Energy Conversion and Management 106 (2015) 127–138

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Nonlinear modeling and stability analysis of hydro-turbine governing system with sloping ceiling tailrace tunnel under load disturbance

Wencheng Guo [a,*], Jiandong Yang [a], Mingjiang Wang [a,b], Xu Lai [a]

[a] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
[b] HYDROCHINA Northwest Engineering Corporation, Xi'an 710065, China

A R T I C L E I N F O

Article history:
Received 26 May 2015
Accepted 9 September 2015

Keywords:
Hydropower station
Sloping ceiling tailrace tunnel
Hydro-turbine governing system
Nonlinear modeling
Stability
Load disturbance
Hopf bifurcation

A B S T R A C T

In order to overcome the problem of nonlinear dynamics of hydro-turbine governing system with sloping ceiling tailrace tunnel, which is caused by the interface movement of the free surface-pressurized flow in the tailrace tunnel, and the difficulty of analyzing the stability of system, this paper uses the Hopf bifurcation theory to study the stability of hydro-turbine governing system of hydropower station with sloping ceiling tailrace tunnel. Firstly, a novel and rational nonlinear mathematical model of the hydro-turbine governing system is proposed. This model contains the dynamic equation of pipeline system which can accurately describe the motion characteristics of the interface of free surface-pressurized flow in sloping ceiling tailrace tunnel. According to the nonlinear mathematical model, the existence and direction of Hopf bifurcation of the nonlinear dynamic system are analyzed. Furthermore, the algebraic criterion of the occurrence of Hopf bifurcation is derived. Then the stability domain and bifurcation diagram of hydro-turbine governing system are drawn by the algebraic criterion, and the characteristics of stability under different state parameters are investigated. Finally, the influence of step load value, ceiling slope angle and section form of tailrace tunnel and water depth at the interface in tailrace tunnel on stability are analyzed based on stable domain. The results indicate that: The Hopf bifurcation of hydro-turbine governing system with sloping ceiling tailrace tunnel is supercritical. The phase space trajectories of characteristic variables stabilize at the equilibrium points and stable limit cycles when the system state parameter point locates in the stable domain and unstable domain, respectively. Under negative disturbance and positive disturbance, the effect laws of step load value, tailrace tunnel slope angle and water depth in tailrace tunnel are inverse. Tailrace tunnel section form has significant influence on the stability under negative disturbance, while it has little influence on the stability under positive disturbance.

1. Introduction

The tailrace tunnel with a sloping ceiling proposed by former Soviet Union scholar Krivehenko in 1970s is a new type of tailrace tunnel [1]. It was later successfully applied to the design of Hoa Binh Hydropower Station in Vietnam. Since then, it has received lots of attention within hydropower engineering community worldwide [2]. In the 1990s, it was introduced to China, and has been successively applied to the Three Gorges Hydropower Station, the Pengshui Hydropower Station, the Xiangjiaba Hydropower Station and other large hydropower stations. This new type of tailrace tunnel has significant technical and economic advantages. The researches on hydropower stations with sloping ceiling tailrace tunnels mainly cover two aspects: (1) the influence of free surface-pressurized flow in sloping ceiling tailrace tunnel on the governing guarantee parameters of the hydro-turbine unit, and (2) the influence of both the length changes of the pressurized flow section, and the water level fluctuation of the free surface flow section caused by the free surface-pressurized flow in the sloping ceiling tailrace tunnel on the unit operational stability and system governing quality. With regard to the first aspect, Yang et al. [3] elaborated the working principle of the sloping ceiling tailrace tunnel based on the inlet pressure of the draft tube, and proposed a basic idea and specific steps of body type design. Lei et al. [4] conducted a model experiment to study the state of flow in the sloping ceiling tailrace tunnel, which revealed the characteristics of its hydraulic operation. Cheng et al. [5], Li and Yang [6] discussed the numerical simulation method of the free surface-pressurized flow in tailrace tunnel with sloping ceiling, and investigated the

* Corresponding author. Tel.: +86 027 68772274; fax: +86 027 68772310.
E-mail address: wench@whu.edu.cn (W. Guo).

http://dx.doi.org/10.1016/j.enconman.2015.09.026
0196-8904/

Nomenclature

L	length of penstock, m
Q	hydro-turbine unit discharge, m^3/s
Z_y	change of water level of free surface flow section (relative to the initial level, positive direction is upward), m
h_f	head loss of penstock, m
H_x	water depth at the interface of the free surface-pressurized flow, m
H	hydro-turbine net head, m
c	wave velocity of free surface flow section, m/s
n	hydro-turbine unit frequency, Hz
r	frequency disturbance
M_t, M_g	kinetic moment, resisting moment, N m
e_h, e_x, e_y	moment transfer coefficients of turbine
e_g	load self-regulation coefficient
f	sectional area of penstock, m^2
V, V_x	flow velocity of penstock, the interface of the free surface-pressurized flow, m/s
L_x	movement distance of the interface of the free surface-pressurized flow (relative to the initial location, positive direction is downstream), m
λ	cross-section coefficient of tailrace tunnel
α	ceiling slope angle of sloping ceiling tailrace tunnel, rad
B	width of sloping ceiling tailrace tunnel, m
T_{wx}, T_{ws}	transient-state, steady-state flow inertia time constant, s
Y	guide vane opening, mm
u	regulator output
K_i, K_p	integral gain, /s, proportional gain
e_{qh}, e_{qx}, e_{qy}	discharge transfer coefficients of turbine
T_a	hydro-turbine unit inertia time constant, s

