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Experimental Study on Noise Characteristics of Centrifugal Compressor Surge

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ABSTRACT

The centrifugal air compressor test rig is designed and established. The experimental study was carried out on the surge characteristics of centrifugal compressor including the pressure in the pipe and the noise under different rotation speed. The tested results showed that both the suction pressure and discharge pressure fluctuation increase with the rising of speed under surge condition. The amplitude of discharge pressure fluctuation is significantly higher than that of suction pressure. In addition, the sound pressure level near the inlet pipe also fluctuates under surge condition. The fluctuation amplitude of sound pressure level is increases with the rising of rotation speed. It is relative to the variation of discharge pressure of centrifugal compressor. The total sound pressure level under surge conditions is larger than that of steady working conditions. The change of sound pressure level reflects the changing of field flow in centrifugal compressor. The signals of sound could be used as a method to predict the occurring of surge. The experimental results will lay the foundation for future research on the monitoring surge of centrifugal compressor and the development of the surge control method.

1. INTRODUCTION

Centrifugal compressor is widely used for various kinds of industrial fields, such as chemical processes, gas transmission, refrigeration, engines. When centrifugal compressor operates at a lower flow rate, the instability phenomena such as rotating stall and surge will occur, which limits the safe operating region and the reliable performance of the centrifugal compressor. Especially, the surge may cause critical operating conditions and strong fluctuations and limit cycle oscillations can generate large vibrations to fatigue and damage of the compressor systems and its components. Therefore, the occurrences of surge or rotating stall have to be prevented in industrial application. The research on the surge mechanism and experimental investigation on surge characteristics are the base to develop the anti-surge control methods and to enhance the stable working range of centrifugal compressor.

In the past, theoretical and experimental study on surge has been done by many researchers (Galindo et al., 2006, Gravdahl et al., 2004, Hansen et al., 1980, Liu and Zheng, 2008, Zheng and Liu, 2015). Arnulfi G L, et al. (2006) reports the results of an extensive study concerning surge instability in an industrial compression system and its dynamic suppression. Both numerical simulations and experiments have been applied to analyze the system behavior under unstable operating conditions and to compare different control devices for surge suppression. Galindo J., et al. (2008) carried out the experimental work on the measurement of centrifugal compressor behavior within the surge zone by means of a specifically designed facility. A model based on a non quasi-steady hypothesis has also been proposed. Kin Tien Lim et al. (2011) study the surge phenomenon in a centrifugal compression system and to investigate a novel method of surge control by active magnetic bearing servo actuation of the impeller axial tip clearance. Hideaki Tamaki (2008) study the effect of piping system on surge in centrifugal compressor and confirmed that the lumped parameter model was a very useful tool to predict the effect of piping systems on surge characteristics in centrifugal compressor. Guillou E. et al. (2011) investigate experimentally on the steady and unsteady flow phenomena at the inlet of the radial compressor of a turbocharger typically used on diesel engines. Particle Image Velocimetry (PIV) was used to identify the aerodynamic changes occurring in the flow field while surge is developing. Digital Particle Imaging Velocimetry (DPIV) is used in conjunction with dynamic pressure transducers to capture transient velocity and pressure measurements simultaneously in the unsteady flow field during compressor surge. (Mark P. Wernet, 2001).

However, most of the research work mainly focused on the numerical analysis on the flow instability especially the surge phenomena. The noise characteristics of centrifugal compressor during the surge condition were less reported. The purpose of this study is to investigate the performance characteristics of centrifugal compressor surge through experiments. The change properties of suction pressure and discharge pressure are obtained. In addition, the noise characteristics under different working conditions and rotational speed are described.

