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A bolt loosening detection method based on patch antenna with overlapping sub-patch

Songtao Xue[1,2], Xianzhi Li[1], Liyu Xie[1], Zhuoran Yi[1] and Guochun Wan[3]

Abstract

Bolts are widely used in civil engineering, and the detection of bolt loosening is of great significance to ensure the safety of a structure. This paper introduces a new method for detecting bolt loosening using a customized detachable strain sensor based on a patch antenna. A patch antenna with overlapping sub-patch is proposed to measure the longitudinal elongation of the entire bolt shaft, indicating the loosening state of the bolt. When the bolt is fastened, the elongation of the bolt under tension will change the combined length of the underlying patch and the radiation sub-patch, consequently increasing or decreasing the resonant frequency of the antenna. The resonant frequency of the antenna can be measured by the vector network analyzer. Furthermore, with wireless interrogation of the strain sensor based on the patch antenna, the proposed method can also be used in the wireless detection of bolt loosening. The authors conducted a finite element analysis of the bolt and the electromagnetic simulations of the antenna. They designed the detection sensor and conducted a series of experimental tests to demonstrate how a bolt under different applied preloads can be effective and feasible under the proposed method.

Keywords

Bolt loosening detection, structural health monitoring, patch antenna, resonant frequency, passive wireless sensor

Introduction

As simple and reliable low-cost connections, bolted joints have been widely used in various engineering structures, especially in steel structures.[1–3] However, many factors such as dynamic loads, chemical attack, and poor working conditions can lead to bolt loosening,[4,5] which damages the connection ability of the bolt and sometimes, it even leads to the failure of an entire structure. For example, in 2012, a tunnel ceiling collapsed in the Yamanashi prefecture in Japan. Nine people died in this accident.[6] The main cause of this collapse was corrosion failure and the bolt loosening in the concrete ceiling. Many similar accidents occur each year as well as delays such as those caused by loosened joints in the UK railroad network.[7] Between 2013 and 2015, UK trains experienced almost 1800 delays due to failure of their insulated block joints fastened by bolts. If the bolt weaknesses could have been detected, it would have saved the railroad approximately $14,000,000 U.S. dollars (10 million pounds).[7] Delays and accidents can be effectively avoided if the bolt loosening is detected in time and the corresponding repair measures are adopted. Therefore, bolt loosening detection is of great importance for the safety and reliability of a structure. These examples clearly state the case for an effective bolt loosening detection method to ensure that the tension of the bolt remains secure during service.[8]

Traditional bolt loosening detection methods, such as regular visual inspection, are sometimes inaccurate and can only qualitatively evaluate bolt loosening. The bolt loosening detection methods based on tap testing, which focused on the change of acoustic signals when tapping on structures and judged the bolt loosening status from the change in those signals,[9,10] However, these methods are not sensitive to the early loosening of the bolt. In past decades, with the rapid development of structural health monitoring, several attractive methods for the detection of bolt loosening were developed, such as impedance-based methods,[11–14]

[1]Department of Disaster Mitigation for Structures, Tongji University, Shanghai, China
[2]Department of Architecture, Tohoku Institute of Technology, Sendai, Japan
[3]Department of Electronic Science and Technology, Tongji University, Shanghai, China

Corresponding author:
Liyu Xie, Department of Disaster Mitigation for Structures, Tongji University, Room B508, Building of Civil Engineering, Siping Road 1239, Shanghai 200092, China.
Email: liyuxie@tongji.edu.cn

vibration-based methods,[15,16] wave-based methods,[17–19] and automated vision-based methods.[20,21] These methods all contributed to the bolt loosening detection, however, some methods still have limitations in practical use such as poor sensitivity to the early bolt loosening, high costs, or high requirements for the detection environment.

In recent years, some bolt loosening detection methods based on embedded sensors have been developed. The principle of these methods is to find suitable sensors to capture the longitudinal elongation of the bolt, and then use the elongation to calculate the variation of loosening status of the bolt. For example, a bolt tension detection system with a strain sensor housed inside the bolt to detect the bolt loosening,[22] or a smart bolt which can detect both the axial and shear forces by using embedded fiber Bragg gratings sensors.[23] The methods mentioned above have demonstrated their effectiveness, but the sensors and the signal acquisition system usually need to be wired, resulting in complex installation and numerous wires. Furthermore, these sensors usually need a real-time power supply during signal acquisition, which limits the practical use of these detection methods.

In this regard, the antenna-based sensing technology, which has the advantages of passive and wireless detection, can overcome the above shortcomings.[24–26] Various antenna-based sensors have been proposed for strain sensing, temperature sensing, displacement sensing, crack sensing, screw relaxing detection, and package opening detection.[27–30] For example, Wen et al. proposed a passive antenna-based sensor to indicate the tightened/relaxed screw status.[29] Wang et al. proposed a package opening detection method based on the unfolding or folding of a flexible antenna.[30] Yi et al. proposed a passive wireless antenna sensor for strain and crack sensing by the resonant frequency shift of the antenna.[31] Tchafa et al. proposed a microstrip patch antenna sensor for simultaneous strain and temperature sensing by the shift of two fundamental resonant frequencies.[32] Daliri et al. proposed a wireless strain sensor using a circular microstrip patch antenna.[33] Cho et al. proposed a frequency doubling antenna sensor for strain and crack sensing.[34] However, for those sensors just mentioned, which are based on the monolithic patch antenna,[31–34] issues of an incomplete strain transfer ratio and insufficient bonding strength compromise the sensitivity of the sensors and limit their use in practice. In recent years, some unstressed antenna sensors were proposed. Xue et al. proposed a displacement sensor based on a normal mode helical antenna, a passive wireless crack sensor based on a patch antenna with an overlapping sub-patch, and a crack sensor based on a patch antenna fed by capacitive microstrip lines.[35–37] Caizzone et al. proposed a crack sensor based on two mutual coupling planar-inverted F antennas.[38] The unstressed antenna sensor focuses on the relative movement of the antenna components, and it has the advantage of being simple to install and detachable, thus, the unstressed antenna sensor can be used as the strain sensor to measure bolt loosening.

In this article, we developed a new bolt loosening detection method based on a patch antenna with an overlapping sub-patch. This antenna when connected to the bolt is used as a detachable strain sensor to measure the longitudinal elongation of the entire bolt shaft, which shows the loosening state of the bolt. The fixing device and the connecting rod of patch antenna were designed, one end of the connecting rod was connected to the bottom of the bolt, and the other end was connected to the movable sub-patch, so as to transfer the elongation of the bolt shaft to the sub-patch and change its position. When the preload of the bolt changes, the bolt's longitudinal elongation changes accordingly; then, the combined length of the underlying patch and the radiation sub-patch changes because of the movement of connecting rod, consequently inducing a shift of the antenna's resonant frequency. In this detection system, the vector network analyzer (VNA) was used to acquire and analyzed the signal from the antenna with overlapping sub-patch, and then the resonant frequency of the antenna can be obtained. The resonant frequency of the antenna with overlapping sub-patch can be measured wired or wirelessly by the VNA. When the patch antenna with overlapping sub-patch was connected to and fed by the VNA through the coaxial line, the antenna reflection loss curve S_{11} can be measured and then the resonant frequency can be obtained. When the wide-band antenna was connected to the VNA and used as interrogation antenna, the backscattering signal of the patch antenna with overlapping sub-patch can be wirelessly received and analyzed by the VNA to get the resonant frequency. In this detection system, the patch antenna with the overlapping sub-patch not only serves as a sensing unit but also has the function of wireless energy transmission and wireless data communication, which gives it the advantage of passive wireless sensing.

