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Design and Fabrication of IoT Sensor in Air-conditioning Equipment for Failure Mode and Effects Analysis

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The energy conservation and carbon reduction required for a sustainable environment also include the reduction of ineffective energy losses. As global warming becomes increasingly serious, the demand for air-conditioning operation will inevitably increase. However, even if most air-conditioning equipment has basic sensors to detect the output pressure, air volume, and temperature, they are rarely able to detect abnormal vibration generated by the equipment. In this study, we developed a microvibration detector with the IoT function and applied this technology to the detection of air-conditioner failure. The research results can lead to the implementation of the self-detection function of air-conditioning equipment in the future, so that when the air-conditioning equipment exhibits initial abnormal vibration, real-time response measures can be taken to reduce energy losses resulting from further failures of the air-conditioning equipment.

1. Introduction

The autonomous detection technologies of commercially available air-conditioning equipment have become very mature, but most of them detect the output temperature and the pressure in the evaporator pipeline. We focus on predicting possible failure modes by another indirect vibration detection method. The results can help to prevent the air-conditioning equipment from consuming ineffective energy under poor operating conditions, which causes the unnecessary waste of resources and may result in equipment failure.

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2. Research Method

2.1 Literature review

The operation of air-conditioning equipment depends on cooperation among many components. Of these, the evaporator and compressor of the core components are two of the main sources of vibration. Therefore, there are many academic articles on studying and analyzing vibration. An adaptive passive vibration reduction control technology was proposed by Franchek *et al.*(1) for the purpose of reducing the vibration in mechanical structures as shown in Fig. 1. They explored the performance of the adaptive passive damper under different frequencies and conditions through experiments and numerical simulation. The results showed that the adaptive passive damping technology could clearly reduce the vibration induced by mechanical structures and improve the system stability and extend the system life.

Sabirin *et al.*(2) discussed the vibration characteristics induced by fluid pulsation in the compressor piping system. They explored the effect of the fluid pulsation on the vibration of the piping system through numerical simulation and experimental analysis. The results showed that the fluid pulsation clearly affected the vibration characteristics of the piping system and led to unstable equipment operation and structural damage.

The arrows in Fig. 2 indicate the displacement directions of the mass blocks, and the stiffness adaptation device shows that the resonant frequency can be changed by adjusting the neutralizer stiffness so as to effectively suppress vibration. In addition, Shi *et al.*(3) optimized the vibration isolation method of air-conditioning compressors to improve the comfort of campers. The results of their study indicated that the vibration generated during the operation of the air-conditioning compressor in the vehicle could clearly be reduced by the vibration isolation technology so as to improve the interior comfort of the vehicle.

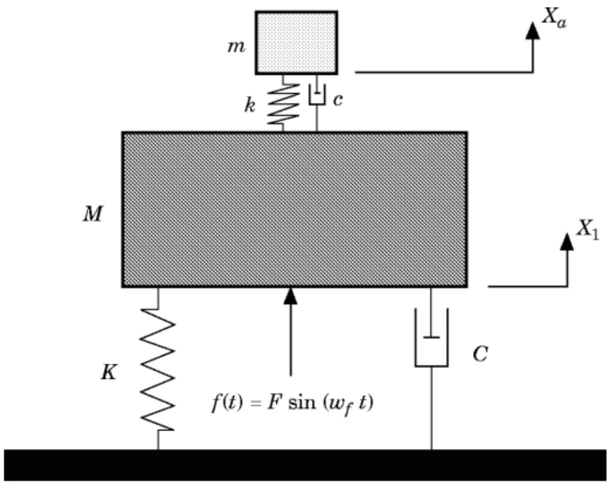


Fig. 1. Adaptive passive vibration reduction control technology.