2. EXPERIMENTAL FACILITIES

Figure 1 shows the test apparatus of the experimental system including the centrifugal compressor employed in this research and the photos of the test rig are shown in Figure 2. It consists of the driving system, the compressor, lubricating oil system, cooling system, data acquisition and control system. The motor driven by a frequency converter is a variable frequency motor that is rated for 250 kW. The maximum speed of the compressor rotor can be reached 30000 r/min. The compressor rotor is supported by a radial bearing and a thrust bearing and consist of a 13-bladed impeller and vaneless diffuser. The impeller was originally designed and the design rotational speed of the compressor is 14250 r/min. The rotational speed and the torque were measured through the torque meter, which was installed between the motor and gearbox. Temperature sensor and pressure sensor were installed at the inlet pipe and discharge pipe to measure the temperature and pressure of the compressor, respectively. The electrically throttle valve located at the discharge pipe was employed to adjust the discharge pressure and the operating point of the centrifugal compressor. In order to investigate the performance and monitor the working conditions of centrifugal compressor, a data collection board providing enough channels of simultaneous sampling analog to digital conversion are employed. The data acquisition and control system based on virtual instrument technology was programed to record the experimental data and adjust the rotational speed and throttle valve precisely. The steady characteristics and unsteady flow phenomena of the centrifugal compressor under different rotational speed with 10725 rpm, 12830 rpm and 15282 rpm. The microphone was located near the inlet pipe of the compressor test rig to evaluate the inlet noise at different working conditions.

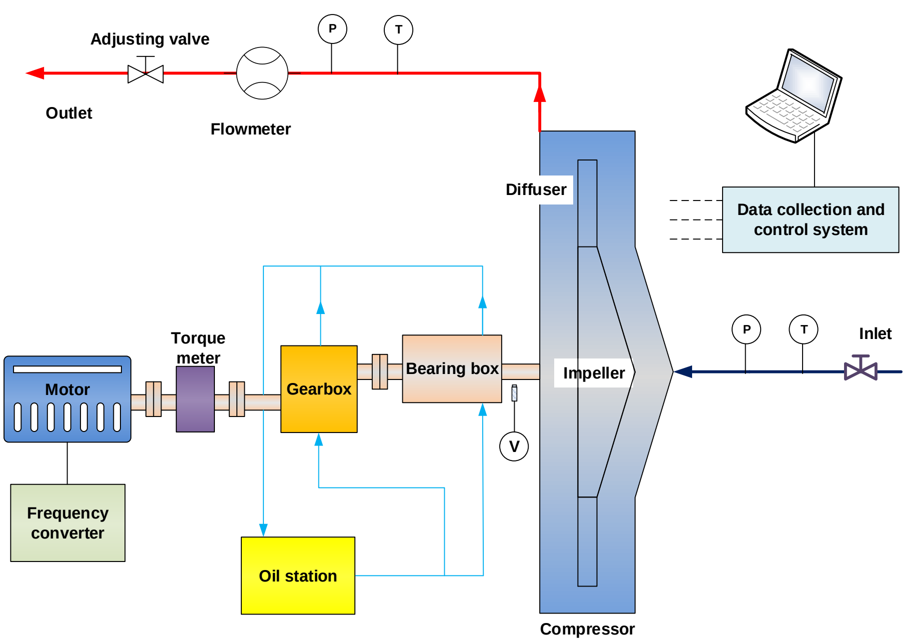


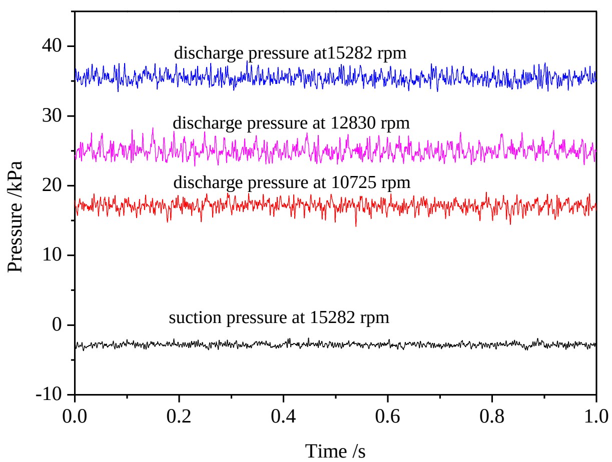
Figure 1: Schematic diagram of centrifugal compressor test system

