

Experimental Study on Frequency Spectrum Characteristics of Pressure Pulsation in Low Specific Speed Centrifugal Pumps (Postprint)

Authors: Zhang Ning Yang Minguang Gao Bo Li Zhong Ni Dan Wang Haoyu

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Abstract

Pressure pulsations induced by the impeller-tongue rotor-stator interaction within centrifugal pumps constitute a significant factor in exciting pump vibration and noise, exerting substantial influence on the stable and safe operation of the pump. To comprehensively characterize the pressure pulsation behavior of centrifugal pumps, this study employs experimental methodology to conduct pressure pulsation tests on a low specific speed centrifugal pump, with pressure signals extracted via 20 high-frequency pressure pulsation sensors uniformly distributed circumferentially in the volute. The results demonstrate that the pressure spectrum exhibits typical discrete characteristics, with peak signals appearing at the blade passing frequency and its higher harmonics; no significant peaks attributable to shaft frequency or its nonlinear interaction with blade passing frequency are observed in the pressure spectrum. The pressure pulsation amplitude varies significantly across different measurement locations; at the design point and high-flow conditions, the maximum pressure pulsation amplitude at the blade passing frequency occurs within the region downstream of the tongue, whereas in the region upstream of the tongue, the pressure pulsation amplitude remains relatively small; furthermore, with increasing angular position, the pressure pulsation amplitude at the blade passing frequency exhibits a decreasing trend, while under low-flow conditions, the maximum pressure pulsation amplitude at the blade passing frequency does not appear within the region downstream of the tongue. Flow rate exerts a significant influence on the pressure pulsation amplitude at the blade passing frequency; the minimum pressure pulsation amplitude occurs near $0.9Q_d$, and deviating from this operating condition results in a rapid increase in pressure pulsation amplitude.

Full Text

Experimental Study on Pressure Pulsation Spectrum Characteristics of a Low Specific Speed Centrifugal Pump

ZHANG Ning, YANG Min-Guan, GAO Bo, LI Zhong, NI Dan, WANG Hao-Yu

(School of Energy and Power Engineering, Jiangsu University, Zhenjiang, Jiangsu 212013, China)

Abstract: Pressure pulsations due to rotor-stator interaction are vital factors inducing vibration and noise in centrifugal pumps, which have a great influence on the stable operation of the pumps. To achieve a comprehensive understanding of pressure spectrum characteristics of a low specific speed centrifugal pump, twenty pressure transducers are evenly mounted on the volute casing to obtain pressure pulsation signals. Results show that the pressure spectrum exhibits typical discrete characteristics, and evident peaks occur at blade passing frequency fBPF and its higher harmonics. Components at shaft rotating frequency fR together with the non-linear peaks between fBPF and fR are not evident. At nominal and high flow rates, the maximum amplitude occurs at the point after the volute tongue, while at the point before the volute tongue, pressure amplitude is much smaller. This phenomenon is not observed at low flow rates. With increasing angle, pressure amplitude shows a decreasing tendency. Minimum amplitude occurs at 0.9Qd, and pressure amplitude increases rapidly when flow rate deviates from 0.9Qd.

Keywords: centrifugal pump; pressure pulsation; experimental investigation; pressure spectrum

0 Introduction

The strong rotor-stator interaction formed by the periodic sweeping of the impeller tongue inside the centrifugal pump is the main source of pressure pulsation, and this unsteady pressure pulsation is a primary factor in hydraulically induced vibration and noise [1]. In certain fields with extremely stringent requirements for centrifugal pump vibration and noise, controlling unsteady pressure pulsation levels constitutes important research content for low-noise centrifugal pump design. Even at the design operating point, where the fluid exiting the impeller and the volute achieve optimal matching characteristics, large-amplitude pressure pulsations excited by rotor-stator interaction still persist. Numerous studies have confirmed that the flow structure within the volute of a centrifugal pump exhibits circumferential non-uniformity, which is closely related to the geometric dimensions of the impeller and volute as well as the pump operating point. The ultimate goal of research on unsteady flow in centrifugal pumps is to explore the true internal mechanisms, establish predictive models for pressure pulsation, and provide a theoretical foundation for low-noise centrifugal pump design.

