Analysis of Influence of Volute Tongue Angle on Flow-induced Vibration and Noise Characteristics of Centrifugal Pump

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Abstract. In order to reduce the adverse effects of flow-induced vibration and noise on the performance of centrifugal pumps, this study focuses on the impact of the volute tongue angle on the internal flow characteristics and the underlying mechanisms. By constructing a three-dimensional geometric model of a centrifugal pump and using computational fluid dynamics (CFD) software for meshing and simulation, this research analyzes how different volute tongue angles influence the internal flow field, pressure pulsation, and noise characteristics. It is found that the volute tongue angle significantly affects the natural frequency, pressure pulsation, and sound pressure level of the centrifugal pump. As the volute tongue angle increases, the natural frequency of the pump rises, leading to a shorter vibration period. This results in an improved internal pressure distribution and a decrease in the average pressure value. Furthermore, through acoustic simulation analysis using Actran software, it is observed that an increase in the volute tongue angle correlates with a reduction in the sound pressure level of the pump. In the experimental verification phase, a centrifugal pump vibration test bench is constructed. By measuring the Root Mean Square (RMS) values of the vibration intensity of centrifugal pumps with varying tongue angles, it is further confirmed that increasing the volute tongue angle helps to reduce the vibration of the pump body. This study demonstrates that optimizing the design of the volute tongue angle is an effective method to mitigate vibration and noise in centrifugal pumps, thereby enhancing the operational performance and stability of the pump.

Keywords: centrifugal pump, volute tongue angle, vibration and noise characteristics, modal analysis

1 Introduction

Centrifugal pumps, as a common type of fluid transmission equipment, are widely used in industries including agriculture and urban water supply [1]. However, in practical applications, centrifugal pumps often face issues of low work efficiency and short service life, caused by vibrations and noise. The noise generated by the operation of centrifugal pumps is primarily due to two factors. Firstly, it is due to the insufficient installation precision, which can lead to collisions between parts and subsequent vibration noise when the motor drives the pump. Secondly, it is due to the turbulence produced by the internal fluid movement during operation, which causes vibration noise upon colliding with the volute shell. The flow-induced vibration and noise in centrifugal pumps represent a forced vibration situation, primarily the result of forces generated by fluid movement within the pump's internal flow field. These forces are mainly the result of unstable phenomena such as turbulence pulsation, rotating stall, cavitation, and dynamic-static interference [2].

In recent years, scholars both domestically and abroad have conducted in-depth research on the hydraulic performance analysis of centrifugal pumps. A. He et al. [3] explored the noise issues induced by gas-liquid two-phase flow within centrifugal pumps, finding that an increase in gas would reduce flow stability and increase noise. R. Gangipamula et al. [4] conducted a comparative study on airborne noise and flow-induced noise in double-suction centrifugal pumps, proposing a method for predicting flow-induced noise. C. Dai et al. [5] studied the drag reduction and noise reduction effects and mechanisms of biomimetic blade centrifugal pumps, finding that biomimetic design can effectively improve pump performance. M. Kaya et al. [6] experimentally studied cavitation-induced noise and vibration in centrifugal pumps, finding that cavitation structures affect the noise and vibration of the pump. Q. Ma et al. [7] investigated the impact of shaft misalignment on the vibration and noise characteristics of ship centrifugal pumps, finding that the misalignment state of the shaft can be judged through vibration characteristics. Y. Yuan et al. [8] designed two new types of composite impellers to replace the original long blade impellers, and verified their effectiveness, significantly improving the vibration characteristics of high-speed centrifugal pumps.

This paper investigates the impact of the volute tongue angle on the flow-induced vibration and noise characteristics of centrifugal pumps. The study employs software simulation to analyze the effects of the volute tongue angle on these characteristics, aiming to offer innovative solutions for reducing the vibration and noise in centrifugal pumps.

2 Geometric Model and Modal Analysis

2.1 Structural Parameters

The IS 80-50-250 centrifugal pump is selected as the test pump, and its main structural parameters are shown in Table 1.

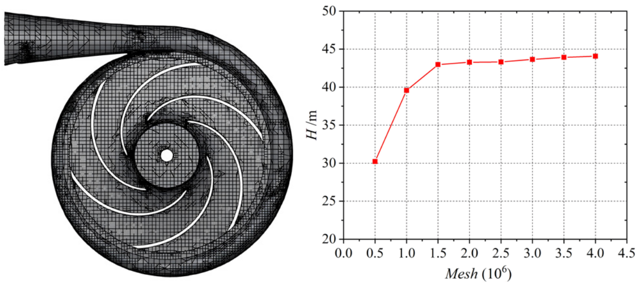
Table 1. Structural Parameters.