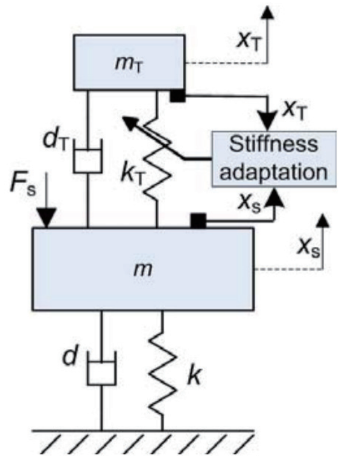
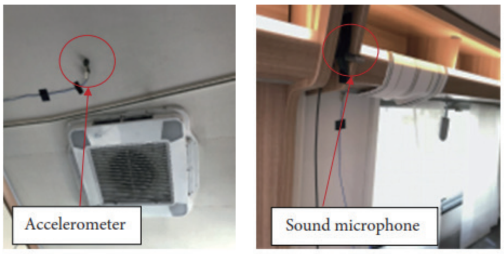


Fig. 2. (Color online) Two-mass oscillator model consisting of a main structure (*m*, *d*, *k*) and a vibration neutralizer (*mT*, *dT*, *kT*).

Figure 3 shows the experimental setup. An acceleration sensor is installed at a position corresponding to the compressor system to measure vibration. The real-time vibration data inside the vehicle during the operation of the compressor can be measured by the sensor and recorded. To confirm the impact of noise on comfort, a microphone is installed at the position shown in Fig. 3 to record ambient noise. With this setup, the ambient noise actually heard by passengers can be recorded to evaluate the noise environment inside the vehicle.

Lee *et al.*[(4)] arranged three measuring points for the compressor in the air-conditioning equipment, as shown in Fig. 4. The first measuring point is located in the upper part of the compressor, near the pipe joint. This position is helpful for recording the vibration transmitted from the evaporator pipe when the compressor is running. Measuring point 2 is located in the lower part of the compressor near the base. The vibration transmitted from the base during the operation of the compressor can be measured at this position. Measuring point 3 is located in the middle part of the compressor. This position can provide the vibration data of the middle section during the operation of the compressor. It can be seen that additional data can be collected by measuring the vibration of the air-conditioning compressor for subsequent improvement.

Bös *et al.*[(5)] discussed the active vibration reduction technology of air-conditioning compressors of an electric multiple unit, as shown in Fig. 5. Their two vibration reduction schemes were an active bracket based on piezoelectric stack actuators and elastomers and a tunable active vibration absorber. The results showed that both schemes could effectively reduce the vibration induced by the compressor and hence reduce the noise inside the cab. The experimental results showed that the compressor installed in the heating ventilation air-conditioning and cooling (HVAC) unit above the electric multiple unit could induce noise of about 50 and 100 Hz bands in the carriage. They also designed an active vibration reduction device to reduce the vibration induced by the compressor to reduce the ambient noise in the carriage. The experimental results showed that the technology reduced the noise in the carriage and improved the driver's working environment.



(a) (b)

Fig. 3. (Color online) Photographs of installed (a) accelerometer and (b) microphone.

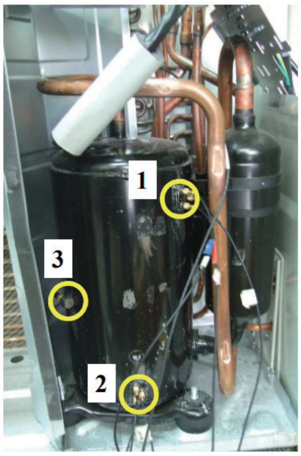


Fig. 4. (Color online) Three accelerometer measuring points on the compressor.

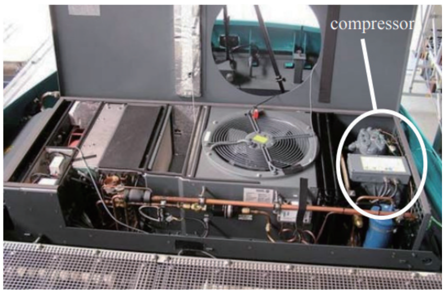


Fig. 5. (Color online) Electric multiple unit compressor.

Gkoumas *et al.*[6] proposed an energy collector made of piezoelectric materials. It can be applied to intelligent buildings, structures, and infrastructures. The device uses piezoelectric components and three types of aerodynamically designed fins. The energy consumption in the building is optimized by the vibration of vortex shedding generated by the HVAC system. The entire test was conducted in a wind tunnel, and the test included different configurations of piezoelectric benders (rectangular, cylindrical, and T-shaped), as shown in Fig. 6. The energy collection in the wind tunnel was evaluated to be effective.

