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A Review on Influencing Factors and Suppression Methods of Centrifugal Pump Vibration

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Abstract

As a core auxiliary equipment in power plants, unplanned shutdowns of centrifugal pumps caused by vibration will result in huge economic losses to the plants. This paper aims to systematically elaborate on the generation mechanism, key influencing factors, and suppression methods of flow-induced vibration in centrifugal pumps. Pump body vibration is mainly derived from pressure pulsation generated by internal fluid flow, which acts on the pump body to induce vibration. The main influencing factors include unreasonable setting of pump body geometric parameters, unstable flow conditions, and cavitation. To reduce the intensity of flow-induced vibration, scholars mainly adopt numerical simulation, experimental testing, and a combination of both to formulate optimization strategies, minimizing pressure pulsation inside the pump by optimizing the design of pump body geometric parameters. Research shows that impeller parameter optimization can reduce the amplitude of pressure pulsation, increase pump efficiency by 1.6%~6.71%, and decrease vibration intensity by more than 30%; the multi-volute structure can maximize the reduction of radial thrust by 72% and improve efficiency by 6%~10%; the optimization method combining artificial intelligence/computational intelligence technology with CFD can increase pump operating efficiency by about 27% and shorten model training time by 180s. By sorting out the influence laws of pump body design and operating conditions on vibration, this paper summarizes the mainstream suppression technologies of flow-induced vibration, and clarifies that the application of multi-parameter collaborative optimization, advanced numerical simulation models (DES/LES), and adaptive intelligent algorithms is the key direction to reduce vibration and bridge the gap between theoretical and engineering applications in the future, providing theoretical support and technical reference for the stable operation and optimal design of centrifugal pumps.

1. Introduction

In the production chain of thermal power plants, centrifugal pumps are indispensable core auxiliary machinery, playing a critical "blood-transporting" role in the working medium delivery process. As important links connecting major equipment such as boilers and steam turbines, typical centrifugal pumps including feedwater pumps, circulating water pumps, and condensate pumps each perform their respective functions: feedwater pumps pressurize and deliver water to boilers to ensure steam generation; circulating water pumps drive cooling water to complete the heat exchange cycle of condensers; condensate pumps recover the condensed water from the exhaust steam of steam turbines to realize the efficient utilization of the working medium. Their stable operation serves as the foundation for the continuous power generation of the unit.

Centrifugal pumps are prone to failures such as mechanical seal leakage, impeller cavitation, and abnormal pump body vibration during operation, among which pump body vibration is particularly harmful. Vibration can be transmitted from the pump body to pipelines and equipment foundations, leading to minor issues like seal failure and leakage at flange joints as well as loosening of fixing bolts, and severe problems such as pipeline cracking and foundation settlement. If the vibration value exceeds the standard without timely treatment, it will also trigger the action of the unit protection system, resulting in unplanned shutdowns. Meanwhile, high-frequency vibration will accelerate the fatigue wear of key components such as bearings and impellers, shortening the service life of the equipment and significantly increasing equipment maintenance costs.

The operating status of centrifugal pumps directly determines the safety and economic benefits of thermal power plants. After a failure occurs, parameters such as pressure and flow rate of the thermal system will deviate from the designed values, leading to reduced boiler combustion efficiency, insufficient steam turbine output, and a significant increase in the unit's power generation coal consumption. If core pump units such as feedwater pumps suddenly fail, it will directly cause unit shutdowns. For each million-kilowatt unit that shuts down for one day, the power generation loss alone amounts to millions of yuan, along with additional chain costs such as equipment emergency repairs and power grid dispatching. Therefore, the operation and maintenance of centrifugal pumps are of vital importance. Excessive vibration is a common fault of multistage centrifugal pumps. There are many factors causing pump vibration, which can be summarized into three categories [1]: (a) vibration caused by installation problems; (b) vibration caused by the water supply system; (c) vibration caused by unreasonable design of the pump body. The first two categories have formed relatively mature theories and experiences, but there is still no good solution to the flow-induced vibration problem caused by the pump body design.

There are many factors causing flow-induced vibration in the pump, which can be roughly divided into two categories: (a) unreasonable design of the pump body structure; (b) unreasonable operating conditions. In terms of pump body structure, the blade inlet and outlet installation angles [2–4], the number of blades [5–9], the wrap angle size[10–14], the blade thickness[15,16], the volute shape and diffuser size parameters[17–22], the impeller ring seal clearance[23–25], and the impeller outlet tip clearance [26,27] will all interfere with the flow in the pump. In terms of the pump's operating conditions, different blade passing frequencies [28], different flow rates and rotational speeds [29–38] will also cause flow-induced vibration of the pump.

This paper discusses and summarizes the research status of vibration mechanisms of multistage centrifugal pumps from the following three aspects: (a) the influence of pump body design on vibration; (b) vibration caused by different working conditions; (c) research on suppression methods for flow-induced vibration of centrifugal pumps.

