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Experimental study on radiated noise characteristics of multi-stage centrifugal pump under variable speed condition

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Abstract: Radiated noise is unavoidable in the operation of multistage centrifugal pumps. In order to study the characteristics of radiated noise of multistage centrifugal pump, radiated noise test system of multistage centrifugal pump was built. Radiated noise experiments were carried out for a medium specific speed multistage centrifugal pump and its modification, which was devised with a new hydraulic design method in the field of sound optimization. The experiment validation on the sound field was performed in a semi-anechoic room and the acoustic parameters of the multistage pump at the different flow rates were gathered with the LMS system(a complete set of solutions for vibration and noise test).The results show that: As the speed is lower than the rated speed, the sound pressure level (SPL) of the radiated noise of centrifugal pump increases with the increase of rotating speed. And the radiated noise of multistage pump rises linearly with the increase of rotating speed. The maximum value of sound pressure level appears around the first stage and the minimum value appears around the middle stage at different flow rates. As the flow rate increases, SPL measured around vane diffuser increases and then decreases. In addition, discrete noise occupies the dominant position in the form of noise for both pumps at large flow rate. Compared with the prototype pump, the intensity of radiated noise of the modified pump weakens in varying degrees in the range of the whole variable speed. Furthermore, the radiated noise exhibits a dipole characteristic at low rotating speed.

1.Introduction

Multistage centrifugal pump is an important equipment to provide high lift and high pressure liquid transportation. It is widely used in high-rise building water supply, seawater desalination, deep sea oil extraction and other national economic areas. Because of the difference in the shape and type of the inlet and outlet pipes of the centrifugal pump and the variety of the working medium, the wide frequency noise is often accompanied when operating [1]. The internal pressure of the multistage centrifugal pump is large, and the mechanism of noise in the internal flow is more complicated. Additionally, there is a strong inter-stage coupling phenomenon, so the noise problem is more significant. Moreover, stringent requirements put forward for work and living environment, vibration and noise reduction have become



an important index to improve the quality of life and the safety of equipment.

The noise of centrifugal pump consists of two major categories: mechanical noise and flow-induced noise, which can also be called fluid noise. The flow induced noise is almost derived from the inner of the pump shell, which is directly related to the flow state of the fluid in the pump[2]. Simpson [3] studied experimentally the discrete noise produced by interference between impeller and vane diffuser of centrifugal pump, and put forward empirical formula to predict noise level at pump outlet. Pointed at the forced vibration and radiated noise of a five stage centrifugal pump volute, a numerical simulation method considering fluid structure acoustic coupling is applied by Jiang[4]. Chu and Dong [5-6] measured the velocity distribution of flow field in a centrifugal pump and calculated velocity field internal pressure distribution based on PIV method. The results show that the pressure pulsation and noise in centrifugal pump are mainly caused by unsteady flow through the impeller outlet and dynamic interaction between impeller and spiral tongue. In the process of the establishment and development of the FE-SEA hybrid model (an analytical model combining the advantages of finite element analysis and statistical energy analysis), Langley [7-8] made a significant contribution. On the basis of modal superposition, Chen [9] proposed a hybrid algorithm for solving structural vibration response. At present, the hybrid model method has been applied in the field of automobile noise, and it is a reference for the solution of pump flow induced radiated noise. Based on large eddy simulation (LES), Ding [10] analyzed the effect of blade exit angle on the hydrodynamic noise of centrifugal pump volute.

So far, scholars have focused on the research of the internal acoustic mechanism and the radiated noise field of the centrifugal pump. However, the degree of radiated noise affected by hydraulic and structural parameters is not clear. Based on LMS test system, the intensity and frequency of noise level of multistage pump radiated noise with the variation of rotating speed were measured. Besides, a new optimization method considering sound pressure level excited by pulse dynamics on impeller and vane diffuser blades is presented.

2. Basic theory

2.1 Sound pressure level

The sound pressure is due to the existence of sound wave and the increase of atmospheric pressure. Sound pressure level (SPL) measured in the experiment is the physical quantity that describes the intensity of the sound pressure and the function can be expressed as:

$$L_p = 10 \lg \frac{p^2}{p_0^2} \quad (1)$$

p is the actual sound pressure and p_0 is the reference sound pressure.