Figure 6(a) shows a cylindrical aerodynamic fin made of piezoelectric materials, mounted on a base, to collect vibration energy. This design is aimed at using the vortex shedding vibration induced by airflow to improve energy collection efficiency. A rectangular aerodynamic fin is shown in Fig. 6(b). The rectangular fin is used to study the effects of different shapes on the vibration energy collection efficiency. A T-shaped aerodynamic fin with a vertical body and lateral reinforcement is shown in Fig. 6(c). The T-shaped design is aimed at improving the stability and vibration response of the system to maximize the energy collected from the airflow. Gkoumas *et al.*[6] indicated that the T-shaped design showed the highest performance in terms of the vibration amplitude and energy collection efficiency among the three designs.

(a) (b) (c)

Fig. 6. (Color online) Three geometries of energy collectors are made with piezoelectric materials. (a) Cylindrical, (b) Rectangular, and (c) T-Shape.

Ruan and Yin(7) discussed the common problems of noise and vibration in the HVAC system of buildings and indicated that the mechanical equipment of the HVAC system (e.g., fans and compressors) was the main source of noise and vibration. To solve these problems, they used the new generation of design and vibration reduction technologies to improve the living comfort and structural stability of the buildings. The following methods were recommended in their paper: (1) Install silencing equipment: installing a silencer, such as a low- or mid-frequency silencer, which can target annoying noise at different frequencies, can directly improve noise. (2) Choose appropriate equipment: it is very important to select the appropriate equipment in accordance with the size and ventilation requirements of the building. (3) Optimize duct design: to design ventilation ducts, it is required to ensure smooth airflow and avoid sudden changes in airflow. Flexible connectors that can be used to absorb vibrations and appropriate sound insulation materials should be selected. (4) Install sound insulation materials: installing a layer of sound insulation material on the outer layer of the return air duct can prevent the transmission of noise through the return air duct. (5) Choose a reasonable location of the cooling tower: the cooling tower is an indispensable part, but the operating noise of the cooling tower is very annoying. In addition to choosing an appropriate installation site and using sound insulation equipment to reduce noise, these design methods and technologies can effectively reduce the noise and vibration problems in a building HVAC system, thereby improving the living comfort and structural stability of the buildings.

Bös *et al.*(8) proposed a method of using active tuned dampers to reduce the compressor vibration. This design was inspired by piezoelectric compensators. The frequency of the damper was adjusted through the piezoelectric patch actuator to match the main frequency of compressor vibration. The experimental results showed that the active tuned damper could effectively reduce the vibration level of the compressor in certain frequency ranges, improving the operational stability of the HVAC unit and reducing noise.

Figure 7 shows a schematic diagram of the active tuned vibration absorber installed under the compressor. The left figure shows the main structure of the active tuned vibration absorber, which consists of two discrete masses *m* and a piezoelectric ceramic patch actuator. The patches

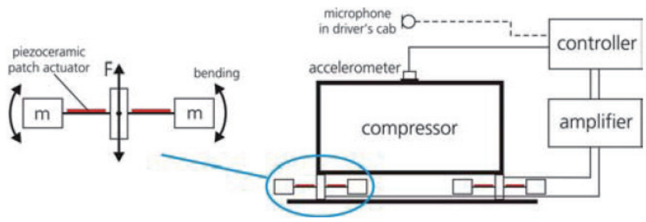


Fig. 7. (Color online) Schematic diagram of installation of vibration absorber.

are mounted on the cantilever beam; when a voltage signal is applied, mass vibration is generated so that a vertical force F is generated at the bending point to neutralize the vibration of the compressor. The right figure shows that the vibration absorber is installed under the compressor. After the vibration is measured by the accelerometer on the compressor, the controller of the active tuned vibration absorber adjusts the output to the piezoelectric ceramic patch actuator in accordance with the vibration measurement results. This configuration can effectively reduce the vibration during the operation of the compressor, thus reducing the noise level in the cab.

Lade and Shah(9) studied the vibration compensation technology of single-rotor compressors in household air conditioners. By analyzing the vibration characteristics of the compressor during operation, they proposed to reduce the mechanical vibration of the compressor by torque compensation in the field-oriented control (FOC) circuit. The vibration could be reduced effectively, contributing to the improvement of the operational stability and comfort of the air-conditioning system.

