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Research on transmission performance of a surface acoustic wave sensing system used in manufacturing environment monitoring*

Cong-cong LUAN[1], Xin-hua YAO[†‡1,2], Qiu-yue CHEN[1], Jian-zhong FU[1,2]
(*[1]State Key Laboratory of Fluid Power and Mechatronic Systems, College of Mechanical Engineering,*
Zhejiang University, Hangzhou 310027, China)
(*[2]Key Laboratory of 3D Printing Process and Equipment of Zhejiang Province, College of Mechanical Engineering,*
Zhejiang University, Hangzhou 310027, China)
[†]E-mail: yaoxinhuazju@foxmail.com

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Abstract: Surface acoustic wave (SAW) sensors show great promise in monitoring fast-rotating or moving machinery in manufacturing environments, and have several advantages in the measurement of temperature, torque, pressure, and strain because of their passive and wireless capability. However, very few studies have systematically attempted to evaluate the characteristics of SAW sensors in a metal environment and rotating structures, both of which are common in machine tools. Simulation of the influence of the metal using CST software and a series of experiments with an SAW temperature sensor in real environments were designed to investigate the factors that affect transmission performance, including antenna angles, orientations, rotation speeds, and a metallic plate, along with the interrogator antenna–SAW sensor antenna separation distance. Our experimental measurements show that the sensor's optimal placement in manufacturing environments should take into account all these factors in order to maintain system measurement and data transmission capability. As the first attempt to systematically investigate the transmission characteristics of the SAW sensor used in manufacturing environment, this study aims to guide users of SAW sensor applications and encourage more research in the field of wireless passive SAW sensors in monitoring applications.

Key words: Transmission performance; Surface acoustic wave (SAW); Sensor; Manufacturing environment; Monitoring
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1 Introduction

Integrating advanced sensor systems into machine tools enables improved understanding of the process conditions and facilitates optimization and control of the quality of the formed part (Marinescu and Axinte, 2011). Up to 75% of all geometrical errors of machined parts can be due to the effects of temperature in the machine tools (Xia *et al*., 2014). Spindle units in machine tools, built within totally closed metallic shells, are hard-to-reach structures of crucial monitoring importance (Yao *et al*., 2015). Due to the necessary intrusion of the rotating process, wired sensors are typically not feasible for monitoring spindle units. Though using wireless sensors is a good solution, the enclosure structure of the spindle unit still poses a challenge for the power supply to those sensors. Because of the difficulty in opening the spindle shell and replacing the battery in it, the idea of battery power for a wireless sensor has to be rejected. In order to create wireless sensors working with

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[‡] Corresponding author

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ORCID: Cong-cong LUAN, http://orcid.org/0000-0001-6289-9400; Xin-hua YAO, http://orcid.org/0000-0003-0261-3938

long-lasting power supplies, several kinds of ambient energy sources (Hudak and Amatucci, 2008; Daxing Marian *et al.*, 2012; Szarka *et al.*, 2012; Zhang *et al.*, 2012) have been tried to generate electrical energy; but it is still hard to drive wireless sensors steadily and continuously (Li *et al.*, 2014). Therefore, the search for an accurate, flexible, and highly dynamic sensor technology continues to inspire researchers, and new developments are constantly emerging from leading research laboratories and companies.

Surface acoustic wave (SAW) sensors, due to their passive operation, wireless installation, freedom from maintenance, and ability to withstand extreme conditions, have emerged as favorable alternatives. Therefore, a number of successful applications of SAW sensors, including a car tire pressure monitoring system (Dixon *et al.*, 2006), monitoring the temperature of the refractory lining of a metal vessel (Fachberger and Erlacher, 2009), temperature measurement of high-speed high-voltage motors (Binder and Fachberger, 2011), concrete temperature monitoring (Kim *et al.*, 2015), monitoring of switchgear temperature (Hu *et al.*, 2014), and monitoring tool condition (Stoney *et al.*, 2012), have been reported in recent years. However, there are still hurdles remaining for the adoption of SAW sensors. The propagation of radio frequency (RF) signals is extremely difficult in complex manufacturing environments due to the abundance of stationary and moving metallic structures. Principally, multipath propagation, delay spread, multipath fading, and Doppler effect are important factors inducing transmission errors (Tang *et al.*, 2009), and these all exist in metallic and rotating structures. Moreover, frequency pulling (Boccard *et al.*, 2013) due to the metallic and rotating machinery in the manufacturing environment will also cause measurement errors. However, very few studies have attempted to evaluate the characteristics of SAW sensors in a metal environment and rotating structure, and it is the subject of this study.

In this paper, the theory and background of a surface acoustic wave are presented. Then, simulations and experiments describing the influence of a metallic plate are introduced. At last, we investigate the transmission performance in different scenarios with rotation experiments.

