Study on Dynamic Characteristics of Rotor-bearing Model in the Hydraulic-mechanical-electric Coupled System of Hydro Generator Unit

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Abstract

A hydraulic-mechanical-electric coupled model for hydroelectric shaft-bearing system was established, which contains the penstock model of water-carriage system, the model of governor system and the model of exciter system. The differential equations for the coupled model, consisting of the key parameters from different systems (such as head, flow, speed and exciting current), were established and solved simultaneously. Further, a rotor-bearing system model is coupled to the whole system by User Programmable Features (UPFs) of Ansys.On this basis, a newly method which was focused on the study of rotor system dynamic nonlinear properties during the process of operation condition's changing was introduced. In this paper, the model was applied in the rotor dynamic analysis in applicable start-up laws with different parameters. The analysis method could provide a reference to the stable and optimum operation of hydro-electric generator units.

Keywords

hydraulic-mechanical-electric coupled — rotor-bearing system —UPFs

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INTRODUCTION

The operation of hydro-electric generator is a complex process with hydraulic-mechanical-electric coupled. A coupled hydro-power system contains the hydro-turbine system, speed control system and generator system, which is involved in hydraulic transient model, mechanical transient and the electric-magnetic transient model, respectively.

The hydro-turbine system may be simplified as linear model and nonlinear model. For the linear model,more assumptions are built (such as non-elastic water,the proportional relationship between flow and gate position and so on) . On the other hand, the nonlinear relationship of the turbine output, the turbine flow, the turbine head and the gate opening are considered in the study of non-linear model. A linear model was used to study the factors' value for operating stability with small load variation by Hovey [1]. With taking into consideration the compressibility of water and elastic of penstock, Wozniak and Fett [2] established a nonlinear model, and special emphasis was given to the pressure conduit in its properties which were mentioned above. On the basis of nonlinear model, Sanathanan [3] discussed the accuration of the low order model for hydro-turbine with long penstock. Similarly, Kishor et al. [4] and Vournas [5] had proposed low order models for above study too.In papers [6][7], several hydropower plant's models of linear and nonlinear were reported by IEEE group to study the effects of non-elastic and elastic water column on the plant. In recent years, many researchers gave significant focus on the model. Over the past decades, many researchers were carried out for the control theory of hydro-turbine governor system. A fundamental and pioneering study has been done by Paynter [8], Hovey and Leum [9], while, their papers established general guideline for hydro-turbine control theory. The permanent droop and generator damping which were neglected by above researchers were considered into the governor models in the papers of Chaudhry [10] and others researchers [11]. The PID control strategy was developed and studied for hydro-turbine control by much literature until recent years. With the development of computer technology, there is growing concern about the digital control system [12][13][14] which is more sensitivity than conventional control system. In modern research, much more control theories were developed such as optimal control, nonlinear control, adaptive control, robust control and so on [15][16][17][18]. The analysis for generator includes analysis of electromagnetic transient and analysis of electromechanical transient, the former focus on the analysis of power system faults and the later focus on the analysis of power system stability. Kilgore[19] and Wright[20] developed the first publications in modeling synchronous generators. The Heffron-Phillips generator model was established in 1952 [21] and was used to analyze the stability of the power system, and the three-order model for generator was developed. F. P. de Mello[22,23,24] et.al studied the stability of the single generator supplying an infinite bus system by the three-order model.

The model of rotor-bearing system is the core component of the hydropower generator unit. Mostly, the model consists of the shaft, the rotor, the turbine and the support structure. The dynamic characteristics of this model are the objective for researchers to study, while the vibration of the rotor system is mainly affected by the vibration source which coupled hydraulic,mechanical and electric factors. The self-excitation oscillation of water seal for turbine has been discussed by many papers. The dynamic response of rotor system under the axial thrust from water was studied in paper [25]. The magnetic effect on the system was commonly manifested as an unbalanced magnetic pull on the rotor centre. The eccentric forces of the rotor and turbine are the mechanical effect.

All of studies in the past of the transient (or coupled transient) and the rotor system are independent. For the former the objective is mainly focused on the stability of the control/power system or condition's change on the basis of parameters optimization.The latter gives a significant attention to the structure dynamic response of the unit shaft system, and the load's effect on the rotor system is summarized form the vibration source system which are time-invariant. In these discussion, the loads are changed with many factors except time. For the reason mentioned above, it is necessary to carry out the research for the dynamic characteristics of the rotor-bearing system coupled with the hydraulic system, mechanical system and electric system.