The experimental results showed that after sine compensation is activated, the orthogonal current waveform and torque in the sine waveform change with the mechanical rotation angle so that the torque curve of the compressor is more stable and small speed fluctuations and vibration of the compressor are reduced, as shown in Figs. 8 and 9. According to the above literature, the operational stability can be effectively improved by adopting air-conditioning equipment vibration detection and related active and passive suppression technologies.

2.2 Design and production of sensor

The sensor architecture used in this study is shown in Fig. 10. The sensor data are analyzed by the central processor, and then the measurement results are transmitted to the receiving device by Bluetooth transmission. The receiving device can be a mobile phone or a customized Bluetooth receiver.

The wiring architecture of the chip is shown in Fig. 11. The printed circuit board (PCB) is designed as two layers to accommodate more components; this is one of the common integrated circuit structures at present. The circuit design is shown in Fig. 12. The key lies in how to implement effective communication between two microprocessors of different brands without losing communication packets when sending the measured data to the external receiver.

The finished product of the sensor is shown in Fig. 13. The circular metal coil is the antenna for sending signals, and the black part under the board is the cell mounting position.

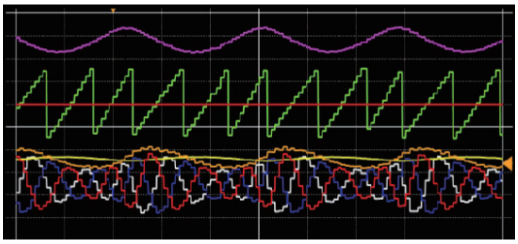


Fig. 8. (Color online) Effect after compensation is activated.

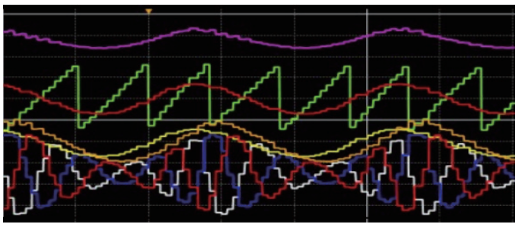


Fig. 9. (Color online) Effect before compensation is activated.

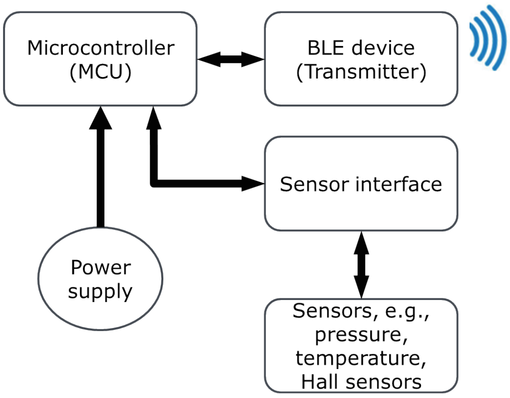


Fig. 10. (Color online) Microsensor architecture diagram.

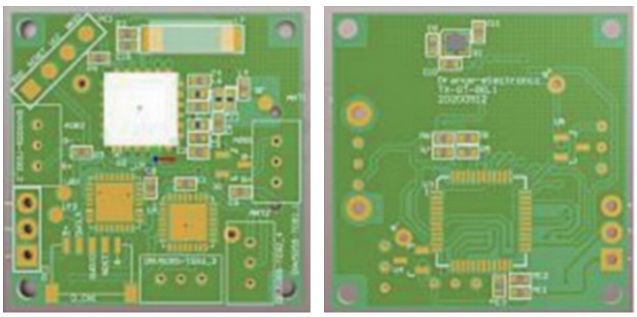


Fig. 11. (Color online) Chip PCB wiring diagram.