2 Surface acoustic wave

In 1965, White and Voltmer (1965) reported direct piezoelectric surface wave transduction by a spatially periodic electrode on the plane surface of a piezoelectric plate. Their discovery led to the development of SAW technology. Conventionally, SAW delay lines and resonators are two structures used in sensing applications (Borrero *et al.*, 2013). A single-port SAW resonator fabricated on the *YX* cut quartz piezoelectric substrate is shown in Fig. 1. An incident short-duration RF signal is transduced into an SAW, which propagates along the surface of the device setting up a standing wave and causing the device to resonate at a so-called center frequency. Several external factors, such as temperature, strain, and torque, will modulate this center frequency. An RF interrogator is used both to supply the energizing RF pulse and to detect the change in the resonant frequency of the SAW device (Stoney *et al.*, 2014). Consequently, the temperature or other measurable parameters applied on the sensor can be obtained by measuring the change of the center frequency.

As a wireless and passive sensor, it is still debatable whether the SAW sensor is suitable for monitoring a manufacturing environment, as in machine tools. The harsh environment for radio waves inside machine tools and spindles in metallic enclosures is primarily due to the complex reflective surfaces of their surroundings and the multiple fast-changing signal paths between rotating and stationary parts, which can cause substantial multipath and Doppler effects, leading to signal loss, distortion, and errors in received data (Wang *et al.*, 2008; Tang *et al.*, 2009; 2012). In (Tang *et al.*, 2009), an experimental testbed composed of a radio sensor mounted on a rotating spindle in a metal enclosure was used to study its data transmission reliability, and the results showed that the transmissions faced >20% packet error rate. Several methods have been suggested to improve the reliability of wireless sensors in such structures, and some of them reduce transmission errors effectively. However, SAW sensors are even more severely affected by harsh monitoring environments than general wireless sensors because the RF signal distortion will not only induce transmission errors but also cause measurement errors. As mentioned before, the

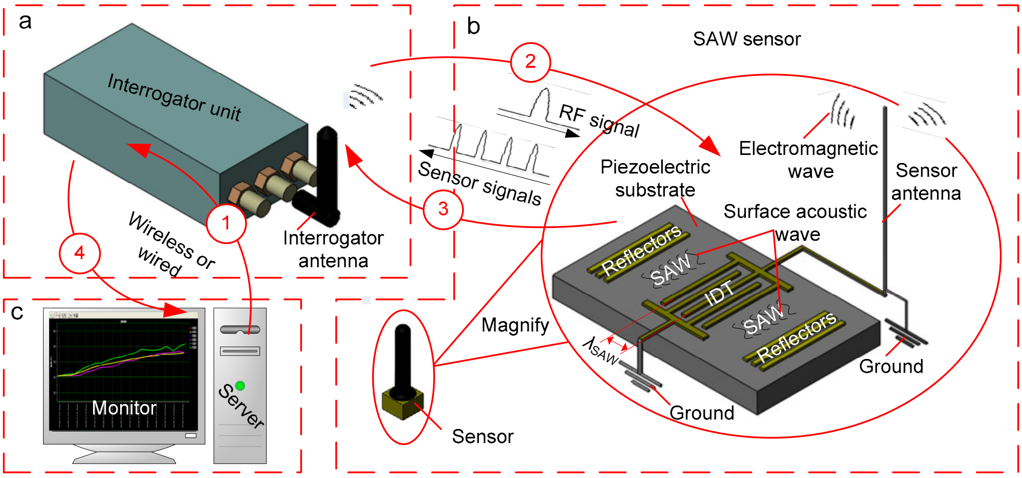


Fig. 1 Wireless passive surface acoustic wave sensing measurement system
λ_{SAW} refers to the period length of the interdigital transducer (IDT)

measurements using the SAW sensor are acquired by calculating the change of the center frequency of RF signals, and therefore a strongly disturbed signal or weakened response signal will lead to erroneous measurements because of the difficulties in measuring the change of the center frequency accurately.

In recent years, work has focused on technologies, including both the structural design of SAW sensors and the modification of communication algorithms, to overcome the constraints discussed above. The former aims to maximize the interrogation coverage, and the latter focuses on the avoidance of transmission errors or their correction. In (Sandacci and Gilkes, 2007), inductive communication elements and capacitive elements are chosen with resonant frequencies compatible with the frequency of the signals to be transferred between two portions that rotate relative to each other. A slot antenna type was identified as best joint solution for rotating shafts considering the radiation pattern and antenna gain based on antenna simulations (Binder *et al.*, 2009). A novel antenna combination involving ceramic and magnetic loop antennas for wireless interrogation of SAW resonators used on rotating machinery is presented by Boccard and Reindl (2012). Simulation, transmission, and dynamic temperature measurement results were carried out. A method based on a low-rank matrix to reduce the influence of interference caused by harsh wireless channel environments during resonance frequency measurements was reported by Liu *et al.* (2015). All these studies improve the performance of the SAW sensor in some respects. However, a systematic performance evaluation of SAW sensors in an environment with metallic parts and undergoing rotation is still lacking, and it is the foundation of performance improvement and the subject of this study.