Spence et al. [2,3] employed numerical methods to investigate the influence of characteristic geometric parameters on pressure pulsation in centrifugal pumps and conducted ranking studies on the degree of influence of different geometric parameters. Yao et al. [4] studied the spectral characteristics of a double-suction centrifugal pump and analyzed typical peak signals in the spectrum. Zhang et al. [5-7] proposed a volute with special sidewall structures to reduce impeller-tongue rotor-stator interaction and investigated its pressure pulsation levels through comparative analysis with conventional volute centrifugal pumps. This paper presents an experimental study on the pressure pulsation spectrum characteristics of a low specific speed centrifugal pump, analyzing its typical peak signal characteristics and examining the relationship between the pressure spectrum and volute circumferential position as well as flow characteristics.

1 Experimental Measurement System

The research object of this study is a low specific speed centrifugal pump with $ns=69$. The impeller adopts a two-dimensional cylindrical blade structure, and the volute cross-section is rectangular. Its main design parameters are shown in Table 1 .

A closed-loop test rig for the centrifugal pump was constructed as shown in Figure 1 [Figure 1: see original paper]. An electromagnetic flowmeter and high-precision pressure gauges were used to obtain the flow-head characteristic curve of the model pump, while a torque meter was employed to measure the pump input power. The overall error of the test system is less than 0.5%. To acquire the spectral characteristics of the model pump under different operating conditions, high-frequency pressure pulsation sensors (PCB113B27) were utilized for pressure signal acquisition. The specific positions of the pressure pulsation sensors are shown in Figure 2 [Figure 2: see original paper]. The pressure sensors were uniformly distributed in the circumferential direction of the volute, with an angle of 18° between adjacent pressure sensors. During pressure signal sampling, the resolution was set to 0.5 Hz. Numerous studies have confirmed that pressure pulsation signals in centrifugal pumps are basically in the low-frequency range (<1000 Hz). Therefore, the sampling frequency was set to 10000 Hz during acquisition to fully satisfy the Nyquist sampling theorem.

2 Experimental Results Analysis

Figure 3 [Figure 3: see original paper] presents the experimental performance curves of the model pump. The results indicate that the model pump has a relatively wide high-efficiency region, with essentially identical efficiency values within the flow range of $1.0Q_d$ to $1.2Q_d$. The highest efficiency point of the model pump is slightly shifted toward $1.1Q_d$. At low flow conditions, the head curve of the model pump exhibits an unstable hump phenomenon, indicating that a rotating stall flow structure has developed inside the impeller.

Figure 4 [Figure 4: see original paper] shows the pressure pulsation spectra

at three different measurement points ($=0^\circ$, $=36^\circ$, $=90^\circ$) under four different operating conditions of the model pump. The centrifugal pump studied in this paper operates at a rotational speed of 1450 r/min with 6 blades; therefore, the impeller rotational frequency f_R is 24.2 Hz and the blade passing frequency f_{BPF} is 145 Hz.

The spectra reveal that the model pump exhibits typical discrete characteristics, with peak signals primarily appearing at the blade passing frequency f_{BPF} and its higher harmonics $2f_{BPF}$ and $3f_{BPF}$. The pressure pulsation amplitude at the blade passing frequency is much larger than that at its higher harmonics. No peak signals are present in the high-frequency range of the spectrum, suggesting that pressure pulsation signals excited by unsteady flow phenomena such as rotor-stator interaction are basically within the 0-500 Hz frequency range. Since the impeller used in this study was manufactured by 5-axis CNC machining, its dynamic balance can be strictly guaranteed; consequently, no evident peak signals appear at the impeller rotational frequency. Meanwhile, peak signals induced by non-linear interference between the impeller rotational signal and blade passing frequency can be effectively suppressed, resulting in peak signals appearing mainly at the blade passing frequency and its higher harmonics without significant peaks at other frequencies.

Pressure pulsation amplitudes vary significantly at different measurement points. Under various flow rates, the pressure pulsation amplitude at the $=36^\circ$ measurement point is greater than at other points. At low flow conditions of $0.2Q_d$ and $0.6Q_d$, the amplitude signal at $2f_{BPF}$ at the $=0^\circ$ measurement point is much larger than the peak signals at the other two measurement points. However, at the design point and high flow conditions, the peak signal at $2f_{BPF}$ at the $=0^\circ$ measurement point is significantly suppressed with small amplitude.

