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Experimental study on the vibrational performance and its physical origins of a prototype reversible pump turbine in the pumped hydro energy storage power station

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ABSTRACT

In the present paper, the vibrational performance and its physical origins of a prototype reversible pump turbine in the pumped hydro energy storage power station is experimentally investigated. Specifically, the vibrations of the unit in the X, Y and Z directions of the top cover, the upper and the lower brackets were all measured for three water heads (from 48% to 90% in terms of non-dimensional values) and nine load conditions (from 34% to 96% of the rated power) together with the pressure measurement at several typical monitoring points. Based on our analysis, it was found that the vibrations of the top cover are mainly induced by the fluid flow inside the reversible pump turbine while the vibrations of the upper and the lower brackets are generated by the mechanical aspects of the rotor. For the top cover, three regions are proposed with their characteristics and its physical origins fully demonstrated with the aid of several typical examples. In region I (with the low partial loads), the vibrational level of the unit is the highest and its physical origin is the pressure fluctuation in the vaneless space with the blade passing frequency. In region II (with the medium loads), the vibrational level of the unit is medium and its physical origin is the swirling vortex in the draft tube. In region III (with the high partial load), the vibrational level of the unit is the lowest and its physical origin is twofold: the pressure fluctuation in the vaneless space with the harmonics of blade passing frequency and the mechanical aspects of the rotor. For different water heads, transitions between aforementioned categorized regions could be observed with the primary characteristics maintained. At last, comparing with the cases of the top cover, the vibrations of the upper and the lower brackets are less affected by the load and the water head variations.

1. Introduction

Pumped hydro energy storage power stations (PHESPS) are being widely built to enhance the stability of the electric grid through providing the large-scale energy storage and the auxiliary services [1]. The reversible pump turbine, which is a key component in the PHESPS, can be operated in both the pumping and the generating modes, respectively. For the pumping mode, the reversible pump turbine mainly utilizes the surplus electricity of the power grid to pump the water from the lower reservoir to the upper reservoir for the purpose of the energy storage. During the peak hour of the electricity usage, the reversible pump turbine works in the generating mode through releasing the water from the upper reservoir to the lower reservoir for the power generation during the peak period. However, the commissioned units of the reversible pump turbine often suffers from the significant vibrations, leading to the abnormal operations of the unit or even the unplanned stop. The vibrational performance and its physical origins of a prototype reversible pump turbine are quite complex and have not been fully investigated yet [2,3]. The primary origins of the vibrations are twofold: one induced by the abnormal fluid flow inside the turbine (e.g. the complex flow passing the blade and the vortex rope in the draft tube section); another one induced by the mechanical aspects of the rotor. Due to the seriousness of the problem, it is badly needed to give a quantitative description of the contributions of the above two mechanisms to the vibrations of the unit. In the present paper, the vibrations of a prototype reversible

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Nomenclature

Roman letters

f	characteristic frequency
g	gravitational acceleration
H	water head in the experiment
p	pressure fluctuation
t	time
T	impeller rotation cycle
V	vibration
A_1	amplitude of characteristic frequency in the frequency spectrum of the vibration signal
A_2	non-dimensional amplitude of the characteristic frequency in the frequency spectrum of the pressure signal
f_1	primary dominated frequency in the frequency spectrum
f_n	rotational frequency of the impeller
H_{max}	maximum water head of the reversible pump turbine
H_{min}	minimum water head of the reversible pump turbine
P_1^*	load condition separating regions I and II
P_2^*	load condition separating regions II and III
P_{output}	output power of the prototype reversible pump turbine
P_{rated}	rated power of the prototype reversible pump turbine
$V_{peak-to-peak}$	the peak-to-peak values of vibration

Greek letters

ρ	water density

Superscript

*	non-dimensional parameters

pump turbine are experimentally investigated based on a series of on-site measurements together with related signal processing.

