Experimental Study on Spectral Characteristics of Pressure Pulsation in Low-Specific-Speed Centrifugal Pumps: Postprint

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

Date: 2017-11-07T00:00:00+00:00

Abstract

Pressure pulsations induced by rotor-stator interaction between the impeller and volute tongue inside a centrifugal pump constitute an important factor in exciting pump vibration and noise, significantly impacting the stable and safe operation of the pump. To comprehensively obtain the pressure pulsation characteristics of centrifugal pumps, this paper employs experimental methods to conduct pressure pulsation tests on a low specific speed centrifugal pump, extracting pressure signals using 20 high-frequency pressure transducers uniformly distributed circumferentially in the volute. The results indicate that the pressure spectrum of the centrifugal pump exhibits typical discrete characteristics, with peak signals appearing at the blade passing frequency and its higher harmonics; no significant peaks associated with shaft frequency or nonlinear interference between shaft and blade passing frequencies are observed in the pressure spectrum. The pressure pulsation amplitude varies significantly across different measurement points. At the design point and large flow conditions, the maximum amplitude at the blade passing frequency occurs within the region downstream of the volute tongue, while the amplitude is relatively small in the region upstream of the tongue; moreover, the amplitude at the blade passing frequency shows a decreasing trend with increasing angular position. However, under small flow conditions, the maximum amplitude at the blade passing frequency does not appear in the region downstream of the volute tongue. Flow rate has a significant influence on the pressure pulsation amplitude at the blade passing frequency, with the minimum amplitude occurring near 0.9Qd, and the amplitude increasing rapidly when deviating from this condition.

Full Text

Experimental Investigation 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 induced by rotor-stator interaction between the impeller and volute tongue are critical factors that excite vibration and noise in centrifugal pumps, significantly affecting their stable and safe operation. To comprehensively characterize the pressure pulsation behavior in a low specific speed centrifugal pump, this study conducts experimental measurements using twenty high-frequency pressure transducers evenly distributed around the volute circumference to capture pressure signals. The results demonstrate that the pressure spectrum exhibits typical discrete characteristics, with prominent peaks occurring at the blade passing frequency (fBPF) and its higher harmonics. Notably, no significant peaks appear at the shaft rotating frequency (fR) or at frequencies corresponding to nonlinear interference between fBPF and fR. The pressure pulsation amplitude varies substantially across different measurement locations. At design and high flow rates, the maximum amplitude at the blade frequency occurs in the region behind the volute tongue, while relatively small amplitudes are observed in front of the tongue. With increasing angular position, the amplitude at the blade frequency shows a decreasing trend. However, this pattern does not hold under low flow conditions, where the maximum amplitude does not appear in the region behind the tongue. Flow rate significantly influences the pressure pulsation amplitude at the blade frequency, with the minimum amplitude occurring near 0.9Qd and increasing rapidly when deviating from this condition.

Keywords: Centrifugal pump; Pressure pulsation; Experimental investigation; Pressure spectrum

0 Introduction

The strong rotor-stator interaction caused by the periodic sweeping of the impeller past the volute tongue constitutes the primary source of pressure pulsations in centrifugal pumps. These unsteady pressure fluctuations represent a major contributor to hydraulically induced vibration and noise [1]. In applications with extremely stringent requirements for pump vibration and noise, controlling unsteady pressure pulsation levels becomes a critical research focus in low-noise centrifugal pump design. Even at the design operating point, where the fluid exiting the impeller achieves optimal matching characteristics with the volute, these substantial pressure pulsations excited by rotor-stator interaction persist. Numerous studies have confirmed that the flow structure within centrifugal pump volutes exhibits circumferential non-uniformity, which is closely related to the geometric dimensions of both the impeller and volute as well as the pump operating condition. The ultimate goal of research on unsteady flow in centrifugal pumps is to explore the underlying physical mechanisms, establish predictive models for pressure pulsations, and provide a theoretical foundation for low-noise pump design.

Spence et al. [2,3] employed numerical methods to investigate the influence of characteristic geometric parameters on pressure pulsations and conducted a comparative study ranking the impact of different parameters. Yao et al. [4] examined 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 rotor-stator interaction and performed comparative studies on pressure pulsation levels against conventional volute designs. This paper presents an experimental investigation of the pressure pulsation spectral characteristics in a low specific speed centrifugal pump, analyzing the features of typical peak signals and exploring the relationship between the pressure spectrum and both circumferential volute position and flow characteristics.

