Ocean Engineering 140 (2017) 258–269

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Investigation of the role of non-uniform suction flow in the performance of water-jet pump

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ARTICLE INFO

Keywords:
Water-jet pump
Non-uniform suction flow
Boundary-layer separation
Vortex
Blade loading

ABSTRACT

Insufficient understanding of performance deviation between the uniform and non-uniform suction flows is a major problem encountered in the design and application of water-jet pumps. In this study, numerical investigation is conducted to illustrate the performance deviation and explain its generating mechanism. Steady simulations are performed to compare the pump performance with two different computational domains. One is a single water-jet pump under uniform inflow and the other is a complete water-jet propulsion system with non-uniform inflow. Results indicate that large non-uniformity of suction flow causes a substantial drop in the pump head. Flow details in the system are comprehensively discussed to describe the non-uniform inflow. Its primary feature is a distinct swirl distortion near the top which evolves into a circumferential vortex. Vortices and blade loadings are also explored. Consequently, the internal correlation between the non-uniform inflow and performance deviation is revealed. Due to non-uniform disturbances, a spanwise vortex shedding from the hub triggers a sharp downward peak of blade loading in the hub section. Moreover, a concentrated vortex deviates from the suction surface and induces an entire reduction in blade loading of the shroud section. These remarkable reductions in the blade loading eventually generate a head deviation.

1. Introduction

The water-jet propulsion system is widely used to drive high-speed marine vessels, because of its higher propulsive efficiency, better maneuverability, and lesser vibration than conventional propellers (Park et al., 2005a, 2005b). The fluid below the hull during operating is strongly ingested through the intake duct and works with the pump to produce reaction force and thus move marine vessels. Therefore, the water-jet pump and intake duct are the key components in the complete water-jet propulsion system. In general, water-jet pumps are designed for purely axial inlet flow at the impeller inlet section, i.e., uniform suction flow. Meanwhile, most water-jet pumps are elected for the propulsion system based on pump performance under uniform inflow. However, in actual application, the water-jet pump exhibits non-uniform suction velocity profile because of the pump closely positioned to the intake duct (Van Esch, 2009). As a result, a performance deviation exists between the design and application of water-jet pumps. In essence, this paper aims to reveal the internal correlation between the non-uniform inflow and the performance deviation.

Many researchers have reported the existence of non-uniform suction flow of the complete water-jet propulsion system, and attempted to identify the origination and structure of non-uniform inflow by numerical or experimental methods. Duerr and Von Ellenrieder (2015) and Wei and Wang (2009) described a two-dimensional velocity field at the pump inlet section. High velocity flow was located on the bottom while low velocity flow was close to the upper portion of the water-jet pump. Bulten (2006) identified three factors contributing to the non-uniform inflow: the ingestion of boundary layer below the hull, the bend in the intake duct and the rotating shaft of the system. He also defined a coefficient to quantify the non-uniformity of the suction flow.

$$\text{Non}-\text{uniformity}\ \zeta = \frac{1}{Q}\int_A \sqrt{(v_x - v_p)^2}\,dA \tag{1}$$

where v_x is the local axial velocity, v_p is the average axial velocity of the pump inlet section, Q is the volume flow rate.

The internal correlation between the non-uniform suction flow and pump performance deviation is barely addressed in literature. Only a few water-jet studies have been conducted to calculate the pump performance deviation through comparing the uniform and non-uniform suction flows. But the obtained results are not unified and even

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http://dx.doi.org/10.1016/j.oceaneng.2017.05.034
Received 26 March 2016; Received in revised form 24 May 2017; Accepted 26 May 2017

Nomenclature

PCV	Perpendicular cavitating vortex
HSV	Hub spanwise vortex
CSV	Concentrated separation vortex
CV	Circumferential vortex
BVF	Boundary vorticity flux
LE	Leading edge
TE	Trailing edge
PS	Pressure surface
SS	Pressure surface
SL	Separation line
C_L	Normalized blade loading
H_n	Normalized helicity
p	Static pressure (Pa)
ζ	Non-uniformity
D_2	Diameter of impeller (m)
Q	Volume flow rate (m^3/h)
H	Head of the pump (m)
P	Shaft power (kW)
δ	Thickness of boundary layer (m)
Re	Reynolds number
Q_c	Q-criterion (s^{-2})
M_x	Axial moment
η	Pump efficiency (%)
η_a	Uniform efficiency (%)
Ω_a	Absolute Vorticity (s^{-1})
w	Relative velocity (m/s)
v_p	Average axial velocity (m/s)
v_m	Meridional velocity (m/s)
v_u	Circumferential component of absolute velocity (m/s)
v_s	Ship speed (knot or m/s)
v_{in}	Actual inlet velocity (m/s)
β	Relative flow angle
β_b	Blade angle
m	Dimensionless meridional distance
$span$	Dimensionless spanwise distance
i	Incidence angle
$_1$	Impeller blade leading edge
$_2$	Impeller blade trailing edge
$_x$	Axial direction
$_e$	Experiment or uniform value
$_d$	Design point