The rest of the paper is organized as follows: In the methodology section, the innovative concept of the bolt loosening detection method based on the patch antenna with an overlapping sub-patch is introduced and the sensing mechanism is illustrated. In the simulation study section, the finite element analysis of the bolt deformation under the preload is performed, and the simulation of the patch antenna with overlapping sub-patch is conducted. In the experimental study section, a series of experimental tests are performed on a bolt under different applied preloads to demonstrate the performance of the proposed method for bolt loosening detection. The section ends with a discussion on further research potential of the proposed bolt loosening detection method and conclusions

Methodology

Bolt loosening detection method based on patch antenna sensor

The principle of the proposed detection method is that the bolt shaft has longitudinal elongation under the preload, and the longitudinal elongation changes with the axial tension of the bolt. Thus, when the bolt is loosened, the axial tension of the bolt changes and the longitudinal elongation of the bolt shaft changes accordingly. The bolt is connected to a customized detachable strain sensor based on a patch antenna with an overlapping sub-patch, and the variation in the bolt's longitudinal elongation induces the change of the overlapped length between the underlying patch and a radiation sub-patch. The change of the overlapped length leads to a changed electric length of the combined radiation patch, which results in the shift of the antenna resonant frequency. The signal of the antenna can be received and analyzed by the VNA; then, the resonant frequency can be obtained. Therefore, by the resonant frequency shift of the patch antenna with overlapping sub-patch, the bolt loosening can be detected immediately and quantitatively. The concepts of the method are summarized as Figure 1.

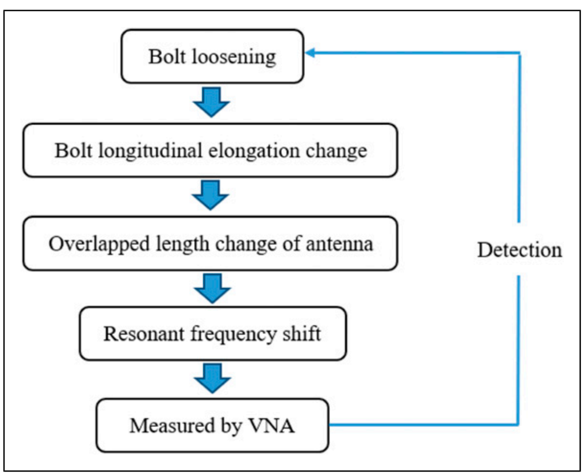

Figure 1. The bolt loosening detection method based on patch antenna sensor.

The patch antenna with overlapping sub-patch

The patch antenna with overlapping sub-patch for bolt loosening detection is shown as Figure 2. The antenna consists of a partially covered underlying patch and a moveable overlapping sub-patch, which connect to the bolt. When the bolt loosens and the longitudinal elongation of the bolt changes, the position of the sub-patch moves with it. According to the cavity model theory, the combined patch can be treated as a resonant cavity, and the resonant frequency is related to the dimensions of the combined radiation patch. Once the relative position between the underlying patch and the movable sub-patch changes, the electric length of the combined radiation patch changes accordingly and induces a shift in the resonant frequency of the antenna.

A rectangular patch antenna with the electrical length is L_e, and the electrical width is W_e. The resonant frequency of the antenna can be calculated as

$$f_{mn} = \frac{c}{2\pi\sqrt{\varepsilon}}\sqrt{\left(\frac{m\pi}{L_e}\right)^2 + \left(\frac{n\pi}{W_e}\right)^2} \tag{1}$$

where m and n represent the order of the longitudinal direction and width direction respectively. c is the speed of light in a vacuum; ε is the dielectric constant of the dielectric substrate; f_{mn} is the resonant frequency when the antenna is resonant at m order in the longitudinal direction and at n order in the width direction.

The top view and side view of the patch antenna with overlapping sub-patch are shown in Figure 3. The two copper radiation sheets of the underlying patch and the sub-

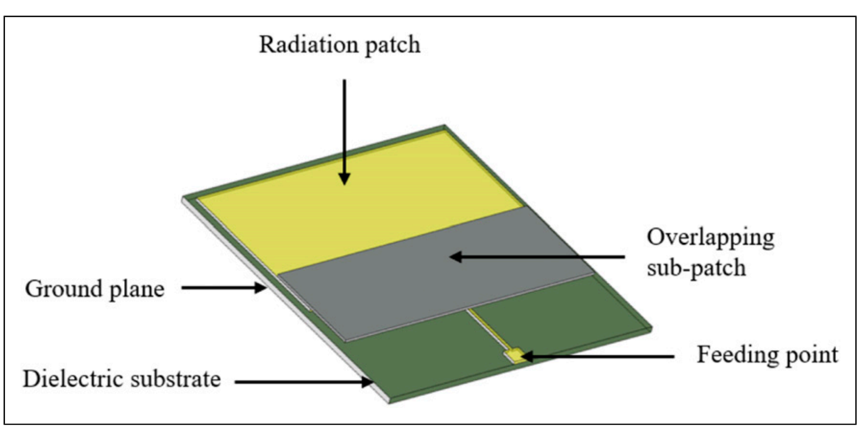

Figure 2. The patch antenna with overlapping sub-patch.

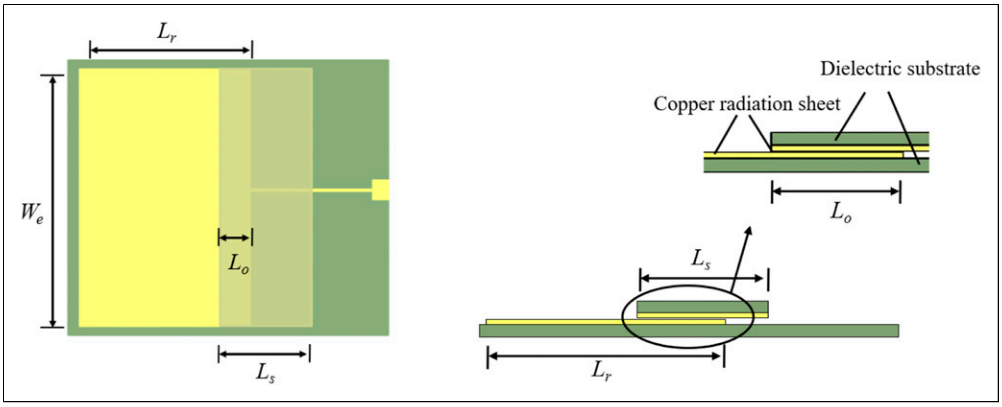

Figure 3. Top and side view of the patch antenna with overlapping sub-patch.

patch are closely attached as a combined radiation patch. Since the overlapped length only affects the length rather than the width of the combined radiation patch, the longitudinal direction's fundamental resonant frequency of the antenna can be calculated as

$$f_{10} = \frac{c}{2L_e\sqrt{\varepsilon}} \tag{2}$$

and the electrical length L_e can be calculated as

$$L_e = L_r + L_s - L_o \tag{3}$$

where L_r is the underlying radiation patch length, L_s is the length of the sub-patch, and L_o is the overlapped length between the underlying radiation patch and the covering sub-patch.