2.2 Acoustic theory

The complex expression of sound pressure m order harmonic generated by the single blade power source model summarized by Lowson[11-12] and the model can be expressed as:

$$c_m = \frac{im\Omega}{2\pi a_0 r_1} \sum_{\lambda=-\infty}^{\infty} (-i)^{n-\lambda} \times \left(\frac{xT_{\lambda}}{r_1} - \frac{m-\lambda}{m} \frac{D_{\lambda}}{M} \right) J_{m-\lambda}(mMy/r_1) \quad (2)$$

Considered the interference between the impeller blade and the vane diffuser blade, the m order harmonic complex expressions of the acoustic pressure excited by the pulse power on the impeller blade

and the vane diffuser are respectively expressed as:

$$c_m = \frac{imB^2\Omega}{2\pi a_0 r_1} \sum_{n=-\infty}^{\infty} (-i)^{mB-nV} \times \left(\frac{xT_n}{r_1} - \frac{mB-nV}{mBM} D_n \right) J_{mB-nV}(mBM y / r_1) \quad (3)$$

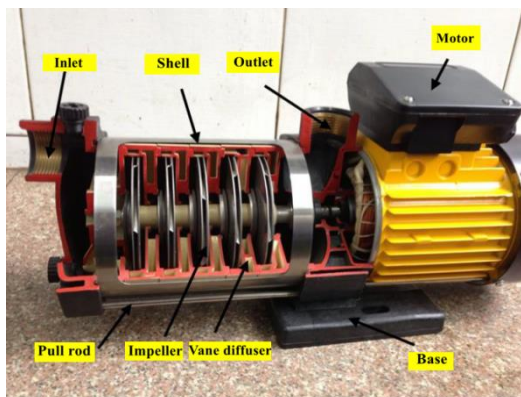
$$c_m = \frac{-imBV\Omega}{2\pi a_0 r_1} \sum_{n=-\infty}^{\infty} (i)^{mB-nV} \times \left(\frac{xT_m}{r_1} - \frac{mB-nV}{mBM} D_m \right) J_{mB-nV}(mBM y / r_1) \quad (4)$$

Equation (2)-(4) are obtained for the case when the rotor and stator are placed in a free space. x, y represent the coordinate value in the space coordinate system. B is the number of rotating impeller blades, Ω is the rotating angular velocity, V is the number of vane diffuser blades, R_1 is the distance from acoustic source to origin of coordinate, r is the distance from acoustic source to the observation point, and r_1 is the distance from the observation point to origin of coordinate. The fluctuating components of thrust and resistance acting on blades are represented by T and D respectively. Furthermore, m, n, λ are mathematical parameters, i represents the imaginary unit, a_0 represents acoustic velocity, $M=\Omega R/a_0$ represents mach number, T_λ and D_λ represent λ order pulsating component of thrust and resistance, while J_λ represents λ order Bessel function.

3. Radiated noise experiment

3.1 Experimental object

The research object is five stage centrifugal pump which is used in the exploitation of deep sea oil. Deep sea oil production has strict control over sound and a large number of studies show that hydraulic design is closely related to radiated noise. As is shown in Fig.1(a), in order to save space, axial flow and radial flow are used in the multistage. In the field measurement, it is found that the radiated noise level of the pump does not meet the requirements of the installation site. Therefore, the basic hydraulic parameters of impeller and vane diffuser are retained, and its structure is simplified to study radiated noise, which is shown in Fig.1(b). The parameters are also shown in Table 1.



