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Dynamics analysis of time-delay hydro-turbine governing system with two time-scales

Bofan Wang[1], Junchen Dong [1], Quankun Li[1], Hengxu Li[1], Yang Chen[1], Jianglin Xia[2]
[1] *School of Mechanical Science and Engineering, Jilin University, Changchun, Jilin 130025, China*
[2]*School of Information and Computer Science, Nanjing Agricultural University, Nanjing, Jiangsu 210095, China*
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Abstract: Due to the existence of inertia and response time, time-delay always exists in the response of the guide vane opening and it may bring about multi time-scale effect. Therefore, time-delay modeling of hydro-turbine governing system with multi time-scale is addressed to investigate the dynamical behaviors of hydro-turbine governing system. The effects of the multi time-scale and time-delay on the dynamical behavior of the proposed system are analyzed. The fast-slow characteristic of the system is discussed via numerical simulations with the change of time-scale or time-delay. Results suggest that not only the time-scale but also the time-delay have significant impact on the dynamical behaviors of the hydro-turbine governing system.

Keywords: Hydro-turbine governing system, Time-delay, Fast-slow effect

1. Introduction

For a long time, the linear turbine model and the first order motor model are adopted to analyze the dynamic stability of hydro-turbine governing system, while ignoring the nonlinear dynamical action of the turbine [1, 2]. This approximate linear simplification has much limitation in application. It can only be acceptable for studying the performance of the turbine system with small fluctuations, and not applicable to the system with large disturbances which may lead to unreasonable results.

As the core part of a hydropower plant, hydro-turbine governing system has critical influence on the stable operation of it. The dynamical behaviors and the model of hydro-turbine governing system attracted researchers' interest and a lot of achievements have been gained. For example, novel nonlinear dynamical models of hydro-turbine governing system are established and the dynamical behaviors of the proposed model are investigated [3, 4]. Hamiltonian mathematical modeling of hydro-turbine governing system is applied to describe general open systems with the structure of energy dissipation and exchange of energy with the environment [5]. Takagi-Sugeno fuzzy system is used to establish the model of a micro hydro power plant [6]. The existing results are of great significance for the actual operation of hydropower station because they not only can explain many complex phenomena, but also can provide theoretical foundation for the safe and stable operation of the hydropower station system.

Under the action of water, machinery, electric and other factors [7-10], hydro-turbine governing system is a complex system. Although remarkable achievement has been made about hydro-turbine governing system, most of the results only consider single time scale. In fact, in real hydro-turbine governing system, there always exists time-relative non-autonomous factors, which can change the structure of the system and make it more complex. Therefore, multi time-scale hydro-turbine governing system is proposed and studied [11, 12].

In this paper, considering the time-delay between the slow variable and fast variable, time-delay is introduced into the multi time-scale hydro-turbine governing system and the dynamical behaviors of the system is investigated.

2. System Description

In Ref.[11], considering Francis turbine as the research object, dynamic model of hydro-turbine governing system is derived as

$$\begin{cases} \dot{\delta} = \omega_0 \omega \\ \dot{\omega} = \frac{1}{T_{ab}}(m_t - D\omega - \frac{E_q^{'} V_s}{x_{d\Sigma}^{'}} sin\delta - \frac{V_s^2}{2} \frac{x_{d\Sigma}^{'} - x_{q\Sigma}}{x_{d\Sigma}^{'} x_{q\Sigma}} sin2\delta) \\ \dot{m}_t = \frac{1}{e_{qh} T_w}[-m_t + e_{my} y - \frac{e e_{qh} T_w}{T_y}(-k_p \omega - \frac{k_i}{\omega_0}\delta - k_d \dot{\omega} - y)] \\ \dot{y} = \frac{1}{T_y}(-k_p \omega - \frac{k_i}{\omega_0}\delta - k_d \dot{\omega} - y) \end{cases}, \tag{1}$$

where the variables δ, ω, m_t, y denote the rotor angle, relative deviation of turbine speed, relative deviation of turbine output torque, relative deviations of the guide vane opening, respectively. The parameter denotations of system (1) are in given in Table 1, which are the same as those in Ref. [11] with intermediate variable