Figure 2: Photos of centrifugal compressor test rig

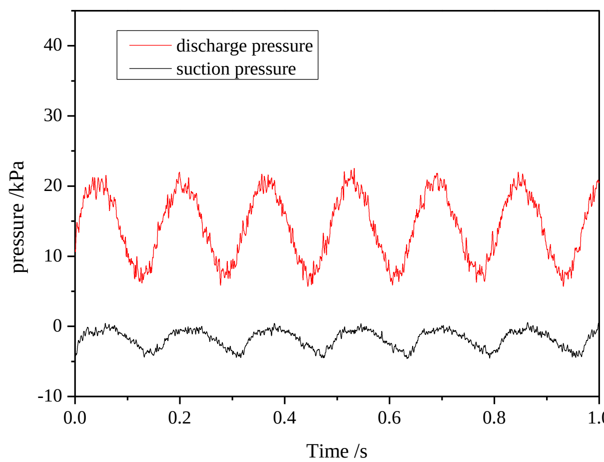
3. EXPERIMETNAL RESULTS AND ANALYSIS

3.1 Pressure characteristics

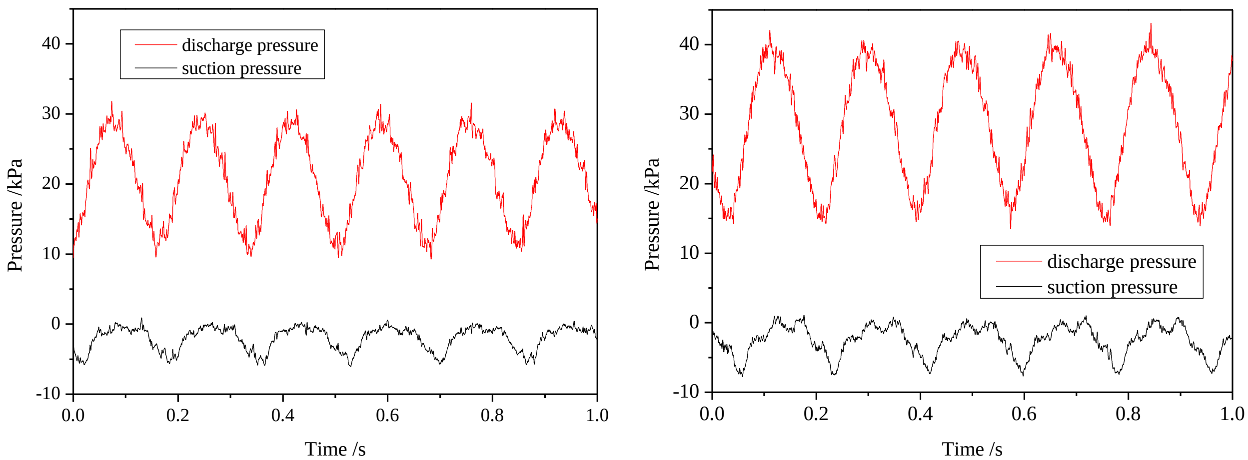
Figure 3 shows the comparison of the inlet and discharge pressure of the centrifugal compressor under different working conditions and different rotational speeds. Figure 3(a) indicates the changing of suction and discharge pressure of the compressor. Suction pressure at three rotational speeds are very similar, therefore, there is only one line at 15282 rpm in Fig. 3(a). With the rising of the rotational speed, the discharge pressure is also increasing and the amplitude of pressure fluctuation is relatively small for different rotational speeds. Figure 3 (b), Figure 3(c) and Figure 3 (d) shows the fluctuation of suction and discharge pressure under surge condition at the rotational speed of 10725 rpm, 12830 rpm and 15282 rpm, respectively. The large fluctuation of pressure occurred under surge conditions. It is obvious that the amplitude of discharge pressure fluctuation is larger than that of suction pressure. Both the fluctuation amplitude of discharge pressure and suction pressure are increasing with the rising of rotational speed. For example, the peak-to-peak value of discharge pressure is about 16.85 kPa and the peak-to-peak value of suction pressure is about 5.15 kPa at 10725 rpm. When the rotational speed is increases to 12830 rpm and 15282 rpm, the peak-to-peak value of discharge pressure is increases to 22.54 kPa and 29.63 kPa, the peak-to-peak value of suction pressure is increases to 6.97kPa and 8.85 kPa. The frequency of pressure fluctuation under surge conditions is low compared to the fundamental frequency of the centrifugal compressor and is decreased with the rising of rotation speed of the compressor. The surge frequency is about 6.3Hz at the rotational speed of 10725 rpm. When the rotational speed is increases to 12830 rpm and 15282 rpm, the pressure fluctuation frequency under surge condition is reduces to approximately 5.95Hz and 5.5 Hz.