When the bolt loosens and the longitudinal elongation of the bolt changes, the connection between the bolt and the sub-patch cause the position of the moveable sub-patch to change. The change of the overlapped length of the underlying patch and the sub-patch affect the resonant frequency of the antenna as

$$f'_{10} = \frac{c}{2(L_r + L_s - L_o - \Delta L_o)\sqrt{\varepsilon}} \tag{4}$$

where ΔL_o is the change of the overlapped length and is equal to the longitudinal elongation change of the bolt shaft. Equation (4) can be rewritten as

$$f'_{10} = \frac{c(L_r + L_s - L_o + \Delta L_o)}{2\left[(L_r + L_s - L_o)^2 - (\Delta L_o)^2\right]\sqrt{\varepsilon}} \tag{5}$$

Since the longitudinal elongation change of the bolt shaft is insignificant compared with the dimensions of the patch antenna, the denominator increment $(\Delta L_o)^2$ can be ignored and equation (5) can be rewritten as

$$f'_{10} = \frac{c(L_r + L_s - L_o + \Delta L_o)}{2(L_r + L_s - L_o)^2\sqrt{\varepsilon}} \tag{6}$$

Based on equations (2) and (6), the fundamental resonant frequency shift of the patch antenna in the longitudinal direction can be determined by

$$\Delta f_{10} = \frac{c}{2(L_r + L_s - L_o)^2\sqrt{\varepsilon}}\Delta L_o \tag{7}$$

where Δf_{10} is the fundamental resonant frequency shift of the patch antenna in the longitudinal direction, which changes linearly with the overlapped length, ΔL_o.

Simulation study

The finite element analysis of the bolt elongation under preload

The bolt tension changes under the preload, and the bolt shaft has longitudinal elongation when the bolt tension changes. To investigate the longitudinal elongation of the bolt shaft under the preload, the finite element analysis was conducted.

A simplified preload-tension relationship is shown in equation (8), which has been widely used in the industry as a basic theory for fastening the bolt.[39,40]

$$P = kDF \tag{8}$$

where P is the preload torque that was applied to the bolt; k is the dimensionless factor, which is influenced by many variables, such as the contact surface conditions and materials; D is the nominal diameter of the bolt, and F is the axial tension of the bolt. Since there are many factors that would affect the dimensionless factor k, $k = 0.15$ can be used as a rough guide of the dimensionless factor.

In the finite element analysis, the bolt size was selected as M20; thus, the diameter of the M20 bolt thread is 20 mm, and the strength grade of the bolt was 6.8. Generally, when the bolt was fastened, the axial pretension of the bolt was about 70% of the yield tension, and the axial pretension decreased as the bolt loosened. When the bolt was fully loosened, the axial pretension of the bolt was zero. The applied axial pretension when the M20 bolt was fastened was about 105 kN, and the corresponding preload of the bolt was about 300 Nm according to the different friction conditions of the contact surface.

The bolt connected to steel plates shown in Figure 4, and the length of the bolt shaft is 100 mm. The bolt is made of steel (with elastic modulus of E = 200 Gpa, and Poisson's ratio is μ = 0.3). The finite element analysis results showed that the longitudinal elongation of the bolt shaft under 105 kN axial pretension was 0.2 mm. Thus, when bolt status varies from fastened to loosened, the longitudinal elongation of the bolt shaft changes by about 0.2 mm.

The simulation of the patch antenna with overlapping sub-patch

The preload of the bolt will elongate the bolt shaft, and the elongation change will induce a sub-patch displacement via a connecting rod. According to the theoretical calculation in the methodology section, the patch antenna with overlapping sub-patch had a resonant frequency shift in the longitudinal direction when the overlapped length of the antenna changed. Therefore, there is a correlated relationship between the antenna resonance frequency, the overlapped length, and the preload of the bolt. In this section, the dimensions of the patch antenna with overlapping sub-patch were determined and modeled using ANSYS High Frequency Structure Simulator (HFSS) Version 19.0 software. A series of simulations were conducted to demonstrate the antenna's operating performance and resonant frequencies with different overlapped lengths.

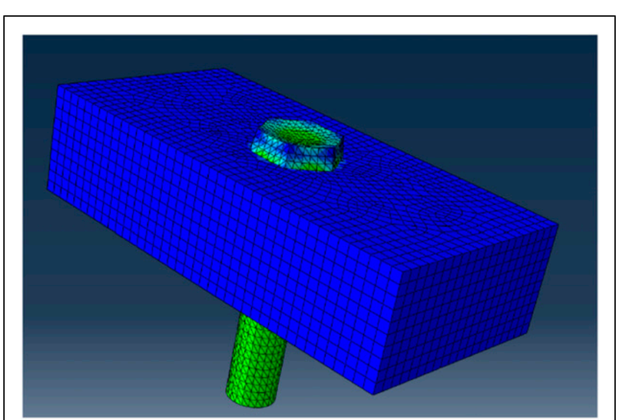

Figure 4. The finite element analysis of the bolt.

The patch antenna with overlapping sub-patch consists of an underlying patch and a sub-patch. They were both modeled in HFSS, as shown in Figure 5. The dimensions of the antenna are shown in Table 1. The underlying patch and the sub-patch were made up of a copper radiation sheet and dielectric substrate, respectively. The dielectric material making up the substrate was the Rogers RT 5880 laminate and the relative dielectric constant of the dielectric substrate is 2.2. The patch antenna with overlapping sub-patch was arranged inside an air-box with a size larger than the antenna about a quarter wavelength to ensure computational accuracy of far-field radiation.

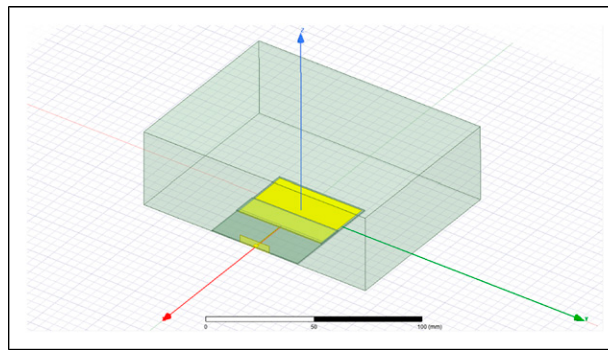

Figure 5. The model of the patch antenna with overlapping sub-patch in HFSS.

Table 1. The dimensions of the patch antenna with overlapping sub-patch.

Parameters	W_e(mm)	L_r(mm)	L_s(mm)	L_o(mm)
Dimensions	47	32	13	11.5–12.0

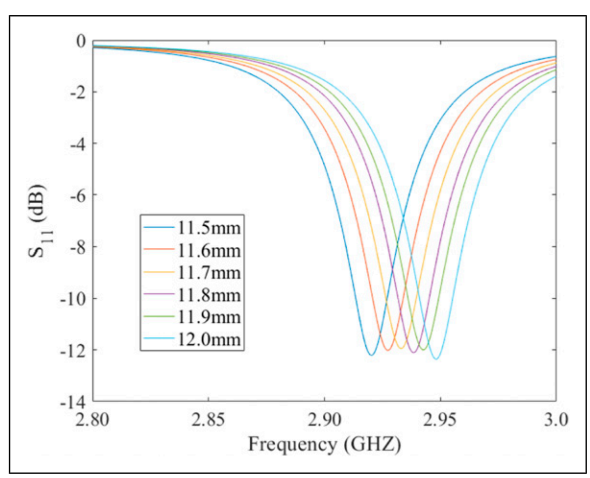

Figure 6. S_{11} curves of the antenna with different overlapped lengths.

