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A Review on the Flow-Induced Excitation Mechanism of Centrifugal Pumps During Off-Design Conditions

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Abstract

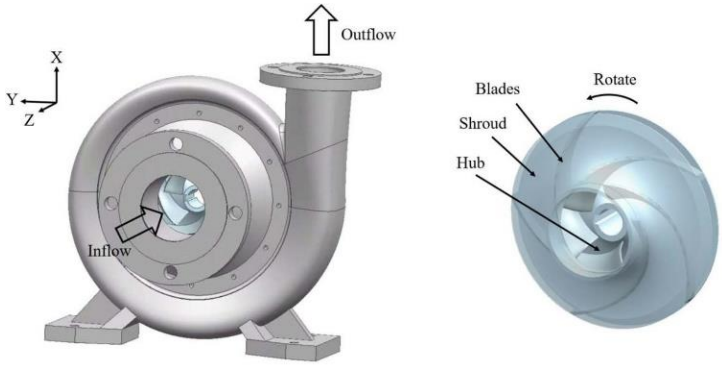
In thermal power plants, both cooling water and boiler feedwater need to be delivered by centrifugal pumps. When centrifugal pumps operate under off-design conditions, significant flow-induced vibration problems often arise due to the complex unsteady flow inside, which in turn affects their operational reliability and service life. This paper presents a comprehensive review of flow-induced vibration issues in centrifugal pumps under off-design operating conditions and the corresponding mitigation methods. Existing studies indicate that off-design unsteady flow phenomena constitute the primary drivers behind pressure fluctuations and vibrational noise. Current countermeasures for mitigating flow-induced vibration encompass structural optimization approaches: refining the impeller-volute gap, adjusting the trailing edge structure of blades, and modifying blade count. Nonetheless, existing research remains deficient in in-depth exploration of the intrinsic correlations between unsteady flow behaviors and vibrational noise, alongside targeted suppression strategies for off-design scenarios. Future investigations ought to more precisely elucidate how flow field properties affect pressure pulsation and to establish a comprehensive quantitative characterization framework for unsteady flows. Such efforts will facilitate the advancement of design theories and methodologies for centrifugal pumps with low vibration and noise emissions.

1. Introduction

In the complex ecosystem of the power industry, centrifugal pumps, as shown in Fig. 1, serve as the core equipment for energy conversion and working medium transportation, running through the entire process of power production. Their structural performance and operational stability directly affect power generation

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efficiency, system safety, and economic costs [1]. From traditional thermal power to nuclear power generation, centrifugal pumps have always played an irreplaceable role and become a key link connecting energy conversion and power output.



(a) **(b)**

Fig. 1 *Centrifugal pump: (a) Volute; (b) Impeller*

Within thermal power plants, centrifugal pumps constitute the "vascular network" of the thermal cycle system. The pressure stability of feedwater pumps directly influences the steam parameters of boilers, while circulating water pumps sustain the vacuum level of condensers through adjusting the circulating water volume—thereby affecting steam turbine efficiency. Additionally, the regulation of the net positive suction head (NPSH) for condensate pumps is closely associated with water quality purity. These three types of pump sets operate in coordination, and the performance degradation of any one pump can cause the unit's thermal efficiency to drop by 1% to 3%, or even trigger unplanned shutdowns of the power plant [2]. In hydropower systems, centrifugal pumps participate in pumped-storage generation via a reversible setup. During periods of low electricity demand, electrical energy is converted into potential energy via pumped storage. The process is reversed during periods of peak electricity demand. This enables two-way energy conversion, making them a core tool for grid peak regulation [3]. In the field of nuclear power generation, the safety of centrifugal pumps has been elevated to a strategic level. The main nuclear pump is the core equipment for the circulation of reactor coolant. Once the main nuclear pump fails, it may cause the risk of core overheating. Therefore, its operational reliability has become an important guarantee for nuclear power safety [4].

In addition, the technological progress of centrifugal pumps has also promoted the upgrading of power production efficiency. The feed water pumps of supercritical generating units adopt a double-shell structure [5], which is conducive to increasing the working medium flow and head; the application of magnetic levitation centrifugal pumps eliminates mechanical contact wear, extending the maintenance cycle from 3 months to 2 years [6]; intelligent centrifugal pumps, by embedding vibration sensors and AI diagnostic algorithms [7], can predict potential faults 1-2 weeks in advance, reducing the maintenance costs of power enterprises by more than 20%. High-efficiency centrifugal pumps can reduce shaft power by 5%-8% compared with traditional models. Taking the circulating water pump of a 300MW thermal power unit as an example, the annual electricity saving can reach 1.2 million kWh. At the same time, the popularization of variable-frequency speed-regulating centrifugal pumps has realized dynamic flow regulation according to load, reducing energy consumption by 15%-20% under partial load conditions, and providing hardware support for the low-carbon transformation of power systems [8].

However, centrifugal pumps are vulnerable equipment. In particular, abnormal vibration of the pump body will bring negative impacts to power enterprises, and pump body vibration exhibits pronounced chain-reaction and cumulative effects. For example, it aggravates the wear of the coupling between the pump body and the motor, and the resulting pipeline resonance will damage the thermal cycle balance of thermal power units. Accordingly, investigating the vibration mechanisms of centrifugal pumps, identifying their contributing factors, and developing targeted mitigation strategies carries considerable academic and practical value.

