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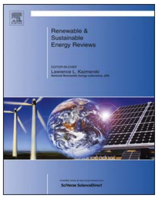

A review of methods for vortex identification in hydroturbines

Yuning Zhang*, Kaihua Liu, Haizhen Xian, Xiaoze Du

Key Laboratory of Condition Monitoring and Control for Power Plant Equipment, Ministry of Education, School of Energy, Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, China

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ABSTRACT

Vortex is one of typical structures of the unsteady flow inside the hydroturbines, leading to significant pressure fluctuation, prominent vibration of the units, and fatigue of turbine components. In order to reveal the complex vortex structures in the hydroturbines, a large amount of advanced methods for vortex identification and visualization have been developed and also are currently being intensively investigated by researchers. In this review, the vortex identification methods are reviewed in great detail with many illustrating examples and quantitative comparisons between different methods. The vortex identification methods are classified based on five different taxonomies. The identification of several typical vortices (e.g. vortex rope in draft tube, Kármán vortex, and inter-blade vortex) in hydroturbines (including reversible pump turbines, Francis turbine, Kaplan turbine etc.) have been shown and discussed. Furthermore, experimental techniques for vortex observation have been also summarized and discussed. This review provides a practical guidance to the researchers for performing vortex identification.

1. Introduction

Renewable and sustainable energies (e.g. hydro, wind and solar energies) represent the future trend of the energy. According to the outlook of energy, renewable energies will play an important role in world electricity [1, p. 13–14] and China [2]. Currently, hydropower is the one of the largest sources of renewable energies serving as both the base load (e.g. large scale Francis turbines) and energy storage (e.g. reversible pump turbines) to compensate the fluctuation nature of the solar and wind energies.

Vortex is a typical flow structure in the hydroturbines, leading to various kinds of instabilities (e.g. large pressure fluctuation [3,4], significant noise, prominent vibrations, rotating stall [5], cavitation erosion [6], and material fatigue). In some extreme cases, the safe operations of the whole power plant could be affected by the generations of vortex in the hydroturbines. Table 1 summarizes several examples of the accidents of hydropower plants relating to the vortex-induced instabilities in the hydroturbines. Hence, it is essential to identify and visualize the vortex structure in the hydroturbines.

In the literature, many vortex identification methods have been proposed. However, a clear classification of above methods (together with their applicable regions) is still absent in the literature. As a result, it causes great difficulties for the researchers in choosing appropriate methods for the data analysis. Specifically, for hydroturbines, the rotating nature of the runner further poses great challenges to the vortex identification inside. For example, for the analysis of the rotating components (e.g. the runner of the Francis turbines), it further requires that the identified vortex should be independent of the choice of the rotating frames (i.e. rotation invariant). However, most of the existing vortex identification methods are dependent on the choice of frames or only independent on the translational motion of the frames (i.e. Galilean invariant). If the above difference is not noticed, some inaccuracies will occur during the analysis of the vortex inside the hydroturbines.

The objectivities of this review are given as follows:

1. The existing vortex methods in the literature are fully reviewed with a detail introduction of the basic principles of the methods.
2. Comparisons between different methods are given with the aid of theoretical analysis. Several selected methods are compared using some typical cases to show their differences on the vortex identification.
3. Vortex phenomena in various kinds of hydroturbines are explained with the demonstrating examples.

In this review, the methods for vortex identification in the literature are reviewed with a focus on their applications in hydroturbines. The structures of the whole review are organized as follows. In the second section, the vortex identification methods are classified based on five taxonomies with several representative methods introduced in great

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* Corresponding author.
E-mail address: y.zhang@ncepu.edu.cn (Y. Zhang).

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Nomenclature

Roman letters

$c(t)$	Time-dependent translation vector
$\bar{\mathbf{c}}(t)$	Tangent of core line
det	Absolute value of the determinant
$\mathbf{e}$	Real eigenvector of the strain rate tensor S
H_n	Normalized helicity
$\mathbf{J}_r$	Invariant Jacobian
M	Strain acceleration tensor
M_z	Restriction of M to cone Z
$\mathbf{n}$	Normalized vector
P	The first invariants of the velocity gradient tensor
Q	The second invariants of the velocity gradient tensor
$\mathbf{Q_0}$	Rotation matrix
Q_n	Normalized Q
$Q(t)$	Time-dependent proper orthogonal matrix
R	The third invariants of the velocity gradient tensor
S	Symmetric tensor
s	Distance of the vortex line
T_P	Maximum integration time
tr	Trace of matrix
$\mathbf{x}_0$	Fixed point
$\nabla\mathbf{v}$	Velocity gradient tensor