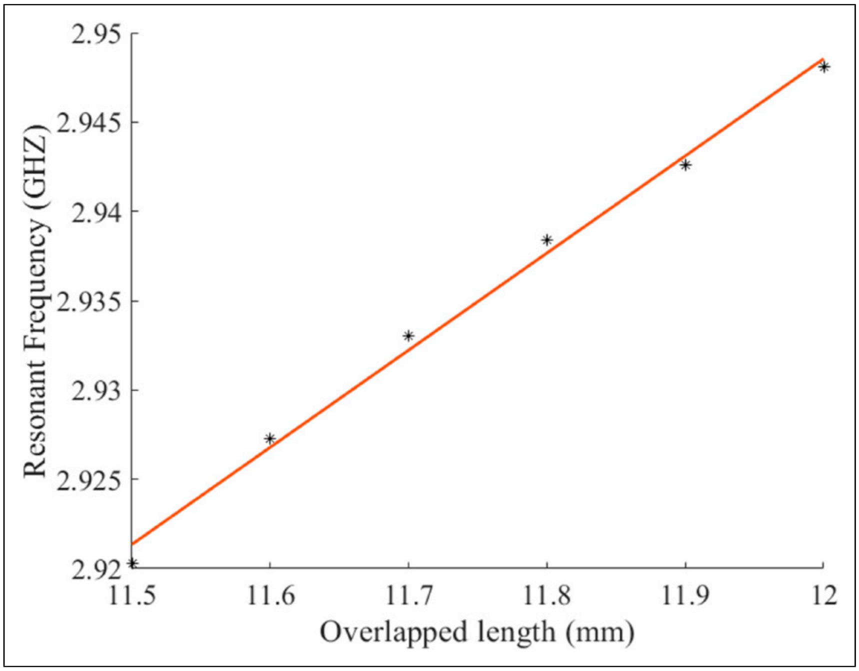

Figure 7. Antenna resonant frequency with different overlapped lengths.

To study the relationship of the antenna resonant frequency and the overlapped length, a series of simulations were carried out where the overlapped length changed from 11.5 mm to 12.0 mm. The patch antenna with overlapping sub-patch was fed by a wave port, and the reflection loss curve S_{11} of the antenna is shown in Figure 6. The frequency corresponding to the minimum point of each curve was the resonant frequency of the antenna with different overlapped lengths, which are shown in Figure 7. The shift of the resonant frequency with different overlapped lengths of the antenna are approximately linear.

From the simulation results of the patch antenna with an overlapping sub-patch, we can see that the resonant frequency of the antenna shifts linearly with the change of the overlapped length. When the overlapped length changes 0.1 mm, the resonant frequency of the antenna shifts to about 5.44 MHz; thus, the longitudinal elongation of the bolt shaft can be measured accurately by the resonant frequency shift, and the loosening state of the bolt can then be obtained.

The wireless interrogation simulation of the patch antenna sensor

The patch antenna with overlapping sub-patch can be interrogated wirelessly by the wide-band antenna to get the resonant frequency shift and detect the bolt loosening wirelessly. The wide-band antenna and the patch antenna with overlapping sub-patch were modeled in HFSS (Figure 8). The distance between the interrogation antenna and the patch antenna sensor was set as 30 mm. The

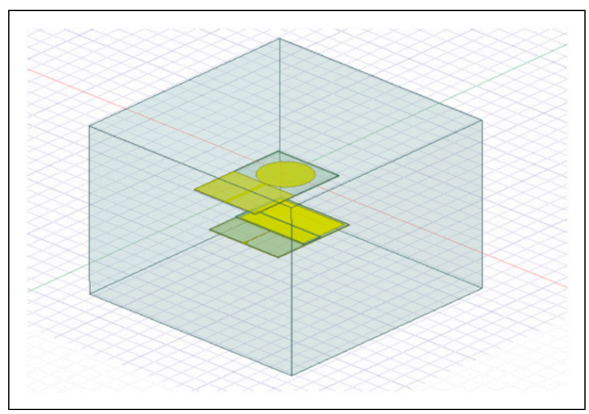

Figure 8. The model of the wide-band interrogation antenna and the patch antenna sensor.

dimensions of the patch antenna with overlapping sub-patch are in Table 1, and the dimensions of the wide-band antenna are shown in Figure 9 and Table 2. The wide-band antenna is made up of a copper radiation sheet and dielectric substrate, and the material of the dielectric substrate was the Rogers RT 5880 laminate.

The wide-band antenna was used as the interrogation antenna and the patch antenna with overlapping sub-patch was used as the strain sensor to detect the bolt loosening. The overlapped length of the underlying patch and the sub-patch changed from 11.5 mm to 12.0 mm to indicate the longitudinal elongation of the bolt shaft caused by the bolt loosening. The wide-band antenna can wirelessly receive

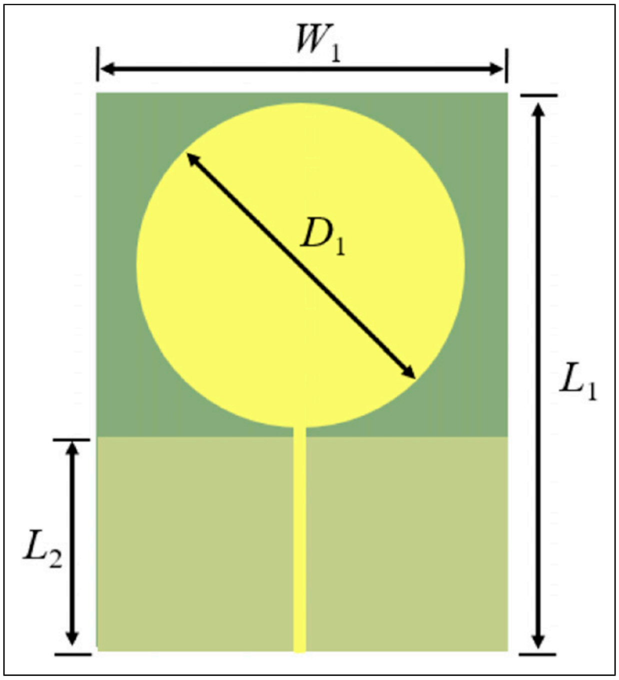

Figure 9. The top view of the wide-band interrogation antenna.

Table 2. The dimensions of the wide-band interrogation antenna.

Parameters	W_1(mm)	L_1(mm)	L_2(mm)	D_1(mm)
Dimensions	45	66	31	32

the backscattering signal of the patch antenna with overlapping sub-patch, as an interrogation antenna to get the radar cross section (RCS) curve. The RCS curve was used to extract the resonant frequency of the patch antenna sensor at the local minimum of the curve. In the simulation study, the excitation of the wide-band interrogation antenna was set as a lumped port, the sweep type was set as interpolating, sweep points were set as 2001 points, and the sweep frequency range was set as 1 GHz–3 GHz. The boundary of the air-box was set as radiation boundary; the size of the air-box was larger than the antenna about a quarter wavelength to ensure computational accuracy. Figure 10 shows the RCS curves of the patch antenna sensor received by the interrogation antenna, and Figure 11 shows the resonant frequency of the patch antenna sensor with different overlapped lengths. The simulation results show that the change of resonant frequency with different overlapped lengths of the patch antenna sensor was approximately linear and can be interrogated wirelessly by the wide-band antenna; thus, the longitudinal elongation of the bolt shaft can be measured wirelessly. In the wireless simulation study, when the overlapped length of the patch antenna sensor changes 0.1 mm, the resonant frequency shifts about 6.33 MHz. Correspondingly, in the wired simulation, when the overlapped length changes 0.1 mm, the resonant frequency of the antenna shifts about 5.44 MHz. There is about 14% difference between the wired and wireless results when the interrogation distance is 30 mm. The main reason for the difference in sensitivity is the mutual coupling between the patch antenna sensor and the wide-band interrogation antenna,