It is worth noting that although several review papers on centrifugal pump vibration and noise have emerged in recent years, their foci differ considerably. Some reviews primarily concentrate on hydraulic efficiency improvement and structural strength optimization at design conditions, providing limited coverage of the causative mechanisms of flow-induced excitation under off-design conditions. Others, while touching upon off-design conditions, tend to emphasize flow-field descriptions of single influencing factors—such as rotating stall or rotor-stator interaction—without achieving a systematic integration from the full-chain perspective of "flow-field characteristics → pressure pulsation → vibration response" . Among the existing works, the most closely related review—Wu et al. [27] published in 2023—provides a relatively comprehensive overview of flow-induced

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vibration in centrifugal pumps, yet still exhibits notable gaps in the following aspects: (1) its literature scope is not explicitly restricted to flow-induced excitation mechanisms under off-design conditions, mixing in some design-condition analyses; (2) it lacks systematic comparative evaluations of the applicability and limitations of various suppression measures; and (3) it does not establish a quantitative correlation framework linking off-design flow-field characteristics to vibration noise.

To address these gaps, the distinctive contributions of this review are fourfold: (1) Off-design specificity—the scope is strictly confined to flow-induced excitation mechanisms under off-design operating conditions, systematically summarizing the unsteady flow characteristics and their vibration-inducing mechanisms under low-load, part-load, and variable-flow scenarios; (2) Methodological rigor—a structured literature search and screening process (covering Scopus, Web of Science, ScienceDirect, and CNKI, with 85 core articles finally included) ensures comprehensiveness and traceability; (3) Critical synthesis—beyond summarizing existing theoretical, numerical, and experimental findings, this review provides comparative analyses of the strengths and limitations of different research approaches, identifies ongoing academic disagreements, and delineates the applicability boundaries of various suppression measures, while proposing a novel quantitative research direction of "flow-field characteristic parameters → rapid prediction of pulsation amplitudes" ; (4) Engineering orientation—we explicitly point out the limitations of current "trial-and-error" empirical approaches in low-excitation design and outline a future research framework oriented toward multi-condition, multi-objective collaborative optimization. These contributions are intended to provide theoretical references and methodological guidance for the low-vibration design of centrifugal pumps and the reliability assessment of their off-design operation.

2. Review Methodology

To ensure the comprehensiveness, traceability, and objectivity of this review, a systematic literature search and screening process was conducted following established guidelines for narrative reviews with systematic elements.

2.1 Literature Search Strategy

The literature search was performed across four major academic databases: Scopus, Web of Science, ScienceDirect (Elsevier), and CNKI (China National Knowledge Infrastructure). The search covered publications from January 2000 to June 2025 to capture both foundational theories and recent technological developments. For English databases, the main search string was constructed using Boolean operators as follows: ("centrifugal pump" OR "centrifugal pumps") AND ("off-design" OR "part-load" OR "low flow" OR "non-design") AND ("flow-induced vibration" OR "pressure pulsation" OR "unsteady flow" OR "rotating stall" OR "rotor-stator interaction"). For the Chinese database (CNKI), equivalent Chinese keywords were applied, including centrifugal pumps, off-design condition, variable operating condition, flow-induced vibration, pressure pulsation, rotating stall, rotor-stator interaction, and unsteady/unstable flow. Additionally, to minimize the risk of omission, a backward snowballing strategy was employed by manually cross-checking the reference lists of the retrieved key articles and existing review papers.

2.2 Inclusion and Exclusion Criteria

To ensure the relevance and academic quality of the cited literature, a predefined set of inclusion and exclusion criteria was established.

2.2.1 Inclusion criteria

- Peer-reviewed journal articles, authoritative conference proceedings, and recognized dissertations;
- Studies focusing on the hydraulic performance, internal flow characteristics, pressure pulsation behaviors, or vibration/noise mechanisms of centrifugal pumps under off-design or variable operating conditions;
- Articles published in English or Chinese;
- Theoretical analyses, numerical simulations, or experimental investigations that provide clear quantitative data or mechanistic insights into flow dynamics.

2.2.2 Exclusion criteria

- Studies on pump types other than centrifugal pumps (e.g., axial-flow pumps, positive-displacement pumps);
- Research concentrating solely on design-point performance without extension to off-design or variable conditions;

- Studies mainly addressing structural strength, material properties, or motor electromagnetic excitations without sufficient emphasis on flow-induced vibration issues;
- Non-peer-reviewed technical reports, commercial brochures, and duplicate publications.