3 Transmission characteristics in metallic environments

Machine tools, with a complex, poly-metallic environment, have significant influence on wireless transmission performance, according to antenna theory. The frequency pulling effect on antenna impedance due to the metallic environment, and the metallic cavity quality factor due to conducting materials in machine tools are two significant issues which may make the measurement impossible. It is necessary to investigate the influence of metals on the performance of an SAW sensing system. In this section, simulations and experiments on the influence of metallic plates are investigated. Radio signal strength is a basic characteristic of RF and it can be easily obtained without requiring additional hardware. A power indicator is defined to express the signal strength in this paper, which is expressed as the logarithm of the received signal power. Electric field strength (E-field) is independent of frequency in free space and the intensity of electric field strength is related to the distance from the sender. Besides, it decreases linearly with increased distance when expressed in logarithmic units (Haslett, 2008). The received signal power can be deduced from the electric field strength according to Eqs. (1)–(5):

$$P_\mathrm{u}\times 10^{-3}=\frac{\left(E\times 10^{-6}\right)^2}{120\pi}, \tag{1}$$

$$\xrightarrow{10\lg(\text{Eq. (1)})} \quad 10\lg P_\mathrm{u}=20\lg E-90-10\lg(120\pi), \tag{2}$$

$$P_\mathrm{u}=P_\mathrm{t}G_\mathrm{t}\big/(4\pi R^2), \tag{3}$$

$$P_\mathrm{r}=\frac{P_\mathrm{t}G_\mathrm{t}G_\mathrm{r}\lambda^2}{(4\pi)^2R^2}=\frac{P_\mathrm{u}G_\mathrm{r}\lambda^2}{4\pi}, \tag{4}$$

$$\xrightarrow{10\lg(\text{Eq. (4)})} \quad 10\lg P_\mathrm{r}=10\lg P_\mathrm{u}+10\lg[\lambda^2/(4\pi)]+10\lg G_\mathrm{r}, \tag{5}$$

where E is the electric field strength at the sensor antenna location, P_u is the power density at the sensor antenna location, P_r is the received power at the sensor antenna location, P_t is the transmitted power from the interrogator unit antenna, G_r is the sensor (receiver) antenna gain, G_t is the interrogator (transmitter) antenna gain, and λ is the wavelength.

3.1 Simulation with CST

Since planar structures are fairly common in machine tools, the simulations of the influence of a metallic plate are executed initially in CST MICROWAVE STUDIO (CST MWS). It is a very general approach based on the finite integration technique (FIT), which describes Maxwell's equations on a grid space and can be written in the time and frequency domains (Hirtenfelder, 2007). In this research, we selected the time domain solver and the time domain solution of Maxwell's equations as well as the boundary conditions as Eqs. (6)–(9).

$$\nabla\times\boldsymbol{H}=\boldsymbol{J}+\varepsilon_\mathrm{r}\frac{\partial\boldsymbol{E}}{\partial t}, \tag{6}$$

$$\nabla\times\boldsymbol{E}=-\mu_\mathrm{r}\frac{\partial\boldsymbol{H}}{\partial t}, \tag{7}$$

$$\boldsymbol{n}\times(\boldsymbol{E}_1-\boldsymbol{E}_2)=0, \tag{8}$$

$$\boldsymbol{n}\times(\boldsymbol{H}_1-\boldsymbol{H}_2)=0, \tag{9}$$

where $\boldsymbol{H}$ is the magnetic field, $\boldsymbol{E}$ is the electric field, ε_r is the relative permittivity, and μ_r is the relative permeability.

Considering actual manufacturing situations, three models have been derived in our simulations as shown in Fig. 2: (a) the model of a metallic plate below the interrogator antenna; (b) the model of a metallic plate in the middle, named the I-M-S model; (c) the model of a metallic plate on the side, named the I-S-M model. Table 1 summarizes the parameters used in the simulation. A 433 MHz helical antenna was established first and simulations were conducted based on this antenna. An aluminium plate of 100 mm×100 mm×1 mm size was chosen as the metal part, and a probe took the place of the SAW sensor to measure the electric field strength at different locations.