Parameters	Values	Parameters	Values
Flow rate Q / $m^3 \cdot h^{-1}$	50	Blade number Z	6
Head H / m	80	Impeller inlet placement angle β_1 / °	30
Rotation speed n / $r \cdot min^{-1}$	2900	Impeller outlet placement angle β_2 / °	20
Impeller inlet diameter D_j / mm	80	Blade wrap angle φ / °	110
Impeller outlet diameter D_2 / mm	240	Blade thickness S / mm	4
Impeller inlet width b_1 / mm	16	Volute Base circle diamete D_3 / mm	250
Impeller outlet width b_2 / mm	6	Volute inlet width b_3 / mm	22

2.2 Grid Division

Based on the centrifugal pump structural parameters in Table 1, a three-dimensional model is established. The grid division is carried out using ICEM-CFD software, as shown in Fig. 1.

As shown in Fig. 1 (a), the impeller part is defined as the rotor, and the volute shell part is defined as the wall. The number of three-dimensional grids generated by the centrifugal pump is 1.513922E+06. To test the extent to which the number of grids affects the external performance characteristics of the pump, internal simulation experiments with different numbers of grids are conducted on the centrifugal pump, as shown in Fig. 1 (b).



(a) Grid division (b) Grid independence

Fig. 1. Centrifugal pump structure model.

The simulation results indicate that the pump head becomes stable when the grid count reaches 1.5E+06. Furthermore, as the grid count increases, the variation in this performance index remains below 1%. This suggests that the designed grid count satisfies the design requirements.

2.3 Modal Analysis of Volute

Modal analysis, the primary method for studying structural characteristics, is widely used in engineering vibration [9]. When analyzing the vibration characteristics of centrifugal pumps, the volute tongue angle is a critical design parameter because it directly affects the pump's natural frequency. This natural frequency, which is the frequency at which the structure vibrates freely, is crucial for predicting and controlling the pump's vibration behavior during operation. To assess the impact of various volute tongue angles on the flow-induced vibration characteristics, four centrifugal pump models with tongue angles of 25°, 28°, 31°, and 34° are designed, each exhibiting unique natural frequencies, damping ratios, and modal shapes. Determining the natural frequencies through modal analysis helps to understand how the volute tongue angle influences the pump's vibration characteristics. The calculated natural frequencies for these angles are detailed in Table 2.

Table 2. Natural Frequency of Volute.

Orders	**Frequency/Hz**				**Cycle/S**
	25°	***28°***	***31°***	***34°***	
1	350.79	361.94	372.22	380.86	0.55556
2	577.68	634.16	694.98	759.92	0.66667
3	1316.02	1357.73	1404.14	1445.73	0.77778
4	2940.03	2933.82	2949.32	2937.02	0.88889
5	3143.54	3226.13	3307.24	3357.43	1

According to the data in Table 2, the natural frequency increases as the volute tongue angle increases. From 25° to 34°, the natural frequency of each order exhibits an upward trend, indicating that an increase in the volute tongue angle leads to an increase in the vibration frequency of the centrifugal pump. The rate of frequency increase is more pronounced when the volute tongue angle is smaller (for example, from 25° to 28°), but the rate of increase diminishes as the volute tongue angle becomes larger (for example, from 31° to 34°). This suggests that minor adjustments to the volute tongue angle have a more significant impact on frequency during the early stages of design. Furthermore, as the volute tongue angle increases, the vibration period of the centrifugal pump is shortened, since the period is the reciprocal of the frequency, and an increase in frequency results in a decrease in the period. Consequently, a larger volute tongue angle indicates that the centrifugal pump requires less time to complete a vibration cycle. Therefore, proper adjustment of the volute tongue angle can significantly influence the vibration characteristics of the centrifugal pump.

3 Analysis of Vibration and Noise Characteristics

3.1 Selection of Volute Monitoring Points

To better analyze the characteristics of the centrifugal pump, eight monitoring points are placed in various parts of the volute, as depicted in Fig. 2. By analyzing the pressure pulsation characteristics at these points, a deeper understanding of the pump's vibration behavior can be achieved [10].

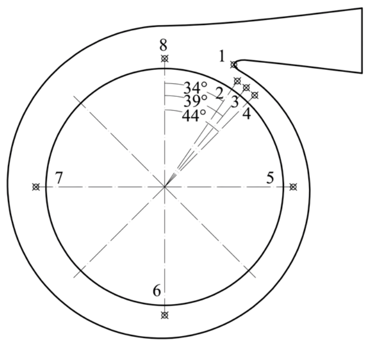


Fig. 2. Distribution of monitoring points.

