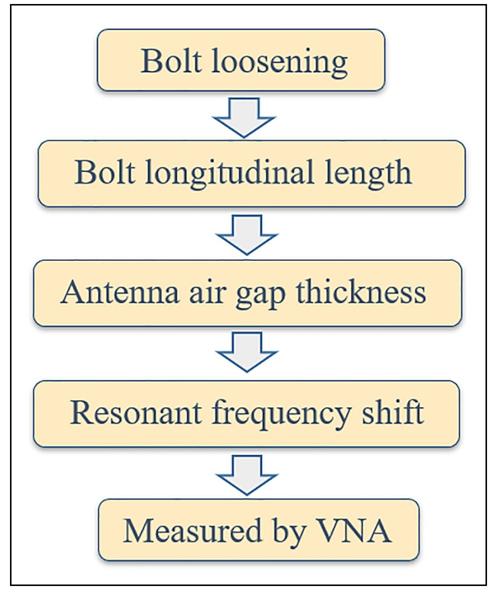

Figure 1. Concepts of the bolt loosening detection based on double-layer patch antenna.

Antenna theory

To measure the longitudinal length change of the bolt, a double-layer patch antenna is proposed based on the monolithic patch antenna. The diagram of the double-layer slotted circular patch antenna is shown in Figure 2. The antenna consists of two layers of dielectric substrate, a radiation patch and a ground plane. There is an air gap between the two layers of dielectric substrate, and the air gap thickness can be changed. The following is the theoretical analysis of the double-layer slotted circular patch antenna based on the antenna theory.

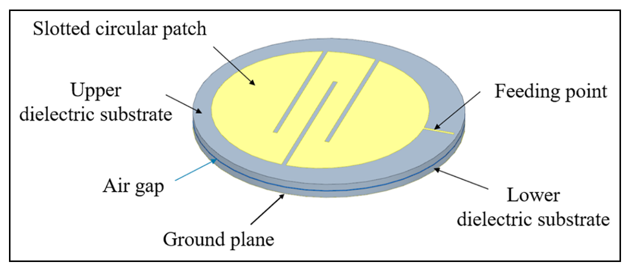

Figure 2. Diagram of the double-layer slotted circular patch antenna.

The resonant frequency of the patch antenna mainly depends on two factors: the effective current flow path length of the radiation patch, and the equivalent relative dielectric constant between the radiation patch and the ground plane. Despite the circular shape of the radiation patch in the double-layer substrate slotted circular patch antenna, the current flow path is represented by the black curve in Figure 3 due to the slot and side feeding.

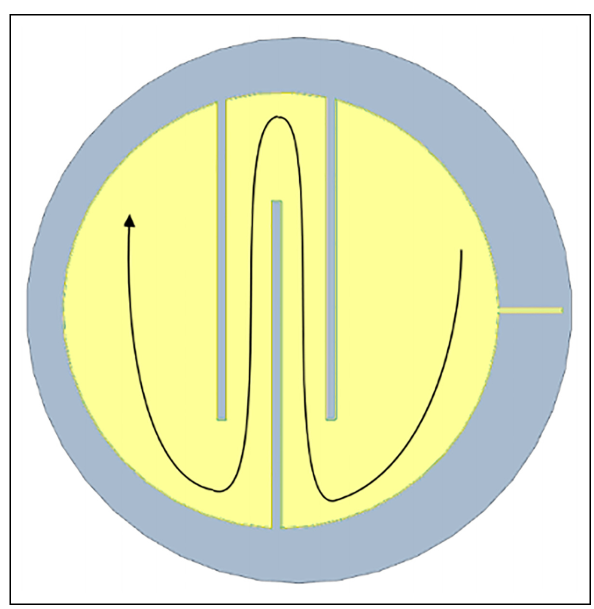

Figure 3. The current flow path on the radiation patch.

The slot on the surface of the radiation patch can increase the effective current flow path length of the radiation patch, thereby significantly reducing the size of the antenna at the same resonant frequency, making the antenna sensor size as small as a coin. This miniaturized antenna sensor design can be better assembled with bolts to meet the needs of actual engineering bolt loosening detection.

According to the resonant cavity theory and the calculation equation of a patch antenna, considering the influence of the air gap between substrates, the resonant frequency of the double-layer substrate slotted circular patch antenna can be expressed as:

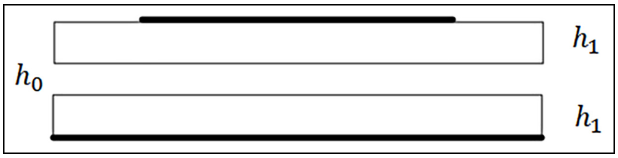

Figure 4. The air gap between the antenna substrate.

$$f_m = \frac{mc}{2L_e\sqrt{\varepsilon_{r,\text{eff}}}} \tag{1}$$

where f_m is the m order resonant frequency when the antenna resonant at current flow path shown as Figure 3, and c is the speed of electromagnetic wave in a vacuum. L_e is the effective current flow path length of the radiation patch, which is related to the factors such as the distance from the patch to the ground plane, the number and location of slots, as well as the length-to-width ratio of the slots. $\varepsilon_{r,\text{eff}}$ is the effective relative dielectric constant considering the influence of the air gap, which is mainly affected by the thickness of the air gap. The substrate of the patch antenna can be divided into two substrates, with an air gap introduced between them to change the antenna resonant frequency, shown as Figure 4.

The effective relative dielectric constant can be expressed as:

$$\varepsilon_{r,\text{eff}} = \frac{4\varepsilon_{r,\text{equ}}\varepsilon_{r,\text{dyn}}}{\left(\sqrt{\varepsilon_{r,\text{equ}}} + \sqrt{\varepsilon_{r,\text{dyn}}}\right)^2} \tag{2}$$

where $\varepsilon_{r,\text{eff}}$ is the equivalent relative dielectric constant of the medium between the radiation patch and the ground plane, and $\varepsilon_{r,\text{dyn}}$ is the dynamic relative dielectric constant considering the static main capacitance, static edge capacitance, and resonant mode, which can be expressed as follows:

$$\varepsilon_{r,\text{equ}} = \frac{\varepsilon_r(2h_1 + h_0)}{(2h_1 + \varepsilon_r \cdot h_0)} \tag{3}$$

$$\varepsilon_{r,\text{dyn}} = \frac{C_{\text{dyn}}(\varepsilon = \varepsilon_0\varepsilon_{re})}{C_{\text{dyn}}(\varepsilon = \varepsilon_0)} \tag{4}$$

$$C_{\text{dyn}} = C_{0,\text{dyn}} + C_{e,\text{dyn}} \tag{5}$$

where h_1 and h_0 are the thickness of antenna substrate and air gap respectively, ε_r is the relative dielectric constant of the substrate, C_{dyn} is the total dynamic capacitance, $C_{0,\text{dyn}}$ and $C_{e,\text{dyn}}$ are the dynamic main capacitance and dynamic edge capacitance respectively. Thus, for the double-layer patch antenna, the value of the effective relative dielectric constant decreases when the air gap thickness increases, and the antenna's resonant frequency increases correspondingly.

Sensing principle

The double-layer slotted circular patch antenna can sense the changes in the air gap thickness through resonant frequency shift, and this principle can be used to design the sensor for bolt loosening detection. The installation diagram of the proposed patch antenna sensor for bolt loosening detection is shown in Figure 5(a) and (b). The antenna has a double-layer structure with an adjustable air gap situated between two layers of dielectric substrate. The upper dielectric substrate is affixed to the top of the bolt using a ring fixation device and glue. The bolt contains a hole within its shaft, through which a connecting rod passes. One end of the connecting rod is anchored to the bottom of the bolt shaft, while the other end is connected to the lower dielectric substrate of the antenna. The lower dielectric substrate is suspended and supported by the connecting rod. When the preload applied to the bolt changes, the bolt's longitudinal length changes; this variation is then transmitted to the lower dielectric substrate through the connecting rod, leading to relative movement between the upper and lower dielectric substrates. The relative movement changes the thickness of the air gap between the two layers of dielectric substrate, thereby inducing a shift in the antenna's resonant frequency. Thus, based on the resonant frequency shift of the double-layer antenna, the bolt's longitudinal length variation can be determined, and the bolt loosening can be detected.