(a) The cutaway view of multistage centrifugal pump



(b) Simplified centrifugal pump

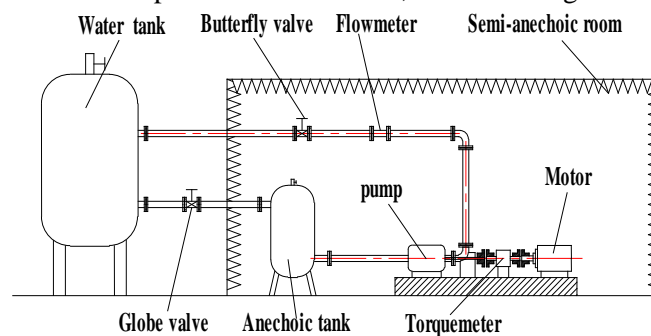
Figure 1. Research object

Table 1. Parameters of the pump

Impeller inlet diameter , D_1	45/mm
Impeller outlet diameter , D_2	103/mm
Impeller outlet passage width, b_2	10/mm
Diffuser inlet diameter, D_3	184/mm
Outlet angle , β_2	37/°
Impeller blade number, Z_a	7
Vane diffuser number, Z_d	12
Specific speed, n_s	86
Flow rate, Q_d	8m ³ /h
Total head, H	10m
Rated speed, n	2800r/min

3.2 Experimental system

The test rig was built in National Research Center of Pumps in Jiangsu University. China, and the layout is shown in Fig.2. All walls have sound absorption tips with good sound absorption performance, which provide half-free field acoustic space for acoustic test, and the background noise is 18dB.

**Figure 2.** The layout of the test rig

3.3 Measuring equipment

LMS system is shown in Fig.3, which can satisfy the 24 channel parallel data acquisition. The highest sampling frequency of each channel is 102.4kHz and the sound pressure level of 146dB can be measured at the highest level. In addition, type 14043 microphone sensors produced by PCB company are used in the experiment, which is shown in Fig.4. The noise measurement meets the national standard 2.0 based on GB/T 29529-2013 of China.

**Figure 3.** LMS system**Figure 4.** microphone sensor

3.4 Measures to reduce interference

In order to reduce the influence of radiated noise caused by pipeline and motor on the experimental results, the gradient sound absorbing cotton was coated on the tank, pipe, valve and flowmeters, which is shown in Fig.5 (a). Fig.5 (b) is the enclosures, the inner layer of which is placed with sound-absorbing cotton for the purpose of isolating motor noise.

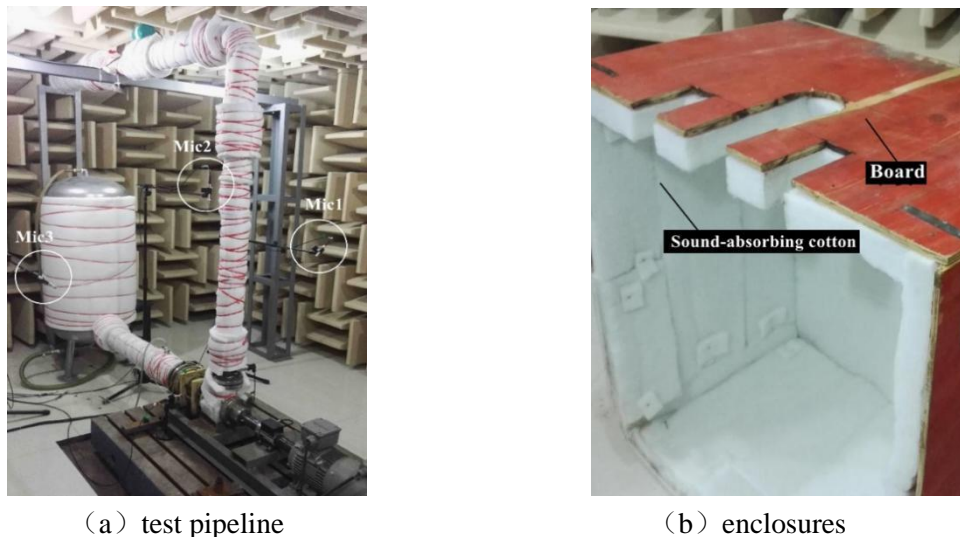


Figure 5. Test pipeline and enclosures

3.5 Steps

The measuring procedure is as follows:

- (1) Arrange the position of the microphone sensors according to the standard of pump noise measurement.
- (2) Gradually open the outlet valves and the measured speed is regulated by the frequency converter.
- (3) Tabulate groups of radiated noise data with the computer connected to LMS system.