$$e = e_{qy} e_{mh} / e_{my} - e_{qh} \tag{2}$$

and

$$x_{d\Sigma}^{'} = \dot{x}_d + x_T + (1/2)x_L , \tag{3}$$

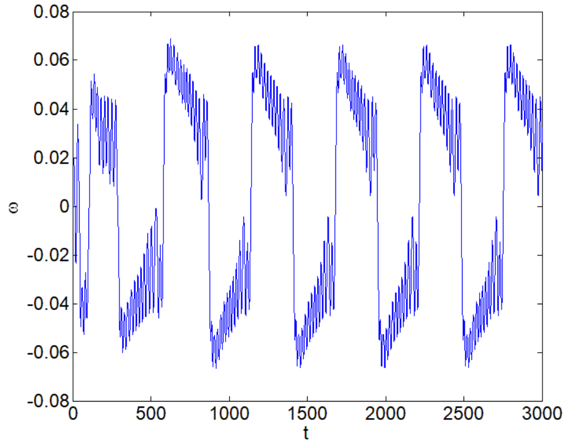
$$x_{q\Sigma} = x_q + x_T + (1/2)x_L . \tag{4}$$

Table 1 Parameter denotations of system (1).

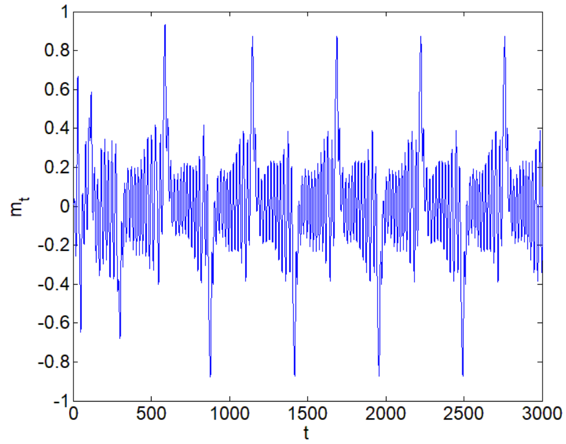
Parameters	denotation	Units
ω_0	Initial value of relative deviation of turbine speed	p.u.
T_{ab}	Hydro-turbine inertia time constant	s
D	Generator damping coefficient	p.u.
E_q'	Transient internal voltage of armature	p.u.
V_s	Voltage of infinite bus	p.u.
$\dot{x}_d$	The direct axis transient reactance	p.u.
x_q	The quartered axis reactance	p.u.
x_T	The short-circuit reactance of transformer	p.u.
x_L	The transmission line reactance	p.u.
e_{qh}	Partial derivatives of the flow with respect to the hydro-turbine head	p.u.
e_{qy}	Partial derivatives of the flow with respect to the hydro-turbine guide vane	p.u.
e_{my}	Partial derivatives of the hydro-turbine torque with respect to hydro-turbine guide vane	p.u.
e_{mh}	Partial derivatives of the hydro-turbine torque with respect to the hydro-turbine head	p.u.
T_w	Inertia time constant of penstock	s
T_y	Engager relay time constant	s

For hydro-turbine governing system (1), due to the existence of inertia and response time, y is a slow variable while δ, ω, m_t are fast variables. It means that there is always a time-delay between y and δ, ω, m_t. Then the hydro-turbine governing system with time-delay can be introduced as

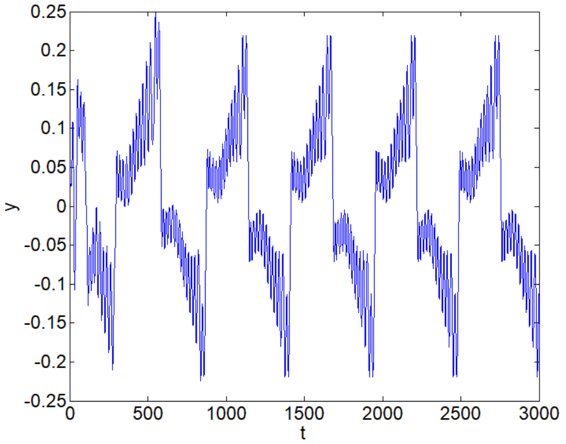
$$\begin{cases} \dot{\delta} = \omega_0 \omega \\ \dot{\omega} = \frac{1}{T_{ab}}(m_t - D\omega - \frac{E_q^{'} V_s}{x_{d\Sigma}^{'}} sin\delta - \frac{V_s^2}{2} \frac{x_{d\Sigma}^{'} - x_{q\Sigma}}{x_{d\Sigma}^{'} x_{q\Sigma}} sin2\delta) \\ \dot{m}_t = \frac{1}{e_{qh} T_w}[-m_t + e_{my} y - \frac{e e_{qh} T_w}{T_y}(-k_p \omega - \frac{k_i}{\omega_0}\delta - k_d \dot{\omega} - y)] \\ \dot{y} = \frac{1}{T_y}(-k_p \omega - \frac{k_i}{\omega_0}\delta - k_d \dot{\omega} - y(t-\tau)) \end{cases}. \tag{5}$$