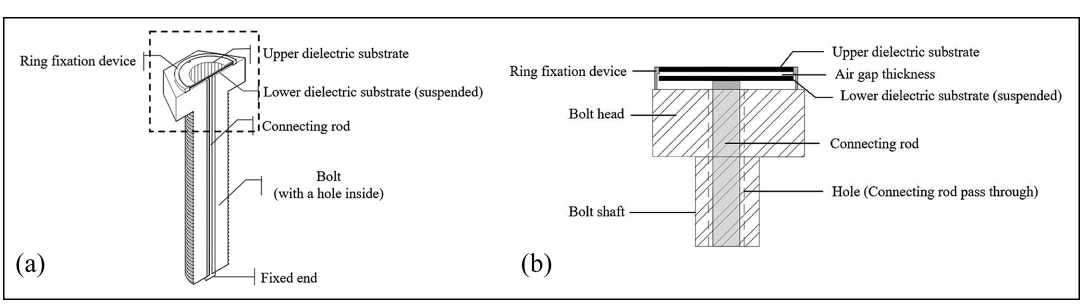

Figure 5. (a) The installation diagram of the proposed antenna sensor: overall diagram and (b) the installation diagram of the proposed antenna sensor: partial detail diagram.

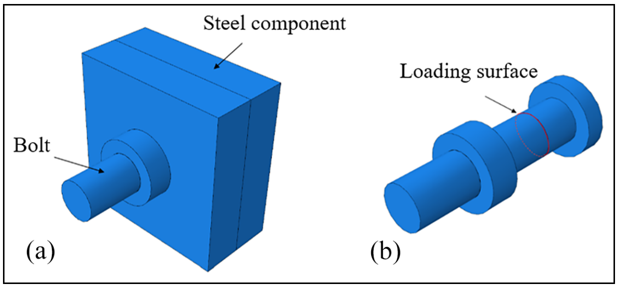

Figure 6. Bolt model in Abaqus: (a) bolt and steel components and (b) bolt loading surface.

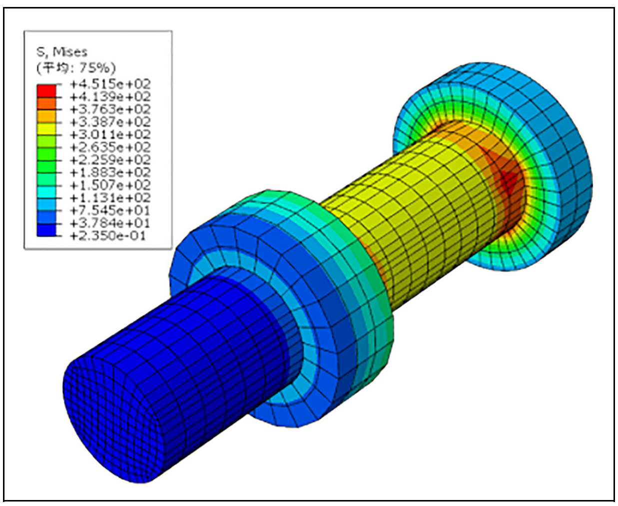

Figure 7. Calculation results of bolt model in Abaqus.

Simulation study

Finite element analysis of the bolt

Since the designed double-layer slotted circular patch antenna mainly detects bolt loosening through changes in the bolt's longitudinal length, it is necessary to investigate the bolt's longitudinal length change before and after preload is applied. This study takes an 8.8 strength grade M24 bolt as an example, and finite element analysis of the bolt was conducted in Abaqus software to determine the deformation and longitudinal length change when it reaches the specified preload.

The diameter of the M24 bolt is 24 mm, and the standard applied axial force was set as 146.4 kN according to the specification. There are two steel components made of Q345 steel and connected by the bolt; the total thickness of the steel components is 50 mm. The bolt model in Abaqus is shown in Figure 6(a), and the loading surface is shown in Figure 6(b). The contact surfaces between the components of the model were set as friction constraints and the tangential friction coefficient was set as 0.15, while the normal direction was set as rigid contact.

In this simulation scenario, the results show that the bolt's longitudinal length is reduced by 0.065 mm from the fully fastened state (with an applied axial force of 146.4 kN) to the fully loosened state (with an applied axial force of 0). The calculation results of the bolt model in a fully fastened state are shown in Figure 7. Based on the finite element analysis results, the longitudinal length change of bolts of similar types is estimated to be about 0.05–0.10 mm from the fully tightened state to the fully loosened state, and the specific longitudinal length variation of the bolt is related to many factors, such as the dimension of the bolt, the bolt's contact surface conditions and materials.[42,43] Thus, the designed antenna sensor should meet the requirement of a 0.01 mm sensitivity when used to measure the bolt's longitudinal length change to detect the bolt loosening.

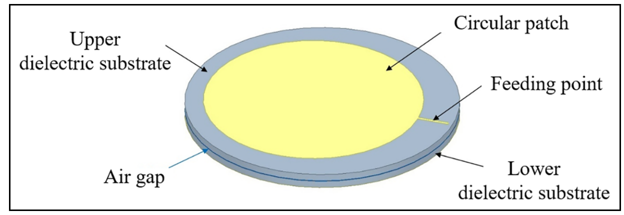

Figure 8. The unslotted double-layer circular patch antenna in HFSS.
HFSS: high frequency structure simulator.

Simulation of the double-layer slotted circular patch antenna for bolt detection

When determining the size of the antenna sensor, the diameter of the designed circular patch antenna should be smaller than the size of the bolt head to facilitate integration with bolts. Based on the size of the M24 bolt head, the diameter of the circular patch antenna sensor was preliminarily set to 30 mm. Firstly, the simulation of unslotted double-layer circular patch antenna was carried out. The antenna consists of two circular dielectric substrates with an air gap between them. The upper substrate has a circular radiation patch and the feeding point, and the lower substrate has a ground plane. The dielectric substrate material was set as FR4 with a relative dielectric constant of 4.4, and the material of the radiation patch and the ground plane was set as copper. The antenna model in the high frequency structure simulator (HFSS) is shown in Figure 8 with an initial air gap thickness of 0.08 mm between the two layers of dielectric substrate, and the thickness of each layer of dielectric substrate was selected as 0.8 mm. The antenna was excited by a lumped port to analyze the reflection signal.

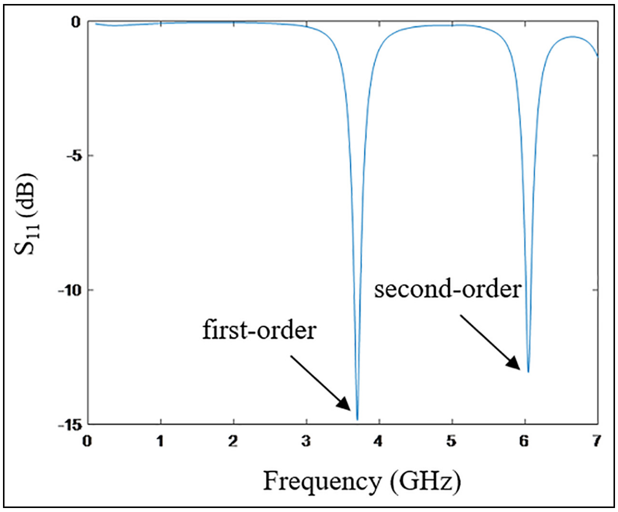

Figure 9. S_{11} curve of the unslotted double-layer circular patch antenna.