1 Experimental Measurement System

The test subject is a low specific speed centrifugal pump with a specific speed of ns=69. The impeller employs a two-dimensional cylindrical blade configuration, and the volute cross-section is rectangular. The main design parameters are summarized 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 pump's flow-head performance curve, while a torque meter measured the input power. The overall measurement uncertainty of the system is less than 0.5%. To acquire spectral characteristics under various operating conditions, high-frequency pressure transducers (PCB113B27) were installed to capture pressure signals. The transducer locations are illustrated in Figure 2 [Figure 2: see original paper], with sensors uniformly distributed circumferentially around the volute at 18° intervals between adjacent sensors. During signal acquisition, the frequency resolution was set to 0.5 Hz. Extensive research has confirmed that pressure pulsation signals in centrifugal pumps primarily reside in the low-frequency range (<1000 Hz). Consequently, the sampling frequency was set to 10000 Hz to fully satisfy the Nyquist sampling criterion.

2 Experimental Results and Analysis

The performance curves of the model pump are presented in Figure 3 [Figure 3: see original paper]. The results indicate that the pump maintains a relatively wide high-efficiency region, with essentially identical efficiency values across the flow range of 1.0Qd to 1.2Qd. The best efficiency point occurs slightly at 1.1Qd. Under low flow conditions, the head curve exhibits an unstable hump phenomenon, suggesting the onset of rotating stall flow structures within the impeller.

Figure 4 [Figure 4: see original paper] shows the pressure pulsation spectra at three different measurement points (=0°, =36°, =90°) under four operating conditions. For the tested pump operating at 1450 r/min with 6 blades, the impeller rotational frequency fR is 24.2 Hz and the blade passing frequency fBPF is 145 Hz. The spectra exhibit typical discrete characteristics, with peak signals appearing predominantly at the blade passing frequency and its higher harmonics (2fBPF, 3fBPF). The pressure pulsation amplitude at the blade frequency substantially exceeds those at its higher harmonics. No significant peaks appear in the high-frequency region of the spectrum, indicating that pressure pulsations excited by unsteady flow phenomena such as rotor-stator interaction are essentially confined to the 0-500 Hz range. Since the impeller was manufactured using 5-axis CNC machining, which ensures strict dynamic balance, no prominent peaks appear at the impeller rotational frequency. Additionally, peaks induced by nonlinear interference between the rotational frequency and blade passing frequency are effectively suppressed.

The pressure pulsation amplitude varies significantly across measurement locations. Under all flow conditions, the amplitude at =36° exceeds that at other measurement points. At low flow conditions (0.2Qd and 0.6Qd), the amplitude at 2fBPF at =0° is much larger than at the other two measurement points. However, at design and high flow rates, the peak at 2fBPF at =0° is substantially suppressed with relatively small amplitude.

As the blade frequency component dominates the pressure spectrum, Figure 5 [Figure 5: see original paper] illustrates the circumferential distribution of pressure pulsation amplitude at the blade frequency under different flow conditions. The distribution exhibits six distinct peaks, a characteristic resulting from periodic rotor-stator interaction between the impeller and volute tongue. At design and high flow rates, the maximum amplitude occurs near =36° behind the volute tongue, while relatively small amplitudes are observed at =18° in front of the tongue. Under low flow conditions (0.8Qd), the maximum amplitude does not occur at =36° but rather near =108°. Rotor-stator interaction intensity is primarily determined by the impingement of blade wake flow on the volute tongue. At =18° in front of the tongue, wake-tongue interaction has not yet occurred, resulting in lower pressure pulsation amplitudes. In contrast, near =36° behind the tongue, strong interaction between the wake flow and tongue generates intense disturbed flow structures, leading to larger pressure pulsation amplitudes. Under low flow conditions, partial fluid recirculation from the volute diffuser back into the volute interior suppresses the wake-tongue interaction structure, diminishing its influence. Consequently, pressure pulsation energy is dominated by non-uniform flow structures at the impeller outlet, preventing the amplitude at =36° from significantly exceeding other locations. At design and high flow rates, increasing the angular position generally leads to decreasing pressure pulsation amplitudes due to the growing gap between the impeller and volute. Under low flow conditions, weaker rotor-stator interaction near the tongue eliminates the amplitude advantage at tongue-proximal locations, resulting in no clear decreasing trend with angle.