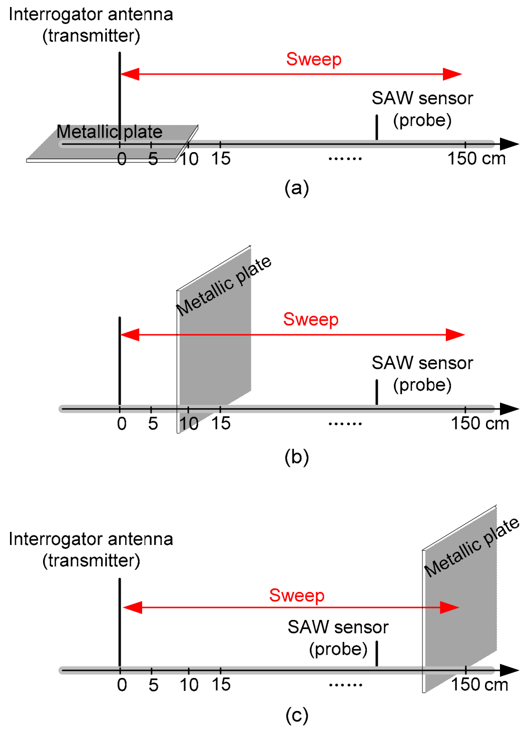


Fig. 2 Simulation models: (a) with the metallic plate underneath; (b) with the metallic plate in between; (c) with the metallic plate on the side

Fig. 3 gives the simulation results, from which it can be seen that the metallic plate has a significant influence on electric field strength. The metallic plate can strengthen the E-field when it is placed under the interrogator antenna, and the curve is not linear any more. Apparently, the effect is more obvious with the increase of the distance. Results with I-M-S or I-S-M simulations demonstrate that the E-field strength decreases dramatically in the vicinity of the metallic plate. Interestingly, some simulation points even strengthen the E-field at the distance of 35–145 cm in the I-S-M model and at the distance of 40–150 cm in the I-M-S model.

Table 1 Summary of simulation parameters

Parameter		Setting
Antenna	Type	Helical
	Center frequency	433 MHz
	Gain	3 dBi
	S-parameter	–49 dB at 433 MHz
Input	Port signal	Pulse
	Power stimulated	0.5 W (RMS)
Metal	Aluminium	100 mm×100 mm ×1 mm
Sweep	Range	0–150 cm
	Step	5 cm
Objective	E-field	dBV/m

RMS means root mean square

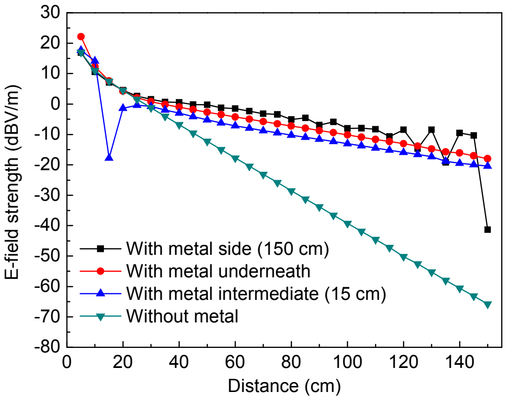


Fig. 3 Simulation results of E-field strength at different distance

Possible explanations for these results are as follows: (1) Metal reflective effect, which may be used to explain the metallic plate strengthening the electric field. Electromagnetic waves will be reflected back when they encounter the metal surface and the E-field will be strengthened when the incident wave and reflected wave undergo constructive interference. (2) Electromagnetic induction effect, which might explain the E-field weakening in the vicinity of the metal surface. An eddy current is created inside the metal due to electromagnetic induction when the RF signal arrives at the metal surface, and some of the E-field energy is absorbed at the same time. Moreover, the eddy currents will produce their own induced magnetic field whose magnetic field lines are perpendicular to the metal surface but in the opposite direction compared to the field strength of the incident wave. Therefore, the E-field strength decreases in the vicinity of the metallic plate. Besides, the metal shielding effect cannot be neglected when the metallic plate is placed between the interrogator antenna and the sensor antenna.

3.2 Experimental verification

Based on above simulation models, the influence of a metallic plate on transmission performance was investigated. A WTS-SG-1 wireless passive SAW sensing system was used, which is provided by the Salisense Technology Company, China. The interrogator unit's operating frequency range was 432–444 MHz. Here only a single-port SAW resonator sensor was used and its center frequency was 433 MHz. Table 2 shows the values of the parameters for the SAW sensing system. Considering the maximum read distance, the measurements were carried out in near field conditions (about 2λ distance), and not in the far field.

Experiments of the first simulation model were carried out as shown in Fig. 4. The interrogator antenna is fixed while the SAW sensor is moved along a given direction in steps of 10 cm. Other than the average power indicator, which is the focus of most attention, temperature standard deviation is another key parameter of concern.