(a) Steady working condition



(b) Surge working condition (10725 r/min)

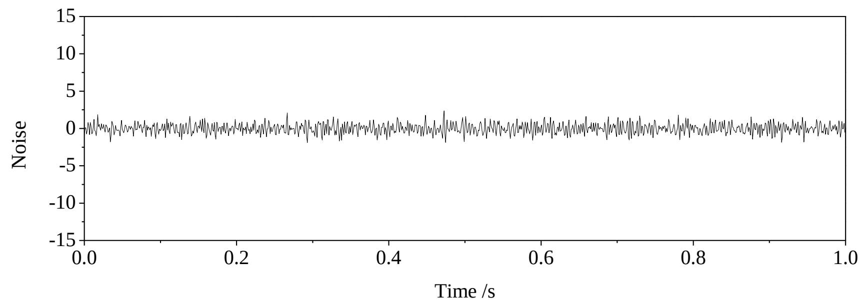


(c) Surge working condition (12830 r/min) (d) Surge working condition (15282 r/min)

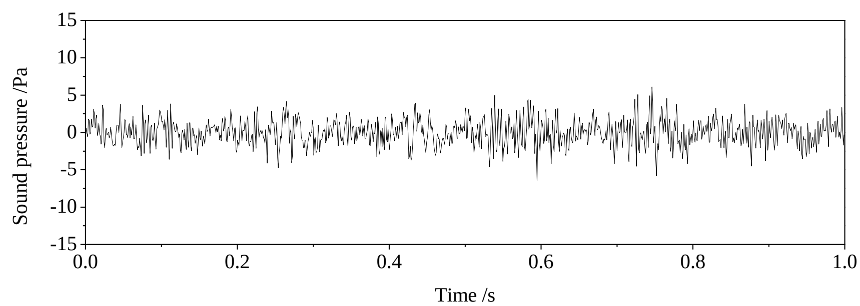
Figure 3: The change of pressure under different speed and working conditions

3.2 Noise characteristics

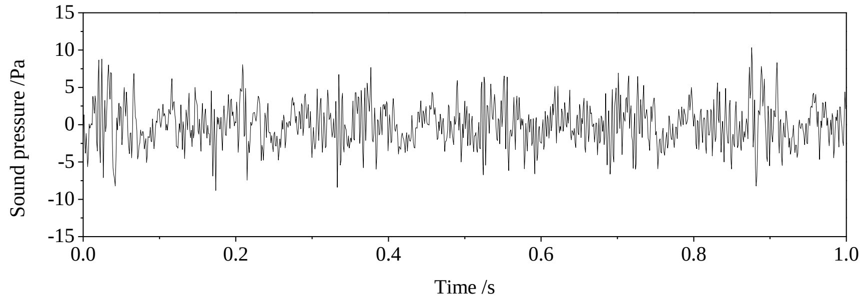
The fluctuations of sound pressure level of centrifugal compressor under the steady working condition and surge condition are shown in Figure 4. It can be seen from Figure 4 (a) that the noise level of the compressor in the time domain under the steady working condition is stable for any rotational speed of the compressor. While under the surge conditions, the sound pressure level will fluctuate and the fluctuation amplitude of sound pressure level is increasing with the rising of rotation speed as showed in Figure 4 (b), Figure 4 (c) and Figure 4 (d).



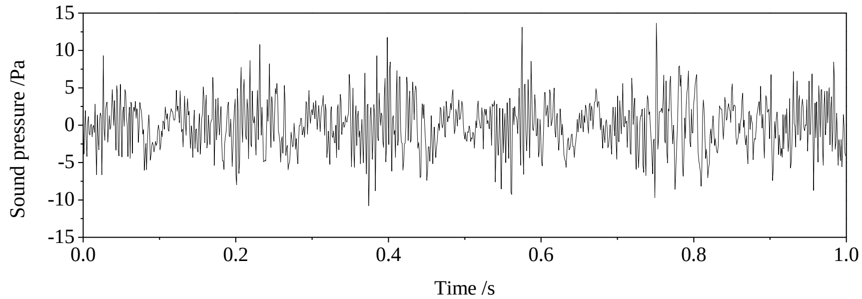
(a) Steady condition (15282 rpm)



(b) Surge condition (10725 r/min)



(c) Surge condition (12830 r/min)



(C) Surge condition (15282 r/min)

