Experimental Study on Radiation Noise Frequency Characteristics of a Centrifugal Pump with Various Rotational Speeds

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Abstract: To investigate the radiation noise frequency characteristics of a centrifugal pump under various rotational speeds, a noise measurement system was established in a soundproof room. Sixteen monitoring points were evenly arranged in a circumferential direction around the pump and the sound pressure levels (SPLs) at different monitoring points were measured by a microphone, then the changing patterns of radiation noise in a wide frequency range and at certain frequencies were studied. The results reveal that the SPLs reach a maximum between 1000 and 2000 Hz, while SPLs are lower in other frequency ranges. Additionally, the acoustic energy was introduced to determine the proportion of radiation noise in different frequency ranges to overall noise. When rotational speed increases from 1700 to 2900 rpm, the proportion of acoustic energy between 1000 and 2000 Hz is higher than 0.50 and shows an increasing trend. Meanwhile, the proportion between 0 and 1000 Hz is about 0.30 and decreases gradually, while that between 2000 and 8000 Hz is about 0.12 and shows little change. Also, the increase in radiation noise at high frequency is higher than that at low frequency. This study could provide theoretical guidance for research regarding radiation noise prediction and control technology at different frequencies of centrifugal pumps.

Keywords: frequency characteristics; radiation noise; acoustic energy; centrifugal pump; experimental study

1. Introduction

The problem of noise has drawn widespread attention and has been the subject of studies in recent years [1–3]. Centrifugal pumps are extensively applied in many fields related to the national economy [4,5]. During the operation of pumps, due to the periodic rotation of rotating parts, the flow inside the pumps and the interference between impeller and volute are both repetitive, and cause periodic pressure fluctuations in the flow field, consequently, repetitive impulsive noise [6] is generated. The noise generated by centrifugal pumps can affect human health, degrade the pump flow performance, consume extra external energy and depreciate the working environment [7]. As the regulations for environmental noise become increasingly strict, methods that lower the noise are becoming more significant. Therefore, it is crucial to have a better understanding of radiation noise frequency characteristics, to provide theoretical guidance for research on radiation noise prediction and control technology at different frequencies of centrifugal pumps.

In the past, considerable research has been carried out in terms of the frequency characteristics of centrifugal pump noise. Rzentkowski and Zbroja [8,9] experimentally analyzed the dynamic pressure pulsations spectrum at the pump discharge site, and summarized that the blade-passing excitation...
amplitude is the highest amplitude in the pressure spectrum. Parrondo et al. [10] analyzed the inner sound field in low frequency ranges and reported that the inner sound field could be characterized by a dipole-like source located near the tongue. Si et al. [11] found that the blade-passing frequency (BPF) and its harmonic frequencies are the main frequencies of the flow noise in pipelines and the sound pressure level (SPL) at BPF is higher than the others. Yang et al. [12] reported that the SPL at BPF reached a peak value near the volute tongue. As is known, centrifugal pumps always work in various conditions with various working demands, Ke [13] concluded that the change of flow rate had a great influence on flow noise, especially on the SPL at BPF. Using the near field acoustic pressure method, Ye et al. [14] measured radiation noise under various flow rate conditions, and discovered that the SPLs with a high frequency of 1000 and 2000 Hz made a significant contribution to the overall A-weighted sound pressure level.

With the development of computational fluid dynamics (CFD) technology, numerical calculation methods have been widely adopted by scholars [15,16]. A hybrid method combining CFD with Lighthill acoustic analogy has been widely used to elucidate and predict acoustic generation [17–19]. Langthjem et al. [20,21] applied it for noise calculation in a two-dimensional centrifugal pump and concluded that the main noise source was the dipole source. The dipole source was defined as an unsteady fluid force acting on the wall surface, including the impeller dipole source and the volute dipole source in centrifugal pumps. The impeller-generated radiation noise at BPF exhibited obvious dipole characteristic behavior [22], while the volute-generated radiation noise clearly showed asymmetric directivity characteristics, i.e., the radiation noise in the direction facing the tongue was higher than that in the direction against the tongue [23]. Liu et al. [24] also validated the important impact of the pump cavity dipole source on calculation results. In addition, the pump structure modal response was considered to obtain more accurate results, Ding et al. [25] studied the effect of different structures on SPL at BPF and provided guidance for structural optimization of centrifugal pumps.