2. Influence of Pump Body Design on Vibration

The unsteady flow and pulsating pressure inside centrifugal pumps are closely related to the geometric parameters of flow passages, which are composed of volutes, impellers, blades, guide vanes, and main shafts. However, with the in-depth research on centrifugal pumps by scholars, it has been found that the leakage from impeller tip clearances and annular seal clearances can also cause pressure pulsation of the fluid, interfere with the flow in the main flow passage, thereby generating eddies and causing pump body vibration. Therefore, clearance flow also needs to be concerned.

2.1 Influence of Impeller on Vibration

The impeller is the work-performing component of a centrifugal pump, which transfers mechanical energy to the working fluid, enabling it to gain greater kinetic energy. Rajavamsi Gangipamula [39] studied low-specific-speed centrifugal pumps and found that jet-wake flows in the impeller passages are the primary factor causing pressure pulsation. Arihant Sonawat [40] modified the impeller stagger angle of a double-suction centrifugal pump and found that a 30° stagger angle minimized pressure pulsation, effectively reducing vibration. The influence of blade thickness [16] on pressure pulsation within the impeller cannot be ignored. Optimizing the blade shape by modifying the thickness of the pressure side (PS) [41] can reduce the intensity of shedding vortices at the trailing edge (TE) of the blade. Additionally, simultaneous modification of blade thickness and inlet/outlet installation angles [42], as shown in Figure 1, can mitigate unsteady flow within the pump.

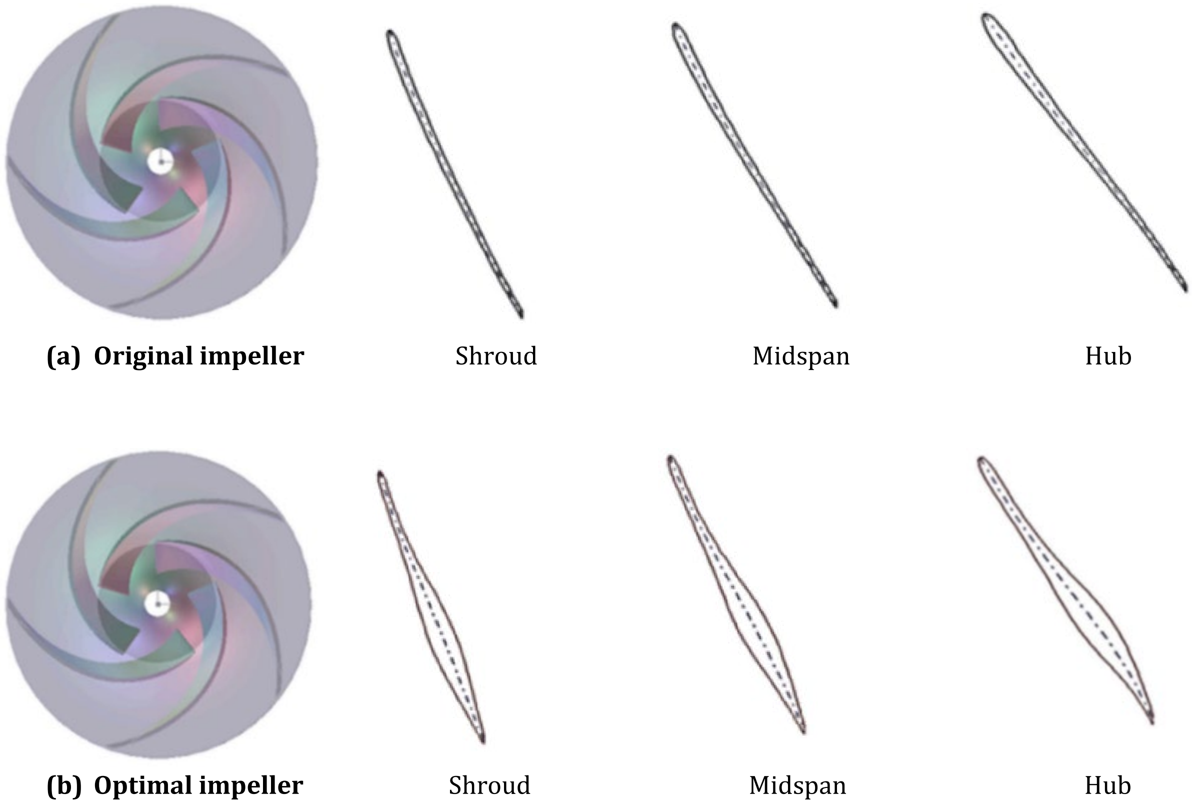

Fig. 1 *Comparison of the original and optimal impellers*

Slitting on the blades [43] can also alter the blade shape, thereby affecting their flow characteristics. Studies have shown that the width and depth of the slots are the main parameters affecting pump performance under small flow rates, while the slot position becomes the key factor under large flow rates. Moderate skewing of the blade outlet edge [44] is also conducive to suppressing flow-induced vibration in the pump.

