



Cyclostationary approach to detect flow-induced effects on vibration signals from centrifugal pumps



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ABSTRACT

This study aims to investigate the mechanism of flow-induced effects on vibration signals from centrifugal pumps by combining computational fluid dynamics (CFD) and signal cyclostationarity. A pump vibration model is established as an amplitude-modulated (AM) model, and the modulation mechanism is elaborated in detail. A general AM model is mathematically analyzed with spectral correlation density and spectral coherence, and analytic solutions of modulation intensity are derived. Transient CFD simulations under design and off-design conditions are conducted to obtain the pressure pulsation in the volute and the radial fluid forces on the impeller. Then, vibration signals from the pump and motor feet with two acceleration transducers are processed by spectral coherence. The signature of second-order cyclostationarity is detected at the shaft rotating frequency and blade passing frequency (BPF). The mean spectral coherence is used to evaluate the intensity of the modulating signals produced by the flow-induced effects. Finally, the signal processing results are compared with the unsteady CFD results under design and off-design conditions. These comparisons show a good agreement. Therefore, this study confirms that the flow-induced signals calculated by CFD can be considered as modulating components for pump vibration signals. The results provide solid supporting theory for designing low vibration pumps.

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1. Introduction

The vibration performance of turbomachines such as pumps has caught the attention of engineers. In some special situations, vibration performance is prioritized over pump efficiency. For fluid engineers, the main method to reduce pump vibration is to optimize the pressure pulsation in the pump and the radial fluid force fluctuation exerted on the impeller and volute. This optimization is achieved by computational fluid dynamics (CFD) simulations. A common approach is to primarily adopt empirical specifications for low-vibration designs instead of CFD simulations because the latter requires massive computational resources and careful model treatments. However, the direct relation between fluid-induced effects and vibration signals has yet to be elaborated clearly using the common approach. Many engineers consider the fluid-induced effects of blade passing frequency (BPF) as the direct excitation source of vibration signals. However, they may fail to detect BPF in

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the Fourier analysis of vibration signals. In fact, pump vibration models based on fluid-induced effects comprise a modulation mechanism that is generally ignored by researchers.

A number of researchers have recently used CFD methods to design low-vibration pumps with low-pressure pulsations. Spence et al. [1] studied the geometrical variations of the pressure pulsations of a centrifugal pump with a CFD parametric method. They concluded that the cutwater gap and vane arrangement would exert the greatest influence across various monitored locations and the flow range; in addition, they offered some recommendations that would enable pump designers to reduce vibrations. Pressure pulsation in pumps is a significant factor in evaluating stability under operating conditions. To investigate pressure pulsation, González et al. [2,3] conducted a 3D unsteady calculation with a sliding mesh technique and investigated the dynamic characteristics inside a low specific-speed pump; they successfully correlated the load and global parameters for the flow in the pump and verified the results by experimental data. Barrio et al. [4] studied radial load and unsteady pressure distribution around the impeller and found that unsteady components could account for a large proportion of the average magnitude during operation under off-design conditions. Yan et al. [5,6] used the standard deviation of the pressure pulsation around the volute to visualize pressure pulsation intensity with contour plots and thereby provide a clear understanding of the distribution of pressure pulsation intensity in the volute.

For signal processing, cyclostationarity is a powerful tool to deal with random signals that are mixed by a hidden periodic phenomenon; these signals are categorized as cyclostationary signals [7]. Classical methods that model signals as stationary cannot effectively deal with cyclostationary signals because they neglect periodic or almost-periodic time variability in statistical moments. Gardner et al. [8,9] developed the theory of cyclostationary processes, which has been widely used in communication fields such as radar, sonar, and telemetry. Recently, researchers [10–14] have started to apply cyclostationarity to mechanics for fault detection, especially those for rotating machines. Antoni et al. [15,16] established a cyclostationary model for the vibration signals of rotating machines, proposed a general methodology for analyzing other types of rotating machine signals, and then introduced spectral correlation density to successfully detect BPF in pump vibration signals. Botero et al. [17] recently adopted cyclostationary analysis to study the rotating stall in a pump turbine with tuft visualization and developed a non-intrusive method for detecting rotating stall instability and number of stall cells. Napolitano [18,19] reviewed the application of cyclostationarity in recent years and identified new trends and limits to provide a comprehensive understanding of cyclostationarity.

The present study investigates the flow-induced effects in centrifugal pumps under design and off-design conditions on the basis of CFD simulations. The results are compared with vibration signals processed with second-order cyclostationary tools. The widely used CFD package Fluent and the mesh generator ICEM are used for all the 3D numerical computations to obtain the pressure pulsation and radial fluid force fluctuation. The mean spectral coherence is used to evaluate the intensity of the modulating signals and prove their effectiveness. The main objective of this study is to elaborate the modulation mechanism of the flow-induced effects on vibration signals and offer guidance for designing low-vibration pumps.

2. Numerical model and method

2.1. Model descriptions

The centrifugal pump under study is a canned motor pump. The pump impeller is mounted at the overhung end of a shared pump-and-motor shaft. The main parameters of the centrifugal pump are presented in Table 1. Fig. 1(a) shows the configuration of the pump on the test rig that is used to test the pump characteristics and vibration performance. Two acceleration transducers are set on the pump and motor feet for vibration data acquisition, and corresponding positions are shown in Fig. 1(a). For the CFD simulations, the calculation model of the centrifugal pump consists of six main domains, which are displayed in Fig. 1(b). Aside from the impeller and volute, the front/rear sidewall gap, balance holes, and inlet guide vanes are considered in the CFD simulations. This consideration provides an accurate result, given that the back flow in the balance holes can deteriorate the flow fields in the impeller domain. Furthermore, the increment of the shaft power by sidewall friction cannot be ignored in the efficiency calculation. The impeller consists of seven main blades and seven splitter blades. Such a combination can produce two types of BPFs, which correspond to the number of total blades and main blades.

Table 1
Main parameters of centrifugal pump.

Parameters		Values
Q_d	(design volume flow rate, m ³ /h)	550
H_d	(design pump head, m)	25
n	(rotation speed, rpm)	1470
D_1	(impeller suction diameter, mm)	117.5
D_2	(impeller outlet diameter, mm)	310
b_2	(impeller outlet width, mm)	55
Z_1	(number of main blades)	7
Z_2	(number of splitter blades)	7
b_3	(volute inlet width, mm)	55
D_3	(volute tongue diameter, mm)	454

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