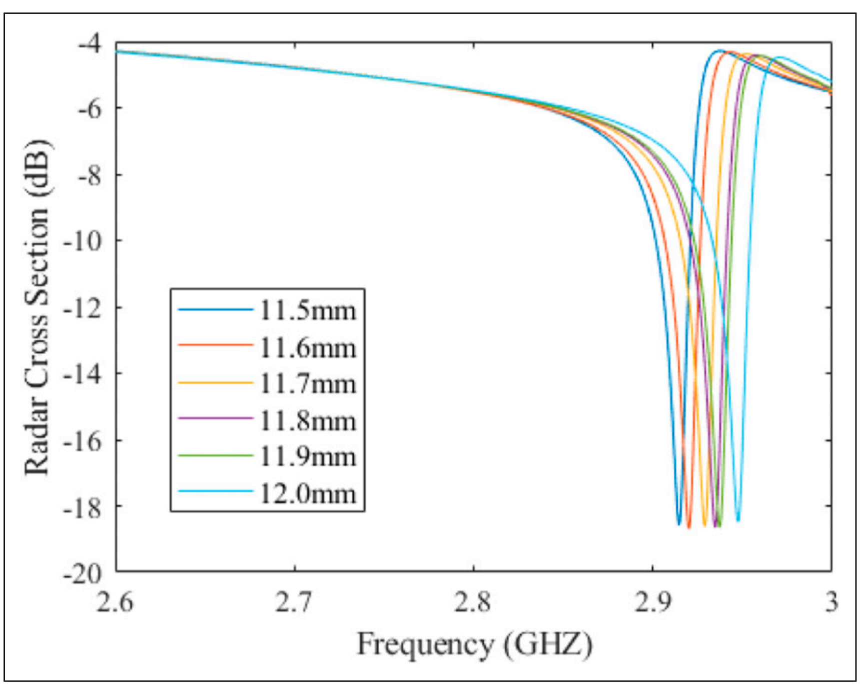

Figure 10. RCS curves of the antenna with different overlapped lengths.

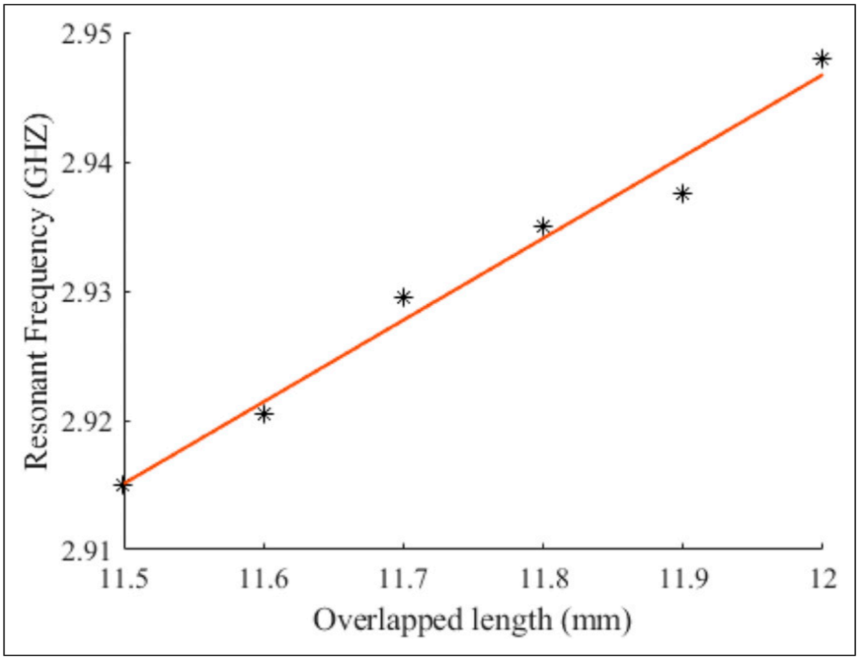

Figure 11. Antenna resonant frequency with different overlapped lengths.

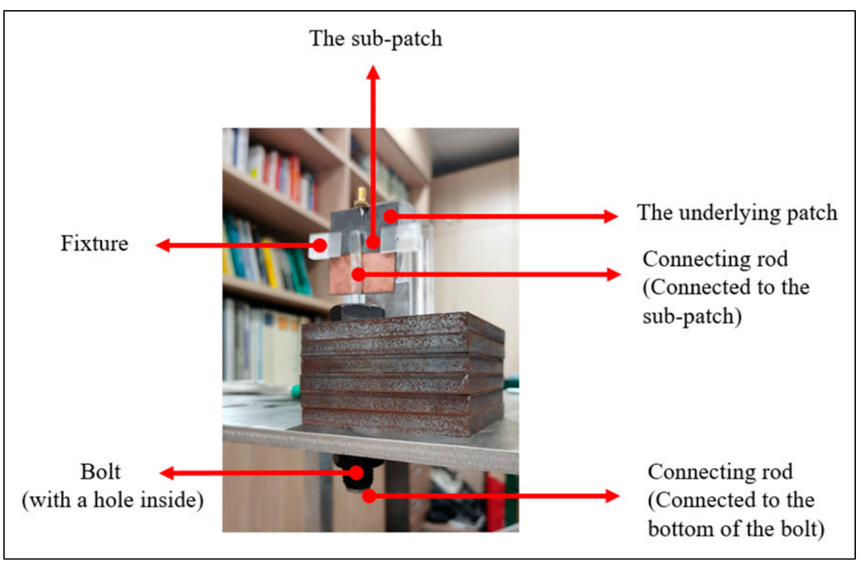

Figure 12. The experimental setup.

and the coupling effect is related to the distance between the two antennas. Therefore the interrogating distance should be fixed when the patch antenna sensor was wirelessly interrogated.

Experimental study

To demonstrate the performance and feasibility of the proposed method for bolt loosening detection, a series of experiments were set up to test the bolt under different applied preloads. The experimental setup is shown in Figure 12. The bolt size was M20, with a 6 mm diameter hole in the middle of the bolt. The fixing device and the connecting rod of patch antenna were made of acrylic, and the connecting rod travels through the conduit in the bolt shaft. One end of the rod was fixed to the bottom of the bolt, and the other end was fixed to the movable sub-patch. When the bolt's longitudinal elongation changes, the connecting rod attached to the sub-patch changes the position of the sub-patch. Therefore, the variation

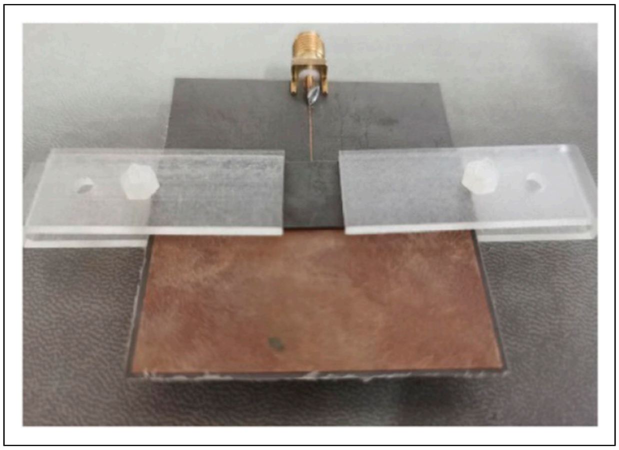

Figure 13. The patch antenna with overlapping sub-patch for bolt loosening detection.