The blade wrap angle, as shown in Figure 2, refers to the angle between two axial planes at the intersection points of the design streamline with the blade inlet and outlet edges. It has a significant impact on pump efficiency. For high-specific-speed centrifugal pumps, the optimal wrap angle is generally around 110° [45]. Excessively large wrap angles will reduce the head and pump efficiency, and are more likely to cause cavitation, thereby inducing high-frequency vibration [12].

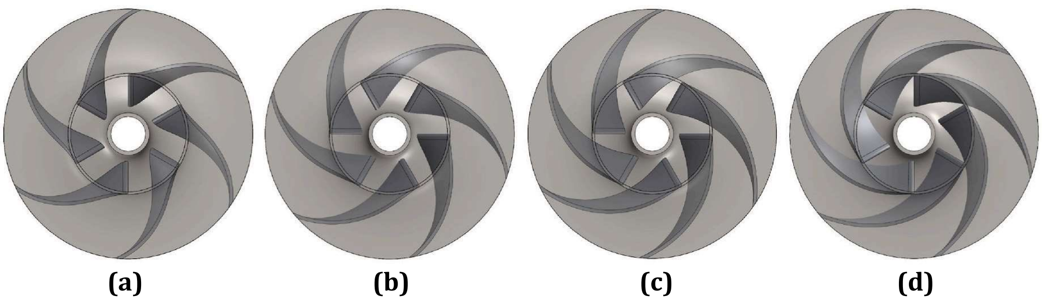

Fig. 2 *3D model of impeller with different wrap angles*

At the same flow rate, the total pressure of the impeller is inversely proportional to the wrap angle [46]. The pump achieves the optimal head and efficiency at the optimal wrap angle, while effectively reducing cavitation [45]. In summary, different impeller parameters affect the flow-induced vibration of centrifugal pumps to varying degrees. Table 1 summarizes the relevant research results of scholars in recent years regarding the influence of impeller parameters on flow-induced vibration.

Table 1 *Analysis of the influence of different impeller parameters on pump performance*

Parameter	Core Research Object	Research Methods	Main Conclusions	Limitations or Future Outlook
The Influence of Blade Number on Pump Performance [6,8,47–49]	1. Vertical two-stage marine centrifugal pumps (unsteady flow & pressure pulsation) 2. High-speed coolant pumps (blade number Z=4–9 on energy performance) 3. Centrifugal pumps (blade number 5/7/9 on performance) 4. Centrifugal pumps (blade number 4/5/6/7 on flow-induced noise) 5. Low-specific-speed centrifugal pumps (blade number on hump characteristics)	1. Hybrid RANS/LES, DMD, closed-loop experiment 2. Experimental testing + CFD 3. Fluent (RNG k-ε, SIMPLE algorithm) 4. CFD (SST k-ω) + CA + noise test platform 5. ANSYS CFX, entropy production theory, energy gradient method, experiment	1. Rotor-stator interaction dominates pressure pulsation; typical frequencies linked to flow structures 2. Head/efficiency show "inverted U-shape" (Z=6–8 optimal); excessive blades increase turbulent kinetic energy 3. 7 blades yield highest head coefficient/efficiency; blade number affects channel aspect ratio and energy loss 4. Volute tongue is main noise source; Z=6 minimizes sound pressure level 5. Increasing blades eliminates humps (Z=16 optimal); reduces entropy production and improves flow uniformity	1. No universal turbulence model; need to validate structural parameter modifications 2. Optimize blade number with other structural parameters 3. Lack coupling analysis of blade number and geometric parameters 4. Ignore backflow/cavitation noise; explore blade-tongue clearance optimization 5. Balance manufacturing cost/economy; optimize inlet structure for cavitation
The Influence of Blade Wrap Angle on Pump Performance [11,13,50,51]	1. Centrifugal pumps (inlet vane/wrap angle at hub/shroud on cavitation) 2. Centrifugal pumps (wrap angle 90°-160° on hydraulic performance/wear of solid-liquid two-phase flow) 3. Semi-open impeller centrifugal pumps (wrap angle 85°-125° on internal flow/wear) 4. High-specific-speed double-blade self-priming	1. 3D two-phase CFD (SST k-ω, Rayleigh-Plesset), parameterization, experiment 2. CFD-DEM, OKA/ARCHARD models, mesh independence verification, experiment 3. Euler-Lagrange, DPM/RNG k-ε, geometric modeling, experiment 4. 3D unsteady CFD (SST k-ω), pressure pulsation standard	1. Angle changes improve BEP cavitation but may worsen high-flow cavitation; propose optimized design 2. Head/efficiency/wear rate show "inverted U-shape" (110° most severe wear) 3. Wrap angle impacts efficiency more; increases reduce vortices/turbulent kinetic energy; wear rate first decreases then increases 4. Head first rises then drops; optimal wrap	1. Lack collaborative optimization of inlet vane/wrap angle; ignore coupling with other geometric parameters 2. Ignore particle size/volume fraction impact; lack multi-parameter collaborative optimization 3. No adaptability analysis for different particle conditions; ignore long-term wear impact 4. Lack cavitation/noise analysis; no