contradictory. Bulten (2006) compared pump performance under five different inflow conditions containing the result of the corresponding simulation with a uniform inflow distribution. The actual pump performance exhibits a small decay owing to the non-uniform suction flow. However, shaft speed or nozzle diameter was properly adjusted for each inflow condition to maintain identical flow rate at all calculations. Additionally, Van Esch (2009) experimentally investigated the impact of non-uniform suction flow on the performance of water-jet pump, with artificially created non-uniformity generators by locating a pipe bundle upstream of the impeller, and compared results with the case of uniform flow. His results showed that a moderate non-uniformity triggers an obvious drop in the pump head of 2.5%. By contrast, Hu and Zangeneh (2001) stated that the inflow non-uniformity at the impeller inlet section insignificantly affects the torque of water-jet pump. However, his calculation domain was an independent impeller without stators and intake duct, and the inlet boundary condition was set as the circumferential-averaged velocity.

This non-uniform suction flow is also encountered in many compressors positioned closely to an upstream flow disturbance such as a pipe bend. Compared with relevant research on water-jet pumps, many studies have been devoted to the role of non-uniform suction flow in the compressor performance (SAE, 2007; Sheoran et al., 2012; Michelassi et al., 2015). Some internal factors are indicated to connect the non-uniform disturbance with the performance drop (e.g. flow rate, flow interaction, and incidence angle). Vagnoli and Verstraete (2015) researched effects of a bent pipe on the performance of centrifugal compressor. Steady analysis with frozen rotor showed a high influence of the pipe on the performance at larger mass flow, with a pronounced reduction in the pressure ratio and efficiency. Zemp et al. (2010) observed the inlet distortion interaction with tip leakage flow in unshrouded centrifugal compressor, and then additional losses in total pressure were found and calculated. Ariga et al. (1982) experimentally investigated the influence of different inlet distortions on the performance of low-speed centrifugal compressor. It is clear that the distorted inlet profile degrades the impeller efficiency by changing the incidence angle.

Apart from the internal factors mentioned in above compressor studies, the boundary-layer separation, vortex, and blade loading also should be considered to identify the internal correlation between the non-uniform suction flow and pump performance deviation. In fact, the boundary-layer separation with the associated vortices increase hydraulic losses and alters the pressure field (Park et al., 2005a, 2005b). The blade loading is also related to the pressure field. Tan et al. (2015) and Zhang et al. (2015) captured a perpendicular cavitating vortex (PCV) in an axial-flow pump. Both results reported that PCV originates from the suction surface (SS) and is linked to the adjacent pressure surface (PS). Its attachment to the PS causes a substantial drop in pressure difference across the blade, i.e., a rapid decrease in blade loading near the tip. In addition, Luo et al. (2016) reviewed cavitation, vortex pattern and associated internal flow inside axial-flow pumps.

The objective of this study is to reveal the non-uniform flow structures and the role of this flow in the pump performance. In this study, the steady simulation of a complete water-jet propulsion system was performed to calculate pump performance under non-uniform suction flow. With the same shaft speed and flow rate, the performance under uniform suction flow was achieved by a water-jet pump simulation and corroborated by experiments. Uniform efficiency was utilized to quantify performance deviation. Meanwhile, the boundary vortex flux and Q criterion were used to identify the separation and vortex, respectively. Furthermore, detailed comparisons of inlet velocity field, separation pattern, vortex structure, and blade loading were conducted to clarify the internal correlation between the non-uniform inflow and the performance deviation.

2. Tested pump and experimental setup

The tested pump is an axial-flow pump from the water-jet propulsion system, which is installed in an inland vessel and driven by a diesel engine. The ship speed ranges from 21 to 42 knots. According to design ship speed (30knots) and resistance curve, performance parameters of the water-jet pump were calculated (Jin, 1986): flow rate Q_d=3000 m^3/h, head H_d=8.8 m, shaft speed n_d=1450 r/min. Assuming the uniform suction flow, an axial-flow pump was designed to satisfy the requirements, and then it was examined by the following experimental setup.

Fig. 1 describes a closed test loop facility for performance measurements in the single water-jet pump under uniform suction flow. The suction flow is improved to be uniform by two honeycombs in a flow straightener upstream of the tested pump (Wu et al., 2011). An AC motor is located outside the loop and provides power for the tested pump instead of the diesel engine, because the AC motor possesses better control precision in the test shaft speed (1450 r/min) than the diesel. The shaft penetrates into the inlet pipe, and passes through the