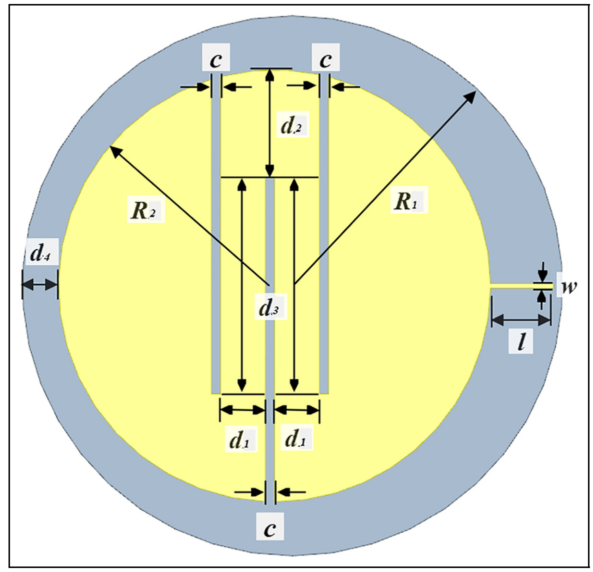

Figure 10. The size parameters schematic diagram of the slotted circular patch antenna.

Table 1. The size of the slotted circular patch antenna radiation patch (mm).

Parameters	R_1	R_2	c	d_1	d_2
Value	15	12	0.5	3	6
Parameters	d_3	d_4	l	w	h_r
Value	12	2	3.5	0.25	0.8

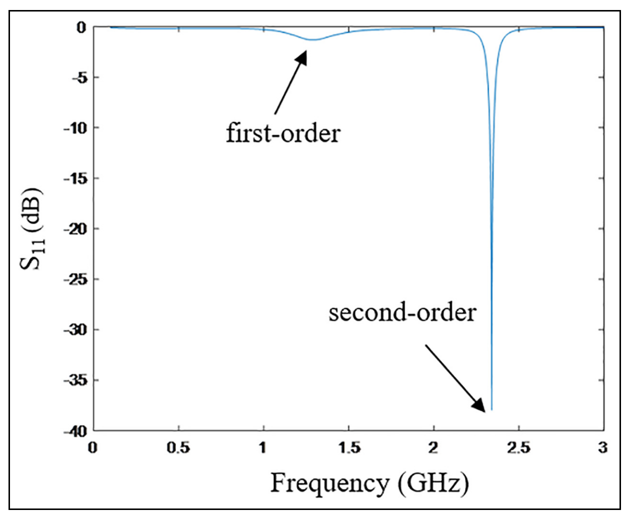

Figure 11. S_{11} curve of the slotted double-layer circular patch antenna.

Figure 9 shows the reflection loss curve S_{11} of the unslotted double-layer circular patch antenna; it can be seen that the first-order resonant frequency of the antenna was approximately 3.7 GHz, and the second-order resonant frequency is approximately 6.0 GHz. However, due to the limited sweep frequency range of the conventional VNA used for antenna interrogation, which is 0–3 GHz, the testing of the antenna with resonant frequency greater than 3 GHz is difficult and requires high-end equipment.

Antenna slotting is an effective miniaturization method. Introducing slots at appropriate positions of the antenna can increase the current flow path length, leading to reduced antenna resonant frequency without increasing the antenna size.[44] Hence, we suggest slotting the circular radiation patch of the double-layer circular antenna to reduce its resonant frequency to below 3 GHz while maintaining its original size. A series of simulations and optimizations were conducted in HFSS to determine the number, position, and size of slots, and the size of the slotted circular radiation patch was selected as shown in Table 1. The size parameters schematic diagram of the slotted circular patch antenna sensor model in HFSS is shown in Figure 10.

The reflection loss curve S_{11} of the slotted circular patch antenna is shown in Figure 11. It can be seen that the slotting significantly reduced the antenna's resonant frequency, with the first-order resonant frequency reduced from about 3.7 to 1.3 GHz and the second-order resonant frequency reduced from 6.0 to 2.3 GHz. However, the impedance matching of the first-order resonant mode deteriorated while the second-order resonant mode showed better matching, with the corresponding S_{11} value reaching about -35 dB. Based on considerations of impedance matching and sensing sensitivity, the second-order resonant frequency was selected as the sensing index, since the higher-order

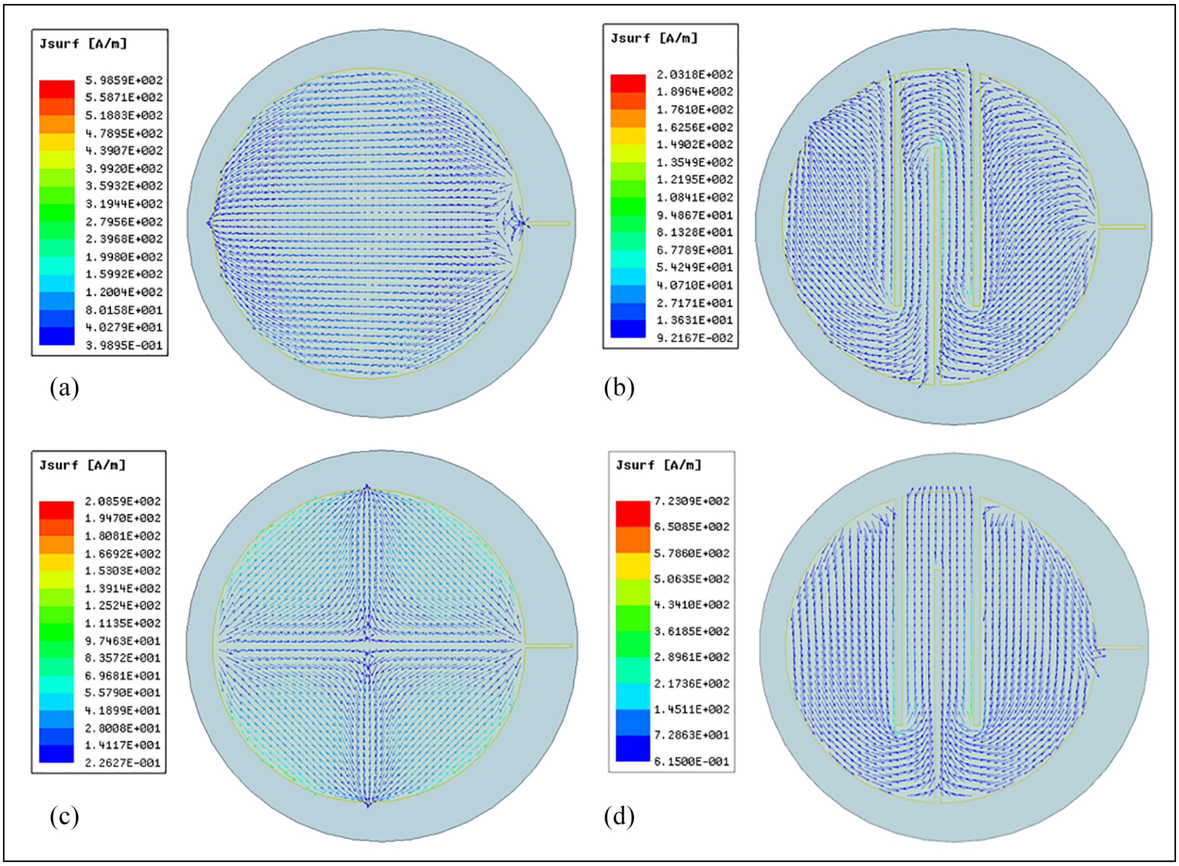

Figure 12. Current distribution of the radiation patch: (a) at first-order resonant mode before slotting, (b) at first-order resonant mode after slotting, (c) at second-order resonant mode before slotting and (d) at second-order resonant mode after slotting.