Figure 4: The change of noise under different speed and working conditions

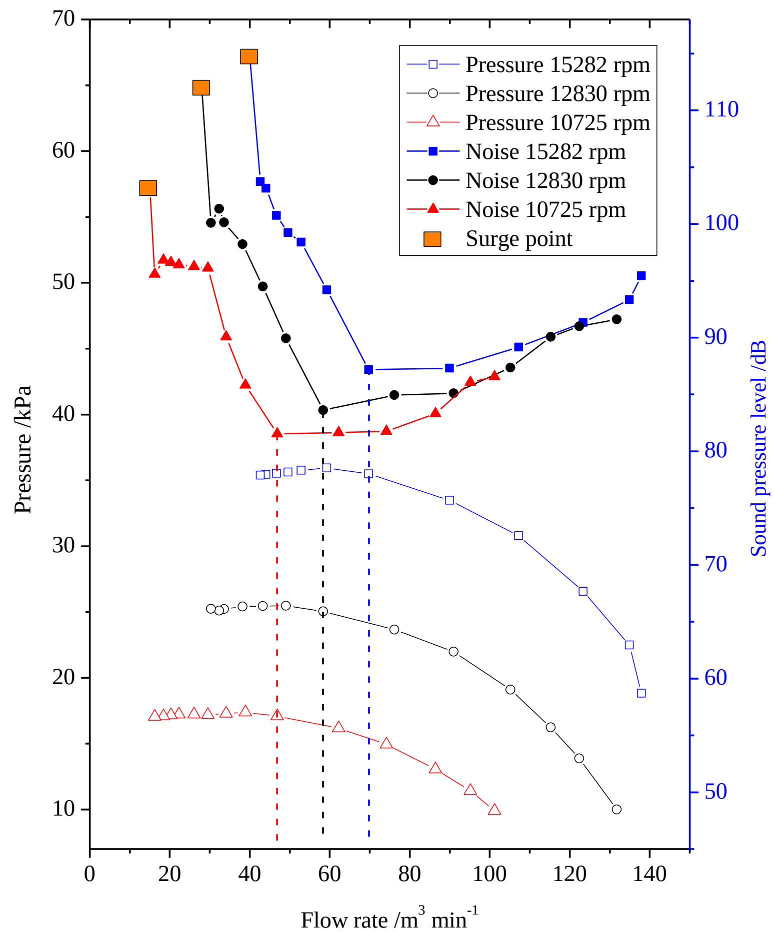
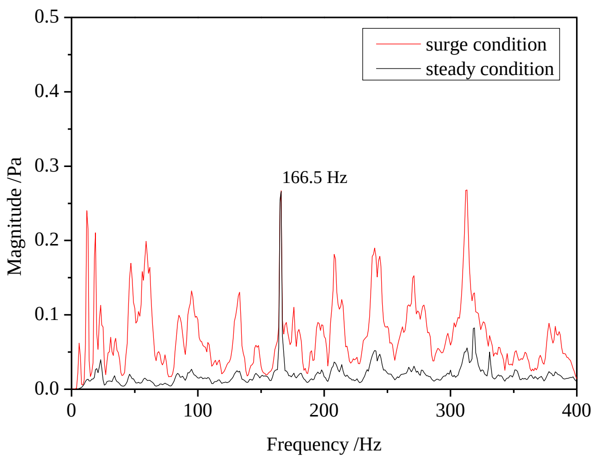
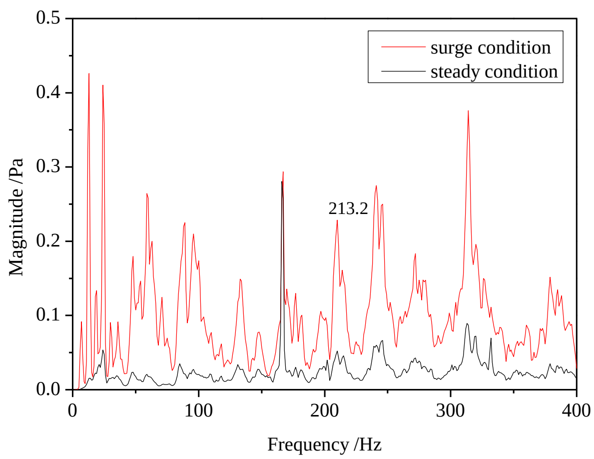


Figure 5: Performance characteristics of centrifugal compressor under different speed