In this paper, a nonlinear coupled model of hydropower plant is developed to study the rotor system's dynamic characteristics during the coupled transients process during the start-up process. First, an elastic penstock model is established on the basis of the continuity and momentum equations describing the general behavious of fluids in a pressure duct in terms of two variables, namely, H, piezometric head, and Q, fluid flow. A PID control strategy is used to model the governor system for hydro-turbine, which is represented as a third order differential equation in mathematics. A third order model of synchronous generator which is depicted by three differential equations is employed. Then, a simultaneously differential equations with above sub-system equations were established for coupled system. Finally, a FEM model of classical rotor-bearing system is developed.

Q_i -discharge in penstock at the node i

H_i -pizeometric head in penstock at the node i

H_n- the operating head of hydro-turbine

D,A -the cross section diameter and area of penstock

D_1-the diameter of hydro-turbine

H_{np}-net water head of turbine

Q_p,Q_1' -hydro-turbine's discharge and unit discharge

a-water hammer wave velocity

n,n_1' -hydroturbine's mechanical speed and unit speed

P_t,P_1' -power and unit power of hydroturbine

ω_m,ω_e-mechanical speed and electrical speed

ϑ_m,ϑ_e-mechanical/electrical rotation angle

ω_{ms},ω_{es}-mechanical/electrical synchronous speed

f_m,f_e-mechanical/electrical frenquency

f_{ms},f_{es}-mechanical/electrical synchronous frenquency P_t,P_e-mechanical/electrical power (active output)

P_c,ΔP_e-certain/incremental generator ouput

τ-gate openning

η-turbine efficiency

b_p-permanent droop

b_t-temporary droop

T_d-reset time or dashpot constant

T_n-governor time constant

T_m-turbine inertia time constant

T_w-water inertia time constant

T_y-main servo time constant

y, Δy, y_0- turbine servomotor stroke and its deviation value,its initial value

J-inertia moment of the unit in direction of rotation (kg m2)

K_P,K_I,K_d-proportional,integral, derivative governor gain

R_a,R_r -radius of shaft and rotor

R_b-journal radius

R_i,R_o-radius of inner ring and outer ring for pad

L_p,L_r-height of pad, rotor length

p-oil pressure

e_b,e_r-eccentricty of shaft axis, rotor centre

c_b,c_r,-clearance of bearing, rotor (air-gap length)

h-thickness of oil film

δ_p-swing angle of pad

α_p-opening angle of pad

η_l-angle between the calculation location and y axis

β-angle between a point of support for pad and y axis

ϑ_b-bearing axis deviation angle

k_{ij},c_{ij}-stifness,damping cofficients,i=x,y;j=x,y

M_t,M_e-mechanical torque and electromechanical torque

I_f,U_f-field excitation current and voltage

X_d -rotate speed relative deviation

E_q-open-circuit terminal EMF(electromotive force)

E' -transient EMF(electromotive force)

E'_q-q-axis transient EMF

U,U_d,U_q - stator terminal voltage,its d-component and q-component

U_G-system voltage

I,I_d,I_q-stator current,its d-component and q-component

X_d,X_q-q and d axis synchronous reactance

X'_d-d-axis transient reactance

δ-torque-angle/power-angle

ψ -inner active power angle

φ-power-factor angle

E_{fd}-imaginary open-circuit EMF generated by field voltage

T_{d0}' -d-axis open-circuit transient time constant(also expressed as T_f)

T_e- time constant of excitation

R-resistance

Z-impedance,

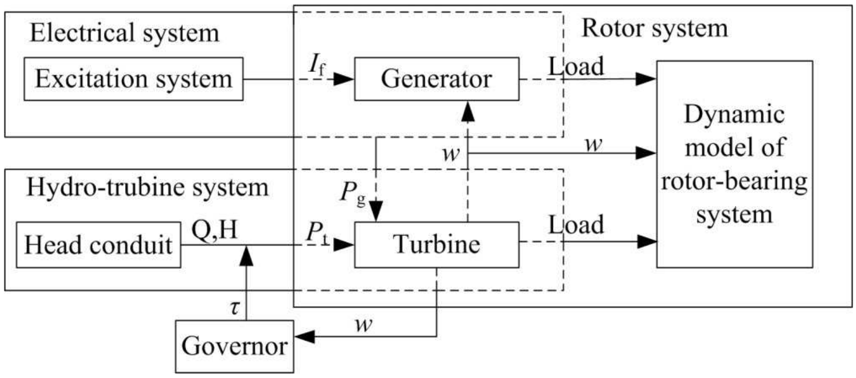

Figure 1 Sketch of Hydropower Plant System

1. MODELS

A complex and coupled nonlinear system of hydroelectric power station is established as illustrated in Fig.1. In order to develop the mathematical model, the system decouples into several modules and then the dynamic nonlinear model is developed for each module.