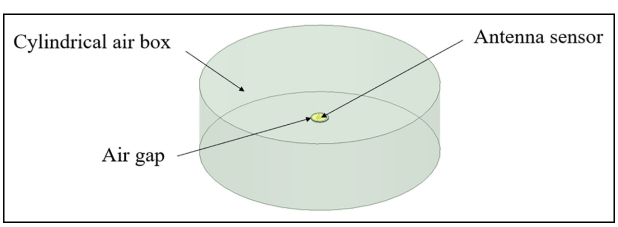

Figure 13. The double-layer slotted circular patch antenna with air gap in HFSS.

resonant frequency usually has a higher sensitivity to the monitored variables.

Figure 12 illustrates the current distribution of the radiation patch at the first-order resonant mode and second-order resonant mode before and after slotting. The current distribution of the radiation patch after slotting shows a significant increase in the length of the current flow path, indicating the effectiveness of slotting for antenna miniaturization. The antenna size can be significantly reduced while maintaining the resonant frequency unchanged, or the resonant frequency of the antenna can be significantly reduced while keeping the antenna size unchanged.

In order to further explore the relationship between the resonant frequency of the proposed double-layer slotted circular patch antenna and the air gap thickness between two layers of the dielectric substrate, simulations were carried out where the air gap thickness changed from 0 to 0.5 mm. Figure 13 shows the double-layer slotted circular patch antenna model in HFSS. The antenna model was placed in a cylindrical air box that is a quarter wavelength larger than the antenna to ensure the accuracy of far-field radiation calculations, and the boundary of the cylindrical air box was set as the "radiation boundary." There was an air gap between the two layers of substrate of the antenna, and the air gap thickness was changed from 0 to 0.5 mm with an increment of 0.05 mm to simulate the relative movement between the two components of the antenna in actual situations.

HFSS: high frequency structure simulator.The reflection loss curves S_{11} of the slotted circular patch antenna with different air gap thicknesses are shown in Figure 14. In this frequency range, the resonant mode of the antenna is the second-order resonant. It can be seen that the resonant frequency of the antenna increases with the thickness of the air gap. Besides, the

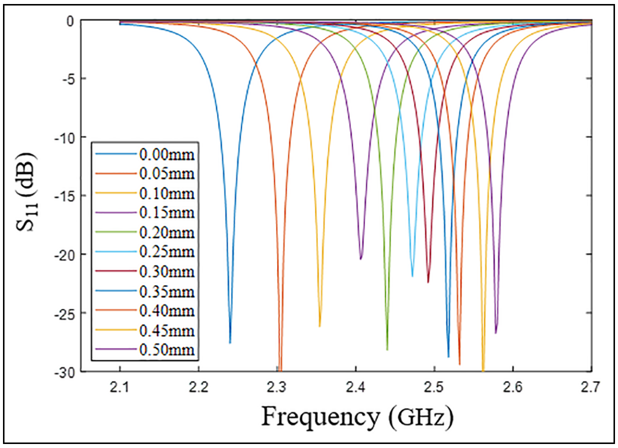

Figure 14. S_{11} curves of the patch antenna with different air gap thicknesses.

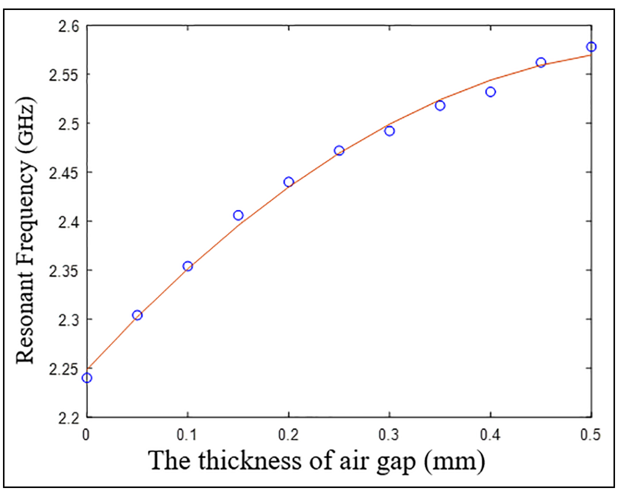

Figure 15. Relationship between the second-order resonant frequency of antenna and the thickness of air gap (0–0.5 mm).

S_{11} curve of the antenna is becoming increasingly dense from left to right in Figure 14, indicating that the thicker the air gap, the smaller the sensitivity of the antenna. This is because the influence of the air gap thickness on the effective relative dielectric constant of the antenna is related to the proportion of air gap thickness to the total thickness of the antenna substrate. As the air gap thickness increases, the total thickness of the antenna substrate also increases, resulting in a corresponding decrease in the influence of the air gap thickness variation on the effective relative dielectric constant.

The relationship between the second-order resonant frequency of the antenna and the air gap thickness is shown in Figure 15, which is obtained by extracting the resonant frequency from the local minimum of each S_{11} curves curve and fitting using a quadratic curve. The simulation results show that with an increasing air gap thickness, the antenna's sensing sensitivity gradually decreases, as evidenced by the decreasing slope of the fitted curve. Therefore, it is recommended to set the initial air gap thickness of the antenna sensor to 0 to ensure high sensing sensitivity.

Considering the bolt loosening simulation results in Abaqus, the longitudinal length change of a common bolt from the fully tightened state to the fully loosened state is approximately 0.05–0.10 mm. Thus, 0–0.1 mm was selected as the main range of the antenna sensor for the bolt's longitudinal length change measure, which is suitable for most bolt loosening detection scenarios while maintaining high sensitivity and better linear relationship of the antenna sensor. The subsequent discussion focuses on the performance of the proposed double-layer slotted circular path antenna sensor within this range.

In order to further study the sensing ability of the proposed double-layer slotted circular patch antenna, the air gap thickness of the antenna was set to vary from 0 to 0.1 mm, with an increment of 0.02 mm. The S_{11} curves of the double-layer slotted circular patch antenna are shown in Figure 16, with each curve corresponding to a different air gap thickness from 0 to 0.1 mm. As depicted in Figure 16(a), the second-order resonance frequency of the antenna is more sensitive to changes in air gap thickness and exhibits better impedance matching. The S_{11} curves in Figure 16(b) and (c) show the first-order and second-order resonant frequencies, respectively, both of which increase with the expansion of the air gap between the substrates.

A series of simulations were also conducted that the air gap thickness of the antenna sensor changes from 0 to 0.1 mm, and the second-order resonant frequencies were extracted from the S_{11} curves. Figure 17 shows the relationship between the resonant frequency of the proposed antenna sensor and the thickness of the air gap when the initial thickness was set as 0 and varies from 0 to 0.1 mm with an increment of 0.01 mm. It can be seen that within this range of air gap thickness, there is a good linear relationship between the second-order resonant frequency of the antenna and the variation of air gap thickness. The linear fitting reveals a high sensitivity of 1134.5 MHz/mm and a correlation coefficient of 0.9922. Compared with the previous study, the sensitivity of the antenna sensor improved significantly. Thus, the proposed double-layer slotted circular patch antenna sensor is more suitable for the detection of bolt loosening.