2.3 Literature Screening and Selection Process

After the initial database searches and deduplication, a total of 486 records were retrieved. Two independent reviewers (Guo J.F. and Zhang D.L.) conducted the screening in two stages. In the first stage, titles and abstracts were screened against the inclusion criteria, which excluded 312 clearly irrelevant records and retained 174 records. In the second stage, the full texts of the retained articles were carefully assessed for eligibility; 89 articles were further excluded due to insufficient in-depth analysis of flow-induced excitation mechanisms or limited relevance to off-design operational issues. Ultimately, 85 articles were identified as highly relevant and included in this review. The included literature covers theoretical modeling, numerical simulation approaches, experimental measurement techniques (e.g., Particle Image Velocimetry—PIV, Laser Doppler Anemometry—LDA/LDV), as well as optimization and suppression strategies for unsteady flows and pressure pulsations under off-design conditions. Among them, peer-reviewed journal articles account for approximately 85%, with the remainder being conference papers and doctoral dissertations.

3. Research on Off-Design Condition Characteristics of Centrifugal Pumps

Centrifugal pumps frequently encounter off-design operation in practical applications, which constitutes a prevalent issue in their real-world service. When such pumps operate within the off-design range, the internal flow field grows intricate and deviates from the ideal flow pattern hypothesized under design conditions. This deviation amplifies noise and vibration during pump operation, thereby undermining the equipment's service lifespan and operational reliability [9]. Scholars worldwide have conducted research on the operating performance of pumps under off-design conditions.

In the domain of theoretical investigations, the matching performance between the volute and the blades is a key factor affecting pump efficiency. Lin [10] conducted relevant research on the matching theory and found that it could accurately predict the pump's best efficiency point. The rotation direction and intensity of the secondary flow inside the impeller allow for the estimation of head loss, and Brun [11] conducted relevant research on this issue. The results indicate that the counterclockwise secondary flow is caused by the uneven distribution of forces acting on the pressure and suction sides of the blade, which provides a theoretical basis for optimizing the flow field structure inside the pump [12]. The force conditions of fluid microparticles in the blade flow passages are shown in Fig. 2.

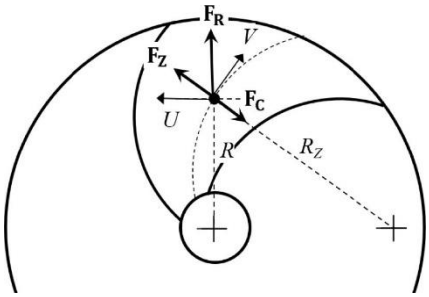


Fig. 2 *The force distribution on a fluid element within the rotating impeller* [11]

The blade inlet angle directly affects the shock loss coefficient. Yang et al. [13] investigated the correlation between the two parameters and established a hydraulic model of the pump based on this finding. In 2021, the same research group [14] adopted three different detached eddy simulation methods to conduct transient numerical simulations of the flow state of the centrifugal pump under rated operating conditions. The results show that there are differences in the calculation accuracy of different simulation methods, among which the delayed detached eddy simulation (DDES) method exhibits the best performance. Hou [15] and Guan [16] introduced the entropy production analysis method to determine the energy loss characteristics of the centrifugal pump. The analysis results indicate that the wall friction entropy production accounts for the largest proportion, followed by the turbulent entropy production, with both proportions exceeding 45%. Wu [17] proposed that the criterion of "*Rossby = 1*" is the key indicator for regulating secondary flows inside the impeller, and verified this viewpoint by designing blades with different thicknesses. Lu [18] introduced an innovative multi-condition design strategy for centrifugal pumps, integrating key geometric features of the impeller. By examining flow behaviors across two

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relative flow surfaces, he pinpointed slip and diffusion effects as contributors to energy losses, thus broadening the pump's high-efficiency operational range. Further related theoretical studies are compiled in Table 1.

Table 1 *Theoretical research methods and conclusions of centrifugal pumps*

Research objectives	Method	Result
Irreversible energy loss due to cavitation flow [19].	Entropy generation analysis framework integrated with CFD	Entropy generation is closely correlated with energy dissipation, with the energy loss of the impeller being more significant. Cavitation and the pressure fluctuations induced thereby are the primary causes of the variation in entropy generation peaks.
Energy loss characteristics of centrifugal pumps [20].	Principle of Entropy Generation	Entropy generation is a characterization of irreversible losses; most regions in the intensity distribution of pressure fluctuations exhibit a consistent variation trend of entropy dissipation, and studies have confirmed a strong positive correlation between entropy generation and pressure fluctuations.
The optimal impeller design for the centrifugal pump, Taking minimal entropy production and maximum operational efficiency as optimization objectives [21].	Principle of Entropy Generation	The irreversible losses caused by the rotor-stator interaction between the volute and the impeller lead to high entropy generation.
Transient performance of a centrifugal pump under start-up conditions [22].	A balanced prediction model between transient water head and pipeline resistance was established.	A unified sine function was established, in which both the transient head and time of the pump are normalized data and integrated with each other; this function demonstrates favorable performance when applied to the same pump during start-up conditions with different acceleration durations
Influence of Varied Volute Area Ratios on Internal Flow Behaviors and Noise Emissions of Centrifugal Pumps [23].	Area ratio theory	An increase in the volute area ratio not only markedly enhances the centrifugal pump's external hydraulic characteristics but also notably diminishes internal vortex intensity, further optimizing the internal flow regime
Effect of Variable Rotational Speed on Axial Thrust of High-Speed Centrifugal Pumps [24].	Axial thrust prediction parameter estimation theory	The relationship between rotational speed and axial thrust predicted based on the parameter estimation theory, as well as the prediction accuracy, are quite satisfactory.
Mechanism of particle movement and its effect on pump performance [25].	High-speed visualization equipment was adopted in the experiment, and an attenuation equation was introduced for theoretical calculation.	The degree of particle accumulation on the blade pressure surface is positively correlated with the Reynolds number.
Energy conversion characteristics of a multistage centrifugal pump [26].	Energy loss assessment method based on energy transfer	Considerable energy dissipation occurs during the transfer process between impeller stages.

