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Impeller radial force evolution in a large double-suction centrifugal pump during startup at the shut-off condition

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HIGHLIGHTS

- Conclude the characteristics of transient radial force in the startup process for a large double-suction centrifugal pump.
- The overall direction of the radial force during startup process is also confirmed.
- A formula used to calculate the transient radial force during startup process is proposed.
- A relationship between radial force variation and axial vortex development in blade channel during the startup process is established. The mechanism of the radial force evolution is revealed.

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ABSTRACT

Double-suction centrifugal pumps play an important role in the main feedwater systems of nuclear power plant. The impeller radial force in a centrifugal pump varies dramatically during startup at the shut-off condition. In this study, the startup process of a large double-suction centrifugal pump is investigated using CFD. During testing, the impeller speed is accelerated from zero to its rated speed in 1.0 s (marked as t_0) and is then maintained at the rated speed. The results show that the radial force increase lags behind the impeller speed increase. At 0–0.4t_0, the radial force is small (approaching zero). At 0.4–1.4t_0, the radial force increases rapidly. After 1.4t_0, the average radial force stabilizes and reaches its maximum value of 55,619 N. The observed maximum radial force value during startup is approximately nine times as high as the radial force under rated condition. During startup, the overall radial force direction is proximate to the radial line located 25° from the volute tongue along circumferential direction. A transient radial force formula is proposed to evaluate the changes in radial force during startup. The streamline distribution in impeller passages and the impeller outlet pressure profile varying over time are produced. The relationship between radial force evolution and the varying axial-to-spiral vortex structure is analyzed. The radial force change mechanism is revealed. This research provides a scientific basis for startup control in large double-suction centrifugal pumps.

1. Introduction

Double-suction centrifugal pumps are widely used in the main feedwater systems (that ensure the cooling of steam generator and continuous function of the nuclear power plant (Ouyang and Jing-Song, 2006; Zhang and Hu, 2011)) because of their large flow rate, small axial force, and ease of maintenance (Kutbi, 1991). Transient operations are common due to the starting or stopping of pumps, increasing and decreasing flow rates, and power failures in the pump motors (Wu et al., 2010). Startup is a necessary process to move from a stopped state to normal pump operation. Centrifugal pumps are often started at the shut-off condition to prevent power overloads (Stepanoff, 1957). During the startup process, the impeller speed is accelerated from zero to its rated speed and then maintains the rated speed. Therefore the impeller radial force varies dramatically. Radial force is a primary contribution to pump shaft fatigue damage or sealing ring wear problems (Barrio et al., 2011; Yao et al., 2015).

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Nomenclature

b_2	symmetrical impeller outlet width (mm)
B_2	the impeller outlet width including the shroud (mm)
D_i	pump inlet diameter (mm)
D_o	pump outlet diameter (mm)
F_R	the radial force calculated using $F_R = 9.81K_rH_nD_2B_2 \times 10^3$ (N)
F'_R	the transient radial force
H_n	rated head (m)
K_r	Stepanoff empirical coefficient ($K_r = 0.36$ when flow rate = 0)
n_d	rated speed (r/min)
n_s	specific speed, $n_s = 3.65n_d\sqrt{Q_n}/H_n^{3/4}$
Q_n	rated flow rate (m^3/s)
t^*	the ratio of current time to startup duration (from zero to the rated speed)
z	number of blades

To measure radial force, two methods are used: (1) direct and (2) indirect. The direct method determines radial force through measurement of the bearing or shaft forces (Agostinelli et al., 1960; Baun and Flack, 1999; Uy and Brennen, 1999). This method is simple, accurate, and reliable but requires special auxiliary apparatus and a large open working space around the pump. Comparatively, the indirect method determines radial force through measurement of the pressure distribution surrounding the impeller. Radial force is subsequently determined through integration of the pressure measurements. (Iversen et al., 1960; Adkins and Brennen, 1988). This method requires perforation and instrumentation of the volute to support measurement, which in turn affects the flow field in the volute. Additionally, this method's measurement accuracy is limited in low flow rate conditions. To date, most radial force experiments have been conducted under constant speed conditions. Researches have previously shown that the maximum radial force occurs at shut-off condition for all flow rate conditions under constant speed (Newton, 1988). Nonuniform pressure distributions surrounding the impeller outlet in the volute result in radial force. For an impeller accelerating from zero to its rated speed, the radial force variation is unclear.