1.1 Penstock model

A one-dimensional penstock model is established in this part. The *Q* and *H* for the hydroelectric power station system can be solved in this model. The pressure conduit on the upstream of the plant is the connection between the hydro-turbine and the reservoir. The transition flow of the penstock can be described as Momentum Equation and Continuity Equation, as shown in Eq.(1)~(2)

$$\frac{\partial Q}{\partial t}+\frac{Q}{A}\frac{\partial Q}{\partial x}+gA\frac{\partial H}{\partial x}+\frac{fQ|Q|}{2DA}=0 \tag{1}$$

$$\frac{\partial H}{\partial t}+\frac{Q}{A}\frac{\partial H}{\partial x}+\frac{a^2}{Ag}\frac{\partial Q}{\partial x}+\frac{Q}{A}\sin\alpha=0 \tag{2}$$

And, an Explicit Finite Differential Method (EFDM) is applied to discretize the Eq.(1) and Eq.(2) at the junction nodes, as

$$Q_i^{n+1}=\frac{1}{2}(Q_{i+1}^n+Q_{i-1}^n)-\frac{\Delta t Q_i^n}{2A\Delta x}(Q_{i+1}^n-Q_{i-1}^n)$$
$$-\frac{\Delta tg}{2\Delta x}(H_{i+1}^n-H_{i-1}^n)-$$
$$\frac{f}{8DA}(Q_{i+1}^n+Q_{i-1}^n)\left|(Q_{i+1}^n+Q_{i-1}^n)\right| \tag{3}$$

$$H_i^{n+1}=\frac{1}{2}(H_{i+1}^n+H_{i-1}^n)-\frac{\Delta t Q_i^n}{2A\Delta x}(H_{i+1}^n-H_{i-1}^n)$$
$$-\frac{\Delta t}{2A\Delta x}\frac{a^2}{g}(Q_{i+1}^n-Q_{i-1}^n)-\frac{\Delta t}{A}Q_i^n\sin\alpha \tag{4}$$

Respectively, the subscripts *i* and superscripts *n* denote the position node *i* and time node *n*.

The equations of boundary were derived by the Method of Characteristics (MOC) which are called characteristic equations.

The hydro-turbine is the boundary condition of downstream for penstock and the Positive Characteristic Equation at time *n* is,

$$Q_P=A(C_P-C_aH_P) \tag{5}$$

Where,

$$C_a=g/a \tag{6}$$

$$C_P=\frac{Q_M}{A}-\frac{\Delta t}{A^2\Delta x}(Q_M+Aa_M)(Q_M-Q_L)+$$
$$C_a\left[H_M-\frac{\Delta t}{A\Delta x}(Q_M+Aa_M)(H_M-H_L)\right]+g(S_0-S_f)\Delta t \tag{7}$$

The reservoir is the upstream boundary condition for penstock, the Negative Characteristic Equation at time *n* is,

$$Q_1^{n+1}=A(C_N+C_aH_1^{n+1}) \tag{8}$$

$$C_N=\frac{Q_1^n}{A}+\frac{\Delta t}{A^2\Delta x}(Q_1^n-Aa_1)(Q_2^n-Q_1^n)-$$
$$C_a\left[H_1^n-\frac{\Delta t}{A\Delta x}(Q_1^n-Aa_1)(H_2^n-H_1^n)\right]+$$
$$\frac{\Delta tgQ_1^n}{Aa_1}\sin\alpha-\frac{f\Delta t}{2DA^2}Q_1^n\left|Q_1^n\right| \tag{9}$$

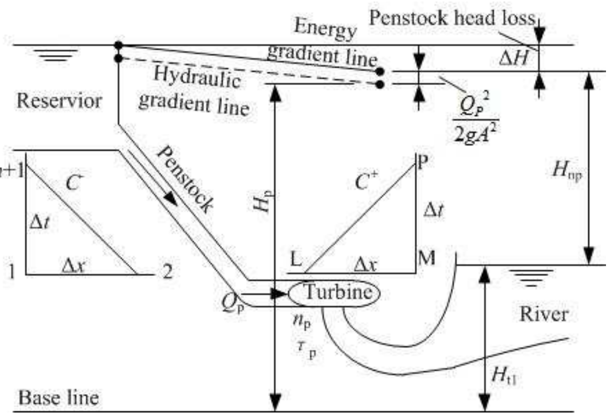

Figure 2 Boundary Conditions

The subscripts *1, 2* and *M*, *L* denote the last two position nodes as shown in Fig.2.

As the analysis above, if the upstream (H_1,Q_1) and downstream (H_p,Q_p) boundary conditions were given, the spatial and temporal changes in the velocity (discharge) and pressure (piezometric head) fields in the penstock system can be obtained by equations (3)~(9). The H_1 is the water level of the reservoir, and the Q_p is the operation discharge of hydro-turbine which is calculated by the model in the follow.