As computational fluid dynamics (CFD) theories and associated technologies advance, a growing number of researchers have turned their focus to investigating the hydrodynamic behaviors of pumps under off-design operating regimes via numerical modeling techniques — with special emphasis on enhancing the simulation precision of both external performance and internal flow dynamics in such non-design scenarios [27]. The Reynolds-averaged Navier-Stokes (RANS) model was proposed relatively early and has been widely adopted by

researchers [28], it exhibits favorable capability in addressing the secondary flow and interference phenomena within the impeller [29].

With the continuous development of various turbulence models and the steady improvement in computing power, these models have been widely applied in the field of numerical simulation, such as the shear stress transport k-ω model (SST k-ω) [27, 30], large eddy simulation (LES), and the Reynolds-averaged Navier-Stokes/large eddy simulation hybrid method [31]. Among them, hybrid RANS/LES represented by the SAS model [32], [33] and the DES (Detached Eddy Simulation) model [14], [34], [35] are considered to effectively capture the rich flow structures under off-design conditions. The research findings of Professor Wang Fujun [36] indicate that the detached eddy simulation (DES) approach is quite suitable for transient simulation under intense turbulent flow conditions.

Although the aforementioned numerical methods are widely employed for flow field prediction under off-design conditions, notable discrepancies exist among different approaches in capturing the unsteady flow characteristics within centrifugal pumps. RANS-based models (e.g., SST k-ω) offer high computational efficiency and good convergence, making them practically attractive for engineering applications. However, due to their reliance on the isotropic eddy-viscosity assumption, they tend to underestimate pressure pulsation amplitudes when predicting strongly swirling flows, separated flows, and turbulent kinetic energy distributions in wake regions. In contrast, Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) can resolve the generation and evolution of large-scale vortex structures, demonstrating distinct advantages in capturing the inception of rotating stall and the detailed rotor-stator interactions between the impeller and volute. Nevertheless, these methods impose extremely high near-wall mesh resolution requirements and entail computational costs several to dozens of times higher than those of RANS. Moreover, near-wall regions still rely on wall-function corrections, introducing uncertainties in predicting the effects of wall roughness and tip leakage flows. It is worth noting that no single universal model exhibits optimal performance across all off-design conditions—DES shows more pronounced accuracy advantages under high-load conditions, whereas all models exhibit varying degrees of inadequacy in capturing low-frequency stall components under low-load conditions. Consequently, researchers must strike a balance between computational accuracy and resource consumption, and the development of adaptive hybrid turbulence models specifically tailored for centrifugal pump off-design conditions represents a promising future direction.

Particle Image Velocimetry (PIV) can be used to capture the flow state of the fluid inside the pump, and this technique is capable of effectively capturing the intensity of secondary flow and the phenomenon of boundary layer separation. Laser Doppler Anemometry (LDA) is also a technical method for conducting internal flow tests of pumps under off-design conditions, which can be applied to characterize the velocity characteristics of wake jets [27]. Fonseca [37] employed the PIV technique to observe the wake-jet structure at the impeller outlet under low-flow conditions, and obtained the velocity structure diagram as illustrated in Fig. 3. The accurate analysis of multi-scale complex turbulence has also been enabled by the advancement of the PIV technique. Relevant studies have indicated that higher turbulence intensity corresponds to greater energy loss [38]. Zhang [39] placed the sensor of the Laser Doppler Anemometer inside the pump casing to capture the pressure fluctuation signals at different positions in the flow field of the pump under various operating conditions. It was found that inside the pump casing, the velocity of the working medium increases and the intensity of the pressure fluctuation becomes stronger as the diffuser passage contracts. In addition, Feng [40] obtained the velocity fields and turbulent kinetic energy intensity at different monitoring points under various operating conditions using LDA measurements. The results indicate that when the pump is under low-load operating conditions, a two-channel flow separation phenomenon occurs inside the impeller passages.

In addition to flow field measurements, diagnostic approaches based on pulsation signals have also been explored. In view of the characteristics of weak variations and strong interference in the pulsation signals of centrifugal pumps under off-rated operating conditions, Liu, Chen [41], [42], and others proposed different off-design condition diagnostic models, all of which achieved high accuracy in operating condition diagnosis.