Table 2 Summary of system parameters

Parameter	Value
Temperature range (°C)	−25–125
Sensor accuracy (°C)	±0.5
Sensor resolution (°C)	0.1
Sensor sensitivity (kHz/°C)	8.66
Power (dBm)	13±1
Maximum read distance (cm)	150
Sensor quality factor	10 000
Center frequency (MHz)	433

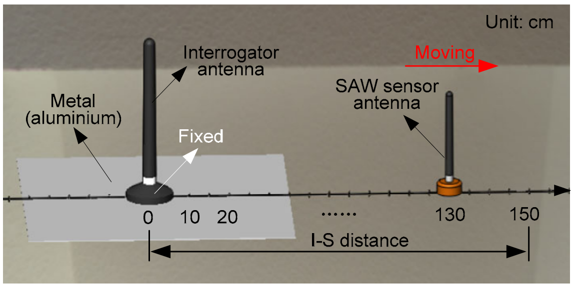


Fig. 4 Experiment on the influence of metal with the aluminium plate under the interrogator antenna

Fig. 5 shows that the power indicator and temperature standard deviation varied with distance irrespective of whether the metallic plate was located under the interrogator antenna or not. This suggests that the metallic plate could strengthen the E-field when it was placed under the interrogator antenna compared to when the plate was absent. An obvious explanation for the result is that the metallic plate plays a role of a non-ideal ground plane which creates virtual mirror charges and makes the monopole antenna a virtual dipole antenna.

It should be pointed out that the power indicator suddenly changed at some positions (such as 65, 105, and 135 cm) in the two experiments and this might be due to reflections from objects in the room. The temperature standard deviation shows that the stability of the testing temperature is related to the transmission distance (or rather, power strength), with enormous temperature fluctuations appearing at large distances. The performance of the SAW sensor improved when the metallic plate was placed below the interrogator antenna according to temperature standard deviations in Fig. 5.

With the metallic plate vertically placed, the experimental setup, as shown in Fig. 6, is built up with the interrogator antenna and SAW sensor fixed at the ordinate origin and at 50 cm, respectively, while the aluminium sheet is moved from −50 to 100 cm.

Fig. 7 shows the influence of the metal on the power indicator in the range of −30–80 cm. The straight line is the power strength without the metallic plate. When the aluminium sheet is placed between the interrogator antenna and the sensor antenna, as in the I-M-S model, the power strength decreases at all testing points (from 10 to 40 cm) and the metal shielding effect plays a dominant role. When the aluminium sheet is placed at the sides of the two antennas, as in the I-S-M model, the power indicator increased except at the points of −2 and 52 cm. The metal electromagnetic induction effect plays a major

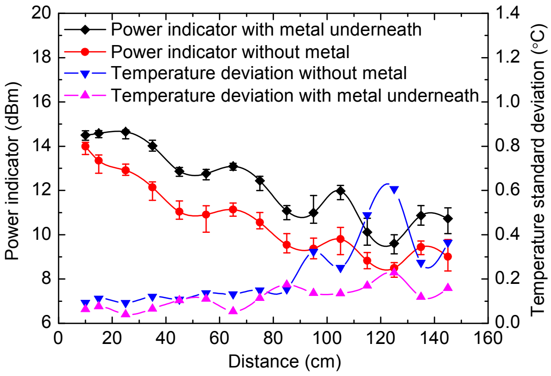


Fig. 5 Experimental results with and without the metallic plate underneath

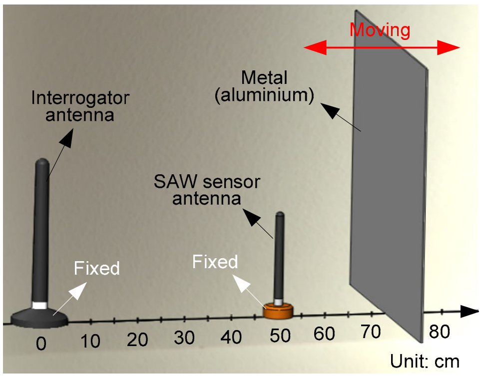


Fig. 6 Experiment of metal influence with the aluminium sheet vertically placed

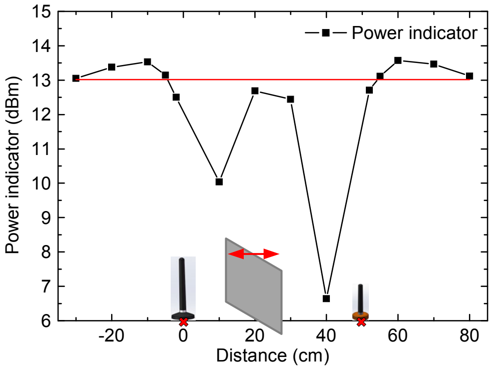


Fig. 7 Power indicator variation with different metallic plate positions

role at the points of −2 and 52 cm while the metal reflective effect does so at the other positions.

Both experimental and simulation results demonstrate that the metal does have significant influence on the radio transmission performance. Fortunately, there are many beneficial impacts that still need to be further tapped to improve the performance of an SAW sensing system. Optimal placement of the antenna is a key factor to be taken into account in view of the complex metal environments of machine tools.

4 Transmission performance with rotation experiments

Rotary motion is a common scenario in a manufacturing environment, such as spindle operation, and antenna orientations will change with spindle motion. In this section, the transmission performance of an SAW sensor on a rotating shaft and spindle model is studied, including the performance of the sensor with different antenna angles, different distances, and different rotating speeds. The received signal strength indicator and temperature measurement capability are the two parameters used to evaluate the SAW sensing system performance.