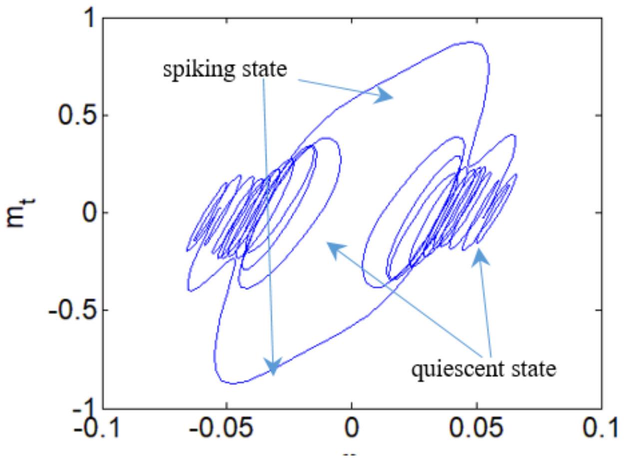
(a) Time series of ω for ε = 0.2.



(b) Time series of m_t for ε = 0.2.



(c) Time series of y for ε = 0.2.



(d) Phase trajectory of $\omega - m_t$ for ε = 0.2.

Fig.1 Time series and phase trajectory of the variables in system (6) when τ = 0.1, ε = 0.2.

Simultaneously, the time-delay can lead to different time-scales in hydro-turbine governing system. Suppose the original time-scale is t, fast time-scale is T_1 and slow time-scale is T_2, then variables δ, ω, m_t are related to T_1 and y is relative to T_2. Let $T_1 = t$, $T_2 = \varepsilon t$, and system (5) can be rescaled as

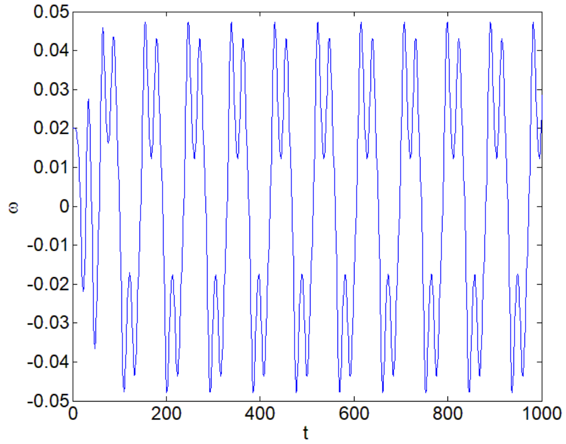
$$\begin{cases} \dot{\delta} = \omega_0 \omega \\ \dot{\omega} = \dfrac{1}{T_{ab}}(m_t - D\omega - \dfrac{E_q^{'} V_s}{x_{d\Sigma}^{'}} sin\delta - \dfrac{V_s^2}{2} \dfrac{x_{d\Sigma}^{'} - x_{q\Sigma}}{x_{d\Sigma}^{'} x_{q\Sigma}} sin2\delta) \\ \dot{m}_t = \dfrac{1}{e_{qh} T_w}[-m_t + e_{my} y - \dfrac{e e_{qh} T_w}{T_y}(-k_p \omega - \dfrac{k_i}{\omega_0}\delta - k_d \dot{\omega} - y)] \\ \dot{y} = \varepsilon \dfrac{1}{T_y}(-k_p \omega - \dfrac{k_i}{\omega_0}\delta - k_d \dot{\omega} - y(t-\tau)) \end{cases}, \quad (6)$$

where ε $(0 < \varepsilon < 1)$ is the small parameter, which rescales the time-delay hydro-turbine governing system into a slow subsystem under the effect of ε and a fast subsystem. τ is the time-delay. It is easy to know that the point (0,0,0) is an equilibrium point of system (6).