Parameter	Core Research Object	Research Methods	Main Conclusions	Limitations or Future Outlook
	centrifugal pumps (wrap angle 230°-300° on external/vibration characteristics)	deviation analysis, experiment	angle for efficiency (280°); reduces eddy viscosity	collaborative design with impeller width/outlet diameter
The Influence of Blade Inlet and Outlet Setting Angles on Pump Performance [2,3,52,53]	1. Low-specific-speed multistage submersible centrifugal pump (blade outlet angle: 16°-32°); 2. High-specific-speed centrifugal pump (ns=192, blade outlet angle: 23°-31°); 3. Single-blade centrifugal pump (blade inlet angle: two groups)	1. Numerical simulation (ANSYS-CFX, k-ε/SST k-ω models); 2. Experimental validation (closed/open test rigs)	1. Larger outlet angle → higher head but higher overload/cavitation risk; smaller angle (16°) prevents overload; 2. Outlet angle affects efficiency more (max 5.7% difference) than head; 3. Group 2 (inlet angle decreasing from front to rear shroud) has wider high-efficiency range and uniform flow	1. Ignores coupling with other geometric parameters; 2. Steady-state simulation limitation; 3. Needs validation for different media/specific-speed pumps
The Influence of Blade Thickness on Pump Performance [15,42,54–57]	1. Pediatric centrifugal blood pumps; 2. Centrifugal pump (thickness distribution optimization); 3. Plastic centrifugal pump (constant/variable thickness); 4. Mixed-flow pump (rotating stall)	1. Numerical simulation (CFD, Lagrangian approach, entropy generation analysis); 2. Optimization (Kriging + NSGA-II); 3. Experimental validation + FEA (strength analysis)	1. Thicker blades → higher shear stress/hemolysis (blood pumps) and performance decline (CTB >6 mm); 2. Optimized thickness distribution → efficiency +4.19%, vibration -62.59%; 3. Moderate thickness delays stall; excessive thickness worsens it	1. Test accuracy affected by clearance/leakage; 2. Increased rotor mass raises manufacturing difficulty; 3. Future research on thickness distribution and NPSHa comparison

By comparing studies on various impeller parameters, it can be concluded that the influences of blade number, wrap angle, inlet/outlet setting angles, and thickness on pump performance exhibit significant operating condition dependence and pump type specificity. The optimization of blade number and thickness mostly follows an "inverted U-shaped" trend, while the wrap angle and inlet/outlet angles require targeted adjustment based on the pump's specific speed. The research methods are mainly dominated by CFD numerical simulation combined with experimental validation, but specialized methods such as CFD-DEM and FEA need to be supplemented in special scenarios. Additionally, existing studies generally lack considerations for multi-parameter coupling analysis and unsteady flow effects.

The core of pump impeller parameter optimization does not lie in selecting the optimal value of a single parameter, but in the multi-parameter collaborative matching based on application scenarios. Future research should further rely on machine learning to establish multi-parameter nonlinear relationship models, while strengthening the study of transient characteristics under off-design conditions, and balancing manufacturing economy and complex medium adaptability, so as to truly narrow the gap between theoretical simulation and engineering practice.

2.2 Influence of Volute on Vibration

The volute guides fluid from the impeller into the outlet pipeline and affects the fluid flow and vibration characteristics. Unreasonable volute design or large surface roughness can generate eddies and pressure pulsations, leading to uneven pressure distribution in the volute flow passage. This uneven excitation force acts on the impeller and bearings, inducing vibration. Scholars have found that increasing the number of partitions to change the number of volutes can improve pump efficiency, and multi-volutes can reduce radial thrust [58]. Additionally, trimming both the blade trailing edge and the volute tongue cannot eliminate the jet-wake flow in the passage, and the tongue contributes significantly to pressure pulsation within the pump [39]. Other studies have shown that pump body vibrations induced by volute surface forces are greater than vibration displacements caused by bearing forces[59]. Table 2 summarizes the influence of different volute types on pump performance.