Experiment limitations preclude determination of the radial force variation mechanism. However, this mechanism may be determined through three-dimensional numerical simulation. Several prior analyses using computational fluid dynamics (CFD) to investigate radial force have been reported in the literature. For example, radial force characteristics under different geometry structures (i.e., blade arrangements (Zhang et al., 2013) or impeller-tongue gaps (Blanco et al., 2005)) have been investigated using CFD and achieved good results. Most of these prior analyses were constrained by the constant impeller speed condition. During startup, however, the impeller speed is not constant, numerical simulation must account for this phenomenon. Using numerical methods to evaluate blade acceleration, Wu et al. (2012) confirmed that the sliding mesh method can achieve comparable accuracy compared with the dynamic mesh method and has high efficiency. The sliding mesh method is now commonly used to describe impeller movement. (Zhang et al., 2011; Qi, 2014; Zhu, 2015; ANSYS Inc, 2013a). Although a laminar flow state exists in the flow field at the beginning of the accelerated motion, the selection of laminar or turbulent model (considering continuity of the transient calculation) is typically based on the final steady-state Reynolds number. For pumps, the characteristic Reynolds number is large (10^7) when the impeller is operating at its rated value. Thus, researchers often adopt a turbulent model (Zhang et al., 2011; Qi, 2014; Zhu, 2015). Studies investigating the startup of centrifugal pumps at the shut-off condition using numerical simulation have focused on the internal flow field and external characteristics of transient change. Zhu (2015) concluded that the radial forces gradually increase with accelerating impeller speeds, however, an explanation of the phenomenon was not provided.

Based on a large number of experimental test results, Stepanoff (1957) derived an empirical formula that predicted radial forces at rated speed conditions. This formula is, however, insufficient for determining radial force variations related to increasing impeller speeds during startup.

To adequately describe the transient radial force variation over time (radial force evolution) and to subsequently identify the mechanism behind the observed temporal variation (radial force evolution mechanism), this study investigated the startup process for a large double-suction centrifugal pump at the shut-off condition using CFD.

2. Investigated pump and numerical analysis methods

2.1. Investigated pump

The investigated pump in this study is a large double-suction centrifugal pump. The pump's parameters are as follows: pump inlet diameter D_i = 1000 mm; pump outlet diameter D_o = 900 mm; impeller diameter D_2 = 1155 mm; number of blades z = 6; rated speed n_d = 590 r/min; rated flow rate Q_n = 3.75 m^3/s; rated head H_n = 53.2 m; specific speed n_s = 150; and symmetrical impeller outlet width b_2 = 240 mm.

For the CFD simulation, the computational domain includes the pump's semi-spiral suction chamber, impeller, cavity and volute. Fig. 1 shows the 3D geometry model of each component.

2.2. Turbulent model and grid

Considering continuity of the transient calculation, a turbulent model is chosen based on the characteristic Reynolds number when the impeller speed reaches the rated speed. The RNG k-ε model has advantages for high strain rate and streamline curvature conditions (Ansys Inc, 2013b), thus, it is used in this study to simulate the transient flow in the pump. During startup, the highest impeller speed that can be reached is the rated speed. Therefore the grid independence test is performed at the shut-off condition with rated speed. Additionally, in the early acceleration stage, the impeller speed and the nondimensional wall distance, y+, used in CFD simulation are small. An enhanced wall treatment is selected

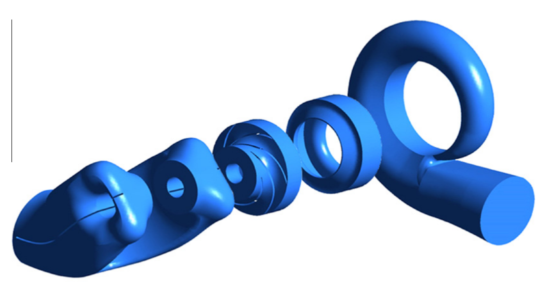

Fig. 1. 3D geometry model of double-suction centrifugal pump.