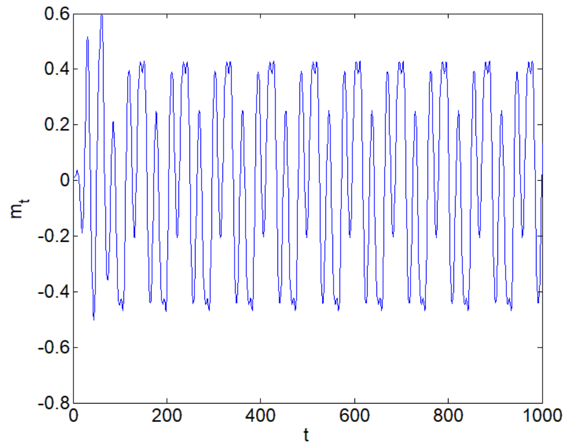
3. Simulation Results

In this section, to study the dynamical behaviors of system (6), some numerical simulations are calculated via fourth Runge-Kutta algorithm, which is a one-step solver in computing y_{t_n}. It needs only the solution at the immediately preceding time point $y_{t_{n-1}}$. In the simulations, some system parameters are given in Table 2. The fixed step size is taken as $h = 0.01$ and the initial values of system (6) are chosen as

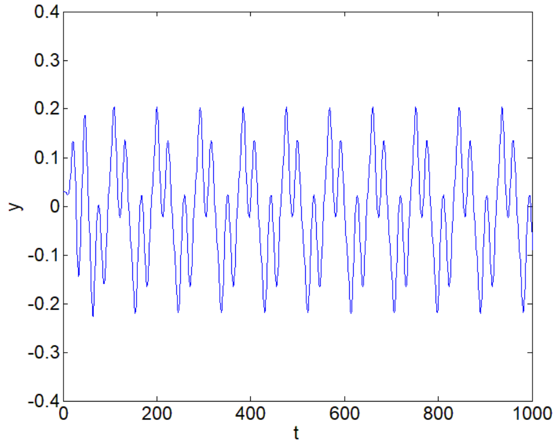
$(\delta, \omega, m_t, y) = (0.001, 0.001, 0.001, 0.001)$. The values of PID parameters are taken as $k_p = 2$, $k_i = 1$, $k_d = 1.5$. Fig.1-Fig.4 depict the time series and phase trajectory of system (6) with $\tau = 0.1$ for $\varepsilon = 0.2$, 0.3, 0.5, 0.7, respectively.



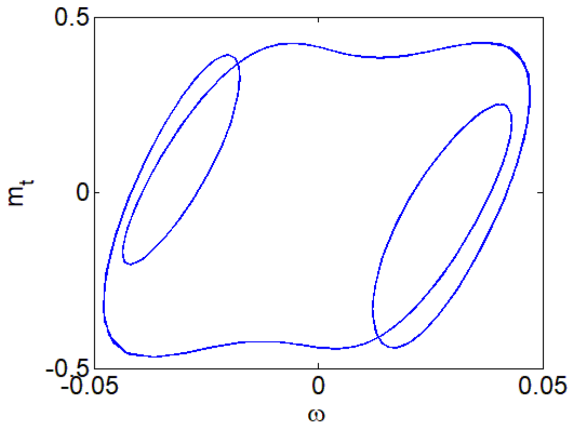
(a) Time series of ω for $\varepsilon = 0.3$.



(b) Time series of m_t for $\varepsilon = 0.3$.



(c) Time series of y for $\varepsilon = 0.3$.



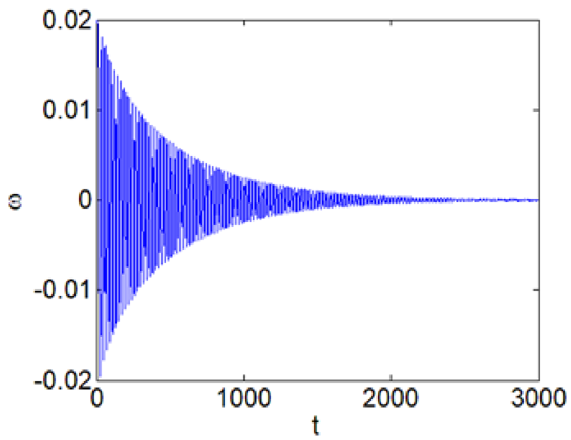
(d) Phase trajectory of $\omega - m_t$ for $\varepsilon = 0.3$.