Table 2 *Influence of different volute types on pump performance*

Volute types	Core Research Object	Research Methods	Main Conclusions	Limitations or Future Outlook
Different volute types [40,58,60–62]	Pressure pulsation characteristics in volute tongue region of centrifugal pump under 0.8Q, 1.0Q, 1.2Q conditions	1. Numerical simulation: ANSYS-CFX, RNG k-ε model; 2. Unsteady 3D simulation	1. Pressure pulsation shows significant periodicity; dominant frequency is 1× blade passing frequency (BPF); 2. Pulsation amplitude decreases with circumferential distance from volute tongue; 3. High-frequency components are scarce in distant monitoring points	1. Limited to specific pump model; 2. No analysis of groove/volute structure optimization
	Pressure fluctuation suppression in double-suction centrifugal pump via impeller stagger angle and split volute	1. Numerical simulation: ANSYS CFX (SST k-ω model); 2. Experimental validation: Closed-loop test bench; 3. FFT analysis	1. 30° stagger angle optimizes hydraulic performance (efficiency +7.62%, head +10.167%); 2. Split volute reduces pressure pulsation; 3. Combination of 30° stagger angle + split volute achieves minimal pulsation	1. CFD overestimates efficiency (ignores mechanical/friction losses); 2. Future optimization with ANN/NSGA-II; 3. Explore fluid temperature effect
	Radial thrust reduction in centrifugal pump with single/double/triple volute	1. Experimental test: 500/800/900 rpm; 2. Pressure distribution measurement	1. Multi-volute does not affect head; efficiency increases by 6% (double) and 10% (triple); 2. At shutoff, double/triple volute reduces radial thrust by 54% and 72%; 3. Minimum radial thrust at 125% design flow	1. Triple volute is difficult to cast/clean; 2. Lack of CFD validation for flow details

Volute types	Core Research Object	Research Methods	Main Conclusions	Limitations or Future Outlook
	Cavitation-induced flow characteristics and pressure pulsation in double-volute centrifugal pump	1. Numerical simulation: SST k-ω model + Schnerr–Sauer cavitation model; 2. Omega vortex identification	1. Severe cavitation shifts maximum BPF amplitude from volute tongue (30°) to downstream (45°); 2. Low flow (0.9Qd) increases cavitation susceptibility but reduces cavity area; 3. Rotor-stator interaction causes vortex elongation/fusion/separation	1. Limited to pure water medium; 2. No experimental validation for cavitation-induced pulsation

These studies have certain limitations, such as being confined to specific pump models, ignoring mechanical losses and friction losses in Computational Fluid Dynamics (CFD) simulations, the high manufacturing difficulty of triple volutes, and the lack of experimental validation for cavitation-induced pulsations. Future research should focus on multi-parameter collaborative optimization (e.g., the combined optimization of volute structure and impeller parameters) and extend validation to various media and pump models to enhance the universality of the research findings.

2.3 Influence of Clearance Leakage on Pump Vibration

During pump operation, due to inadequate sealing or component wear, the medium leaks from the high-pressure area to the low-pressure area. This phenomenon reduces pump efficiency, increases energy consumption, exacerbates cavitation, and deteriorates performance. Current scholars mainly focus on tip clearance leakage and wear ring clearance leakage.

Studies have shown that the size of the guide vane end face clearance affects the flow rate at the maximum efficiency point [63]. As the flow rate increases, the dynamic-static interference between the impeller and guide vanes gradually weakens, while the dynamic-static interference between the impeller and volute becomes increasingly prominent [64]. Tip clearance leakage also causes cavitation, where cavitation clouds affect pressure distribution, thereby intensifying vibration [65]and reducing efficiency.

The wear ring clearance is another factor affecting pressure pulsation within the pump. With the increase of wear ring clearance, the natural frequency and critical speed of multistage pumps both increased, especially having the greatest impact on the first-order natural frequency [66]. The wear ring seal also significantly increases the first two orders of bending vibration critical speeds while decreasing the critical speed of torsional vibration [67]. Scholars have further found that the fluid excitation force of the seal exhibits a nonlinear relationship with the seal length but a linear relationship with the seal clearance size [68].

3. Influence of Flow Rate on Pump Vibration

Pumps exhibit optimal performance under rated operating conditions. However, changes in inlet pressure, valve opening, and working fluid temperature can cause fluctuations in flow rate, leading to pressure pulsation, turbulence, vortex formation, and vortex shedding within the pump, which in turn induce vibration. Studies have shown that the shell vibration intensity does not have a linear relationship with flow rate changes. While the peak value of shaft vibration displacement increases with flow rate, it also does not follow a linear pattern [69]. At low flow rates, the blade passing frequency (BPF) significantly affects pressure pulsation.

Kai Wang [35] tested the pressure pulsation, vibration, and noise characteristics of a five-stage centrifugal pump under different flow rates. Experiments showed that pump vibration first increases and then decreases with increasing flow rate, with vibration at the outlet significantly higher than that at the inlet. Additionally, motor vibration is directly proportional to flow rate changes. Ahmed Ramadhan Al-Obaidi [38] found that the rotor's annular trajectory of a cantilever multistage centrifugal pump is most stable, and the vibration velocity amplitude is minimized at the design flow rate. For each stage of the volute, the primary vibration frequencies under different flow conditions are the first and second blade passing frequencies. Yan Zhang [37] conducted a numerical analysis of the vibration of a seven-stage centrifugal pump rotor system under three flow conditions and found that pump shell vibration is determined by the shaft frequency, twice the shaft frequency, and twice the blade passing frequency. Ling Bai [29] tested the vibration of a cantilever multistage centrifugal pump under different flow rates and found that vibration is caused by mass imbalance at the shut-off flow point. Under different flow rates, the pump vibration frequency remains at the blade passing frequency, with the first and second blade passing frequencies being the main excitation frequencies.