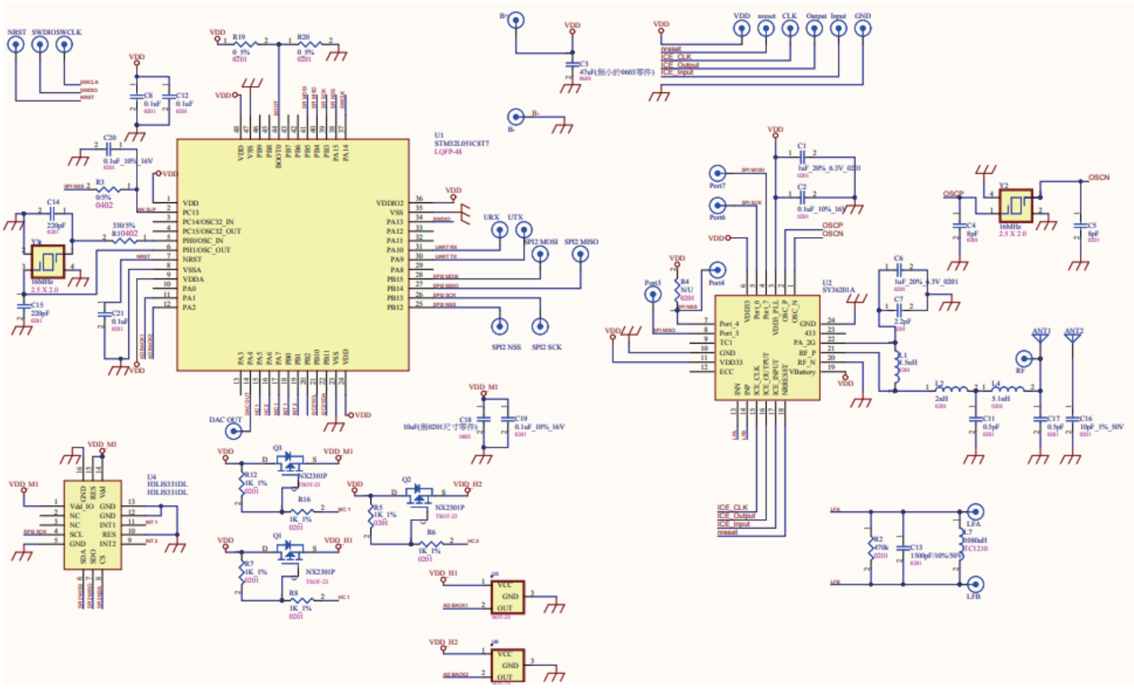


Fig. 12. (Color online) Circuit diagram.

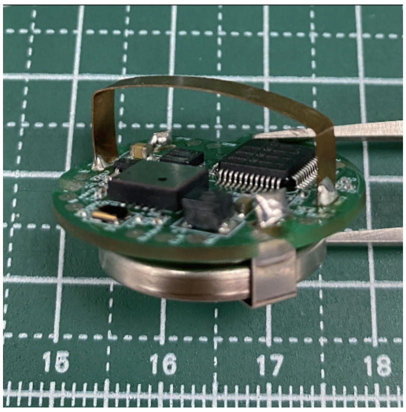


Fig. 13. (Color online) Finished microsensor.

2.3 Measurement setup

The window air conditioner and refrigerator discussed in this study are commercially available products installed in the laboratory with controlled safe conditions for vibration detection. Figure 14 shows the measurement setup in this study. The developed microprocessor is installed on the base of the compressor and uses the program developed by us to collect and analyze data. Figure 15 shows the experimental setup of the window air conditioner. The sensor

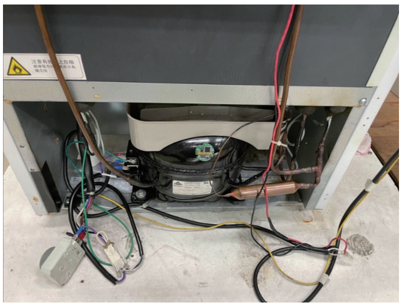


Fig. 14. (Color online) Sensor installed on refrigerator.

Fig. 15. (Color online) Sensor installed on window air conditioner.

is again installed on the base of the compressor to collect vibrations. Figure 16 shows the screen recorded in real time during the experiment. After data collection, the data can be stored in the computer for subsequent analysis.