Fig.2 Time series and phase trajectory of the variables in system (6) with $\tau = 0.1$ for $\varepsilon = 0.3$.

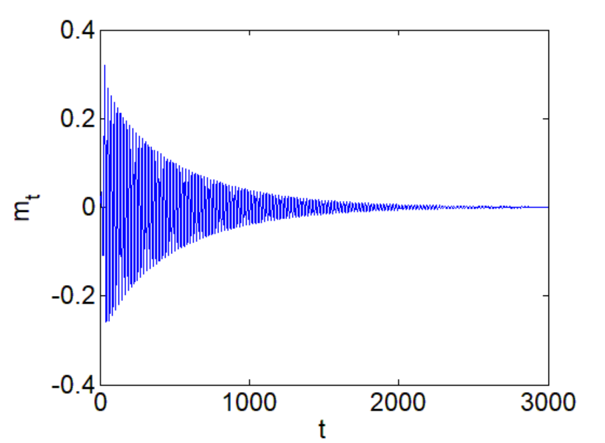
In Fig.1, for $\tau = 0.1$ and $\varepsilon = 0.2$, variables ω, m_t and y are in quiescent state with small oscillation for most of the time and the range of quiescent states is much bigger than that of spiking state, which can be confirmed in the phase trajectory of $\omega - m_t$. This fast-slow characteristic is bad for the stable operation of the system. Simultaneously, it can be seen that, the time waves of relative deviation of guide vane opening y is similar to that of turbine speed ω, whose quiescent states approach the maximum amplitude of corresponding variables and are connected by spiking states. While for the variable of relative deviation of turbine output torque m_t, the quiescent states are near the equilibrium point while the spiking states reach the maximum amplitude. These dynamical behaviors are similar to those of the multi time-scale hydro-turbine governing system [11] without time-delay.

Table 2 Values of some system parameters in system (6).

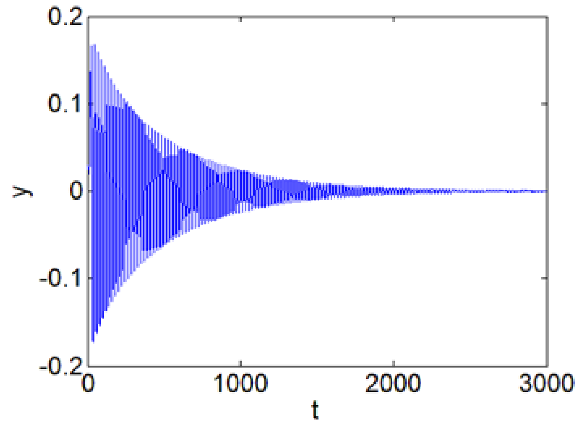
Parameters	Values	Units	Parameters	Values	Units
ω_0	314	rad/s	$x_{q\Sigma}$	1.474	p.u.
T_{ab}	9	s	e_{qh}	0.50	p.u.
D	2	p.u.	T_w	0.8	s
E'_q	1.35	p.u.	e_{my}	1.0	p.u.
V_s	1	p.u.	e	0.7	p.u.
$x'_{d\Sigma}$	1.15	p.u.	T_y	0.1	s



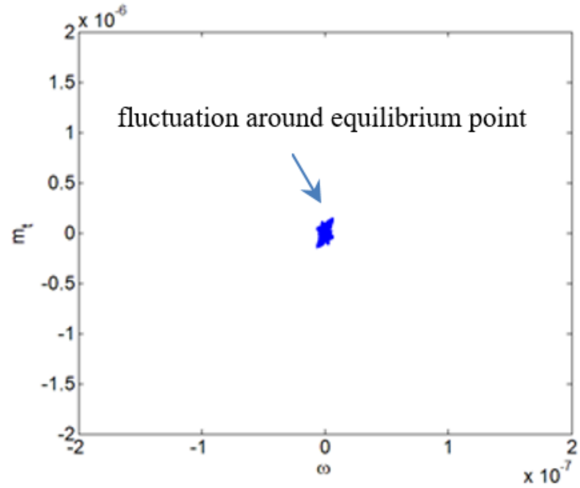
(a) Time series of ω for ε = 0.5.



(b) Time series of m_t for ε = 0.5.