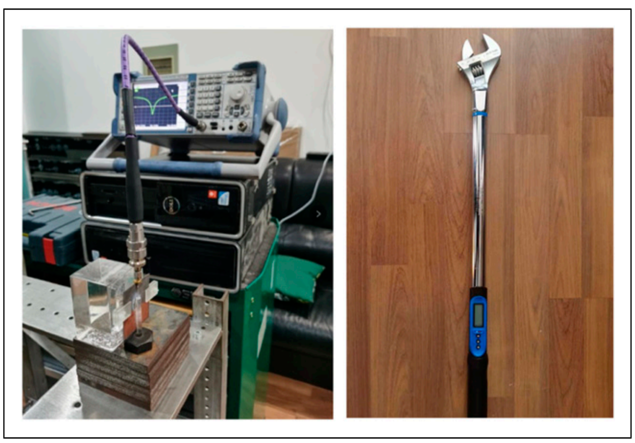

Figure 14. The vector network analyzer and torque wrench used in the experiment.

in the bolt's longitudinal elongation induces the change of the overlapped length between the underlying patch and a radiation sub-patch.

For the patch antenna with overlapping sub-patch, the dimensions of the underlying patch and the sub-patch were the same as the model in the simulation study section. Copper was selected as the material for the radiation sheets, Rogers RT 5880 laminate was selected as the middle dielectric substrate of the underlying patch and the overlapping sub-patch. The patch antenna with its overlapping sub-patch for bolt loosening detection is shown in Figure 13.

The wired bolt loosening detection

In the wired experimental tests, the patch antenna with the overlapping sub-patch was connected to and fed by the VNA through the coaxial line, and the VNA analyzed the reflected signal of the antenna as shown in Figure 14. The sweeping range of the VNA was selected to range from 2.8 GHz to 3 GHz. The antenna reflection loss curve S_{11} can be measured by the VNA, and the frequency corresponding to the minimum point of the curve is the resonant frequency of the antenna.

A torque wrench shown in Figure 14 was used to apply the preload. The applied preload when the bolt fully fastened was 180 Nm in the experimental tests; it is less than the value according to the specification since there was a hole in the middle of the bolt shaft and the cross-sectional area of the bolt shaft decrease. The applied preload corresponding to a half of the fully fastened preload was defined as the half-fastened preload. First, use the torque wrench to fasten the bolt and the indication of the torque wrench was 180 Nm. Then loosen the bolt with the torque wrench until the indication of the torque wrench was 90 Nm,

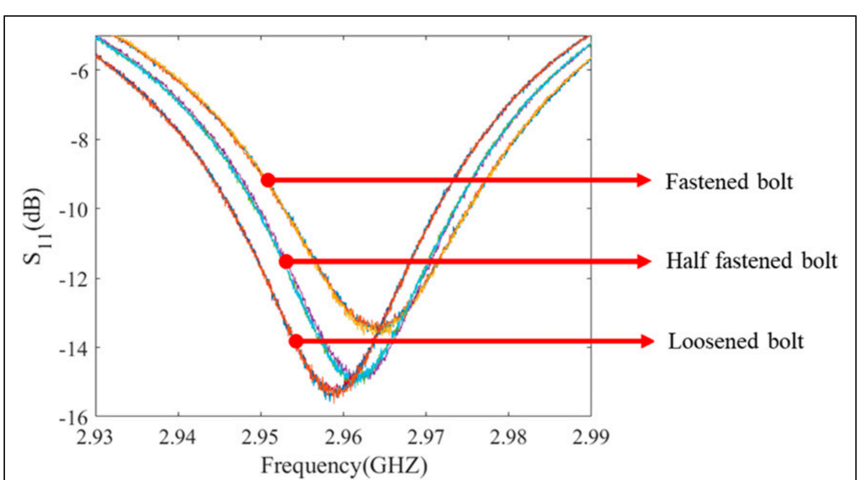

Figure 15. S_{11} curves of the antenna under different bolt loosening states.

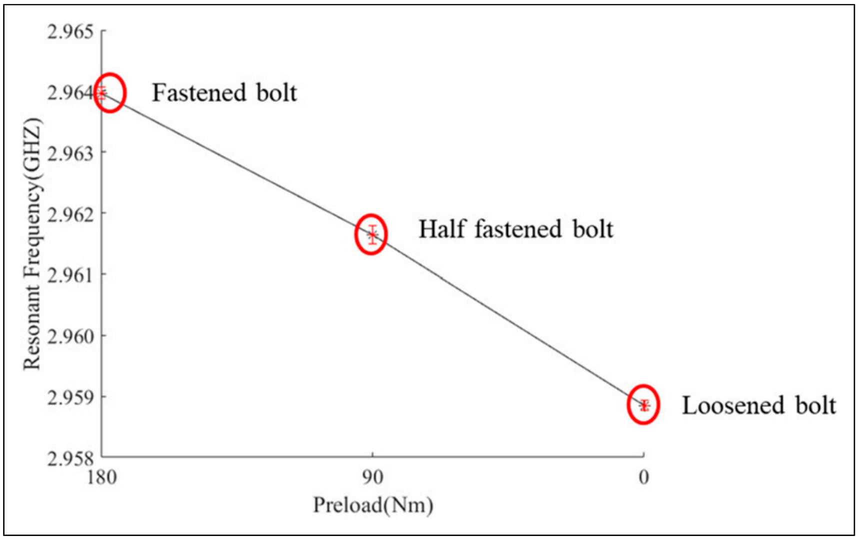

Figure 16. Antenna resonant frequency under different bolt loosening states.

the bolt state was half-fastened. Finally, use the torque wrench to loosen the bolt completely and the indication of the torque wrench was 0 Nm. In every state that the bolt from fastened to loosened, the S_{11} curves of the patch antenna with overlapping sub-patch were measured three times, the curves shown as Figure 15. The curves were fitted by a quadratic function in the range near the minimum point, and the frequency that corresponding to the minimum point of the curve was the resonant frequency of the patch antenna with overlapping sub-patch. The corresponding antenna resonant frequency that the bolt under different loosening states as shown in Figure 16, the variation of the bolt loosening state can induce a significant change in the resonant frequency of the antenna.

The experiment results show that the resonant frequency of the patch antenna with overlapping sub-patch shift with the bolt loosening, since the bolt loosening changes the bolt's longitudinal elongation and then changes the relative position of the sub-patch and the underlying patch. The resonant frequency of the patch antenna with overlapping sub-patch changed about 5 MHZ when the bolt from fastened to loosened.

To quantitative study the relationship of the antenna resonant frequency and the applied preload to the bolt, the torque wrench was used to apply eight preload levels from 20 Nm to 180 Nm with an increment of 20 Nm. Figure 17 and Figure 18 show the variation of the S_{11} curve and antenna resonant frequency in the process of the bolt being fastened.

The experimental results were linearly fitted to the straight line shown in Figure 18, different resonant frequencies states of the antenna corresponding to different preloads of the bolt, and the resonant frequency of the antenna changed linearly with the different preloads applied

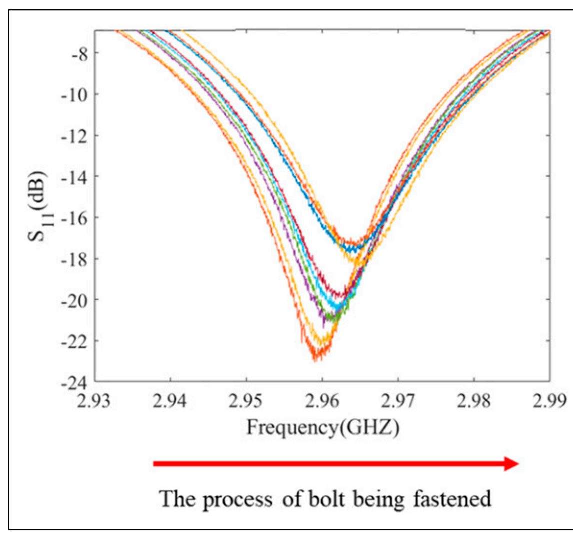

Figure 17. S_{11} curves of the antenna under different preloads.

to the bolt. Thus, the bolt loosening can be quantitatively detected by the measurement of the antenna resonant frequency shift.