4. Influence of Cavitation Erosion on Vibration

Cavitation which is shown in Figure 3, refers to the vaporization phenomenon of a medium near the solid wall in a low-pressure area. After vaporization, the generated bubbles will collapse when the pressure increases. The surrounding medium will rapidly fill the space of the bubbles, thus producing strong high-frequency impacts on the solid wall, leading to metal fatigue, spalling, cracks, and even fracture of the solid wall. At the same time, it will also cause severe vibration of the pump body.

Fig. 3 *Common cavitation erosion positions of pump body*

Flow visualization technology is one of the main technical means for cavitation erosion research. This technology can observe the generation and development process of cavitation in the impeller, among which the shape geometric parameters of the blades are key factors affecting the occurrence of cavitation [70]. In addition, even when the device's net positive suction head (NPSH) is sufficient, cavitation in each gap of the pump will cause damage to various components. The greater the pressure difference before and after the gap, the more obvious the cavitation phenomenon [71]. The change of flow conditions is also one of the main causes of inducing cavitation, especially under small flow conditions.

5. Methods for Suppressing Flow-Induced Vibration

Although numerous scholars have conducted extensive research on vibration reduction methods for pumps, there is currently no single method that can completely eliminate the pressure pulsation of fluid inside pumps. Such pulsation is prone to induce vibration and noise of the pump body, thereby affecting the operational stability and service life of the equipment. Only by improving the pump components or flow channel parameters through various optimization methods, and reasonably regulating the flow rate and rotational speed to achieve the optimal hydraulic design conditions, can the intensity of pressure pulsation be effectively reduced. Numerical simulation, experimental testing, and the combination of these two methods are three commonly used research approaches in this field, providing solid technical support for the vibration reduction and optimization of pumps.

In terms of numerical simulation research [42,59,72–74], the study conducted by Zou Fen [59] on the flow-induced vibration and noise characteristics of sodium pumps is widely representative. Its core process is as follows: determine the research object → establish a high-precision calculation model based on the actual operating conditions of the pump → set boundary conditions that conform to the physical scenario → perform refined calculations using specialized software such as CFD → verify the reliability of the simulation results in key indicators such as vibration frequency and amplitude through experiments, ensuring that the simulation data can be directly applied to engineering analysis.

In the aspect of experimental testing, spectrum analysis technology can be used to detect abnormal vibrations of pumps, accurately capture the characteristic frequencies in vibration signals to locate fault sources; meanwhile, Particle Image Velocimetry (PIV) technology is employed to conduct visualized measurements of the internal flow field of centrifugal pumps [72,73], obtaining key flow field information such as velocity field and vorticity field. To facilitate the experimental device to accurately identify the morphology and size of secondary flows and wake-jet structures, the volute of the test pump is specially processed into a transparent structure using high light-transmittance organic glass, ensuring no blind spots in observation (as shown in Figure 4).

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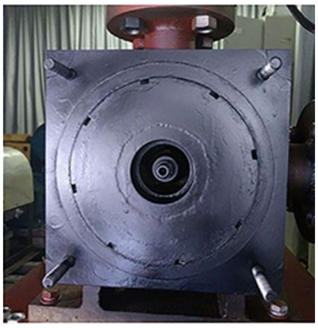
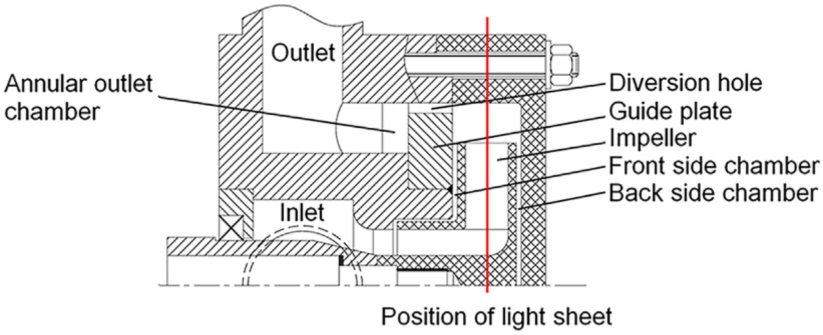
(a) Impeller



(b) Pump body

(c) Rear cover



(d) Cross-section

Fig. 4 *Test pump for observing internal flow*

In the research field combining numerical simulation and experimental verification [75], to efficiently control material and time costs, researchers have innovatively constructed a progressive research framework of "simulation—analysis—optimization—verification", with the specific implementation steps as follows:

Conduct preliminary numerical simulation on the prototype pump, accurately locate the core areas of flow-induced vibration such as the rotor-stator interaction region between the impeller and volute through spectrum analysis technology, and quantify the vibration amplitude and frequency characteristics of each part, so as to clarify the target direction for subsequent optimization.