Obviously, radiation noise has direct impacts on living and working environments. According to the above literature review, previous experimental research has mainly focused on the internal flow noise characteristics in centrifugal pump pipes, while little experimental research has focused on radiation noise outside the pumps. Additionally, the SPLs at each order of BPF have been the main concern of both experimental and numerical studies. However, it seems clear that the noise radiated by centrifugal pumps is a kind of broadband noise and it has different characteristics at different frequencies, thus, it is necessary to find out the radiation noise distribution in a wide frequency range. In general, pumps work in various conditions with various working demands and the radiation noise at different frequencies changes accordingly, so it is also necessary to study various operational conditions for radiation noise.

Therefore, a centrifugal pump radiation noise measurement system was established in a soundproof room. Then, the changing patterns of radiation noise in a wide frequency range and the proportion of noise in different frequency ranges to overall noise, as well as the noise at certain frequencies were analyzed under various rotational speeds. The conclusions could lay the foundation for further research regarding radiation noise prediction and control technology at different frequencies of centrifugal pumps.

2. Experimental Facility and Procedure

2.1. Parameters of the Test Pump

The test is conducted with a single-stage pump, water at normal temperature is used as working fluid. The geometric and performance parameters of the test pump are listed in Table 1.
was used to measure the radiation noise. The AWA6290M+ type two channel signal analyzer was used for the radiation noise signal acquisition and analysis, moreover, 1/3 Octave analysis method was adopted. Further details regarding the measurement characteristics of instruments used in the system are listed in Table 2.

### Table 1. Geometric and performance parameters of the test pump.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet diameter, mm</td>
<td>80</td>
</tr>
<tr>
<td>Impeller diameter, mm</td>
<td>250</td>
</tr>
<tr>
<td>Outlet diameter, mm</td>
<td>50</td>
</tr>
<tr>
<td>Rated flow rate, m³/h</td>
<td>50</td>
</tr>
<tr>
<td>Design head, m</td>
<td>80</td>
</tr>
<tr>
<td>Rated rotational speed, rpm</td>
<td>2900</td>
</tr>
<tr>
<td>Blade number</td>
<td>6</td>
</tr>
<tr>
<td>Blade-passing frequency, Hz</td>
<td>290</td>
</tr>
<tr>
<td>Shaft-passing frequency, Hz</td>
<td>48.3</td>
</tr>
</tbody>
</table>

### 2.2. Radiation Noise Measurement System

As shown in Figure 1, the experimental apparatuses include a soundproof room, water circulation system, circuit control system, data acquisition and storage system. During the operation, to absorb the external noise and reduce the influence of the surrounding environment and motor operation on the measurement results, the motor and centrifugal pump were insulated in a soundproof room; the exterior walls of the soundproof room, along with the motor, were clad with soundproof cotton. In addition, the internal walls of the soundproof room were protected by soundproof cotton to reduce the noise reflection.

The AWA14423L type microphone (Hangzhou Aihua Instruments Co., Ltd., Hangzhou, China) was used to measure the radiation noise. The AWA6290M+ type two channel signal analyzer was used for the radiation noise signal acquisition and analysis, moreover, 1/3 Octave analysis method was adopted. Further details regarding the measurement characteristics of instruments used in the system are listed in Table 2.

![Figure 1. Layout and instrumentation of measurement system. 1: soundproof room; 2: valve; 3: flow meter; 4: radiation noise monitoring point; 5: computer; 6: two channel signal analyzer; 7: pressure recorder; 8: pressure monitoring point; 9: pump; 10: motor; 11: acoustic enclosure; 12: water tank; 13: frequency converter; and 14: bracket.](image-url)
Table 2. Measurement characteristics of instruments.