1.2 Hydro-turbine model

A highly nonlinear model of hydro-turbine with the comprehensive characteristic curves is applied in this part.

The Hydro-turbine converts the hydraulic power to the mechanical power which can supply the motivity (as M_t shown in Eq.(10)) to drive the shaft of rotor system, the rotation equation is,

$$J\frac{d\omega_m}{dt} = J\frac{d^2\theta_m}{dt^2} = M_t - M_e \quad (10)$$

Eq.(11) to Eq.(12) express the nonlinear relationship of the comprehensive characteristic curves, which reflect the turbine's nonlinear dynamic behaviors.

$$\tau = f(n_1', Q_1') \quad (11)$$

$$\eta = g(n_1', Q_1') \quad (12)$$

The data of the curves input into the computer. Then the parameters for whole operations can be obtained by fitting and interpolation methods.

In this model, when the values of discharge, rotate speed and gate opening are prior estimated from the previous time steps, the H_{np} and P_t (M_t) can be solved by iteration method and the similitude law of turbine. And as shown in the Fig.2, the relationship between H_p and Q_p can be expressed as Eq.(13) with H_{np},

$$H_p = H_{np} + H_{t1} - \frac{Q_p^{\ 2}}{2gA^2} \quad (13)$$

The H_p and Q_p can be solved by Eq.(13) with Eq.(5).The gate opening in this time step is calculated by the model of governor. In order to calculate the n in this time step, it is necessary to obtain the P_e (M_e) from the model of synchronous generator.

1.3 Governor model

The hydraulic governor provides a reliable rotate speed regulation of turbine with load variation in the power system.The model of governor controls the change law of the gate opening. In this paper, a classical PID control strategy is applied in the model of governor on the basis of the predecessors' studies.

As shown in Fig.3, the C_f is frequency command. The transfer function from x to y in Fig.3 can be written as,

$$G(s) = \frac{Y(s)}{X(s)} = \frac{K_D S^2 + K_P S + K_I}{b_p K_D S^2 + (b_p K_P + 1)S + b_p K_I}\frac{1}{T_{yB}T_y^{*}S^2 + T_y^{*}S + 1} \quad (14)$$

Where x *and* y are the input (deviation ratio of rotate speed) and output (servomotor stroke) variable, respectively. A third order differential equation can be derived from Eq.(14) by the Inverse Laplace Transformation, as

$$b_p K_D T_y^{*} y''' + (b_p K_P T_y^{*} + T_y^{*} + b_p K_D)y'' + (b_p K_I T_y^{*} + b_p K_P + 1)y' + b_p K_I y = K_D x'' + K_P x' + K_I x \quad (15)$$

Further, an equation of state is obtained from Eq.(15) according to the Modern Control System [09], which is a first-order differential equations. As shown in Eq.(16).

$$\begin{aligned} \dot{x}_1 &= x_2 + \beta_1 x \\ \dot{x}_2 &= x_3 + \beta_2 x \\ \dot{x}_3 &= -a_3 x_1 - a_2 x_2 - a_1 x_3 + \beta_1 x \end{aligned} \quad (16)$$

The x_1 can be solved from the equations by Multistage Runge-Kutta algorithm in Eq.(16). Then, the y is represented as Eq.(17). Finally, the gate opening can be obtained.

$$y = x_1 + \beta_0 x \quad (17)$$

Where, $\beta_0=b_0$, $\beta_0=b_1-a_1\beta_0$, $\beta_2=b_2-a_1\beta_1-a_2\beta_0$, $\beta_3=b_3-a_1\beta_2-a_2\beta_1-a_3\beta_0$.
$a_1=(b_pK_PT_y^{*}+T_y^{*}+b_pK_D)/b_pK_DT_y^{*}$,
$a_2=(b_pK_IT_y^{*}+b_pK_P+1)/b_pK_DT_y^{*}$, $a_3=b_pK_I/b_pK_DT_y^{*}$.
$b_0=0$, $b_1=K_D/b_pK_DT_y^{*}$, $b_2= K_P/b_pK_DT_y^{*}$, $b_3=K_I/b_pK_DT_y^{*}$.

1.4 Synchronous generator model

The model of the synchronous generator describes the relationship of electrical parameters. We can obtain the P_t, U_G, and I of the system in this model.The phasor diagram of the salient-pole synchronous generator is shown in Fig.4.