Greek letters

γ	Cauchy-Green deformation tensor
Δ	Parameter for Δ-criterion shown in Eq. (8)
ε	Infinitesimal value
$\lambda_1,\ \lambda_2,\ \lambda_3$	The eigenvalues of $S^2 + \Omega^2$
$\lambda_r,\ \lambda_{cr} \pm i\lambda_{ci}$	Eigenvalues of the velocity gradient tensor $\nabla\mathbf{v}$
$\lambda_{max}(\Delta)$	Maximum eigenvalue of Δ
$\phi_{t_0}^t(x)$	Variable functions from x_{t_0} to x_t
Ω	Antisymmetric tensor
ω	Vorticity
$\mathbf{w}(\mathbf{x})$	Reduced velocity

Abbreviations

DLE	Direct lyapunov exponent
HWA	Hot-wire anemometry
IDDES	Improved delayed detached eddy simulation
LCS	Lagrangian coherent structures
LDV	Laser doppler velocimetry
SPIV	Stereo particle image velocimetry
TLV	Tip leakage vortex
2D	Two-dimensional
3D	Three-dimensional

detail. In the third section, comparisons among several typical vortex identification methods are performed with illustrating examples. In the fourth section, analysis of the vortex structures (e.g. vortex rope, Kármán vortex, inter-blade vortex, and cavitating vortex) in various kinds of hydroturbines (e.g. Francis turbine, reversible pump turbine, propeller turbine, Kaplan turbine) are introduced. In the fifth section, vortex identification in other fluid machineries (e.g. pumps) is also studied. In the sixth section, experimental visualization techniques of vortex structures are briefly introduced. In the seventh section, the concluding remarks of the present review are given together with the suggestions of future research directions.

2. Classifications of vortex identification methods

2.1. An overview

In this section, classifications of vortex identification methods are given based on five different taxonomies as shown in Table 2. In the following sections, several representative methods are introduced with details. For other reviews relating with this topics, readers are referred to Jiang et al. [15] and Holmén [16].

The first taxonomy is based on the invariant of vortex structures identified under different frames (e.g. Galilean invariant, Lagrangian invariant and rotation invariant). Here, invariant means that the identified vortex does not change with the different selections of the frames. Considering the complex rotating nature of the internal flow of the hydroturbines, we focus on this taxonomy in the following discussions.

The second taxonomy is based on the patterns of the identified vortex (region or line). The region method is to identify the contiguous grid nodes of the vortex in a certain region. The line method tracks particle trajectory through extracting the cores of the swirling particle motion in the given area. The region method could describe the extended distance from the vortex core, but it is difficult to distinguish the concentrated vortex structures from each other.

The third taxonomy is based on the local or global nature of the identified vortex. The local method only focuses on the variables in the neighborhood of a given grid cell. However, in the global method, many grid cells will be examined in order to accurately identify vortices. Comparing with the local method, the global method requires more computational time.

The four taxonomy is classified by the applicable domain of these methods (two dimensional or three dimensional domains). Some methods are only suitable for two-dimensional domain (e.g. referring to pressure minima method in Section 2.5.4). And, a majority of the methods in this review can be applied to the three-dimensional space.

The fifth taxonomy is based on the objective or subjective nature of the identified vortex. If the identified vortex structure using a vortex identification method depends on the choice of the frames, it means that this method is subjective. Otherwise, it is objective. For details of the objective method, readers are referred to the Section 2.3 for details.

The vortex structures identified by the methods depending on the

Table 1
Problems identified in hydropower plants together with specific reasons.

Stations	Country	Problems	Location	Reasons	Reference	Year
Little long	Canada	Crack	Stay vane	Kármán vortices	Wang [7]	1956
Sayano Shushenskaya	Russia	Crack	Blade	Kármán vortices	Brekke [8]	1983
Tamla	Pakistan	Crack	Draft tube	Vortex rope	Grein and Goede [9]	1994
Xiaolangdi	China	Resonance fatigue	Runner	Kármán vortices	Fisher et al. [10]	2001
Dachaoshan	China	Crack	Blade	Kármán vortices	Yin and Shi [11]	2001
G.M. Shrum	Canada	Crack	Runner	Inter-blade vortices	Finnegan et al. [12]	2002
Gongzui	China	Noise	Channels	Inter-blade vortices	Shi et al. [13]	2004
Three Gorges	China	Damage	Spiral casing and wicket gates	Cavitation	Li [14]; Chen et al. [3]	2006