It is worth noting that although optical non-intrusive measurement techniques such as PIV and LDA can provide high spatiotemporal resolution instantaneous flow field data, their application in the confined structure of actual centrifugal pumps still faces multiple constraints. Firstly, the placement and dimensions of optical windows restrict the measurement domain, making it difficult to capture complete velocity field data in near-wall boundary layers and deep zones within the impeller flow passages. Secondly, these techniques demand high transparency of the working medium and good tracer-particle fidelity, which limits their applicability under gas-liquid two-phase flow or high-temperature/high-pressure realistic fluid conditions to a certain extent. Furthermore, most of these experimental campaigns are conducted at design or moderately off-design conditions; their capability to capture transient flow fields in deep stall regimes (e.g., below 0.3 times the design flow rate) is constrained by sampling frequency and data processing algorithms. Consequently, the relationship between experimental investigations and numerical simulations is not simply one of validation—they are naturally complementary in terms of spatial coverage and temporal resolution: experiments provide locally reliable data under real boundary conditions, while simulations offer full-field continuous information. Future research should

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place greater emphasis on experimental-numerical synergistic validation strategies rather than relying on a single approach.

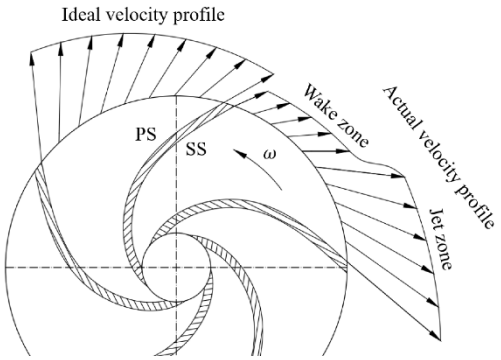


Fig. 3 *Velocity distribution of wake– jet at the impeller outlet* [27], [36]

4. Causal Factors of Flow-Induced Excitation Under Non-Design Conditions

In the selection process of industrial pumps, due to factors such as potential special conditions in actual production of the system, capacity expansion, and fluctuations in process requirements, it is often necessary to consider design margins. This makes it inevitable that the optimal operating conditions of most centrifugal pumps do not match the pipeline system. When centrifugal pumps operate under non-design conditions for a long time, they will face problems of vibration and noise caused by non-design conditions. The conventional design method for centrifugal pumps is generally developed around the rated operating conditions. Under such conditions, the pump flow rate is equal to the designed flow rate; the pressure distribution on both sides of the blade is relatively uniform; the flow field inside each blade passage is basically similar; the working medium exhibits a good coupling relationship with the blade leading edge and no obvious flow impingement occurs when entering the impeller passage; and the flow direction and velocity gradient of the working medium can perfectly match the shape of the flow passage.

As outlined in Zhang et al.'s findings [43], flow separation on centrifugal pump blade surfaces presents as backflow generated by separation bubbles. It strengthens the jet-wake structure and exacerbates flow-induced vibration. In addition, under low-flow operating conditions, flow stall inside the blade passages increases the flow irregularity at the impeller outlet, which further elevates energy loss, causes blockage of 50% of the outlet flow passage area, and ultimately induces the low-flow hump phenomenon—a direct indicator of the pump performance instability.

The internal flow field of a centrifugal pump under off-design operating conditions is completely different from that under the designed operating conditions. The flow field under off-design operating conditions is more complex, and the transient excitation is more intense, thus inducing abnormal vibration of the pump body. Numerous studies have conducted in-depth investigations into the mechanism of flow-induced vibration inside the pump [44,45], while the fluid interaction between the volute and the impeller is the core cause of the amplification of pressure pulsation amplitude [46,47], unstable flow inside pumps [48-50], as well as efficient flow channel design methods [51], [52], etc. They have also proposed some guiding principles for low hydraulic excitation design, including blade trailing edge modification and shape control [53], guide vane leading edge design [54], volute tongue spacing control [9], [55], blade number control [56-59], blade inlet end control [60], etc.

The intensity of pressure pulsation is a commonly used evaluation index in the low-vibration optimization design of modern centrifugal pumps, since this parameter can be easily obtained both in experiments and simulations. However, the simulation of pressure pulsation relies on unsteady numerical modeling methods — a process that consumes substantial computational resources. Therefore, using specific steady-state characteristic parameters to characterize unsteady flow phenomena [17] is an excellent measure to effectively improve the optimization design efficiency of low-vibration centrifugal pumps.

Although the aforementioned suppression measures—including blade trailing-edge modification, blade count adjustment, volute tongue clearance optimization, and blade inlet-end control—have been confirmed by numerous studies to effectively reduce pressure pulsation amplitudes under specific conditions, they still face notable limitations in practical engineering applications. First, the vast majority of optimization strategies are tailored to specific off-design operating points (e.g., 0.5 or 0.8 times the design flow rate) for localized improvements, yet lack validation across the full operating range. Consequently, the operational adaptability of these optimized schemes is poor, and in some cases, pressure pulsation amplitudes may even increase when the flow rate deviates from the optimized point. Second, the coupling effects and interactive influences among the

above measures have not been systematically investigated—for instance, simultaneously modifying blade number and trailing-edge geometry may produce either superposition or cancellation effects, yet quantitative analyses of multi-parameter collaborative optimization are rarely found in the existing literature. Third, current evaluations of suppression measures rely predominantly on the single metric of pressure pulsation amplitude, with insufficient attention paid to their potential negative impacts on other key performance indicators, such as hydraulic efficiency, cavitation performance, and operational stability. The root cause of these limitations is the absence of a theoretical design criterion that unifies the flow-field characteristics under off-design conditions, pressure pulsation responses, and geometric parameter adjustments into an integrated framework. Consequently, existing suppression strategies remain largely "trial-and-error" empirical improvements rather than mechanism-based precision designs. Future research should systematically elucidate the influence laws of various geometric parameters on pressure pulsation under off-design conditions, and establish multi-objective, multi-condition constrained low-excitation design methodologies with clearly defined applicability boundaries for each suppression measure.