As shown in Fig.4, the relationship between terminal voltage and current of the generator cab be expressed in Eq.(18),

$$\begin{cases} U_{Gq} = E'_q - I_d X'_d \\ U_{Gd} = I_q X_q \\ U_G^2 = U_{Gq}^{\ 2} + U_{Gd}^{\ 2} \end{cases} \quad (18)$$

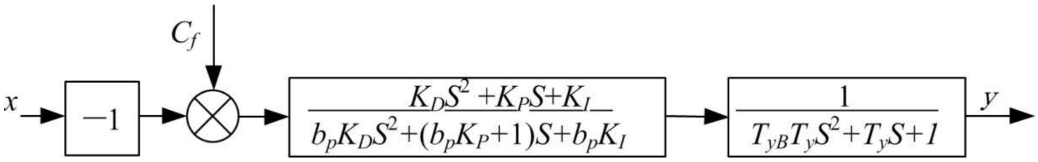

Figure 3 The Transfer Function of the Frequency Regulation Mode

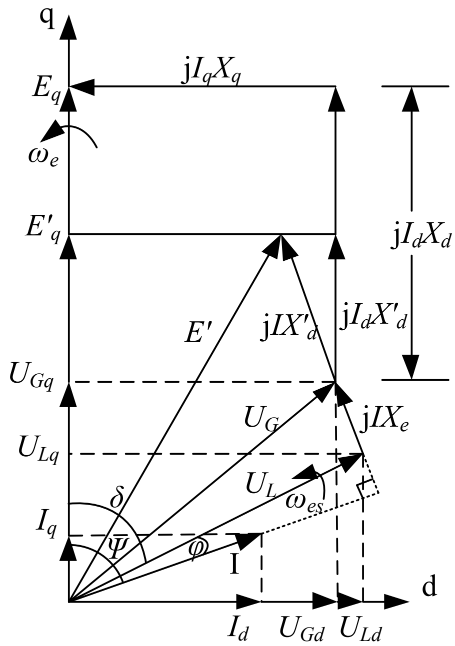

Figure 4 Phasor Diagram

And the relationship between the terminal voltage and load voltage is,

$$\begin{cases} U_{Ld} = U_{Gd} + I_d R_e - I_q X_e \\ U_{Lq} = U_{Gq} + I_q R_e + I_d X_e \end{cases} \tag{19}$$

The open-circuit terminal EMF(Electromotive Force) is represented as

$$E_q = E'_q + I_d (X_d - X'_d) \tag{20}$$

And the differential equation for the transient process of transient EMF in q-axis is,

$$T'_{d0} \frac{dE'_q}{dt} = E_{fd} - E'_q - I_d (X_d - X'_d) \tag{21}$$

In the derived process of Eq.(20) the damp winding of rotor and the resistance of stator are neglected.

In order to calculate the E_{fd}, the excitation system is applied, which is regulated by voltage deviation,

$$T_e \frac{d\Delta E_{fd}}{dt} = -\Delta E_{fd} - K_v \Delta U_G \tag{22}$$

The motion equation of the rotor is the same form as Eq.(10). The expression becomes

$$T_a \frac{d\omega_e}{dt} = \frac{\omega_{es}}{P_0} (P_t - P_e) / \omega_e \tag{23}$$

Where $\omega_e = p\omega_m$, $P = M\omega_m$, $T_a = J\omega_{ms}^2 / P_0$. The p is the number of pole pairs, P_0 is the nominal power.The P_e is calculated as

$$P_e = U_{Gq} I_q + U_{Gd} I_d \tag{24}$$

Where the parameters in Eq.(24) are solved from the Eq.(18)~(23).

1.5 The hydroelectric generator unit model

The hydroelectric generator unit is modeled as a rotor-bearing system by FEM method as shown in Fig.5. The beam 188 element is employed to simulate the shaft of the rotor system. The rotor and the turbine are simplified as mass 21 element in the model. The combine 14 element is used to simulate the guide bearings, and the dynamic characteristics of the bearings are equivalent to the coefficients of stiffness and damping (k_{ij}, c_{ij}) of the element parameters. The rotor system model (as shown in Fig.5) is mounted on the model of powerhouse.