In practical applications, the double-layer slotted circular patch antenna should be integrated with the bolt. To investigate the effect of nearby steel on the antenna's resonant frequency, simulation study was conducted in HFSS. A piece of block was placed 2 mm from the bottom surface of the antenna sensor, and the

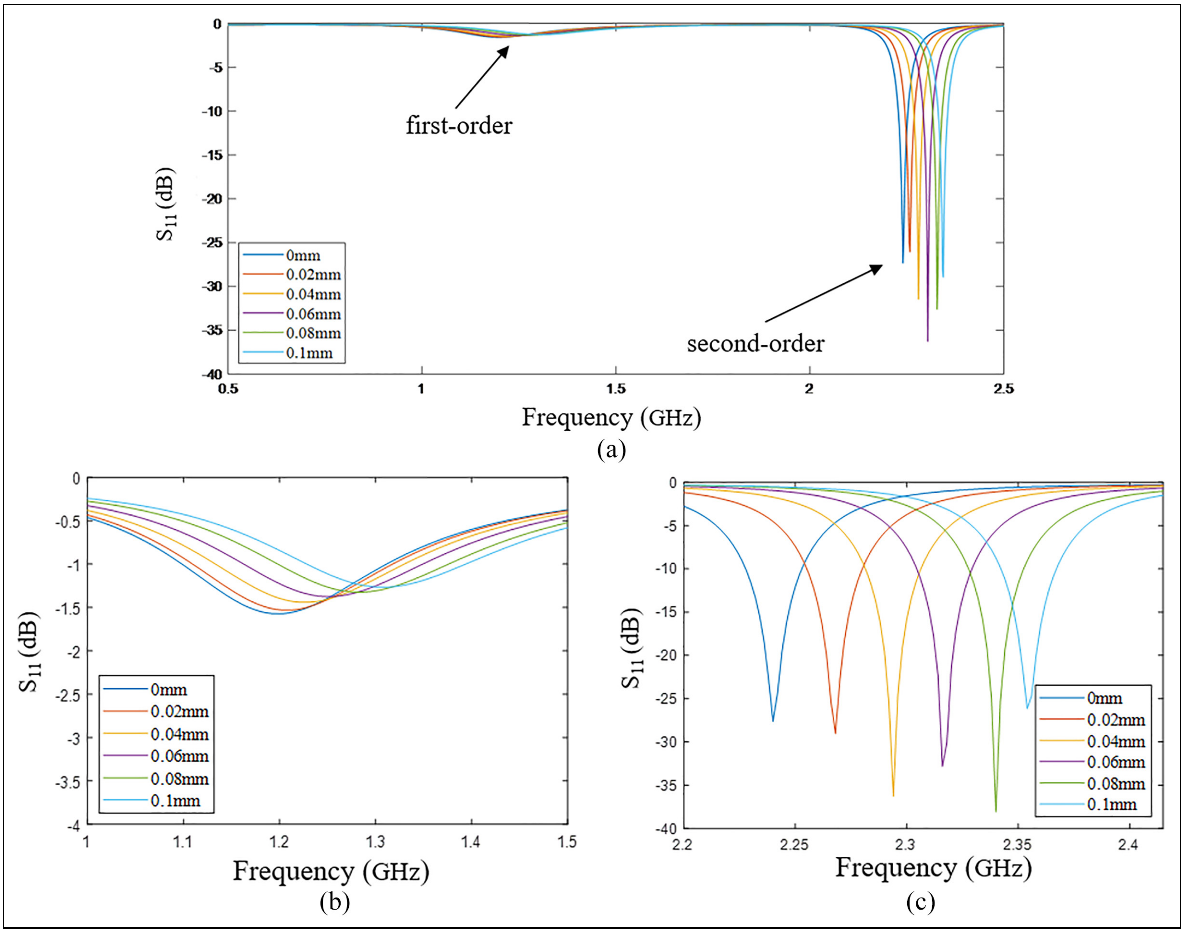

Figure 16. S_{11} curves of the patch antenna: (a) overall diagram of the resonant frequency, (b) first-order resonant frequency and (c) second-order resonant frequency.

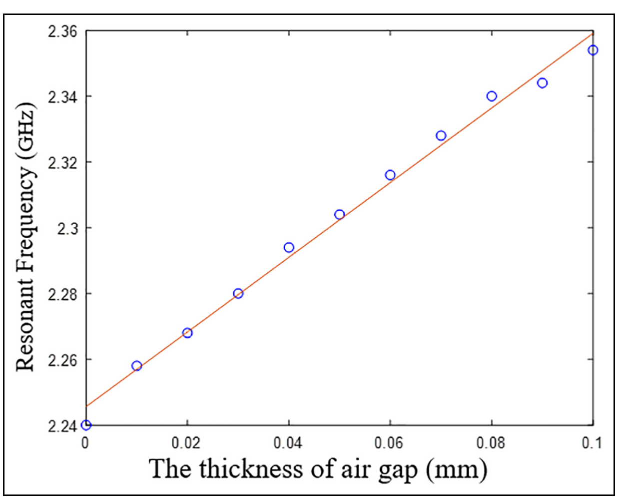

Figure 17. Relationship between the second-order resonant frequency of antenna and the thickness of air gap (0–0.1 mm).

antenna's sensing ability was tested, as depicted in Figure 18.

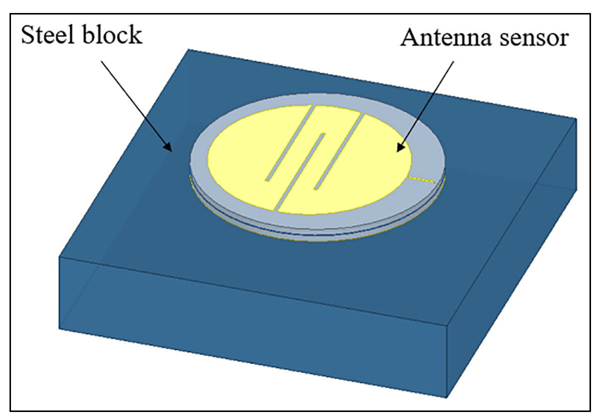

Figure 18. The antenna sensor with a steel block nearby.

When there is steel nearby, the relationship between the thickness of the air gap and the second-order resonant frequency of the antenna is shown in Figure 19. The simulation results show that the antenna's sensitivity in the presence of a nearby steel block is

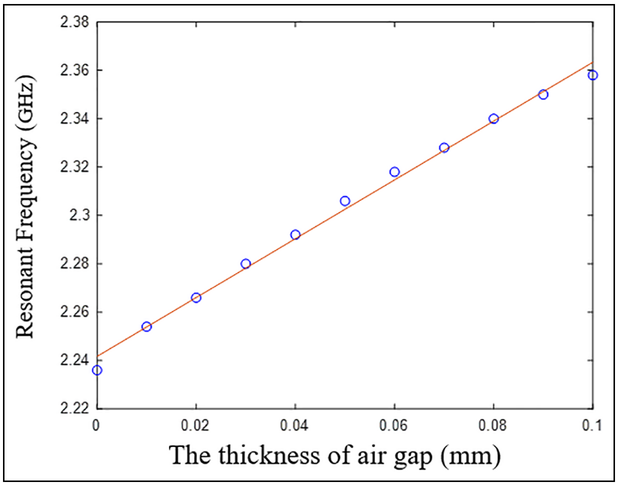

Figure 19. Relationship between the second-order resonant frequency of antenna and the thickness of air gap (with a steel block nearby).

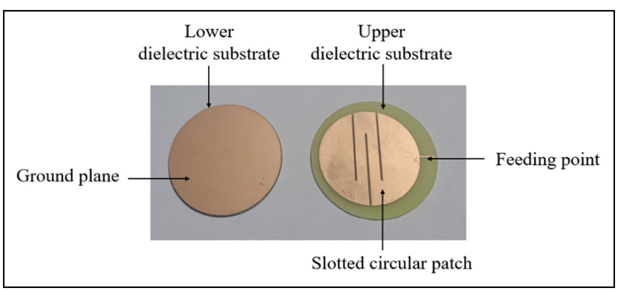

Figure 20. The fabricated double-layer slotted circular patch antenna.