On this basis, systematically sort out key influencing parameters such as the number of blades, blade inlet and outlet installation angles, wrap angle, blade thickness, and volute profile, define the value range and adjustment step size of each parameter, and avoid parameter redundancy or deficiency during the optimization process.

Considering that multi-variable optimization will significantly increase the number of experiments and impose stringent challenges on hardware resources and computing time, the parameter sensitivity analysis method is introduced in the research to screen out core factors with significant impacts on vibration, such as blade inlet and outlet installation angles and volute profile. Subsequently, Design of Experiment (DOE) methods such as orthogonal test [76] and Latin Hypercube Sampling [35,77] are adopted to carry out efficient grouped tests on optimization variables. Based on surrogate models combined with machine learning algorithms, in-depth analysis of test data is performed to construct high-precision fitting equations, realizing the scientific prediction of the optimal parameter combination. Finally, the feasibility of the optimization scheme is verified through physical experiments, and the overall research process is shown in Figure 5.

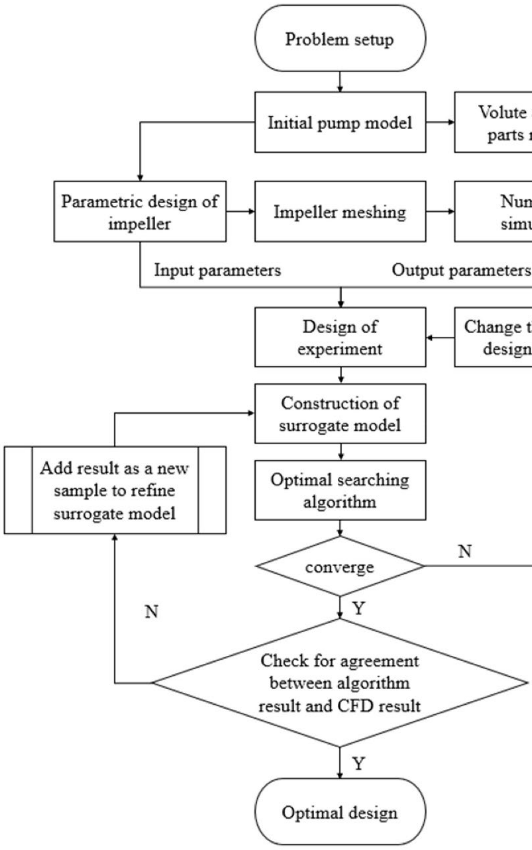


Fig. 5 *Optimization flowchart*

Table 3 summarizes the common methods adopted by scholars in centrifugal pump optimization research in recent years, and comparatively analyzes the core conclusions of different studies as well as their respective limitations.

Table 3 *Common centrifugal pump optimization methods*

Paper Title	Core Research Object	Research Methods	Main Conclusions	Limitations or Future Outlook
The investigation of flow mechanism and energy dissipation in multi-stage pump impeller based on energy balance theory [78]	Flow mechanism & energy dissipation in multi-stage centrifugal pump impeller	1. Numerical simulation: ANSYS Fluent, Realizable k-ε model, SIMPLEC algorithm; 2. Energy balance theory; 3. Experimental validation (closed-loop test bench)	1. Impeller optimization improves efficiency to 70.22% (↑1.6%) and reduces energy dissipation by 12.3%-12.4%; 2. Turbulent kinetic energy generation term (L3) dominates energy loss; 3. Inter-stage flow matching optimization suppresses flow separation	1. Steady-state RANS ignores unsteady flow; 2. Lack transient behavior study (startup/shutdown); 3. Future use of DES/LES and advanced visualization