(c) Time series of y for ε = 0.5.



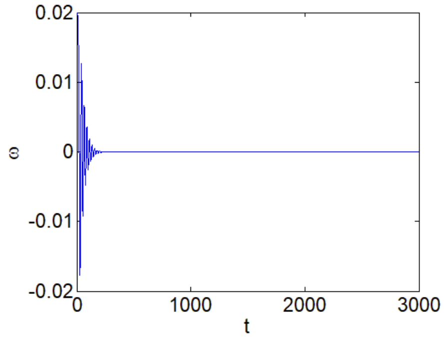
(d) Phase trajectory of $\omega - m_t$ for ε = 0.5.

Fig.3 Time waveforms and phase trajectory of the variables in system (6) with τ = 0.1 for ε = 0.5.

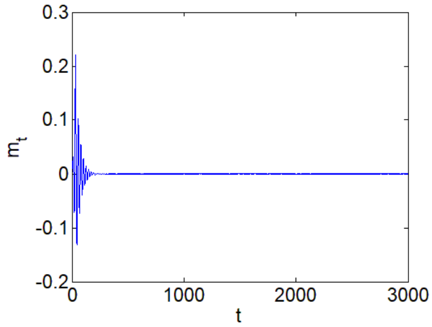
To investigate the effect of time-scale on the dynamical behaviors of system (6), time-delay is fixed as τ = 0.1, time-scale is taken as different values, and the dynamical behaviors of some variables in system (6) are given in Fig.2-Fig.4. Fig.2 suggests that, for ε = 0.3, the variables ω, m_t and y are periodic, which can be confirmed by the phase trajectory of $\omega - m_t$. Figs.3-4 indicate that, for ε = 0.5 and ε = 0.7, with the time evolution, ω, m_t and y all gradually converge to a very small region around the equilibrium point (0,0,0) with small amplitude vibration. Furthermore, the convergence speed for ε = 0.7 is much faster than the speed for ε = 0.5 and the amplitude of vibration for ε = 0.7 is smaller than that for ε = 0.5.

From Fig.1-Fig.4, it's known that the time-delay hydro-turbine governing system shows great fast-slow effect for small time-scale. But with the increase of the time scale ε, this fast-slow effect will be reduced.

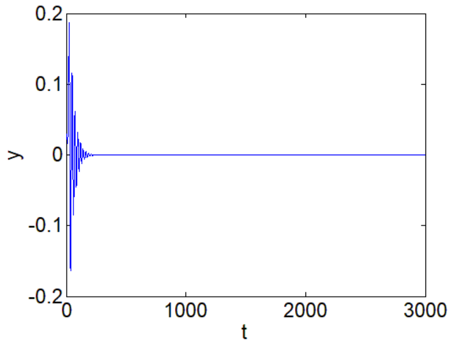
Next, to explore the influence of time-delay on the fast-slow effect of system (6), time scale is fixed as ε = 0.2 and time-delay τ is chosen as different values. For example, when τ = 0.2, 0.3 and 0.4, time waveforms and phase trajectory of the system (6) are presented in Fig.5, Fig.6 and Fig.7, respectively. Fig.5 shows that, for τ = 0.2, ε = 0.2, the time series of the variables in system (6) have fast-slow effect, which is similar to the phenomenon in Fig.1. For τ = 0.3, ε = 0.2, the dynamical behaviors of variables in system (6) tend to be periodic state, which can be seen in Fig.6. When τ = 0.4, ε = 0.2, the variables in system (6) exhibit chaotic behaviors, which is given in Fig.7. By analyzing the results in Fig.1 and Figs.5-7, it can be known that, for fixed time-scale, the fast-slow effect of the variables in system (6) is weakened with the increase of time-delay. The time-delay has a significant impact on the multi-scale effect of system (6).



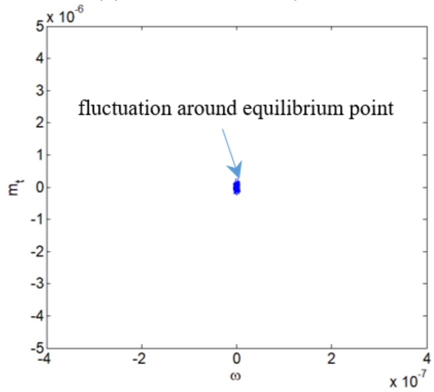
(a) Time series of ω for ε = 0.7.