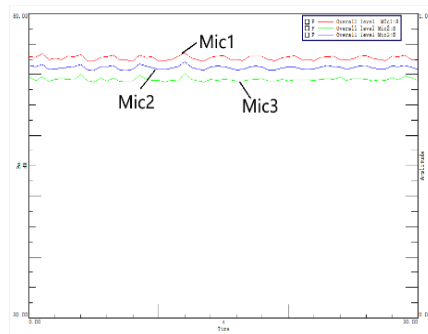
4. Analysis of experimental results

4.1 Time domain analysis

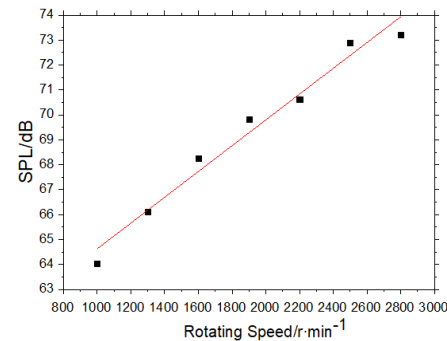
Fig.6 (a) shows the time domain signal from the microphones, from which we can find that the waveform without obvious fluctuation in whole time domain is dense. As is shown in Fig.6(b), the fitting curve is as follows:

$$y=0.00517x+59.46 \quad (4)$$

In the formula, y represents the total sound pressure level and x represents rotating speed; The linear correlation degree between the fitting curve and the test data is 0.96948. Therefore, when the speed is lower than the rated speed, the SPL of radiated noise from the multistage pump shows a linear growth with the increase of rotating speed. According to the slope of fitting curve, the nature of radiated noise in the experiment is mainly flow induced noise, which may be mixed with some mechanical noise.



(a)time domain signal

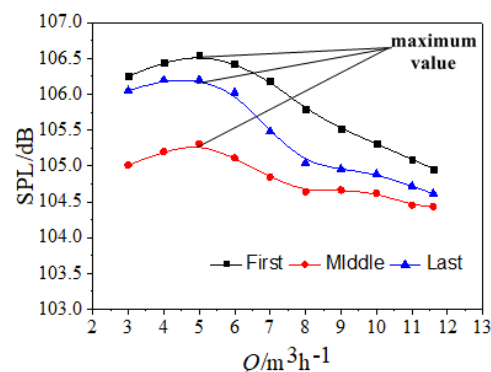


(b)fitting curve

Figure 6.Time domain analysis

4.2 Distribution of inter-stage noise

Three microphone sensors were placed at a distance of 1mm away from the three stages of multistage centrifugal pump. Intensity of radiated noise from each stage is shown in Fig.7. SPL value of radiated noise measured around the middle stage is the minimum, and the first stage is the maximum at different flow rates. In addition, as the flow rate increases, SPL measured around vane diffuser increases and then decreases. The maximum value of SPL appears at about $0.6Q_d$.

**Figure 7.**SPL of noise from each stage

4.3 Discussion of optimization results

With the application of Lawson's power theory and the consideration of hydraulic performance, 6 impeller blades and 9 vane diffuser blades were selected for the modification. Fig.8 shows the SPL spectrum at different rotating speed. The main form of radiated noise from the multistage centrifugal pump is discrete noise and the peak frequency is blade passing frequency. Compared with the prototype, when the rotating speed raises to 1000r/min, SPL value of peak frequency in the spectrum of modified pump drops by 2.97dB. When the rotating speed raises to 1900r/min, SPL value of peak frequency in the spectrum of modified pump drops by 2.21dB. When the rotating speed raises to 2800r/min, SPL value of peak frequency in the spectrum of modified pump drops by 2.41dB. In the large flow rate, vortex noise is the main form of radiated noise in the high frequency region.

In addition, there is a matching relationship between the impeller number and the vane diffuser number for fluid machinery, which has an impact on the operation stability of the pump. After optimization, flow channels are broadened and fluid permeability is improved, and frequency of

movement interference between the impeller and the vane diffuser becomes de-escalating, which can be a reasonable explanation to the reduction of radiated noise compared with prototype.