The wireless bolt loosening detection

To demonstrate the feasibility of the proposed method for wireless bolt loosening detection, experimental tests were conducted wherein the patch antenna sensor interrogated wirelessly. A wide-band antenna shown in Figure 19 was used as the interrogation antenna and connected to the VNA through the coaxial line. The working band of the wide-band antenna was from 1 GHz to 3 GHz. The backscattering signal of the patch antenna with overlapping sub-patch

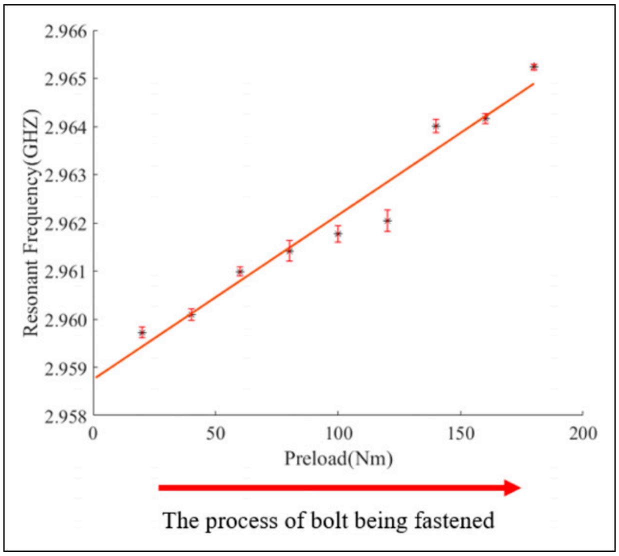

Figure 18. Antenna resonant frequency under different preloads.

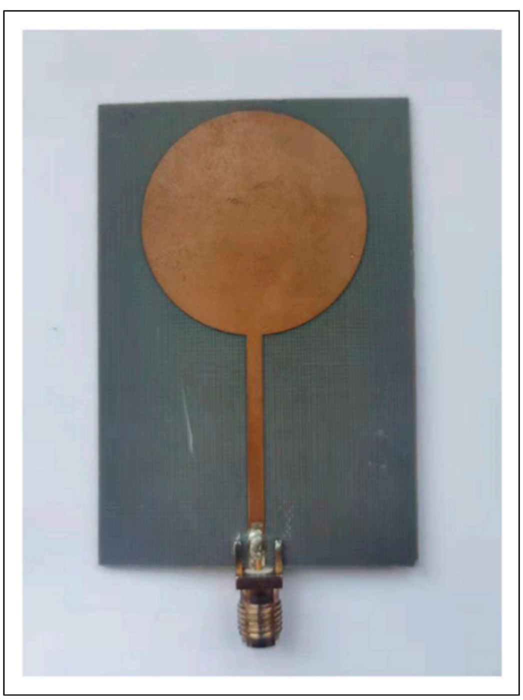

Figure 19. A wide-band interrogation antenna.

could be wirelessly received by the wide-band antenna, and the signal was analyzed by the VNA to get the RCS curves. Then, the resonant frequency was extracted from the patch antenna sensor at the local minimum of the curve. Figure 20 shows the interrogation antenna and the patch antenna sensor. The distance between the interrogation antenna and the patch antenna sensor was about 30 mm since the

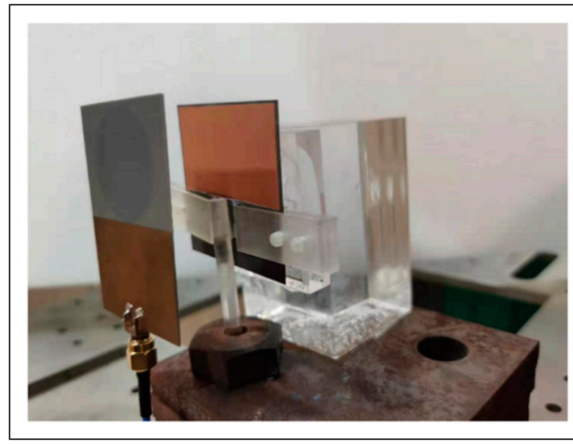

Figure 20. The interrogation antenna and the patch antenna sensor.

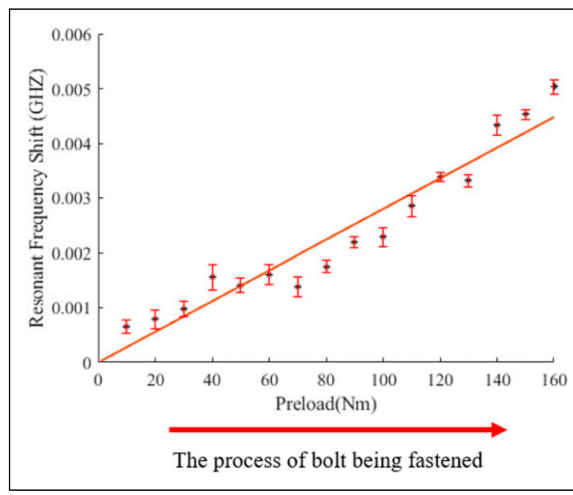

Figure 21. Antenna resonant frequency shift in wireless interrogation experiment.

influence of environment noise increased with the interrogation distance.

The torque wrench was used to apply the preload with a increment of 10 Nm, and the resonant frequency shift is shown in Figure 21. The resonant frequency under different preloads were linearly fitted to the straight line. The wireless interrogation experimental results show that the resonant frequency of the patch antenna sensor shifts linearly when the preload of the bolt changes. In the experimental study, there is about 19% difference in sensitivity between the wired and wireless results when the distance between the wireless interrogation antenna and the antenna sensor is 30 mm. The mutual coupling between the two antennas can disturb the sensitivity and the initial resonant frequency of the combined patch antenna. And environmental electromagnetic interference will influence the sensitivity as well.

The interrogating distance is required to keep constant during the test so that the wirelessly interrogated resonant frequency shift of the patch antenna sensor can be used to detect the loosening of bolts quantitatively.

Conclusions

This paper introduced a new bolt loosening detection method based on patch antenna with overlapping sub-patch. The bolt loosening can be quantitatively detected by the resonant frequency shift of the patch antenna sensor. The finite element analysis of the bolt and the electromagnetic simulations of the patch antenna with overlapping sub-patch were conducted to demonstrate the relationship between the antenna's resonant frequency shift and the bolt loosening. The resonant frequency of the patch antenna sensor shift with the bolt loosening and the sensitivity was studied. A series of experimental tests were also conducted to demonstrate the effectiveness of the proposed method for bolt loosening detection. Furthermore, with wireless feeding and interrogation of the patch antenna sensor, the proposed method can also be used in wireless bolt loosening detection. Simulations and experimental tests verified the feasibility of the proposed method. Despite the promising results reported in this study, some problematic issues and challenges must be met, including the need for a study of environmental effects and the wireless interrogation distance limitations, which will be investigated in future work.