(b) Time series of m_t for ε = 0.7.

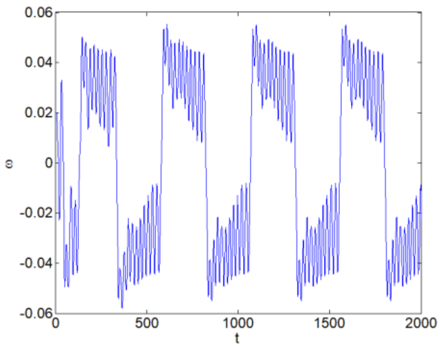


(c) Time series of y for ε = 0.7.

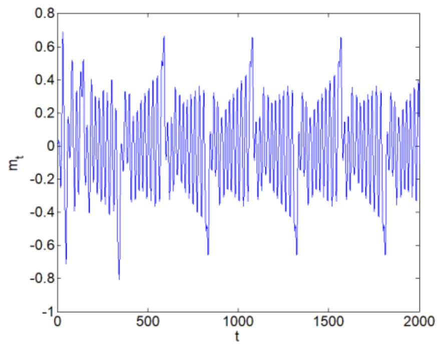


(d) Phase trajectory of $\omega - m_t$ for ε = 0.7.

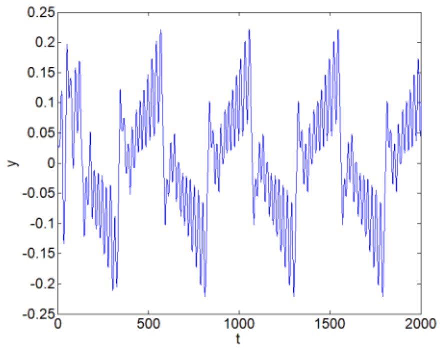
Fig.4 Time waveforms and phase trajectory of the system (6) with τ=0.1 for ε=0.7.



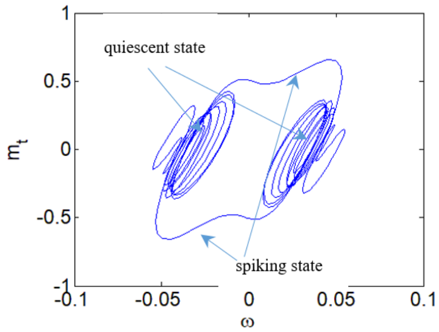
(a) Time series of ω for τ = 0.2.



(b) Time series of m_t for τ = 0.2.

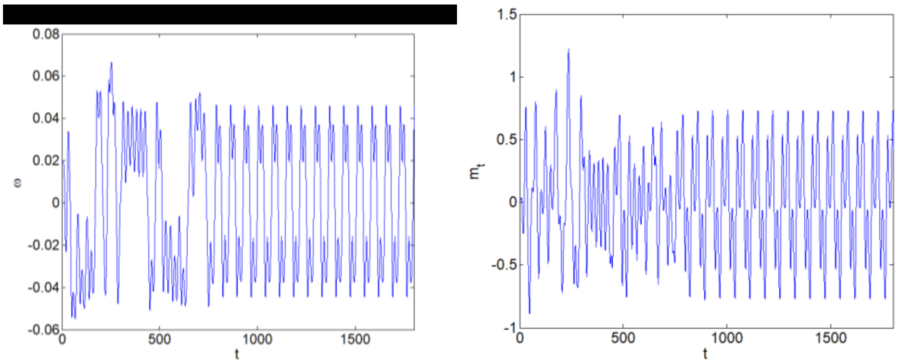


(c) Time series of y for τ = 0.2.

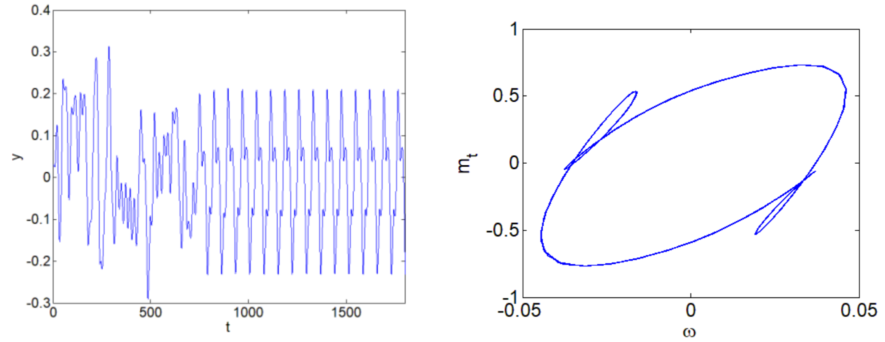


(d) Phase trajectory of $\omega - m_t$ for τ = 0.2.