5. Study on the Mechanism of Pressure Pulsation

Vibration within pump assemblies primarily stems from three core sources: first, shaft frequency excitation induced by rotor imbalance; second, electromagnetic excitation from the motor; third, unsteady fluid excitation inside the centrifugal pump. Vibration occurring during pump operation, on the one hand, leads to damage of hydraulic components; on the other hand, it spreads to upstream and downstream through connecting pipelines, giving rise to seal deterioration, aggravated rotor misalignment, and even bearing breakage, which has created potential risks for the safe and stable operation of the pumping system. the vibration transmission path is depicted in Fig. 4.

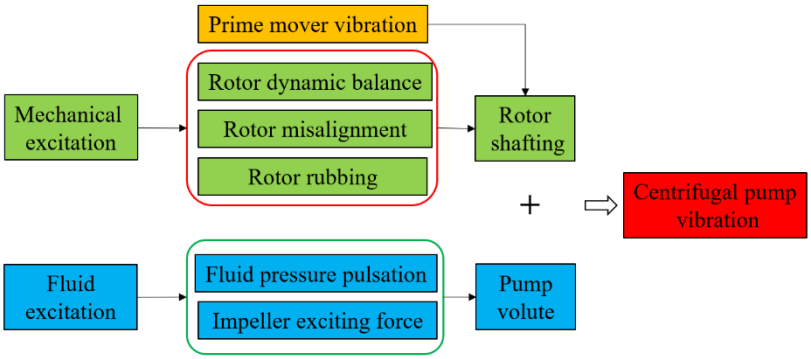


Fig. 4 *Centrifugal pump vibration transmission path*

With the development of mechanical manufacturing technology, the pump vibration problems caused by the first two types of excitations have been basically solved, while fluid excitation remains significant [61]. Among them, unstable flows such as turbulent boundary layers, vortices, and vortex shedding generated in the flow passages produce a broadband frequency spectrum; the high-velocity outflow at the impeller outlet exerts intense excitation forces on the volute, especially at the tongue, which causes large pressure pulsation amplitudes; and the asymmetry of fluid flow also leads to an increase in pulsation amplitudes.

When a centrifugal pump operates under off-design conditions, it is highly likely to generate various unsteady flow phenomena. Large-scale vortices, wake-jet flows, backflows, and other such phenomena inside the blade passages are all typical unsteady flows. Among these factors, rotor-stator interaction contributes the most to flow-induced vibration in centrifugal pumps [46], [47], followed by rotating stall [62-64].

To date, academic research has predominantly centered on the mechanisms underlying rotor-stator interference, with a broad consensus that this phenomenon can be categorized into two distinct flow mechanisms: potential flow interaction and wake interaction. In the 1980s, Dring [65] carried out experimental research on the pressure pulsations induced by the interaction between the impeller and the volute, and found that the outflow disturbance from the rotating blades was strongly correlated with the pressure distribution on the stationary blades. Subsequent studies further indicated that the BPF is the primary cause of intense flow-induced excitation.

There is no seamless engagement between the impeller outlet and the volute inlet; instead, a gap of approximately 2 mm is reserved between them to prevent rotor-stator collision. However, the existence of this gap exerts a certain influence on fluid flow. Akin et al. [66] explored the transient wake structures within this gap and the interaction mechanism between these structures and the blade surface pressure based on PIV. The results showed that shedding vortices are generated in the gap, and the interactions between these shedding vortices further deteriorate the inflow conditions at the leading edges of the guide vanes [27]. Zhang [67] conducted a

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study on the flow structure and velocity gradient at the impeller outlet based on the Particle Image Velocimetry (PIV) technique. With the aid of this technique, the distinct wake-jet structure at the impeller outlet was successfully captured. In addition, the effect of this structure on the volute tongue intensifies the excitation force, which in turn induces shear deformation of the vortices. Furthermore, Ji et al. [46] obtained the rotor-stator interaction flow fields of the pump under different flow conditions by means of the PIV, in Fig. 5, and also investigated the relationship between wake intensity and interaction intensity. The results show that obvious separated vortices are generated in the blade passages of the centrifugal pump under low-flow conditions, and the wake vortices remain attached to the trailing edges of the blades without significant detachment — this phenomenon is illustrated in Fig. 6.