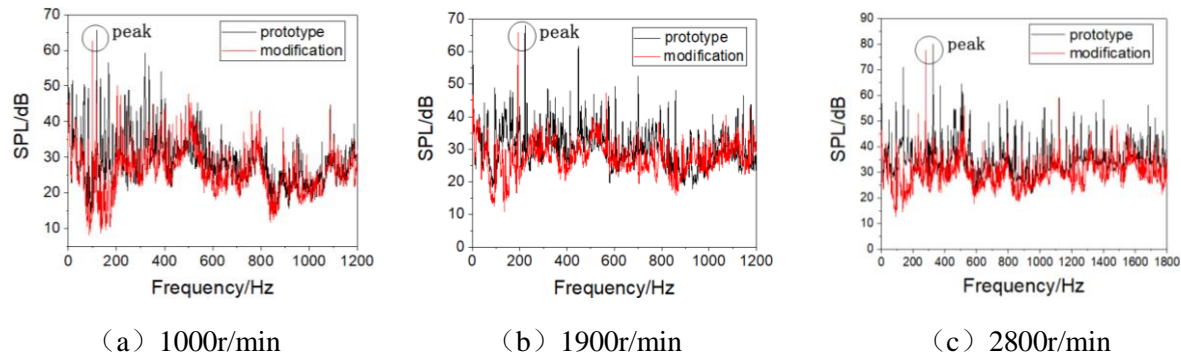


Figure 8. SPL spectrum of multistage centrifugal pumps

4.4 Analysis of distribution of radiated noise

In order to study the distribution of radiated noise, in the center of the impeller rotating surface ($z=0$) 19 measuring points shown in Figure.9 are arranged, and the black circle is the measuring point.

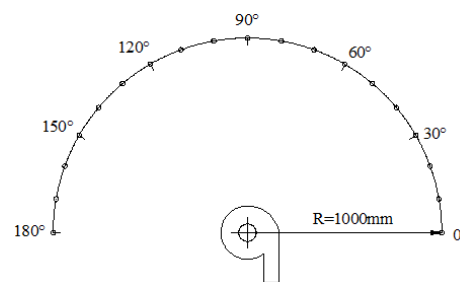


Figure 9. Position of measurement point

Fig.10 shows a distribution diagram under variable speed. When rotating speed is below 1600r/min, the maximum value of SPL appears at the 90° position and the minimum value appears both at 0° and 180° positions. Therefore, the radiated noise source tends to the dipole sound source. When the speed is above 1600r/min, the speed is close to its rated speed, and there is no obvious sound pressure fluctuation. The load distribution tends to be uniform and the running stability is improved.

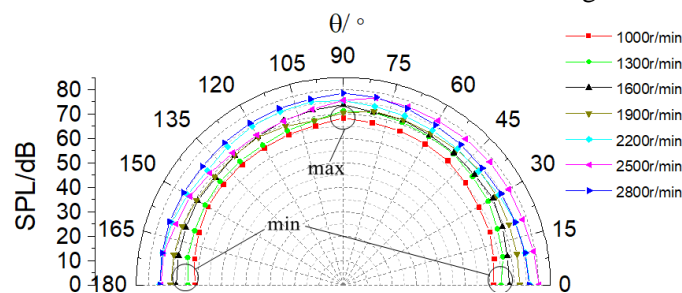


Figure 10. Distribution of radiated noise

5. Conclusion

In this paper, the experimental characteristics of multistage centrifugal pumps are studied from the perspective of radiated noise, and the following results are obtained:

- (1) When the speed is lower than the rated speed, SPL of the radiated noise has a nearly linear growth with the increase of speed.

- (2) Lawson's power theory has a significant effect on the acoustic optimization of multistage centrifugal pump. From the view of acoustic optimization, there is an optimal match between the number of impeller and diffuser vane in multistage centrifugal pump.
- (3) Under the condition of large flow rate and low rotating speed, the radiated noise source of the multistage centrifugal pump is a dipole source in the aspect of acoustic mechanism.

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