Flow structure variations across operating conditions significantly affect pressure pulsation amplitudes. Figure 6 [Figure 6: see original paper] presents the variation of pressure pulsation amplitude at the blade frequency with flow rate at four measurement points near the tongue. Overall, the amplitude is substantially larger at off-design conditions than near design conditions, particularly increasing rapidly under low flow conditions. The performance curves indicate that the optimal operating point occurs near 1.1Qd, where the matching between impeller outflow and volute is optimal. However, Figure 6 shows that the minimum pressure pulsation amplitude for all four measurement points occurs near 0.9Qd. As shown in Figure 4, the pressure spectrum contains not only the blade frequency component but also its higher harmonics, meaning the total spectral energy equals the sum of all discrete signal energies. Although the blade frequency component dominates, it represents only a portion of the total energy, which may explain why the minimum amplitude occurs at 0.9Qd rather than at the best efficiency point. Furthermore, the best efficiency point and the hydraulic efficiency optimum do not necessarily coincide. At the hydraulic efficiency optimum, the internal flow structure is most uniform, and we infer that this optimum occurs near 0.9Qd, which may also contribute to the minimum pressure pulsation amplitude appearing at this condition.

This study experimentally investigated the pressure pulsation characteristics of a low specific speed centrifugal pump using high-frequency pressure transducers distributed circumferentially around the volute. The main conclusions are as follows:

1. The pressure pulsation spectra at different measurement points exhibit typical discrete characteristics, with peak signals appearing predominantly at the blade passing frequency and its higher harmonics.

2. At design and high flow rates, the maximum amplitude at the blade frequency occurs near =36° behind the volute tongue, whereas this phenomenon is not observed under low flow conditions.

3. The pressure pulsation amplitude at the blade frequency reaches a minimum near 0.9Qd, increasing rapidly when operating away from this condition.

References

[1] Rodriguez C G, Mateos-Prieto B, Egusquiza E. Monitoring Rotor-Stator Interaction in a Pump-Turbine Using Vibration Measured with Onboard Sensors Rotating with Shaft[J]. Shock and Vibration, 2014:276796.

[2] Spence R, Aaral-Teixeira J. A CFD Parametric Study of Geometrical Variations on the Pressure Pulsations and Performance Characteristics of a Centrifugal Pump[J]. Computers & Fluids, 2009, 38(6):1243–1257.

[3] Yuan Jianping, Fu Yanxia, Liu Yang, et al. Analysis on Pressure Fluctuation within Volute of Centrifugal Pump Based on Large Eddy Simulation[J]. Journal of Drainage and Irrigation Machinery Engineering, 2010, 28(4):310-314.

[4] Yao Zhifeng, Wang Fujun, Qu Lixia, et al. Experimental Investigation of Time-Frequency Characteristics of Pressure Fluctuations in a Double-Suction Centrifugal Pump[J]. Journal of Fluids Engineering, 2011,133(10):101303.

[5] Zhang Ning, Yang Minguan, Gao Bo, et al. Experimental Investigation on Unsteady Pressure Pulsation in a Centrifugal Pump With Special Slope Volute[J]. Journal of Fluids Engineering, 2015, 137: 061103.

[6] Zhang Ning, Yang Minguan, Gao Bo, et al. Experimental and Numerical Analysis of Unsteady Pressure Pulsation in a Centrifugal Pump with Slope Volute[J]. Journal of Mechanical Science and Technology, 2015, 29(10): 4231-4242.

[7] Zhang Ning, Yang Minguan, Gao Bo, et al. Unsteady Pressure Pulsation and Rotating Stall Characteristics in a Centrifugal Pump With Slope Volute[J]. Advances in Mechanical Engineering, 2014, 11:710791.

Corresponding Author: ZHANG Ning
Address: School of Energy and Power Engineering, Jiangsu University, Zhenjiang, Jiangsu 212013, China
Tel: 18806101236
E-mail: zhangningwlg@163.com

Note: Figure translations are in progress. See original paper for figures.