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Type</th>
<th>Application</th>
<th>Measuring Range</th>
<th>Accuracy or Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow meter</td>
<td>SLDG-800</td>
<td>Measuring flow rate</td>
<td>0–100 m³/h</td>
<td>0.2% (accuracy)</td>
</tr>
<tr>
<td>Pressure transducer</td>
<td>MIK-300</td>
<td>Measuring inlet pressure</td>
<td>−100–0 kPa (inlet pipe)</td>
<td>0.5% (accuracy)</td>
</tr>
<tr>
<td>Pressure recorder</td>
<td>RX-200D</td>
<td>Recording pressure</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Microphone</td>
<td>AWA14423L</td>
<td>Measuring radiation noise</td>
<td>10–20,000 Hz</td>
<td>50 mV/Pa (sensitivity)</td>
</tr>
<tr>
<td>Two channel signal analyzer</td>
<td>AWA6290M+</td>
<td>Analyzing radiation noise signal</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

Additionally, during the operation, the flow valve installed downstream on the outlet pipe was kept fully opened and unchanged. The pump was driven by the YVF2180L-2 type three-phase asynchronous motor and the rotational speed was regulated by the Y0300G3 type frequency converter, then the radiation noise frequency characteristics were studied under various rotational speeds. According to the similarity law, the relationship between rotational speed and flow rate is defined as,

\[
\frac{Q_1}{Q_2} = \frac{n_1}{n_2}
\]

where \( Q \) and \( n \) represent the flow rate and rotational speed, while the subscript 1 and 2 represent two different operation conditions. To ensure the safety of the running system, seven different rotational speeds that are less than or equal to rated rotational speed, i.e., varying from 1700 to 2900 rpm in increments of 200 rpm were considered. Table 3 shows the rotational speeds and corresponding flow rates.

Table 3. Rotational speeds and corresponding flow rates.

<table>
<thead>
<tr>
<th>Rotational Speed, rpm</th>
<th>Flow Rate, m³/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1700</td>
<td>56.9</td>
</tr>
<tr>
<td>1900</td>
<td>64.8</td>
</tr>
<tr>
<td>2100</td>
<td>69.6</td>
</tr>
<tr>
<td>2300</td>
<td>74</td>
</tr>
<tr>
<td>2500</td>
<td>78.2</td>
</tr>
<tr>
<td>2700</td>
<td>82.1</td>
</tr>
<tr>
<td>2900</td>
<td>86</td>
</tr>
</tbody>
</table>

2.3. Arrangement of the Monitoring Points

To acquire the frequency distribution characteristics of radiation noise in different direction and corresponding amplitudes, 16 monitoring points were arranged on the measurement surface around the pump. As shown in Figure 2, the monitoring points were 1000 mm away from the center of the impeller and arranged evenly in a circumferential direction [26]. During the measurement process, the SPL of every monitoring point was measured sequentially by a microphone. Here, SPL is defined as,

\[
SPL = 20\log \frac{P_e}{P_{ref}}
\]

\[
P_e = \sqrt{\frac{1}{T} \int_0^T [p']^2 dt}
\]

where \( P_{ref}, P_e \) and \( p' \) represent the reference sound pressure \((2 \times 10^{-5} \text{ Pa in air})\), effective sound pressure and instantaneous sound pressure, respectively. Additionally, acoustic energy was introduced to compare the proportion of radiation noise in different frequency ranges because it can be superimposed by arithmetic, moreover, the propagation of sound is essentially the propagation of energy. Briefly,
the application of acoustic energy can reveal the proportion of radiation noise in different frequency ranges to overall noise intuitively. Therefore, the average acoustic energy density [27] is analyzed and it is defined as,

\[ \varepsilon = \frac{p^2}{\rho c^2} \]  

(4)

where \( \varepsilon \), \( \rho \) and \( c \) represent the acoustic energy density, medium density (1.29 kg/m\(^3\) in air) and the sound speed in medium (343 m/s in air), respectively.