influence of free surface-pressurized flow on water hammer pressure. Miu and Zhang [7] deduced the approximate theoretical formula of the vacuum degree at the inlet of a draft tube in a tailrace with sloping ceiling. So far, the problems within the first aspect have been satisfactorily solved. With regard to the second aspect, Lai et al. [8] analyzed the operational stability of the unit of hydropower station with sloping ceiling tailrace tunnel by using the simulation calculation software MATLAB and gave the influence of the governor on operational stability. Based on the method of characteristics (MOC) of pressurized pipeline and the improved slot method of open-channel, Zhou et al. [9] studied the stability characteristic of the sloping ceiling tailrace tunnel under small fluctuation, and compared it with the tailrace surge tank. However, earlier researches on the second aspect are mostly based on numerical simulations and simplified linear mathematic models, and have neglected the effects of the water level fluctuation in the free surface flow section. As a consequence, these researches basically focus on simple sensitivity analyses of influencing factors without any significant theoretical achievements. As such, they have failed to reveal the working principle of the stability of the sloping ceiling tailrace tunnel. They have also failed to propose a stability-based design principle of the sloping ceiling tailrace tunnel. Hence, the understanding of the mechanism of the working stability of such tailrace tunnels is not clear. Li and Yang [10], and Wang et al. [11] tried to take the free surface-pressurized flow in the sloping ceiling tailrace tunnel as open channel flow or a given water level fluctuation, and used theoretical analysis methods to study the stability of the governing system. However, their analysis neglected the movement of the interface of the free surface-pressurized flow, and thus ignored the nonlinear dynamic characteristics of the system. Hence, the conclusions drawn by them are significantly limited. To be specific, the difficulties of theoretical analysis lie in the nonlinear and multi-disturbance problems of the hydro-turbine governing system caused by the reciprocating interface movement of the free surface-pressurized flow in the sloping ceiling tailrace tunnel in the process of transients (i.e. load disturbance as well as water level fluctuation disturbance in the free surface flow section). These are compounded by the problems of nonlinear modeling and nonlinear dynamic analysis of the hydro-turbine governing system with sloping ceiling tailrace tunnel. To sum up, researches on the second aspect of the tailrace tunnel with sloping ceiling, due to the lack of effective mathematical methods, are not making progress. In this case, starting with the characteristics of the free surface-pressurized flow in the sloping ceiling tailrace tunnel in the process of transients, it is necessary to put forward a novel and rational nonlinear mathematical model and then identify suitable mathematic theories to discuss the characteristics of the nonlinear dynamic system on the basis of the physical characteristics.

As far as the hydro-turbine governing system is concerned, the nonlinear characteristics are manifested in many aspects, such as the hydro-turbine nonlinearity incurred by load rejection and other large-disturbance transient processes [12,13], the nonlinearity brought about by the saturation characteristic and dead zone characteristic of the governor [14–16], the generator nonlinearity [17] and the hydraulic system nonlinearity caused by the setting of surge tank [18]. For these nonlinear characteristics, mathematical models have been proposed [12–18], except for the tailrace tunnel with a sloping ceiling.

The most critical link in the research of nonlinear problems is the processing methods of nonlinear mathematical models and the means of researching the dynamic characteristics of the nonlinear system [19–21]. Researchers in this field have proposed many nonlinear analysis methods, such as: bifurcation analysis method [15,22], improved particle swarm optimization (PSO) algorithm [23], deterministic chaotic genetic evolutionary algorithm [24,25], linear quadratic (LQ) control method [26], continuous pressure condensation regulation method [27], improved parameter gravity search method [28], parameter identification [29], and nonlinear predictive control [30]. Among them, Hopf bifurcation relates to a type of relatively simple yet important bifurcation problems in nonlinear dynamic systems. It also falls within the range of local dynamic bifurcation. To be specific, it describes the phenomenon of the system at the non-hyperbola equilibrium point engaging in a limit cycle from the sudden bifurcation of the equilibrium point with the change of the bifurcation parameter [31–33]. It is extensively used in the researches on the dynamic characteristics of nonlinear dynamic systems [34,35], especially the nonlinear aspect of power systems [36–40]. The purpose of the research using Hopf bifurcation is to determine the intrinsic nonlinear dynamic characteristics of these systems and to propose relevant control strategies and optimization methods. In recent years, Hopf bifurcation theory has been introduced to researches on hydropower regulation systems [12,14,15], and the method is mainly used to determine the influence of nonlinearity of governor and excitation system on the dynamic quality of systems. As to the system optimization techniques and methods, there are many research achievements in the field of water resources engineering can be referenced [41–47].

The paper uses Hopf bifurcation theory to study the stability of the hydro-turbine governing system of hydropower station with sloping ceiling tailrace tunnel under load disturbance. It proposes