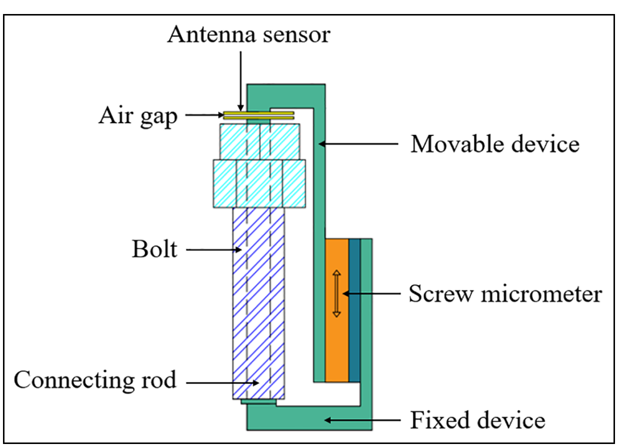

Figure 21. Diagram of the experimental setup.

1116.4 MHz/mm, and the correlation coefficient is 0.9943. Despite a minor reduction in sensitivity, the presence of the steel block has no significant impact on the sensitivity of the antenna sensor and can be ignored.

Experimental study

To investigate the actual sensing capability of the proposed double-layer slotted circular patch antenna, we fabricated the patch antenna and conducted a series of experimental tests to investigate the relationship between the air gap thickness and resonant frequency of the antenna, and to verify its feasibility for the detection of bolt loosening. The fabricated double-layer slotted circular patch antenna through chemical etching technique and FR4 copper clad laminate material is shown as Figure 20.

Air gap thickness and the resonant frequency of the antenna sensor

Firstly, the double-layer slotted circular patch antenna was installed on the experimental device shown in Figure 21 to study the relationship between air gap thickness and the resonant frequency of the antenna. The bolt was mounted on a fixed device made of acrylic, and a movable device was connected to the fixed device through a screw micrometer. The upper layer of the slotted circular patch antenna was fixed on the movable device, while the lower layer of the patch antenna was fixed on the bolt head. The moveable device could be pushed by the screw micrometer rod with a precision of 0.01 mm; thus, the moveable and the fixed device can move relative to change in the thickness of the air gap between two layers of the antenna.

The picture of the experimental setup is shown in Figure 22. The double-layer slotted circular patch antenna was connected to the VNA via a coaxial line, and the VNA can analyze the reflection loss curve S_{11} of the antenna sensor and then get the resonant frequency information. The initial thickness of the antenna sensor air gap was set to zero, and then use the screw micrometer to change the air gap thickness from 0 to 0.1 mm with an increment of 0.01 mm. The VNA sends a sweep signal ranging from 2 to 2.8 GHz and the reflection loss curves S_{11} are shown as Figure 23. The second-order resonant frequencies of the antenna were extracted from the S_{11} curves and shown in Figure 24. According to the experimental results, we can see a good linear correlation between the second-order resonant frequency of the antenna and the thickness of air gap, and the experimental measured sensitivity is about 626.57 MHz/mm with a correlation coefficient of 0.9980.

Even though the good linear relationship between the resonant frequency shift and the thickness of air gap, there are some differences in the sensitivity obtained from simulation and experimental test. The difference is mainly due to the manufacturing errors in

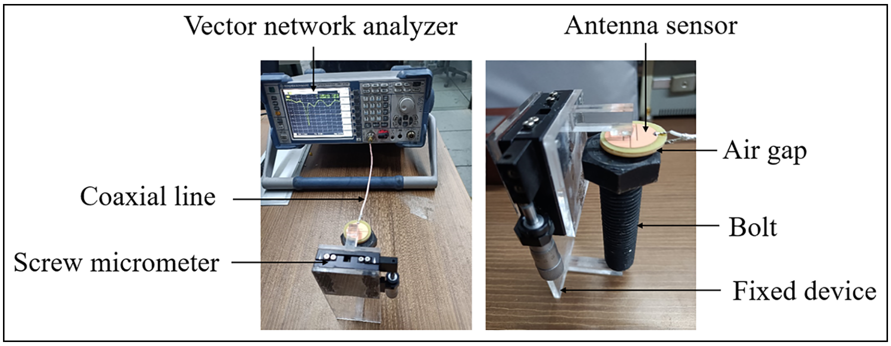

Figure 22. The picture of the experimental setup.

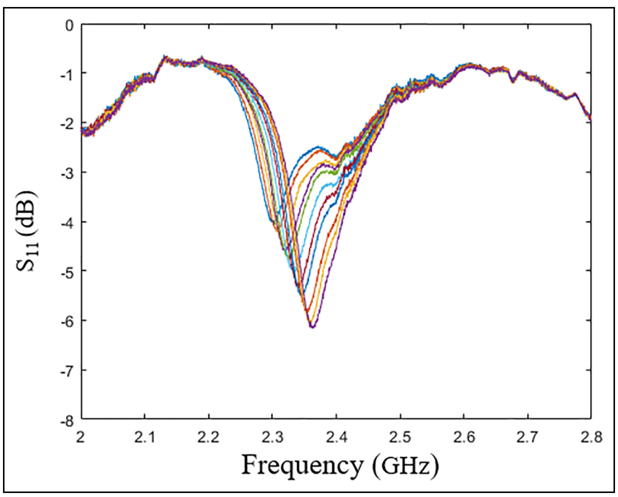

Figure 23. Experimentally measured S_{11} curves.

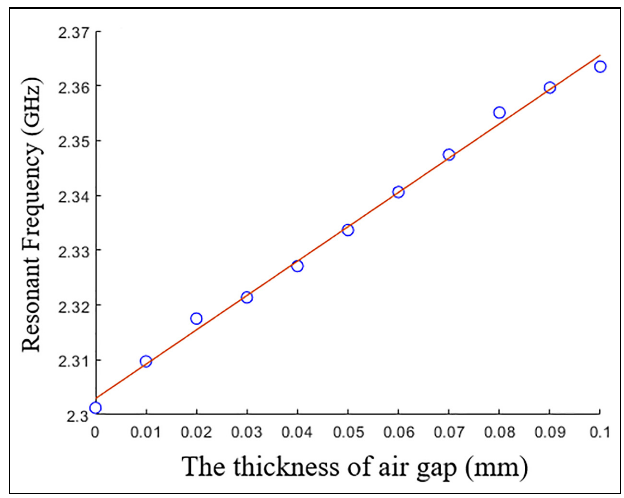

Figure 24. Relationship between the second-order resonant frequency of antenna and the thickness of air gap (Experimentally measured).

antenna sensor and influence of the welding points, as well as the initial status still having air gap thickness, which can lead to a significant decrease in the sensing sensitivity. Besides, the electromagnetic interference in the environment is also an issue that cannot be ignored. Therefore, the fabricated antenna sensor is suggested to be calibrated before use to get the actual sensitivity and ensure the measurement accuracy.

Wireless interrogation of the double-layer patch antenna sensor

Antenna sensors have the potential to be interrogated wirelessly, which is a significant advantage compared to other types of sensors. In this section, a wireless interrogation test of the double-layer slotted circular patch antenna was conducted to demonstrate its feasibility for wireless sensing. The resonant frequency of the proposed antenna sensor was interrogated wirelessly using a dual wide-band antenna interrogation system, the experimental setup is shown in Figure 25.