3. Results and Discussion

At present, most air conditioners are equipped with pressure or temperature sensors, but the inventory detection of refrigerant, a key filling material that is crucial to the smooth operation of air-conditioning equipment, is not a standard configuration of every equipment. The energy loss induced by insufficient refrigerant is usually considerable and will affect the life of the compressor. Therefore, in this study, we used a wireless microsensor developed by us to analyze the vibrations of a commercially available refrigerator and window air conditioner with insufficient, standard, and excessive amounts of refrigerant. Figure 17 shows the results of the vibration data analysis of the window air conditioner. The experimental results showed that the vibration quantity is relatively high when the refrigerant is insufficient (rated filling amount of the equipment: −20%). It is speculated that there are many liquid gaps in the compressor; when the compressor operating conditions remain unchanged, more disturbances will cause vibration. To the contrary, when there is excessive refrigerant (rated filling amount of the equipment: +20%), the gaps are small, so the vibration is minimized.

The experimental results showed that the vibration of the window air conditioner used in this study mainly occurs at 17, 62, and 221 Hz. Additional results of the vibration that occurs at specific frequencies are shown in Fig. 18. Under the condition of insufficient refrigerant filling, the vibration quantities of the main frequencies are 0.046 g, 0.067 *g*, and 0.097 *g*, respectively. The vibration quantities under the condition of a standard refrigerant filling amount respectively are 0.046 g, 0.048 g, and 0.066 g. When the refrigerant filling amount is excessive, the respective vibration quantities are 0.046 g, 0.048 g, and 0.076 g. It can be seen that the vibration differences are very small, but the accurate measurement by the accelerometer can still be used to predict the failure mode.

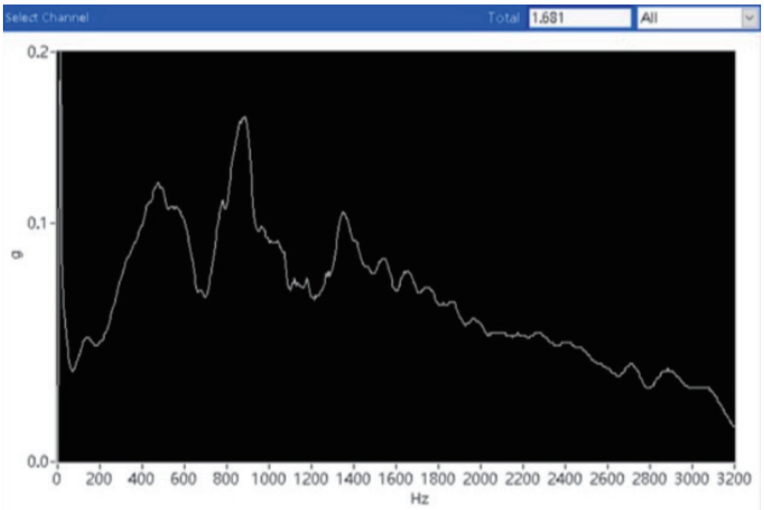


Fig. 16. (Color online) Real-time vibration data reception.

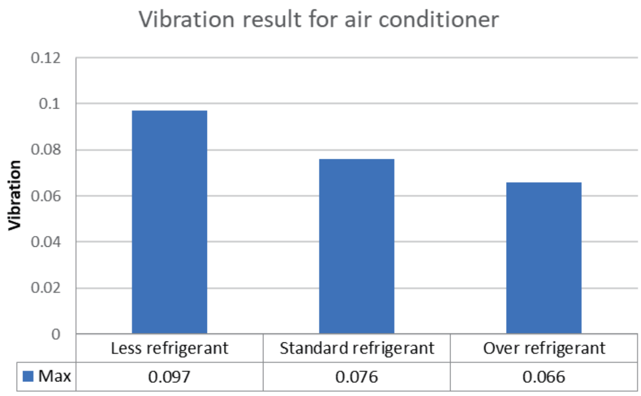


Fig. 17. (Color online) Analysis results of vibration quantity of window air conditioner.

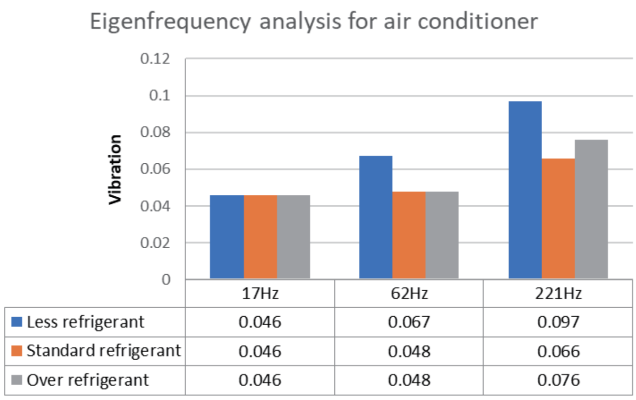


Fig. 18. (Color online) Analysis results of vibration quantity at main characteristic frequencies.