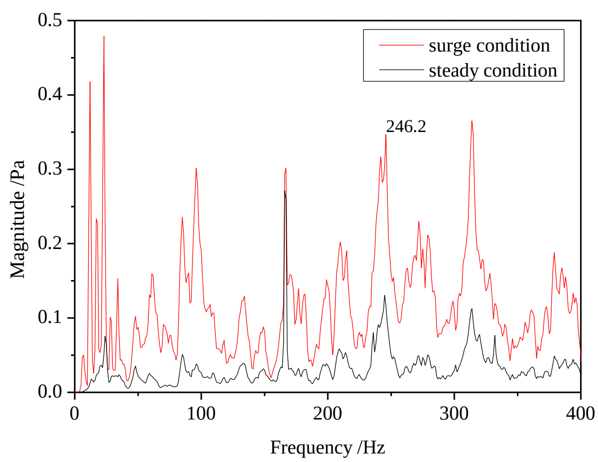
Figure 5 shows the performance characteristics including the noise properties of the centrifugal compressor under different rotational speed of 10725 rpm, 12830 rpm and 15282 rpm. It can be found that the changing of sound pressure level of the compressor is relative to the changes of the discharge pressure of the compressor. In general, the discharge pressure of centrifugal compressor is increasing with the decreasing of the flow rate under the constant rotational speed and then decreasing. Maximum discharge pressure exists for the compressor. The tested results on sound pressure level of this open cycle compressor system indicate that there exists a minimum sound pressure level that is corresponding to the maximum discharge pressure. At the beginning, the sound pressure level is decreasing with the decreases of the flow rate of the compressor, and then increasing rapidly. At the surge conditions, the sound pressure level reached the maximum value. For example, at the rotational speed of 15282 rpm, when the flow rate is 59.29 m^3/min, the discharge pressure of the centrifugal compressor reached the maximum value of 35.94 kPa and the sound pressure level can achieve the lowest value of 87.19 dB. Although the error exists between the changing point of the discharge pressure and sound pressure level, the tested results still proven that the rotation stall occurred after the maximum discharge pressure. The total sound pressure level under surge conditions is larger than that of steady working conditions. At the surge conditions, the sound pressure level can reach to a very high value. For example, the sound pressure level under the surge condition at 15282 rpm can got to 114.76 dB, which is higher than the sound pressure level value of 103.73 dB at the near surge point and is much higher than the sound pressure level value of 87.19 dB at the design working conditions. The same change tendency was found at other rotational speed of 10725 rpm and 12830 rpm. Therefore, the change of sound pressure level during the operation of centrifugal compressor could be used as a characteristic signal to predict the occurring of rotation stall and surge phenomenon.



(a) 10725 rpm



(b) 12830 rpm



(c) 15282 rpm

Figure 6: Frequency spectrum at different rotational speed

The results of the frequency analyses on the sound pressure level signals are shown in Figure 6. Since the frequency of surge is often low, analysis on experimental tests focus on the frequency range less than 400 Hz. Experimental tests were carried out at three speeds to evaluate the effect of speed change on the observed dominant frequencies. Figure 6(a) shows the results at 10725 rpm. Figure 6(b) shows the results at 12830 rpm, Figure 6(c) shows the results at 15282 rpm. In Figure 6 (a), the 166.5 Hz are the fundamental frequency of the tested centrifugal compressor. At steady working conditions, the dominant frequency is the fundamental frequency related to the rotation speed of centrifugal compressor. The other harmonic frequency is rather low. However, the low frequency appears and becomes strong under the surge condition and the harmonic frequency are also becoming larger.

4. CONCLUSIONS

The centrifugal air compressor test rig is designed and established. The experimental study was carried out on the surge characteristics of centrifugal compressor including the pressure in the pipe and the noise under different rotation speed. The tested results showed that both the suction pressure and discharge pressure fluctuation increase with the rising of speed under surge condition. The amplitude of discharge pressure fluctuation is significantly higher than that of suction pressure. In addition, the sound pressure level near the inlet pipe also fluctuates under surge condition. The fluctuation amplitude of sound pressure level is increased with the rising of rotation speed. It is relative to the variation of discharge pressure of centrifugal compressor. The total sound pressure level under surge conditions is larger than that of steady working conditions. The change of sound pressure level reflects the changing of field flow in centrifugal compressor. The signals of sound could be used as a method to predict the occurring of surge phenomenon. The experimental results will lay the foundation for future research on the monitoring surge of centrifugal compressor and the development of the surge control method.

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