Declaration of conflicting interests

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ORCID iDs

Songtao Xue https://orcid.org/0000-0002-1314-5781
Zhuoran Yi https://orcid.org/0000-0002-4204-2079

References

1. Wang T, Song G, Liu S, et al. Review of bolted connection monitoring. *Int J Distrib Sens Netw* 2013; 9: 871213.
2. Xu J, Chen R, Chen H, et al. Fast registration methodology for fastener assembly of large-scale structure. *IEEE Trans Ind Electron* 2017; 64: 717–726.
3. Wang F, Mobiny A, Van Nguyen H, et al. If structure can exclaim: a novel robotic-assisted percussion method for spatial bolt-ball joint looseness detection. *Struct Health Monit* 2020: 1475921720923147.
4. Wang F and Song G. Bolt-looseness detection by a new percussion-based method using multifractal analysis and gradient boosting decision tree. *Struct Health Monit* 2020; 19: 2023–2032.
5. Wang F, Ho SCM, Huo L, et al. A novel fractal contact-electromechanical impedance model for quantitative monitoring of bolted joint looseness. *IEEE Access* 2018; 6: 40212–40220.
6. Kyodo, 2012/12/04. *KOFU, Fatal Tunnel Collapse Blamed on Aging Bolts*, The Japan Times, https://www.japantimes.co.jp.
7. Temitope SJ. *Condition Monitoring of Bolted Joints*. Sheffield, South Yorkshire, England: Ph.D. Thesis, The University of Sheffield, 2015.
8. Ding Y, Ren P, Zhao H, et al. Structural health monitoring of a high-speed railway bridge: five years review and lessons learned. *Smart Struct Syst* 2018; 21: 695–703.
9. Kong Q, Zhu J, Ho SCM, et al. Tapping and listening: a new approach to bolt looseness monitoring. *Smart Mater Struct* 2018; 27: 07LT02.
10. Zhang Z, Liu M, Su Z, et al. Quantitative evaluation of residual torque of a loose bolt based on wave energy dissipation and vibro-acoustic modulation: a comparative study. *J Sound Vib* 2016; 383: 156–170.
11. Parvasi SM, Ho SCM, Kong Q, et al. Real time bolt preload monitoring using piezoceramic transducers and time reversal technique-a numerical study with experimental verification. *Smart Mater Struct* 2016; 25: 085015.
12. Wang T, Liu S, Shao J, et al. Health monitoring of bolted joints using the time reversal method and piezoelectric transducers. *Smart Mater Struct* 2016; 25: 025010.
13. Yang J, Liu P, Yang S, et al. Laser based impedance measurement for pipe corrosion and bolt-loosening detection. *Smart Struct Syst* 2015; 15: 41–55.
14. Chen D, Huo L and Song G. EMI based multi-bolt looseness detection using series/parallel multi-sensing technique. *Smart Struct Syst* 2020; 25: 423–432.
15. Amerini F, Barbieri E, Meo M, et al. Detecting loosening/tightening of clamped structures using nonlinear vibration techniques. *Smart Mater Struct* 2010; 19: 085013.
16. Kopsaftopoulos FP and Fassois SD. Vibration based health monitoring for a lightweight truss structure: experimental assessment of several statistical time series methods. *Mech Syst Signal Process* 2010; 24: 1977–1997.
17. Zhao N, Huo L and Song G. A nonlinear ultrasonic method for real-time bolt looseness monitoring using PZT transducer-enabled vibro-acoustic modulation. *J Intell Mater Syst Struct* 2019; 31: 364–376.
18. Fierro GPM and Meo M. IWSHM 2017: Structural health monitoring of the loosening in a multi-bolt structure using linear and modulated nonlinear ultrasound acoustic moments approach. *Struct Health Monit* 2018; 17: 1349–1364.
19. Yang Y, Ng C-T and Kotousov A. Bolted joint integrity monitoring with second harmonic generated by guided waves. *Struct Health Monit* 2018; 18: 193–204.

20. Zhang Y, Sun X, Loh KJ, et al. Autonomous bolt loosening detection using deep learning. *Struct Health Monit* 2019; 19: 105–122.
21. Ramana L, Choi W and Cha Y-J. Fully automated vision-based loosened bolt detection using the Viola-Jones algorithm. *Struct Health Monit* 2018; 18: 422–434.
22. Mekid S, Bouhraoua A and Baroudi U. Battery-less wireless remote bolt tension monitoring system. *Mech Syst Signal Process* 2019; 128: 572–587.
23. Ren L, Feng T, Ho M, et al. A smart "shear sensing" bolt based on FBG sensors. *Measurement* 2018; 122: 240–246.
24. Zhang J, Tian G, Marindra A, et al. A review of passive RFID tag antenna-based sensors and systems for structural health monitoring applications. *Sensors* 2017; 17: 265.
25. Xu X and Huang H. Battery-less wireless interrogation of microstrip patch antenna for strain sensing. *Smart Mater Struct* 2012; 21: 125007.
26. Tata U, Huang H, Carter RL, et al. Exploiting a patch antenna for strain measurements. *Meas Sci Technol* 2009; 20: 015201.
27. Ozbey B, Erturk V, Demir H, et al. A wireless passive sensing system for displacement/strain measurement in reinforced concrete members. *Sensors* 2016; 16: 496.
28. Chung K L, Wang L, Luo J, et al. Comparative study on directional sensitivity of patch-antenna-based strain sensors. *Int J RF Microw Comput-Aided Eng* 2020; 30: e22398.
29. Inserra D, Hu W, Li Z, et al. Screw relaxing detection with UHF RFID tag. *IEEE Access* 2020; 8: 78553–78564.
30. Wang W, Sadeqi A, Nejad HR, et al. Cost-effective wireless sensors for detection of package opening and tampering. *IEEE Access* 2020; 8: 117122–117132.
31. Yi X, Cho C, Cooper J, et al. Passive wireless antenna sensor for strain and crack sensing-electromagnetic modeling, simulation, and testing. *Smart Mater Struct* 2013; 22: 085009.
32. Tchafa FM and Huang H. Microstrip patch antenna for simultaneous strain and temperature sensing. *Smart Mater Struct* 2018; 27: 065019.
33. Daliri A, Galehdar A, John S, et al. Wireless strain measurement using circular microstrip patch antennas. *Sens Actuators A Phys* 2012; 184: 86–92.
34. Cho C, Yi X, Li D, et al. Passive wireless frequency doubling antenna sensor for strain and crack sensing. *IEEE Sens J* 2016; 16: 5725–5733.
35. Xue S, Yi Z, Xie L, et al. A displacement sensor based on a normal mode helical antenna. *Sensors* 2019; 19: 3767.
36. Xue S, Xu K, Xie L, et al. Crack sensor based on patch antenna fed by capacitive microstrip lines. *Smart Mater Struct* 2019; 28: 085012.
37. Xue S, Yi Z, Xie L, et al. A passive wireless crack sensor based on patch antenna with overlapping sub-patch. *Sensors* 2019; 19: 4327.
38. Caizzone S and DiGiampaolo E. Wireless passive RFID crack width sensor for structural health monitoring. *IEEE Sens J* 2015; 15: 6767–6774.
39. Nassar SA and Sun TS. Surface roughness effect on the torque-tension relationship in threaded fasteners. *Proc Inst Mech Eng J: J Eng Tribol* 2007; 221: 95–103.
40. Nassar SA, El-Khiamy H, Barber GC, et al. An experimental study of bearing and thread friction in fasteners. *J Tribol* 2005; 127: 263–272.