Another common air-conditioning equipment is a refrigerator, which also must be filled with refrigerant to maintain cooling capacity. Therefore, we also discuss the vibration quantity of a commercially available refrigerator with three refrigerant filling amounts. Figure 19 shows that the refrigerant filling amount is set to the standard filling amount marked on the equipment (±20%). The experimental results showed that the vibration quantities under the three refrigerant filling conditions are 0.023 g, 0.02 g and 0.017 g, respectively. Therefore, it can be seen that a large amount of vibration is induced with an insufficient amount of refrigerant filling.

Further analysis revealed that the vibration regularly occurs at three characteristic frequencies, namely, 17, 62, and 135 Hz. The analysis results of the values of the three main characteristic frequencies are shown in Fig. 20. Under the condition of insufficient refrigerant filling, the vibration quantities of the main characteristic frequencies are 0.023 g, 0.002 g, and 0.001 g, respectively. When the refrigerant filling amount conforms to the equipment standard rating, the respective vibration quantities are 0.02 g, 0.003 g, and 0.002 g. When the refrigerant filling amount is excessive, the vibration quantities respectively are 0.017 g, 0.004 g, and 0.004 g. The experimental results showed that the vibration at 61 Hz is similar to that at 135 Hz under

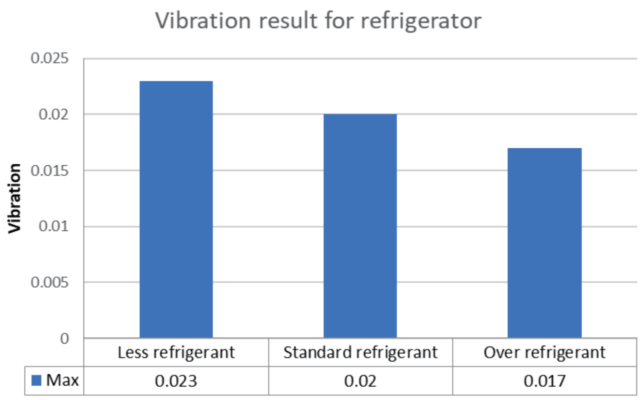


Fig. 19. (Color online) Analysis results of vibration quantity of refrigerator.

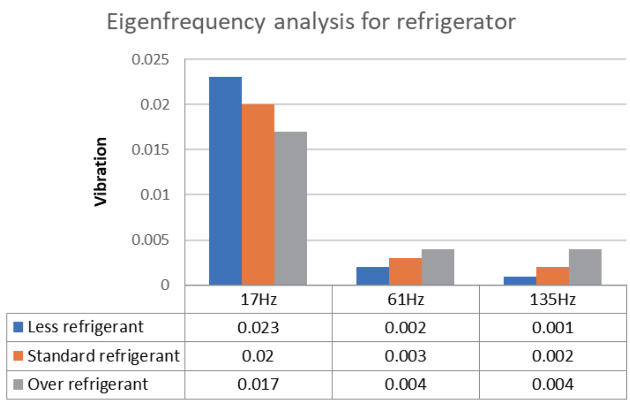


Fig. 20. (Color online) Analysis results of vibration quantity at characteristic frequencies.

the condition of over or less refrigerant. Therefore, 17 Hz can be used as the main characteristic frequency for evaluating the failure mode of the air-conditioning equipment.

4. Conclusions

In the past, the vibration detection of equipment mostly required precision measurement equipment. The microsensor developed in this study solves the trouble resulting from wiring, and the continuous data upload to the cloud contributes to subsequent database analysis. In addition, the vibration difference between two common air-conditioning equipment may be very small, but both insufficient and excessive amounts of refrigerant filling affect the operation of the equipment and produce annoying noise. Therefore, the results of this study indicate that possible equipment failure expansion and ineffective energy waste can be prevented through the real-time detection of anomalous vibration.

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