3.2 Analysis of Pressure Pulsation Characteristics

To ensure the accuracy of the numerical simulation results from the analysis of centrifugal pumps, the instantaneous values monitored at each point by the last set of data from unsteady flow are selected for pressure pulsation analysis. The average pressure values at each monitoring point are presented in Table 3.

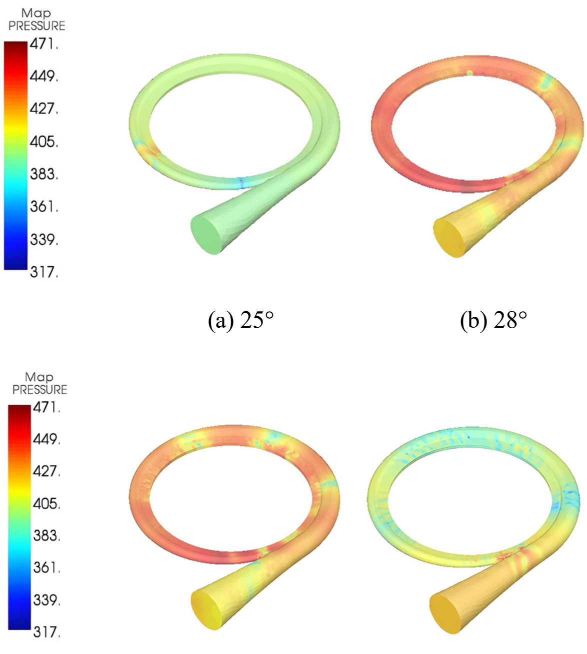
Table 3. Average Pressure Value (Pa).

Monitoring points	**25°**	**28°**	**31°**	**34°**
Point 1	69248.15	155952.54	97828.47	105208.24
Point 2	386377.99	357862.93	331582.99	305833.70
Point 3	446965.48	417088.66	389407.99	369252.35
Point 4	476046.59	448274.24	412277.98	398581.42
Point 5	572422.94	551597.29	520309.86	514216.98
Point 6	506000.22	498464.55	491055.42	491805.94
Point 7	390649.14	387574.79	367447.28	369886.06
Point 8	221323.48	198148.99	181194.49	159641.26

According to the data in Table 3, the average pressure values at each monitoring point exhibit a similar trend across different volute tongue angles. As the volute tongue angle increases, the average pressure values at most monitoring points decrease, indicating that the volute tongue angle significantly affects the internal pressure distribution within the pump. Among all monitoring points, Point 1 and Point 8 have relatively low average pressure values, while Point 2 and Point 3 have relatively high values. This is primarily because when the impeller periodically sweeps over the tongue, the outlet velocity of the blade directly interferes with the tongue, causing strong extrusion and disturbance of the fluid near the tongue. The outlet velocity of the blade drops sharply due to the tongue's obstruction, and this change in velocity is converted into a pressure change, leading to an increase in pressure near the tongue. Point 5 records the maximum value because when the water flow first enters the volute, the speed has not yet stabilized, resulting in the largest pressure pulsation value. Numerical analysis indicates that when the volute tongue angle is set at 34°, the average pressure pulsation value during centrifugal pump operation is minimized.

3.3 Analysis of Noise Characteristics

Actran software is a specialized tool primarily used for acoustic simulation analysis [11]. The mesh is exported through Ansys Workbench, and the density of unsteady flow calculation results simulated in Fluent software is taken as the time-domain signal variable for sound field simulation analysis. A flow-induced noise analysis of the centrifugal pump is conducted, with the simulated results of sound pressure level contour diagrams at various volute tongue angles illustrated in Fig. 3.



(a) 25° (b) 28°

(c) 31° (d) 34°

Fig. 3. Sound pressure level cloud map of centrifugal pump.

As shown in Fig. 3, the sound pressure level near the tongue is the highest for centrifugal pumps with different tongue angles. This is because when the fluid enters the impeller and flows along the volute channel, it causes a decrease in flow velocity and an increase in pressure within the channel. When the fluid passes near the tongue, the protruding part of the tongue changes the direction of the fluid flow. Such sharp changes in flow velocity and direction can induce vortex and reflux phenomena near the tongue, thereby generating dynamic-static interference effects between the impeller and the volute. Therefore, the sound pressure level near the tongue increases.

The frequency domain response curves of sound pressure levels for centrifugal pumps with different volute tongue angles are shown in Fig. 4.