There were two linearly polarized wide-band antennas; the wide-band antenna A was connected to the Nano VNA via a coaxial line, and the other wide-band antenna B was connected to the double-layer slotted circular patch antenna sensor via another coaxial line. The wide-band antenna A was used to transmit sweeping electromagnetic waves, and then the electromagnetic waves can be received by the wide-band antenna B. The double-layer slotted circular patch antenna sensor was used as a load for wide-band antenna B; therefore, the resonant mode of the double-layer slotted circular patch antenna sensor can be excited by the sweeping electromagnetic waves received by wide-band antenna B. The backscattering signal of wide-band antenna B can be received by wide-band antenna A and then analyzed by the VNA to get the resonant frequency of the double-layer slotted circular patch antenna sensor.

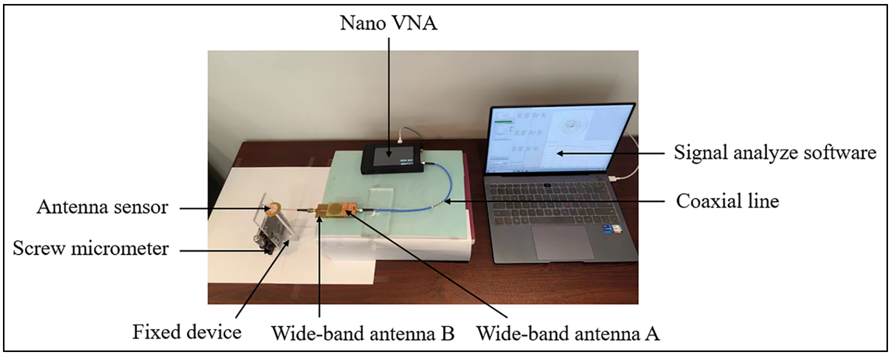

Figure 25. The picture of the wireless interrogation experimental setup.

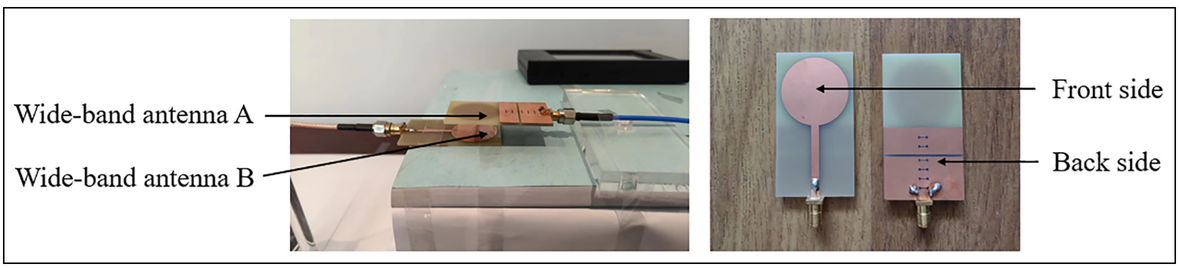

Figure 26. The picture of two wide-band interrogation antennas.

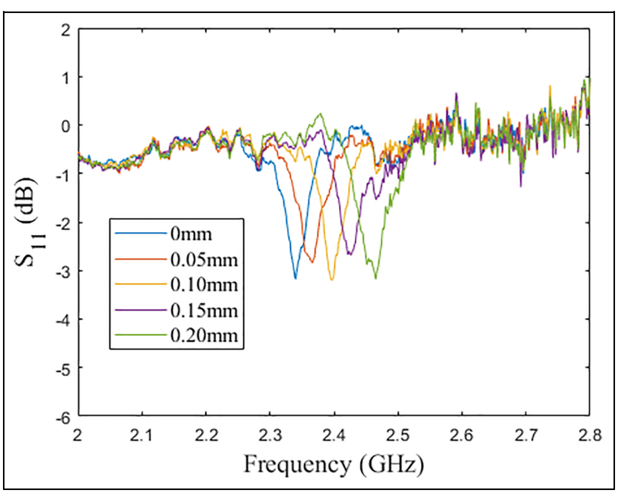

Figure 27. S_{11} curves of the wide-band antenna A in the wireless interrogation experiment.

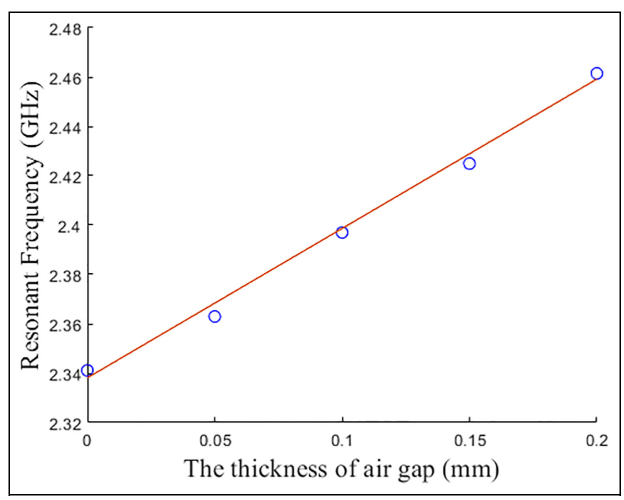

Figure 28. The resonant frequencies of the double-layer patch antenna sensor corresponding to different air gap thicknesses.

The wireless interrogation distance between the two wide-band antennas was set as 20 mm. The experimental setup details of the two wide-band interrogation antennas are shown in Figure 26. Before the experiment, the wireless interrogation system composed of two wide-band antennas was calibrated as a whole system to avoid the influence of coaxial line. The air gap thickness between the two layers of the antenna sensor was set from 0 to 0.2 mm with an increment of 0.05 mm in the experiment.

Figure 27 shows the reflection loss S_{11} curves of the wide-band antenna A. When the sweeping frequency corresponds to the resonant frequency of the double-layer patch antenna sensor, a resonant peak appears on the S_{11} curve of wide-band antenna A. There were still some fluctuations in the S_{11} curves obtained from

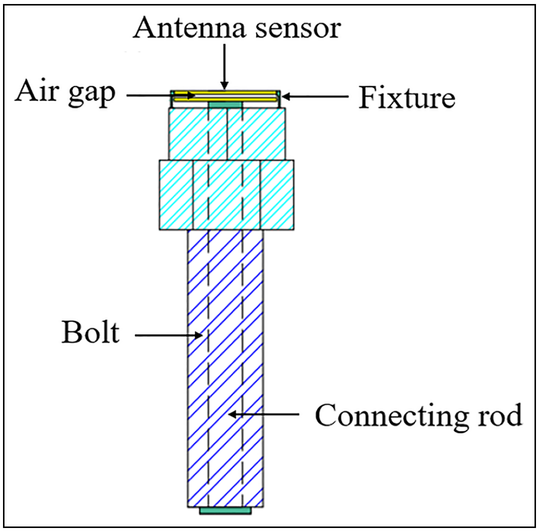

Figure 29. Diagram of the experimental setup.

the wireless interrogation experiment; thus, the S_{11} curves were fitted with a quadratic function within the vicinity of the minimum peak point, and the frequency corresponding to the curve's minimum peak point was extracted as the resonant frequency of the double-layer patch antenna sensor. Figure 28 shows the resonant frequencies of the double-layer patch antenna sensor corresponding to different air gap thicknesses. The wireless interrogation experimental results indicate that the resonant frequency of the double-layer patch antenna sensor shifts linearly as the air gap thickness increases. The sensing sensitivity of the antenna sensor is approximately 605.31 MHz/mm. Therefore, when the sensor is installed on a bolt, it can measure the change in longitudinal length of the bolt with high sensitivity and thus characterize the status of bolt looseness.