4.1 Antenna angle influence

Previous research has shown that antenna orientation has a significant impact on radio signal strength (Zhang *et al.*, 2014). Seeking the optimal angle between the interrogator antenna and the SAW sensor antenna to ensure the performance of the SAW sensing system is necessary. Fig. 8 shows the configuration of the antenna angle experiment. The SAW sensor is driven by a stepper motor in 30° increments stepwise to 12 angular positions counterclockwise during the experiment. With this setting, the transmission performance is expected to be affected by the angular position setting.

The average power and temperature standard deviations are shown in Fig. 9. The antenna angle has an important influence on the power strength, which decreases when the angle increases in the range of 0°–90°. It is worth mentioning that the metallic plate is undesirable for temperature measurement based on the temperature standard deviation in the figure as the angle becomes larger. The smaller is the angle, the better is the performance. The results will be different for different types of antenna, but the antenna angle should be regarded as a key factor to be considered when installing interrogator or sensor antennas.

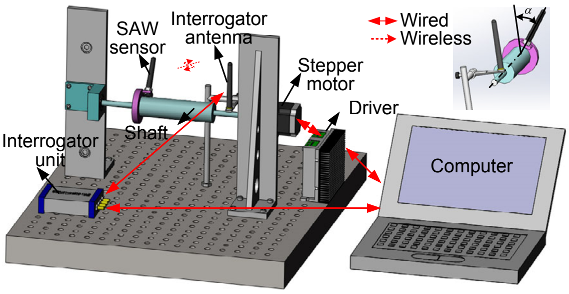


Fig. 8 Antenna angle experimental model

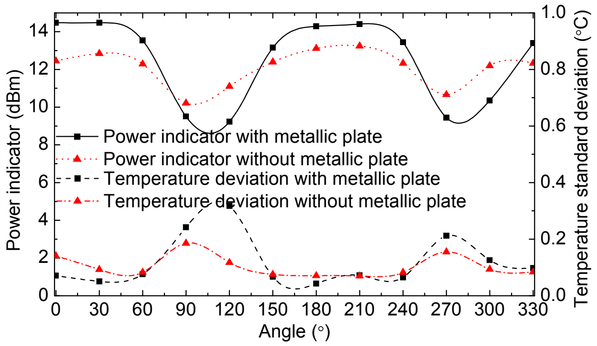


Fig. 9 Power indicator and temperature standard deviation with different angles

4.2 Influence of the location of the antenna on the shaft

Before mounting the SAW sensor on the spindle, the influence of the sensor antenna location is investigated independently. The experimental apparatus consists of a shaft (metallic bar) and a rotating plate (polylactic acid, PLA). The rotating plate equipped with the SAW sensor is rotated through four steps of 90° around its axis to measure the power indicator and temperature performance with respect to the interrogator antenna at 30 cm separation distance, as shown in Fig. 10. The ambient temperature is 19.3 °C. The distance between the sensor antenna and shaft (ds) is kept at 5, 10, 15, 20, and 25 mm, and the performance is investigated.

The graphical representation in Fig. 11 shows how the power indicator and temperature vary with different distances. The largest power strength is at the location of 90° and the lowest is 270°. This is because the distance between the interrogator antenna and SAW sensor is the smallest and has a clear line of sight (LOS) at the 90° position, whereas the LOS is entirely blocked at the 270° position, leading to the lowest power strength; sometimes even no RF signal was received. With careful observation, we find that the measured temperature seems to be related to the distance ds. When the distance ds is less than 10 mm, the temperature becomes lower than the room temperature, and when the distance ds is more than 15 mm, the temperature becomes nearly equal to the room temperature. No temperature value is given at 270° when ds is equal to 10 mm, because the signal power strength is too low to be eliminated during data processing in the interrogator unit. The results indicate that sensor location should be taken into consideration to ensure the SAW sensor performance.

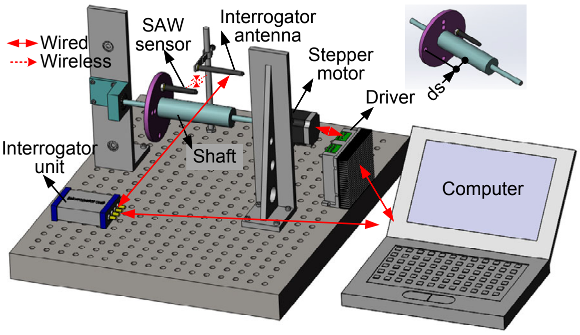


Fig. 10 Experimental setup for studying the influence of the location of the antenna on the metallic shaft