Fig.5 Time waveforms and phase trajectory of the system (6) with τ=0.2 for ε=0.2.

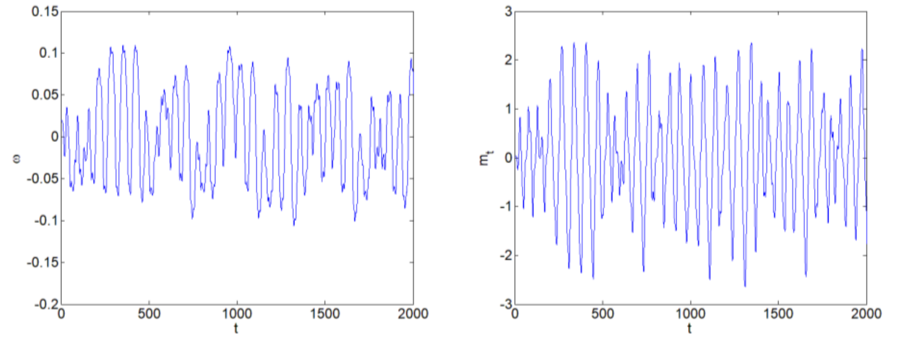


(a) Time series of ω for τ = 0.3. (b) Time series of m_t for τ = 0.3.

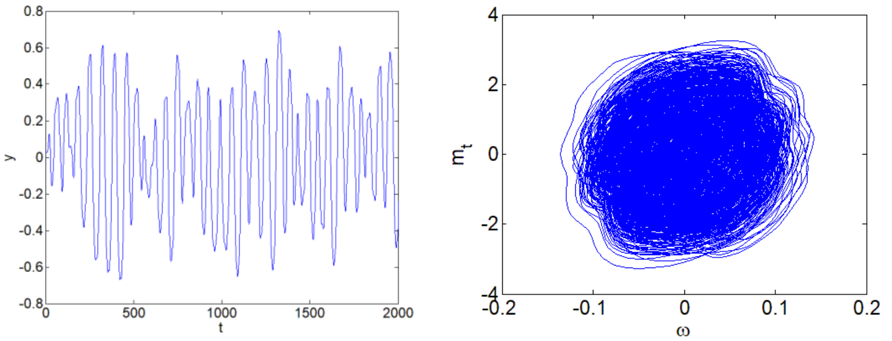


(c) Time series of y for τ = 0.3. (d) Phase trajectory of $\omega - m_t$ for τ = 0.3.

Fig.6 Time waveforms and phase trajectory of the system (6) with τ=0.3 for ε=0.2.



(a) Time series of ω for τ = 0.4. (b) Time series of m_t for τ = 0.4.



(c) Time series of y for τ = 0.4. (d) Phase trajectory of $\omega - m_t$ for τ = 0.4.

Fig.7 Time waveforms and phase trajectory of the system (6) with τ=0.4 for ε=0.2.

4. Conclusions

In this paper, the fast-slow hydro-turbine governing system with time-delay is addressed and the dynamical behaviors of the proposed model are discussed from two aspects.

Firstly, given time-delay τ=0.1, the fast-slow effects of hydro-turbine governing system with time-delay are discussed for different time-scales. Simulation results suggest that, when time-delay is fixed, the larger the time-scale is, the weaker the fast-slow effect of the hydro-turbine governing system is, which is helpful for improving the stability of time-delay hydro-turbine governing system.

Secondly, suppose time-scale is a constant and change the time-delay, then the dynamical behaviors of the proposed model are explored via numerical simulations. Analysis of the simulation results show that time-delay has a significant impact on the dynamical behaviors of the multi-scale system. Larger time-delay will make the fast-slow effect of the fast-slow hydro-turbine governing system with time-delay become unstable and is bad for the safe and stable operation of hydro-turbine governing system.

The results obtained above can provide some theoretical basis for making hydropower stations stable and avoiding the fast-slow effect of the hydro-turbine governing system as much as possible.

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