![Figure 2. Arrangement of monitoring points in a circumferential direction.](image)

To figure out the radiation noise overall intensity of the 16 monitoring points at certain frequencies, total sound pressure level (TSPL) is introduced and expressed as,

\[ \text{TPSL} = 10 \log_{10} \sum_{i=1}^{16} 10^{SPL_i/10} \]  

(5)

3. Frequency Characteristics of Radiation Noise under Various Rotational Speeds

3.1. Changing Patterns of Radiation Noise in a Wide Frequency Range

By measuring the SPL characteristics of different monitoring points in a circumferential direction, the changing patterns of radiation noise in a wide frequency range were studied.

P1 (270°, in the direction against the outlet), P5 (0°, the minimum noise point), P9 (90°, in the direction facing the outlet) and P13 (180°, the minimum noise point) [28] are selected. Figure 3 illustrates the frequency characteristics of the four monitoring points in a wide range of frequencies. It can be observed that at rated rotational speed (2900 rpm), the SPLs of different monitoring points show a fluctuating ascending trend in the low frequency range from 31.5 to 1000 Hz, due to the excitation results of periodic interference between the impeller and volute [29], according to Equations (6) and (7),

\[ f_{bpf} = \frac{nz}{60} \]  

(6)

\[ f_{spf} = \frac{n}{60} \]  

(7)

where \( f_{bpf} \) and \( f_{spf} \) represent BPF and shaft-passing frequency (SPF), \( z \) is the number of blades and \( l \) is harmonic sequence number (\( l = 1, 2, 3, \ldots \) ), SPLs reach a peak value at each order of BPF and SPF.

Unlike the frequency characteristics of flow noise in pump pipelines [11], the maximum value of radiation noise outside the pump appears in the range from 1000 to 2000 Hz, i.e., in the range of high order harmonics of BPF. The possible reason is that the native vibration frequencies of pump structure
belong to this range [30]. After that, the SPLs of different monitoring points decrease gradually when the frequency is higher than 2000 Hz. Besides, the SPLs at most frequencies of P9 are generally higher than those of other monitoring points. This can be explained by that P9 is located in an outlet direction, the radiation noise at P9 is more affected by the internal flow noise in the outlet pipeline and the vibration of the outlet pipeline.

In addition, the radiation noise frequency characteristics of P9 under various rotational speeds are compared in Figure 4. The radiation noise shows the same pattern of changes as those shown in Figure 3 under various rotational speeds. Moreover, with the increase in rotational speed, SPLs at various frequencies show an ascending trend and reach a maximum at 2900 rpm.

**Figure 3.** Changes in sound pressure level (SPL) at different monitoring points in a wide frequency range (2900 rpm).

**Figure 4.** Changes in SPL in a wide frequency range under various rotational speeds (P9).
3.2. Changing Patterns of Radiation Noise in Different Frequency Ranges

As mentioned above, SPLs reach a maximum between 1000 and 2000 Hz. The noise in this range also belongs to the resonant frequency range of the ear cavity and has the greatest impact on people [31], so it is necessary to find out its proportion to overall noise. Therefore, the proportion of radiation noise in different frequency ranges to overall noise is studied quantitatively. The ratio of acoustic energy in the range from 0 to 1000 Hz ($\varepsilon_1$), 1000 to 2000 Hz ($\varepsilon_2$), as well as from 2000 to 8000 Hz ($\varepsilon_3$) to the total acoustic energy ($\varepsilon_t$) was analyzed under various rotational speeds.