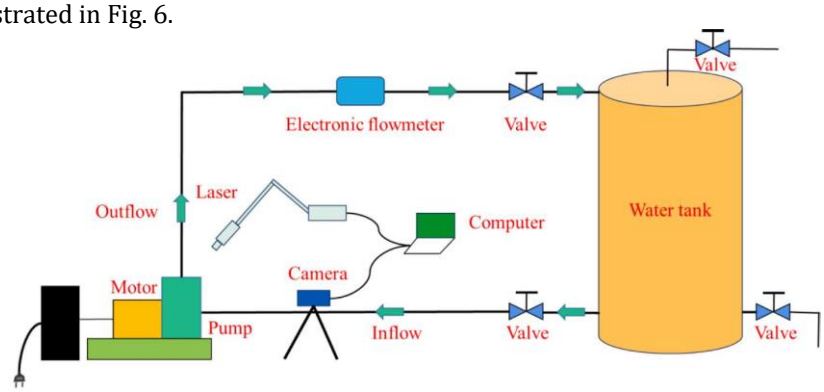


Fig. 5 *PIV test bench* [65]

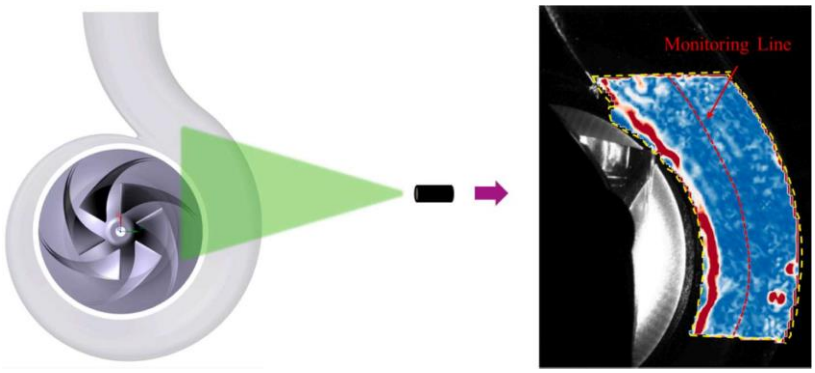


Fig. 6 *The adhesion condition of vortices on the volute wall* [45]

In terms of numerical simulation, González et al. [68] adopted the three-dimensional unsteady numerical simulation method to investigate the fluid flow characteristics inside the pump, and successfully established a quantitative correlation between the pump's flow load and global performance parameters. On this basis, subsequent researchers carried out in-depth studies on the causes of flow-induced excitation and flow structures of various pump types by means of numerical modeling techniques [69-74]. Existing research results indicate that under various flow conditions, the dominant frequency of pressure pulsation inside the pump is the blade passing frequency and its harmonic frequencies, with higher pulsation amplitudes observed under high-load conditions. In contrast, at low loads, the reduced fluid inflow into the impeller leads to a relatively wider flow passage area within the blade channels, which enhances the motion disorder of fluid particles inside the blade channels. This flow characteristic is manifested by a large number of low-frequency components below the shaft rotational frequency. These low-frequency components are closely related to the evolutionary dynamics of vortices, including their generation, migration, and dissipation processes.

To address the low-frequency components arising under low-flow rate conditions, scholars have paid considerable attention to the mechanism of rotating stall — a typical unsteady flow phenomenon. Academic investigations have centered mainly on stall frequency, the propagation of stall cells, and stall states, with a broad consensus that rotating stall frequencies below the rotational frequency do exist under low-flow rate conditions [75]. Research teams from Nanchang University and Jiangsu University [76-80] have carried out a series of numerical simulation studies on the interaction phenomenon between the impeller and volute inside the pump. The results demonstrate that when the centrifugal pump operates under low-flow conditions, the amplitude of pressure pulsation inside the pump increases significantly; this phenomenon exerts a notable influence on the shaft orbit of the pump shaft and further exacerbates the vibration intensity of the pump body. Miyabe [81]

observed the fluid flow structures inside the pump and measured the pulsation intensity based on the PIV technique, and the study demonstrated that rotating stall leads to non-uniform spatial flow distribution, unstable performance curves, and distinct rotating stall frequencies in the pressure pulsation spectrum. The study conducted by Hang Ning [43] further verifies that when a centrifugal pump operates under low-flow conditions, the irregular flow phenomenon inside the blade passages intensifies, leading to the generation of vortex backflow. This in turn causes the distortion and disorder of the fluid flow structures at the blade trailing edges and impeller outlet, resulting in flow passage blockage and the aggravation of flow losses. Feng [43] adopted the Laser Doppler Velocimetry (LDV) technique to measure the flow structures inside the pump under four low-flow operating conditions. It was found that when the inflow rate is lower than half of the design flow rate, similar to the situation described previously, complex flows such as vortices and backflow also occur in the impeller channels, and the turbulent kinetic energy loss increases with the decrease of the flow rate. In their subsequent 2018 study [82], the research team found that under the operating condition of 0.35 times the design flow rate, five stall cells existed in the impeller channels, and there was a certain interaction effect between these stall cells, whose mechanism remains to be further studied. To improve the hydraulic performance of centrifugal pumps under low-flow conditions, the research team added a cavitation cavity structure to a mixed-flow pump in 2019 [83], resulting in a more uniform fluid distribution in the flow passages. Zhao [84] also carried out research on the internal flow of pumps under low-flow conditions, and found that the stall phenomenon inside the pump is inevitable, with the flow rate being inversely proportional to the intensity of the stall.