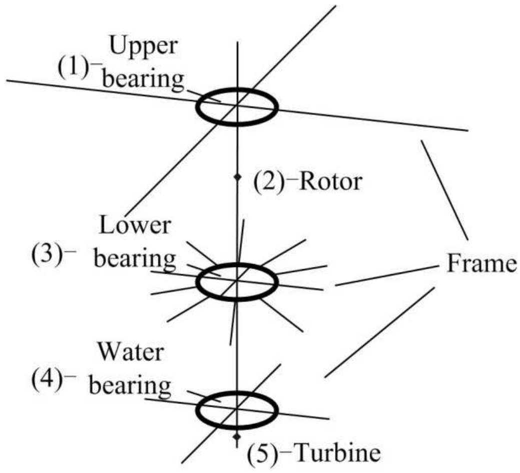

Figure 5 Rotor-bearing model

A tilting pad guide bearing model as shown in Fig.6 is used in the rotor system. The Reynolds Equation is used to describe dynamic oil film pressure fields around the pads in radial direction when the rotate speed value of the turbine is not very higher.

$$\frac{\partial}{\partial x}\left(\frac{h^3}{\mu}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{h^3}{\mu}\frac{\partial p}{\partial y}\right) = 6U\frac{\partial h}{\partial x} \tag{25}$$

Where p is the pressure of oil film. The equation in non-dimensional form can be written as

$$\frac{\partial \bar{h}}{\partial \eta_l} \bar{h}^3 \frac{\partial \bar{p}}{\partial \eta_l} + \gamma^2 \bar{h}^3 \frac{\partial \bar{p}}{\partial \lambda} = 6 \frac{\partial \bar{h}}{\partial \eta_l} \tag{26}$$

$x = R\eta_l$, $\lambda = y/(L_b/2)$, $\lambda \in [-1,+1]$, the non-dimensional parameters for the thickness of the oil film is,

$$\bar{h} = 1 + \varepsilon \cos(\eta_l - \theta_p) - (1 - c'/c_b)\cos(\beta - \eta_l)$$

$$+\delta_p / b\sin(\beta - \eta_l) \quad (27)$$

Where, $\varepsilon = e_b / c_b$ is eccentricity of the guide bearing, the $b = c_b / R_b$ is the ratio of clearance and radius. If the u and v are the circumferential velocity and radial velocity speed of the oil film, the Dynamic Reynolds Equation can be expressed as,

$$\frac{\partial \bar{h}}{\partial \eta_l}\bar{h}^3\frac{\partial \bar{p}}{\partial \eta_l} + \gamma^2\bar{h}^3\frac{\partial \bar{p}}{\partial \lambda} = 6\frac{\partial \bar{h}}{\partial \eta_l} + 6(u\sin\eta_l + v\cos\eta_l) \quad (28)$$

Where, $a = \frac{3}{4}\frac{\partial \bar{h}}{\partial \eta_l}\Big/\bar{h} + \frac{2}{\bar{h}}\frac{\partial^2 \bar{h}}{\partial \eta_l^2}$

The oil pressure can be obtained from Eq.(16) by FEM method, then the loads of the oil film can be generated through the integration of element solution [26].

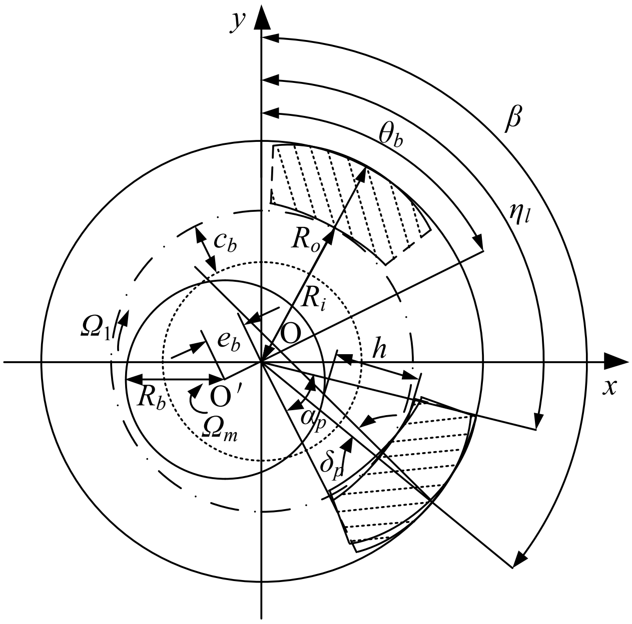

Figure 6 Tilting pad guide bearing

The loads' partial derivatives represent the displacement and velocity are ($i,s=x,y$),

$$K_{is} = \frac{\partial f_i}{\partial s}, C_{is} = \frac{\partial f_i}{\partial \dot{s}} \quad (29)$$

Which are the coefficients of the stiffness and damping for each bearing pad. Then, the total coefficients (k_{ij}, c_{ij}) of the bearing can be generated by combining the coefficients of all of the pads.

2. The hydroelectric power station system

A whole system for the hydroelectric power station is established with the models as mentioned above. The system is described as Fig.7. The models of the structures were built by Ansys, and the other models were established by Fortran language. Then, the programs which are written by Fortran are compiled as external command in Ansys with the UPFs function. The command can be called to simulate the Hydraulic-mechanical-electric coupled transient process in every time step of the structural dynamic calculation.