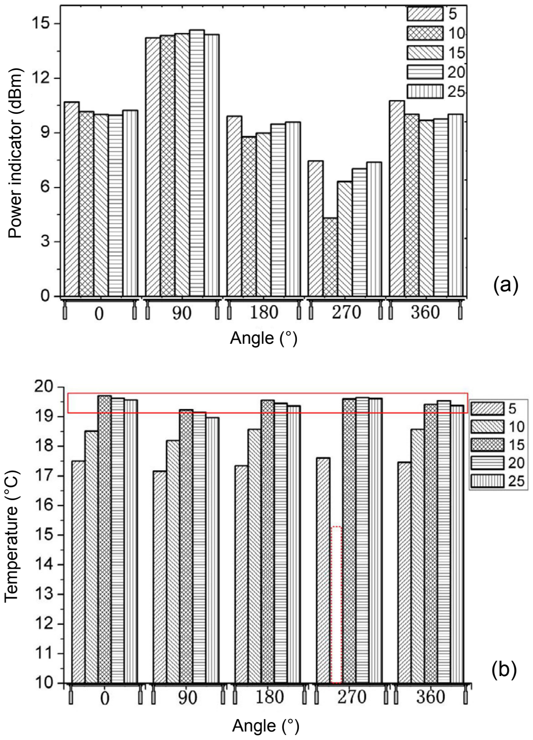


Fig. 11 Influence of the location of the antenna on the shaft at different distances (unit: mm): (a) power variation with different angles; (b) temperature variation

Fig. 12 shows the frequency pulling results at different angles and at different distances. The frequency corresponding to room temperature (432.3516 MHz) is taken as the reference frequency, which had been found beforehand for the SAW sensor used. The observed pulling effect is related to both the angular position and the distance. The angular position has major influence when the distance is more than 15 mm and has a maximum value of 4.645 kHz at 90°. The main reason for such a large frequency offset is that the sensor has a single-resonator rather than a dual-resonator architecture, and this structure is more influenced by the environment. Parasitic impedances due to the metallic environment will induce an impedance change of the sensor system. Since the SAW sensor equivalent circuit model is a series of inductors and capacitors, adding a transmission line whose characteristics vary with angular position will vary the global circuit impedance and hence the resonance frequency detected by the interrogator (Boccard *et al.*, 2013). Besides, conducting materials around the sensor will form some cavities, known as metallic cavities; when their quality factors overwhelm the sensor resonators, measurement is made impossible. All these factors will cause a frequency pulling which

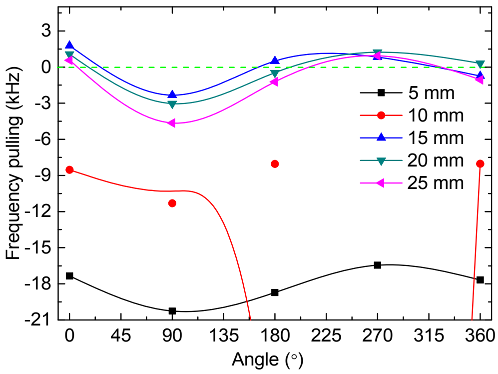
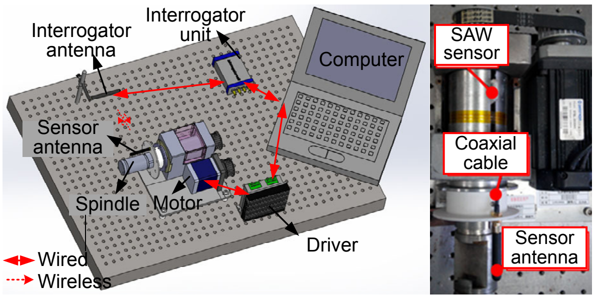


Fig. 12 Measured frequency pulling with different angles at different distances

will always yield a frequency decrease with respect to the sensor resonator resonance frequency. The location of SAW sensor optimization appears all the more important when using this kind of sensor in a manufacturing environment.

4.3 Experiment with spindle model

Based on all the above stationary results, a rotating experimental system was set up as shown in Fig. 13 and the home-made sensor was installed on the rotating spindle to monitor the temperature rise, as can be seen in Fig. 13b. The diameter of the spindle is 60 mm and the speed of rotation can be adjusted continuously in the range of 0–3000 r/min. For safety, the maximum rotating speed was selected as 2000 r/min in our experiment. In addition, a vibration isolation platform was used for the testbed to exclude external vibration.



(a) (b)

Fig. 13 Experiment with spindle model: (a) experimental setup; (b) sensor installation

With the motor driver turned off, the spindle with the SAW sensor was rotated in 45° steps to eight angular positions around the spindle to measure its power indicator. Two SAW sensor installation positions were measured whose ds values were equal to 10 and 20 mm. The results are shown in Fig. 14, and indicate that power increases in most positions when the SAW sensor is installed on a spindle compared with the shaft (Fig. 11a), especially in the range of 180°–360°. With the spindle rotating, the power indicator at different distances ds was measured with speed increment steps of 200 r/min up to 1600 r/min. The measurement results summarized in Fig. 14 show that the average power increased slightly with the rotation speed, and the power indicator standard deviation decreased remarkably when the spindle speeds were less than 600 r/min.