As shown in Figure 4, the pressure pulsation amplitude at the blade passing frequency dominates the spectrum. To analyze the circumferential distribution of amplitude at the blade passing frequency, Figure 5 [Figure 5: see original paper] presents the angular distribution characteristics of pressure pulsation amplitude at the blade passing frequency under different operating conditions. The results show that under different conditions, the blade passing frequency distribution exhibits typical six-peak characteristics caused by periodic rotor-stator interaction between the impeller and tongue. At design and high flow conditions, the maximum pressure pulsation amplitude occurs at the monitoring point $=36^\circ$ located after the volute tongue, while the amplitude is relatively small at the monitoring point $=18^\circ$ before the tongue. At low flow condition $0.8Q_d$, however, the pressure pulsation amplitude at monitoring point $=36^\circ$ does not reach the maximum value; instead, the extremum appears near the monitoring point $=108^\circ$. According to the rotor-stator interaction mechanism, the interaction intensity between impeller and tongue is mainly determined by the impact of blade wake flow on the tongue. At the front tongue monitoring point $=18^\circ$, the impact interference between wake flow and tongue has not yet occurred, resulting in lower pressure pulsation amplitude. Near the rear tongue position

$=36^\circ$, after the wake flow interacts with the tongue, a high-intensity disturbed flow field structure is generated in this region, causing larger pressure pulsation amplitudes. At low flow conditions, we believe that some fluid recirculates from the volute diffuser section back into the volute interior, which significantly suppresses the interference structure between wake flow and tongue. Consequently, pressure pulsation energy is mainly determined by the non-uniform flow structure at the impeller outlet, causing the pressure pulsation amplitude at $=36^\circ$ to no longer be significantly larger than at other monitoring points. At design and high flow conditions, as the angle increases, the pressure pulsation amplitude at different measurement points generally shows a continuous decreasing trend, resulting from the increasing gap between the impeller and volute. At low flow conditions, due to weaker rotor-stator interaction near the tongue, the pressure pulsation amplitude at monitoring points near the tongue no longer has obvious advantages, and thus the decreasing trend of pressure pulsation amplitude at different measurement points is no longer evident.

Flow structures inside the centrifugal pump vary significantly under different operating conditions, thereby affecting pressure pulsation amplitude. Figure 6 [Figure 6: see original paper] shows the variation trend of pressure pulsation amplitude at the blade passing frequency with flow rate at four different monitoring points near the tongue. Overall, pressure pulsation amplitude at off-design points is much larger than near the design condition, particularly increasing rapidly near low flow conditions. The energy performance curves indicate that the optimal operating point of the model pump is slightly near $1.1Q_d$, where the matching relationship between the fluid exiting the impeller and the volute reaches optimum; therefore, the pressure spectrum energy of the model pump should reach a minimum value. However, the minimum amplitude points at the four different measurement points in Figure 6 are all located near the $0.9Q_d$ condition. As shown in Figure 4, besides the blade passing frequency signal, the pressure spectrum of the model pump also contains its higher harmonic signals; thus, the total energy of the pressure spectrum should be the sum of energies of each discrete signal. Although the blade passing frequency signal dominates the pressure spectrum, it only represents part of the spectrum energy, which may explain why the pressure pulsation amplitude at the blade passing frequency tends toward the $0.9Q_d$ condition. Furthermore, the highest efficiency point and the hydraulic efficiency optimum point of the model pump often do not coincide. At the hydraulic efficiency optimum point, the flow structure inside the model pump is most uniform; therefore, we infer that the hydraulic efficiency optimum point of the model pump tends toward the $0.9Q_d$ condition, which may also explain why the minimum pressure pulsation amplitude appears at $0.9Q_d$.

This paper experimentally investigated the pressure pulsation characteristics of a low specific speed centrifugal pump. Pressure pulsation spectrum characteristics of the model pump were obtained through high-frequency pressure pulsation sensors arranged in the circumferential direction of the volute. The main conclusions are as follows:

1. The pressure pulsation spectrum at different measurement points exhibits typical discrete signal characteristics, with peak signals appearing mainly at the blade passing frequency and its higher harmonics.
2. At the design point and high flow conditions, the extremum of the blade passing frequency appears near $\pm 36^\circ$ after the tongue, whereas at low flow conditions, no maximum peak appears in this region.
3. The pressure pulsation amplitude at the blade passing frequency reaches a relatively small value near the 0.9Qd operating condition, and increases rapidly under off-design conditions.

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Corresponding Author: ZHANG Ning

Add: School of Energy and Power Engineering, Jiangsu University, Zhenjiang, Jiangsu 212013

Tel: 18806101236

E-mail: zhangningwlg@163.com

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