3. Numerical calculation and result analysis

The process of electro-magnetic transient is not involved in the process of start-up, except the change of the field current during the process of voltage build up in the no-load operation, so, in this paper, the electrical system model is not taken into account.

The type of turbine studied in this paper is named HL180-LJ-410, which is complied with the China's naming code. It means that a Francis turbine with runner type of 180, vertical arrangement, metallic spiral casing, and the diameters of runner is 410mm.

The mechanical eccentric forces of rotators and the unbalanced magnetic pull of the rotor are considered for the kinetic rotor-bearing model[27].The data of the penstock, governor and generator models are listed in Table 1.

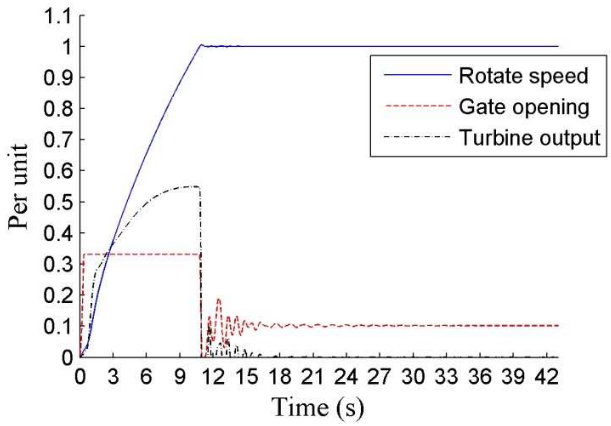

Figure 8 Simulation result of start-up transient

During the process of start-up which as shown in Fig.8, the speed rise up smoothly with little dynamic response, short response time, small overshoot and fast attenuation. The gate opening fast reached the start opening at first, when the speed arrived at the rated point, the opening begins to attenuate with fluctuation until it stability at no-load opening. At the same time, in order to supply the power for growing speed, the turbine output increased rapidly. When the speed is stable, the active output is reduced to 0 with a short fluctuation process at the no-load operation point. The changing laws in Fig.9 are consistent with other papers and actual process of the station.

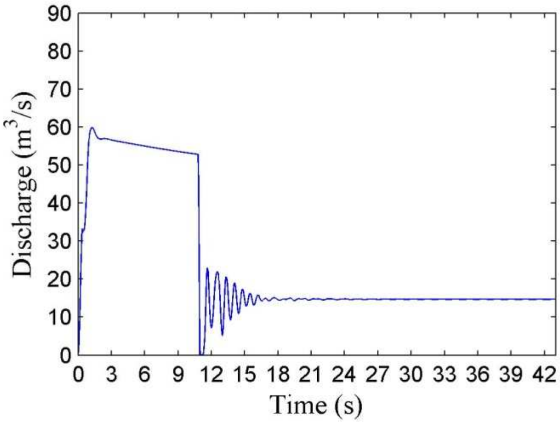

Figure 9 The discharge change during start-up

As shown in Fig.9, the discharge of the hydro-turbine increased fast in seconds at first, because of the quickly change of opening. Then it decreased smoothly with the stable opening. Near the point at 12th seconds, the discharge suddenly arrived at 0 m^3/s because the opening arrived at zero.The discharge started to fluctuate from the 12th seconds until it becomes stable near the 20th seconds.

As shown in Fig.10, when the gate is quickly opened at first, the head decreased and the flow increased quickly for the hydro-turbine. At the 12th seconds, the head rose rapidly and arrived at a peak value because the opening was closed suddenly. Then, the change of head started to fluctuate for a long time before it becomes stable.