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Paper Title	Core Research Object	Research Methods	Main Conclusions	Limitations or Future Outlook
Analyzing the impact of blade geometrical parameters on energy recovery and efficiency of centrifugal pump as turbine installed in the pressure-reducing station [79]	Blade geometrical parameters (inlet angle, wrap angle, curvature) on PAT energy recovery/efficiency	1. Numerical simulation: ANSYS CFX, SST k-ω model; 2. Experimental validation (SPRS test platform); 3. Statistical flow rate analysis	1. Simultaneous parameter modification widens high-efficiency range; 2. Efficiency improves by 0.83% (0.8QBEP), 2.69% (QBEP), 6.71% (1.2QBEP); 3. Forward-curved blades + optimized inlet angle reduce flow separation	1. Optimize volute parameters (diameter, tongue shape); 2. Explore impeller-volute simultaneous optimization
Liquid-vapor two-phase flow in centrifugal pump: Cavitation, mass transfer, and impeller structure optimization [80]	Cavitation & mass transfer in centrifugal pump; impeller structural optimization	1. Numerical simulation: ANSYS CFX, SST k-ω + VOF model; 2. Experimental validation (cavitation test platform); 3. Variance-based sensitivity analysis	1. Optimal impeller parameters: 7 blades + 120° wrap angle + 30° installation angle; 2. 7 blades minimize bubbles and secondary vortices; 3. 120° wrap angle reduces flow diffusion and hydraulic loss	1. Simplified geometric structure in simulation; 2. Lack multi-parameter coupling analysis; 3. Improve cavitation prediction under real operating conditions
Applications of artificial intelligence and computational intelligence in hydraulic optimization of centrifugal pumps: a comprehensive review[81]	AI/CI applications in centrifugal pump hydraulic optimization	1. Literature review; 2. Comparative analysis of optimization methods (ML, CI, CFD integration)	1. AI+CI outperforms traditional methods for low-medium dimensional optimization; 2. CI+CFD excels in high-dimensional multi-objective optimization; 3. ANN/Kriging models achieve high-precision performance prediction	1. High computational cost of CI+CFD; 2. Sample explosion in high-dimensional ML; 3. Future focus on PINNs and adaptive CI algorithms

Paper Title	Core Research Object	Research Methods	Main Conclusions	Limitations or Future Outlook
Innovative data techniques for centrifugal pump optimization with machine learning and AI model [82]	Data preprocessing & ML/AI-based centrifugal pump optimization	1. Data acquisition: Dewesoft FFT DAQ system; 2. Data processing: EDA, feature engineering, hypothesis testing; 3. ML/DL model training	1. Proposed data framework improves operational efficiency by 27.25% (F1 score); 2. Reduces model training time by 180s; 3. Enables predictive maintenance and fault detection	1. Relies on sufficient labeled data; 2. Limited scalability across diverse pump types; 3. Future explore semi-supervised learning for multi-fault scenarios

In summary, impeller geometric optimization and multi-parameter collaborative improvement can effectively enhance efficiency and reduce energy dissipation as well as flow separation, and artificial intelligence or computational intelligence technologies outperform traditional methods. However, existing studies also have certain limitations, such as simplified simulated geometric structures, lack of multi-parameter coupling analysis, and high computational costs of intelligent methods. Future research should address these shortcomings by adopting advanced simulation models (DES/LES) and developing adaptive intelligent algorithms to reduce computational costs and improve model generalization ability, thereby bridging the gap between theoretical optimization and engineering applications.

6. Conclusion

Centrifugal pumps are core auxiliary equipment in thermal power plants, and their stable operation is crucial to the safety and economic efficiency of power units. Flow-induced vibration, a typical fault of centrifugal pumps, often leads to component damage and unplanned shutdowns, resulting in substantial economic losses. This paper systematically reviews the mechanisms, influencing factors, and suppression methods of flow-induced vibration in centrifugal pumps, with key conclusions summarized as follows:

Flow-induced vibration originates from internal unsteady flow and pressure pulsation, jointly driven by pump body structural design and operating conditions. Unlike vibrations caused by installation errors or system defects, its mechanism is more complex and cannot be completely eliminated, but its intensity can be effectively mitigated through targeted optimization.

In terms of structural design, impeller parameters play a decisive role in pressure pulsation control: a 30° stagger angle for double-suction pumps minimizes pulsation, and an approximate 110° wrap angle for high-specific-speed pumps balances efficiency and cavitation resistance. Multi-volute structures can reduce radial thrust by up to 72% and improve efficiency by 6%~10%, while the volute tongue is a key source of pulsation that requires multi-parameter collaborative optimization. Clearance leakage exacerbates vibration by inducing cavitation and altering dynamic characteristics, requiring strict control in engineering practice.

Cavitation is another critical factor inducing vibration, closely related to blade parameters, clearance pressure difference, and operating conditions. Optimizing blade profiles and reducing clearance leakage are effective suppression measures.

Mainstream vibration suppression methods include numerical simulation, experimental testing, and their combination. The "simulation-analysis-optimization-verification" framework, combined with parameter sensitivity analysis and DOE methods, significantly improves optimization efficiency. The integration of AI/CI technologies with CFD further enhances optimization precision and reduces computational costs.

Future research should focus on multi-parameter coupling optimization, adopting advanced simulation models (DES/LES) to capture unsteady flows, developing adaptive intelligent algorithms to reduce computational costs, and expanding research to complex media and transient conditions. This will help bridge the gap between theoretical optimization and engineering applications, providing stronger technical support for the stable operation of centrifugal pumps.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Guo JiaFu and Sim SyYi;* ***summary of the research on optimization methods:*** *Zhang DongLi and Zhang JinPing;* ***draft manuscript, review and correction****: A.M Leman. All authors reviewed the results and approved the final version of the manuscript*

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