Lu [85] revealed the correlation mechanism between stall and vibration under low-flow conditions through experiments, as shown in Fig. 7. This study also confirmed that a low inflow rate would intensify the complexity of the internal flow of the pump, and found that the vortex structures in different blade passages were basically similar.

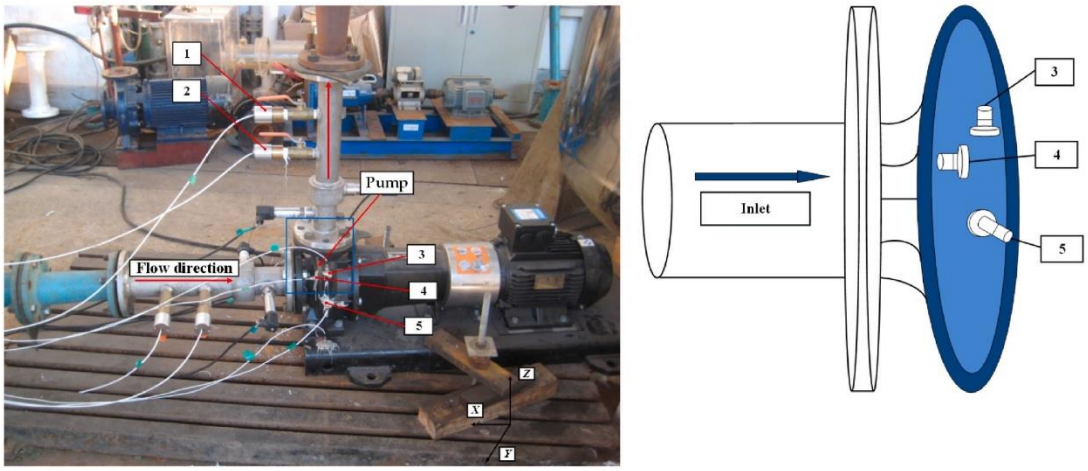


Fig.7 *Distribution of sensors on the experimental centrifugal pump* [83]

In light of the above findings, it is evident that although the research community has accumulated substantial knowledge regarding the mechanisms of pressure pulsation in centrifugal pumps under off-design conditions, notable disagreements persist on several key issues. First, regarding the relative contributions of low-frequency components induced by rotating stall versus those of blade passing frequency (BPF)-dominated rotor-stator interaction components to vibration responses, conclusions reported by different studies vary considerably—some attribute the dominant vibration excitation under low-load conditions to stall-induced low-frequency oscillations, whereas others demonstrate that BPF and its harmonics consistently dominate the frequency spectrum across a wide flow-rate range. This discrepancy likely originates from differences in pump configurations (specific speed, blade number, volute geometry) and experimental boundary conditions; however, systematic parametric comparative studies to quantify the weighting of these factors are currently lacking. Second, most existing investigations have concentrated on flow field analyses near the stall inception point or close to the design point; the evolution, splitting, and merging mechanisms of multiple stall cells under deep-stall conditions, as well as their coupling with the impeller outlet jet-wake structure, remain insufficiently elucidated. This implies that the current understanding of flow-induced excitation under off-design conditions remains largely at the level of "phenomenological description" and has not yet reached the stage of "quantitative prediction."

6. Conclusion

In summary, current research on the flow-induced excitation mechanisms of centrifugal pumps under off-design conditions is transitioning from steady-state analyses at single operating points toward multi-condition, multi-physics coupled unsteady analyses, with artificial intelligence-assisted modeling and optimization beginning to permeate the field of low-excitation pump design. Nevertheless, two core challenges persist in this field. First, the full-chain quantitative transfer relationship of "flow-field characteristics → pressure pulsation → vibration noise" under off-design conditions has not yet been established; most existing studies discuss flow structures or pressure spectra in isolation, lacking a unified transfer function model that quantifies all three aspects in an integrated manner. Second, existing suppression measures—such as blade trailing-edge modification, blade count adjustment, and volute tongue clearance optimization—remain local improvements targeting specific geometric parameters, and a global, multi-objective collaborative design framework for low-flow-excitation pumps is conspicuously absent. Consequently, the operational adaptability and robustness of these optimized schemes are insufficient.

Future investigations urgently need to achieve breakthroughs in the following directions: (1) establishing rapid prediction models for pulsation amplitudes based on characteristic flow-field parameters to replace costly unsteady numerical simulations; (2) developing multi-source information fusion methods that integrate experimental data and high-fidelity simulations to reveal the nonlinear mapping between stall evolution and vibration responses; and (3) constructing multi-objective optimization design systems that comprehensively account for hydraulic efficiency, vibration suppression, and operational adaptability.

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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*

Appendix

CFD	Computational Fluid Dynamics
DDES	Delayed Detached - Eddy Simulation
DES	Detached Eddy Simulation
LDA	Laser Doppler Anemometry
LES	Large Eddy Simulation
NPSH	net positive suction head
PIV	Particle Image Velocimetry
RANS	Reynolds - Averaged Navier – Stokes
SSTk-ω	Shear Stress Transport k-ω turbulence

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