In the literature, the reversible pump turbine has been intensively investigated recently and a brief review of the previous investigations relating with the present work will be given below. Generally speaking, the published papers in this field could be categorized into the following topics e.g. on-site monitoring [4–6], rotating stall [1,7–10], S-shaped instability [11–17], rotor–stator interaction (RSI) [18–20], hysteresis [21,22], and hump regions [23,24]. For recent reviews, Zhang et al. [1] summarized the main features of the complex fluid flow inside the reversible pump turbine operated in generating mode with their generation mechanisms. Egusquiza et al. [6] analyzed the vibration data of several prototype reversible pump turbines and identified several paramount topics for the on-site monitoring (e.g. data interpretation). Comparing with other hydroturbines (e.g. Francis turbine), the vortex flow inside the reversible pump turbine is quite significant. Recently, Zhang et al. [25] systematically reviewed the existing vortex identification methods with their application examples in hydroturbines. For the experimental measurement, Zhang et al. [4] systematically performed an on-site measurement of a large-scale prototype reversible pump turbine in the full load range and identified the primary characteristics of the pressure fluctuations of the unit in different load ranges. Rodriguez et al. [20] proposed the usage of on-board sensors rotating with the shaft to detect the RSI characteristics in a pump-turbine to reduce the error. With the existence of the cavitation, a strong micro-jet will be generated during the collapse of the cavitation bubbles [26,27], leading to the erosive damage of the reversible pump turbine [28]. Furthermore, the cavitation bubbles could deteriorate the inner fluid flow inside the turbine and also interact with the pressure wave [29] through various kinds of bubble oscillations [30,31], leading to the reduction of the turbine performance [32].

For the fluid flow inside the reversible pump turbine, the pressure fluctuation in the S-shaped region has been systematically simulated by several researchers e.g. Wang et al. [11], Sun et al. [12] with the misaligned guide vanes, Xia et al. [13] with the runaway instability, and Zeng et al. [14] with the guide-vane closing schemes. Multi-objective optimizations (e.g. efficiency, cavitation, pressure fluctuation) have been also intensively conducted for the parametric design of high-profile turbines [33–35]. Based on the literature review, the features of the vibrations of a prototype reversible pump turbine together with its physical origins have not been fully revealed.

In the present paper, the vibrations of a prototype reversible pump turbine in the X, Y and Z directions of the top cover, the upper and the lower brackets were all measured for three water heads (from 48% to 90% in terms of non-dimensional values) and nine load conditions (from 34% to 96% of the rated power) together with the pressure measurement at several typical monitoring points. Effects of the load and the water head variations on the vibrational performance are analyzed in great detail with their physical origins identified quantitatively. The structure of the present paper is organized as follows. In section 2, the experimental setup is introduced with the basics of the turbine together with the experimental instruments, operational conditions and procedures. In section 3, the vibrational performance of the top cover and its physical origins are investigated and identified based on the on-site measurement data with three characteristic regions proposed. In section 4, the vibrational performance of the upper and lower brackets are demonstrated. In section 5, the primary findings of the present paper are given with suggestions of future work.

2. Experimental setup

In this section, the experimental setup of the present paper will be introduced in detail together with a brief introduction of the basic parameters of the unit, instruments and experimental procedures. Furthermore, the symbols employed in the present paper will be also defined (also referring to the nomenclature) and non-dimensionalized for the reader's convenience.

2.1. Basics of the reversible pump turbine

The experiment was carried out on a prototype reversible pump turbine located within the PHESPS. Fig. 1 shows a schematic view of the investigated prototype reversible pump turbine. During the experiments, only the operational conditions in generating mode were tested. The basic information of the fluid flow inside the reversible pump turbine and the structural components of the unit will be briefly introduced as follows. In generating mode, the fluid enters into the turbine through the inlet of the spiral casing, then passing through the guide vane (for adjusting the flow rate), vaneless space, impeller and finally enters the draft tube cone and