As shown in Fig. 4, with the increase of the tongue angle from 25° to 34°, the sound pressure level shows a gradually decreasing trend at most frequency points. In the low-frequency region (48.333 Hz to 241.665 Hz), the centrifugal pump has a generally higher sound pressure level because fluid fluctuations are more likely to resonate with the pump's structure at low frequencies. As the tongue angle increases, the sound pressure level decreases significantly. In the medium and high-frequency region (above 241.665 Hz), the sound pressure level shows a decreasing trend because, as the frequency increases, the period of fluid fluctuation becomes shorter, reducing the resonance effect with the pump's structure. At these frequencies, the decreasing trend of the sound pressure level still exists, but compared with the low-frequency region, the amplitude is reduced.

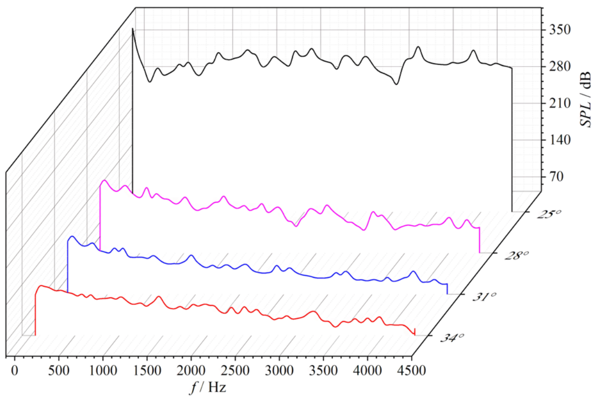


Fig. 4. Frequency domain response curve of sound pressure level.

In the low-frequency band, the sound pressure level generally decreases with increasing frequency, and the difference between different tongue angles is very pronounced. The smaller the tongue angle, the higher the sound pressure level, indicating that the cochlear tongue angle significantly affects the sound pressure level in the low-frequency band. After entering the high-frequency band, the trend of the sound pressure level becomes more complex. Although the overall trend is still to decrease with increasing frequency, the differences between different tongue angles are reduced, and some frequency bands may even exhibit a crossover phenomenon. This is because, at high frequencies, fluid flow is more complex and influenced by multiple factors. Therefore, an appropriate increase in the tongue angle can effectively reduce pressure pulsations. By optimizing the design of the tongue angle in the volute, the noise level in the pump can be significantly reduced, thereby improving the pump's operating performance and stability.

4 Experimental Verification

To further examine the impact of different tongue angles on the internal vibration noise of centrifugal pumps, a centrifugal pump vibration test bench is set up, as shown in Fig. 5.

Fig. 5. Centrifugal pump vibration test bench

The RMS value of vibration intensity is a key indicator for evaluating the degree of vibration of centrifugal pumps. By detecting the RMS value of vibration intensity, it can be judged whether the operation of the pump is normal, and potential problems can be discovered in time for maintenance, thus avoiding possible equipment damage or production interruption. Acceleration sensors are used to measure the vibration intensity at the positions of the centrifugal pump body and pump corner. Through test experiments on centrifugal pumps with different tongue angles, the RMS values of vibration intensity under different working conditions are obtained as shown in Table 4.

Table 4. RMS Values of Vibration Intensity (m/s²).

Flow rate	**Measuring position**	**Pump body**			**Pump corner**		
	Measuring direction	***X***	***Y***	***Z***	***X***	***Y***	***Z***
0.6*Q*	25°	5.325	3.932	2.896	4.656	2.897	1.872
	28°	4.116	2.645	1.643	4.026	1.849	1.326
	31°	3.598	1.862	1.246	2.883	1.256	0.657
	34°	1.863	0.887	0.635	0.559	0.329	0.369
1.0*Q*	25°	7.241	5.662	4.658	6.553	4.298	3.226
	28°	6.133	4.273	3.348	5.992	3.543	2.548
	31°	5.563	3.624	2.762	4.687	2.776	1.645
	34°	3.259	2.364	1.165	2.336	1.872	0.649
1.4*Q*	25°	8.861	7.236	6.262	8.223	5.925	4.883
	28°	7.534	5.956	5.653	7.349	5.332	3.956
	31°	7.065	4.993	4.392	6.562	4.462	3.265
	34°	4.668	3.882	2.598	3.954	3.658	2.113