Bolt loosening detection

In this section, the proposed double-layer slotted circular patch antenna was installed on an actual bolt to test its sensing performance. The diagram of the bolt loosening detection experimental setup is shown as Figure 29.

The upper dielectric substrate of the antenna was fixed on the bolt head using a ring fixture, and the lower dielectric substrate was suspended and supported by the connecting rod. There was an air gap between the two layers of dielectric substrate. The bolt has a hollow shaft with a connecting rod passing through it. One end of the connecting rod was fixed to the bottom of the bolt shaft, while the other end was connected to the lower dielectric substrate of the antenna. Therefore, when the bolt loosening causes the longitudinal length variation of the bolt, the change will change air gap thickness of the antenna sensor and lead to a shift in the antenna resonant frequency. The picture of the experimental setup is shown as Figure 30. A torque wrench was used to apply the preload to quantitatively control the tightening degree of the bolt. In addition, a portable Nano VNA was used in this experimental test to acquire and analyze the signal from the antenna sensor, which is smaller than the traditional VNA and more suitable for bolt loosening detection in actual projects. In this experiment, the sweeping range was set from 2.4 to 2.8 GHz.

Use the torque wrench to tighten the bolt from completely loosened state to fully fastened state. The S_{11} curve of the antenna sensor was recorded when the indication values of the torque wrench increased by 20 Nm every time. The experimental measured second-order resonant frequency of antenna and the preload of bolt is shown as Figure 31. It can be seen that the second-order resonant frequency of the double-layer slotted circular patch antenna shifts with the bolt preload variation. During the process of tightening the bolts, the resonant frequency of the antenna sensor increases since the longitudinal length variation of the bolt increases the air gap thickness of the antenna sensor. The experimental results also show that the resonant frequency shift is not significant in the initial stage of applying preload, which is mainly due to the

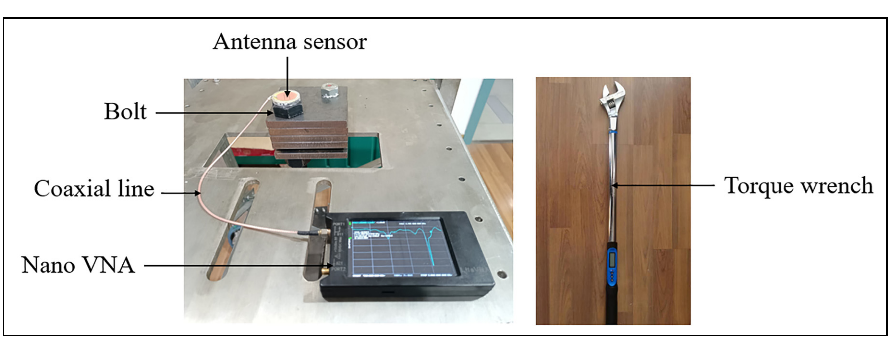

Figure 30. The picture of the bolt loosening detection experimental setup.

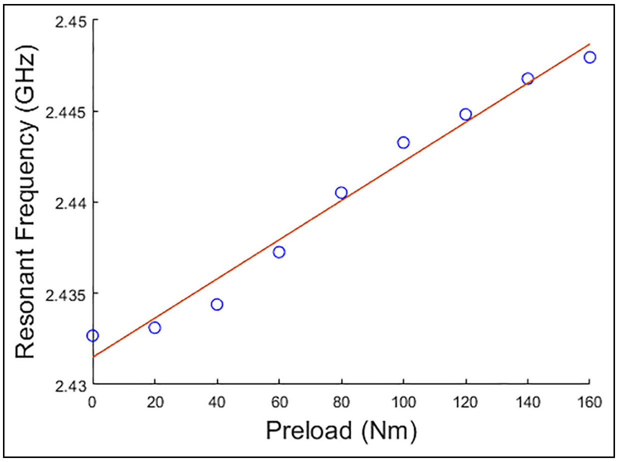

Figure 31. Relationship between the second-order resonant frequency of antenna and the preload of bolt.

presence of frictional force at the bolt interface. In the subsequent bolt tightening stage, the relationship between the bolt preload and the antenna resonant frequency is relatively linear, with a sensitivity of 0.107 MHz/Nm. The resonant frequency of the antenna changes about 18 MHz from the M24 bolt completely loosened to fully fastened. Thus, the resonant frequency shift of the proposed double-layer slotted circular patch antenna can be used for bolt loosening detection with a high sensitivity.

The influence of external factors, such as temperature fluctuations or external vibrations, can affect the performance of the proposed antenna sensor. The influence of temperature on antenna sensors is complex. Temperature changes cause thermal expansion of the antenna dielectric substrate, thereby affecting the air gap thickness of the double-layer antenna sensor. The temperature expansion coefficient of the FR4 dielectric substrate is about 1.5×10^{-5}/°C, which causes a slight change in the air gap thickness under temperature changes. However, due to the relatively small variation, it does not have a significant influence on the antenna's resonant frequency. In addition, temperature can also affect the relative dielectric constant of the antenna dielectric substrate, and the thermal coefficient of the relative dielectric constant of FR4 is 200 ppm/°C.[39] The changes in the air gap thickness and relative dielectric constant resulted in a synthetical change in the resonant frequency of the antenna, and the temperature effects on antenna sensors can be addressed through the temperature compensation of resonant frequency. In addition, the sensor proposed in this paper generally needs to be measured under static conditions, and external interference such as structural vibration may lead to inaccurate measurement results. To avoid the influence of external vibration on the antenna's resonant frequency, it is advisable to measure the resonant frequency multiple times and take the average value to ensure measurement accuracy. In addition, in some relevant literature, scholars are studying the dynamic interrogation methods of antenna sensor's resonant frequency, which can achieve hundreds of interrogations per second.[35,45] These technologies are expected to be applied in bolt loosening detection to explore the influence of vibration on antenna's resonant frequency.

In terms of limitations of the proposed bolt loosening detection method based on double-layer slotted circular patch antenna, the installation of the antenna sensor needs to be simplified, and the wireless interrogation distance also needs to be further improved. The installation of this antenna sensor requires a hole to be reserved inside the bolt shaft, thereby rendering the bolt processing and sensor installation relatively complex. Furthermore, the current wireless interrogation distance of the antenna sensor remains limited in its applicability; exploring wireless interrogation methods with longer distances could enhance their suitability for engineering practice. Investigating a more stable resonant frequency interrogation method under varying environmental conditions also helps to overcome the limitation of this bolt loosening detection method, which is suitable only for static monitoring scenarios.

Conclusion

This paper presents an innovative method for detecting bolt loosening using a double-layer slotted circular patch antenna. The designed antenna sensor can be installed on the bolt head. As the preload on the bolt changes, the longitudinal length of the bolt undergoes a corresponding variation, affecting the air gap thickness in the double-layer antenna. This change in air gap thickness leads to a shift in resonant frequency, which enables the detection of bolt loosening through the resonant frequency shift of the antenna sensor. In this article, simulations of the double-layer slotted circular patch antenna were conducted to study the relationship between the air gap thickness and the resonant frequency of the antenna. A series of experimental tests were also conducted to demonstrate the effectiveness of the sensing performance of the proposed double-layer slotted circular patch antenna sensor. The proposed double-layer slotted circular patch antenna significantly reduces the sensor size compared to previous antenna sensors and has a higher sensitivity of 626.57 MHz/mm, which makes it more suitable for bolt loosening detection. Despite the promising results, some concerns still need to be addressed, such as the environmental temperature influences on the antenna-based bolt loosening sensor, the need for simpler and more convenient sensor installation methods, as well as the long-distance wireless interrogation technique. These issues will be investigated in further work to improve the effectiveness of the antenna-based bolt loosening detection method.

Declaration of conflicting interests

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