Figure 5 shows the proportion of the acoustic energy in different frequency ranges to the total acoustic energy under various rotational speeds. In general, the radiation noise between 1000 and 2000 Hz makes the most significant contribution to overall noise, the value of $\varepsilon_2/\varepsilon_t$ is higher than 0.5 and increases by 22.61% when rotational speed increases from 1700 to 2900 rpm. Moreover, the acoustic energy between 0 and 1000 Hz accounts for about 0.30 of the total acoustic energy, however, the proportion decreases by 38.55% when rotational speed increases from 1700 to 2900 rpm. The change in rotational speed affects not only the radiation noise levels at different frequencies, but the proportion of radiation noise in different ranges, specifically, the increase in rotational speed causes an increase in the proportion of radiation noise from 1000 to 2000 Hz and a decrease in the proportion of radiation noise from 0 to 1000 Hz. When the frequency is higher than 2000 Hz, the radiation noise contributes very little to overall noise, but the proportion of this range shows little change with a change in rotational speed and the value of $\varepsilon_3/\varepsilon_t$ fluctuates around 0.12.

![Figure 5. The ratio of acoustic energy in different frequency ranges.](image)

3.3. Changes in Radiation Noise at Certain Frequencies

In this section, the changes in radiation noise at certain frequencies were studied. TSPLs of 16 monitoring points were calculated and the results of TSPLs at 500, 1000, 2000, 4000, 8000 Hz with various rotational speeds were compared and are presented in Figure 6.
As shown in Figure 6, TSPLs at 1000 and 2000 Hz are higher than the others, while TSPL at 8000 Hz is lower than the others under all of the operational conditions. Additionally, there is a TSPL turning point at 500 Hz when rotational speed is set as 2500 rpm, which is the 2-order BPF under 2500 rpm. Moreover, TSPLs at various frequencies show an ascending trend with the increase in rotational speed and the increase in TSPL at high frequency is higher than at low frequency. More specifically, when rotational speed increases from 1700 to 2900 rpm, TSPLs at 500, 1000, 2000, 4000 and 8000 Hz increase 8.72%, 13.46%, 10.77%, 14.01% and 17.66%, respectively. On the one hand, with the increasing of rotational speed, the pressure fluctuation intensity on wall surfaces consequently increases [32], so TSPLs at various frequencies increase simultaneously. On the other hand, as the rotational speed increases, the required net positive suction head (NPSHr) also increases, however, the available net positive suction head (NPSHa) has different change rules, and is defined as,

$$NPSHa = \frac{p_s}{\rho g} + \frac{v_s^2}{2g} - \frac{P_v}{\rho g}$$  \hspace{1cm} (8)$$

where $p_s$, $v_s$ and $P_v$ represent the inlet pressure (Pa), inlet velocity (m/s) and saturated vapor pressure at the corresponding temperature (25 °C). The NPSHa and NPSHr change patterns under various rotational speeds are presented in Figure 7.

As shown in Figure 7, with an increase in rotational speed, the NPSHa decreases immediately and is even lower than NPSHr under 2700 and 2900 rpm. The decrease in NPSHa can lead to the development of cavitation. Furthermore, the development of cavitation can cause both pump body vibration [33] and acoustic pressure pulsation [34], especially in high frequency ranges, and further cause a dramatic increase in radiation noise at high frequencies.
C.G., D.L. designed the study, conducted the experiment and collected the experimental data; H.G. analyzed the experimental data; C.G. wrote the manuscript; M.G. reviewed and edited the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.
References


6. Zhou, Y.L.; Yin, Y.X.; Zhang, Q.Z. Active control of repetitive impulsive noise in a non-minimum phase system using an optimal iterative learning control algorithm. J. Sound Vib. 2013, 332, 4089–4102. [CrossRef]


23. Gao, M.; Dong, P.X.; Lei, S.H.; Turan, A. Computational Study of the Noise Radiation in a Centrifugal Pump When Flow Rate Changes. Energies 2017, 10, 221. [CrossRef]


34. Lu, J.X.; Yuan, S.Q.; Yuan, J.P.; Ren, X.D.; Pei, J.; Si, Q.R. Research on the noise induced by cavitation under the asymmetric cavitation condition in a centrifugal pump. In Proceedings of the 9th International Symposium on Cavitation, Lausanne, Switzerland, 6–10 December 2015.

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