Fig. 15 shows the rise of spindle temperature during its rotation with different rotation speeds when the distance was 20 mm. Outliers occasionally occur because of the shadowing effect or external interference, and measures should be taken to reduce these fluctuations. Furthermore, the fluctuations decreased with increasing rotation speeds but they were always more than when stationary.

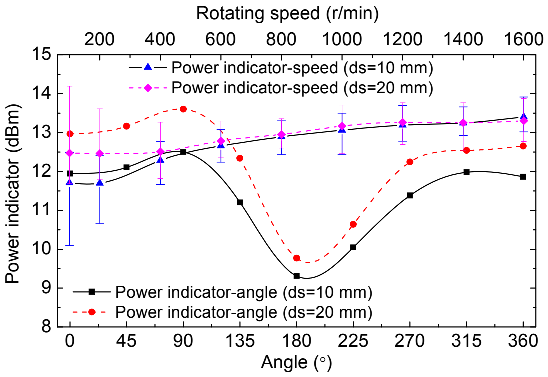


Fig. 14 Power indicator variation with angles and speeds

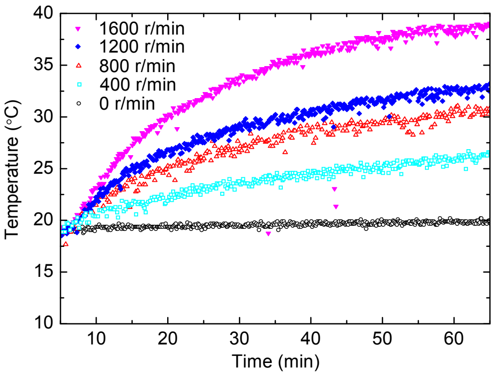


Fig. 15 Temperature rise with different rotation speeds

5 Conclusions

A series of experiments were carried out with an SAW temperature sensor in a metallic environment and rotating structures. Power indicator and temperature measurement capability were investigated under both stationary and rotating conditions. From this study, the following conclusions could be drawn regarding the transmission characteristics of the SAW sensor in metallic environments: (1) The results of experiment and simulation both demonstrate that the metal can strengthen the power when it is placed below the interrogator antenna but it can weaken or even block the power when it is placed beside the interrogator antenna in particular positions. (2) The angle between the interrogator and sensor antennas should be considered for different types of antennas. Circularly a polarized antenna is one of the best options to realize a larger signal coverage area. For a helical antenna, the sensor antenna should remain parallel to the interrogator antenna. (3) The distance between the sensor antenna and shaft surface also affects the power and temperature measurement capability, and the optimal distance needs to be determined. (4) Dynamic experiments in a rotating spindle apparatus demonstrate that using wireless passive temperature SAW sensor on spindle monitoring is feasible but some large temperature fluctuations exist, which have to be further studied. All the above factors should be taken into consideration when installing and arranging SAW sensors in a manufacturing environment.

As the first attempt to systematically investigate the transmission characteristics of an SAW sensor used in manufacturing environment, this study aims to guide users for applications of SAW sensors and to encourage more research in the field of wireless passive SAW sensors in monitoring applications. In future work, the performance of SAW sensors in a high-speed rotation spindle will be investigated in detail, with the optimal placement of sensors and error-avoidance methods, so as to realize their industrial applications.

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中文概要

题　目：声表面波传感系统制造环境监测通信性能研究

目　的：旋转和高速运动机械结构的状态监测因缺少有效的技术手段而成为制约其性能提升的关键因素。声表面波传感实现了传感器的无线和无源化，有望解决上述难题。本文旨在研究复杂制造环境中金属件和旋转运动对声表面波传感器通信性能的影响，为其应用提供理论基础和技术参考。

创新点：1. 揭示了金属件和传感器之间不同相对位置和距离对传感系统测量和通信性能的影响；2. 分析了机械结构旋转运动中影响传感系统通信性能的因素，为传感器结构设计和配置优化提供了参考依据。

方　法：1. 通过仿真计算，研究金属件对声表面波传感系统的影响；2. 实验研究金属环境及旋转运动中影响声表面波传感系统通信性能的关键因素。

结　论：1. 金属环境对声表面波传感系统有重要影响，传输天线下方的金属能够增强系统传输功率，但平行于天线附近的金属会削弱传输功率；2. 质询器天线与传感器天线的相对夹角对传感器通信性能有重要影响；3. 安装位置对传感器测量性能和信号传输功率均有显著影响；4. 动态实验证明了声表面波传感系统应用于主轴温度监测的可行性。

关键词：通信性能；声表面波；传感器；制造环境；监测