As shown in Table 4, the vibration response of the pump body and the pump angle on the three coordinate axes of X, Y and Z increases with the increase of the amount of fluid flowing through the pump body. This phenomenon can be attributed to the corresponding increase of the flow velocity in the pump cavity due to the increase of the flow rate, which in turn stimulates a more significant hydrodynamic effect. When the fluid passes through the pump body, it will cause pressure fluctuation and velocity difference inside it, and these differential flows will exert a changing force on the pump body, which will lead to a significant increase in vibration response. Meanwhile, with the increase of the tongue angle, the RMS values of vibration intensity in the X, Y, and Z directions gradually decrease. At the pump body position, the vibration intensity in the X direction decreases from 7.241 m/s^2 at a tongue angle of 25° to 3.259 m/s^2 at a tongue angle of 34°, and similar decreasing trends are also observed in the Y and Z directions. This indicates that increasing the tongue angle is beneficial in reducing the internal vibration of the pump body. Similarly, the vibration intensity in the X, Y, and Z directions at the pump casing also decreases gradually with the increase of the tongue angle. At the pump casing position, the vibration intensity in the X direction decreases from 6.553 m/s^2 to 2.336 m/s^2, and the vibration intensity in the Y and Z directions also significantly decreases. This trend is consistent with the change in vibration of the pump body, indicating that the design of the tongue angle has a significant effect on the overall vibration characteristics of the pump.

The design of the tongue angle directly affects the flow path and velocity distribution of the fluid in the pump. A smaller tongue angle may cause a larger impact and reflux near the tongue, increasing the instability of the flow, which will then cause stronger vibrations and noise. As the tongue angle increases, the smoothness of the fluid flow is improved, reducing the impact and reflux, and thus reducing the vibration and noise levels. In addition, changes in the tongue angle may also affect the turbulence intensity inside the pump. A larger tongue angle may help suppress the development of turbulence, making the fluid flow smoother and reducing the generation of turbulence noise.

It can be seen that the sound pressure level and vibration intensity near the tongue of the centrifugal pump with different tongue angles both show a decreasing trend as the tongue angle increases. The internal mechanism of this trend mainly involves the improvement of flow stability, optimization of turbulence control, and reduction of structural response. By reasonably designing the tongue angle, the vibration and noise levels of the centrifugal pump can be effectively reduced, improving the operating efficiency and stability of the pump.

5 Conclusion

(1) The volute tongue angle is a key design parameter affecting the internal flow characteristics and noise generation of centrifugal pumps. Through CFD simulation, it can be observed that the adjustment of the volute tongue angle can significantly alter the flow field distribution inside the pump, thereby affecting the pressure pulsation and noise level. The results of modal analysis indicate that an increase in the volute

tongue angle leads to an increase in the natural frequency of the centrifugal pump, which helps to avoid the coincidence of the working frequency with the natural frequency of the pump, thereby reducing vibration caused by resonance.

(2) The noise characteristic analysis reveals the influence of the tongue-baffle angle on the sound pressure level of a centrifugal pump. With an increase in the tongue-baffle angle, the sound pressure level of the centrifugal pump near the tongue baffle decreases, indicating that the acoustic performance of the pump can be optimized by adjusting the tongue-baffle angle.

(3) In the experimental verification section, this paper sets up a centrifugal pump vibration test bench to conduct vibration intensity tests on centrifugal pumps with different tongue angles. The experimental results show that with the increase of flow rate, the vibration response of centrifugal pump is significantly enhanced. In addition, as the tongue angle increases, the RMS values of the vibration intensity in the X, Y, and Z directions of the pump body and casing all significantly decrease. This trend is consistent with the numerical simulation results, further verifying the impact of the volute tongue angle on the vibration and noise characteristics of centrifugal pumps.

(4) The optimization strategy proposed in this study offers a new perspective for centrifugal pump design. By reasonably adjusting the volute tongue angle, not only can the vibration and noise of the pump be reduced, but also the operating efficiency and stability of the pump can be improved. This finding provides an important theoretical basis and experimental support for the optimization design of centrifugal pumps, which is of great significance for enhancing the operating efficiency and stability of centrifugal pumps and prolonging their service life. In the future, more design parameters affecting the vibration and noise characteristics of centrifugal pumps can be further explored to promote the continuous development of centrifugal pump technology. Especially, the multi-objective function of impeller and volute structural parameters is established, and the parameters are optimized by intelligent control algorithm in order to improve the vibration characteristics of centrifugal pump in an all-round way.

Acknowledgements

This project is supported by Anhui Province Young Backbone Teachers Domestic Visiting and Training Funding Project (No. JNFX2024051); University Natural Science Research Project of Anhui Province (No. 2024AH051336, No. KJ2021A1026); and Anhui Province University Discipline (Professional) Top Talent Academic Funding Project (No. gxbjZD2021076).

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