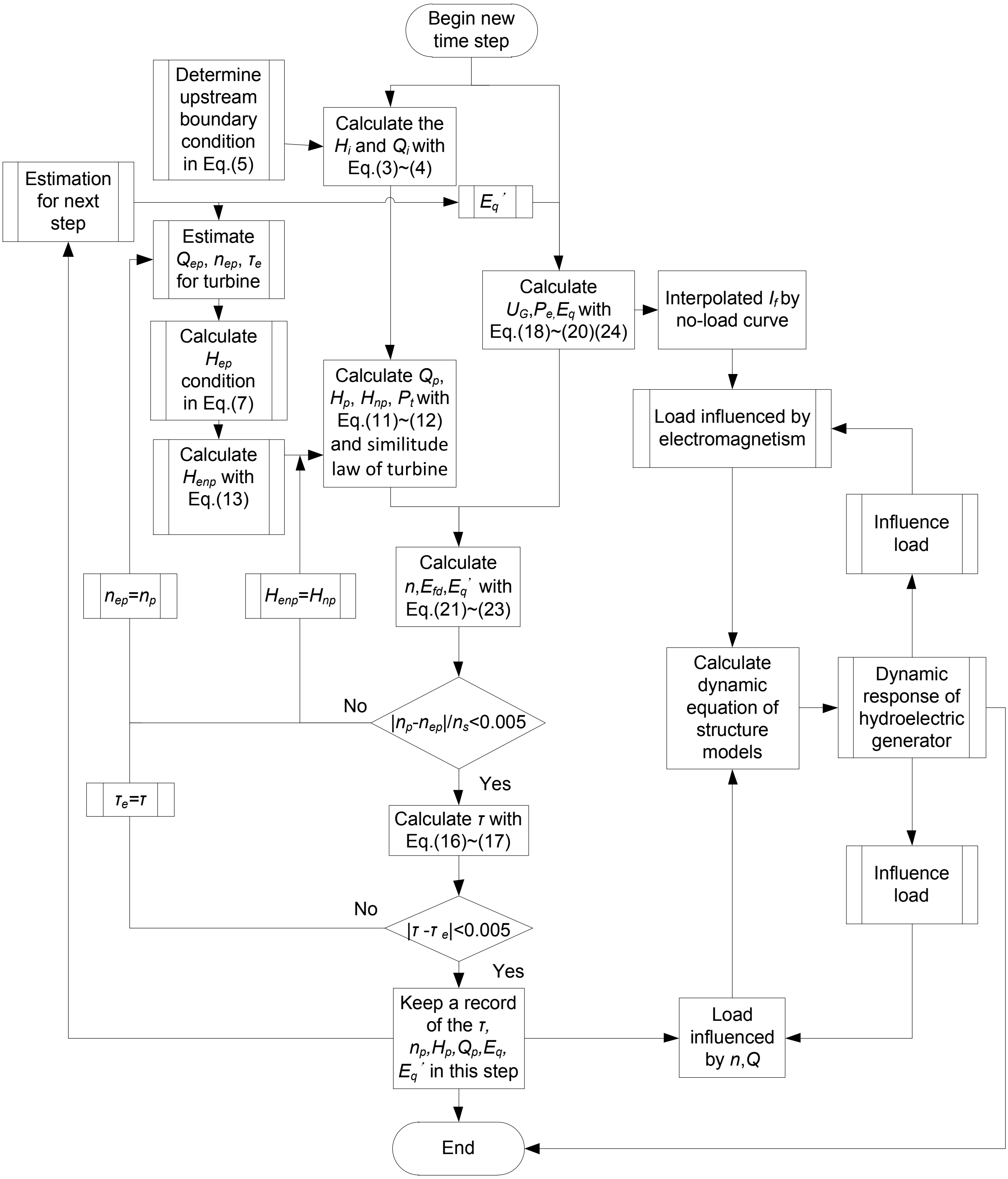

Figure 7 Computational process of the system

Table 1. Data of models

Nominal/no load value of Turbine					Length/diameter of penstock (m)	
Head(m)	Weight (t)	Discharge(m^3/s)	Power(kVA)	Speed(r/min)		
117/124.9	420	86.65/14.7	88*	150*	495/8.5	
Time constants of governor in start-up (s)						
T_m	T_w	T_d	T_n	b_p	b_t	T_y

9	1.10		$4T_w$	$0.5T_w$	0.01		$2(T_w/ T_m)$	0.1
Parameter value of rotor-bearing system (m)								
R_a	R_b	R_r	R_i	R_o	L_p	L_r	c_b	c_r
0.9	2.12	5	2.12036	2.185	0.587	2.5	0.36E-3	16E-3
Nominal/no load value of excitor and Generator								
I_f(A)		I(kA)		U(kV)	$\cos\varphi$		U_{sN}(KV)	Weight (t)
1300/850*		4.22*		13.8	0.91		12.05*	91

The '*' represent the basic value of the per unit

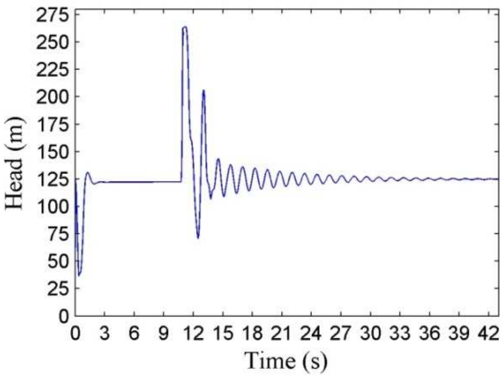

Figure 10 The net head change during start-up

As shown in Fig.12, the displacements of rotators increased with the growing of rotate speed, the trajectories were stable since rotate speed arrived at the rated point. With the beginning of the voltage buildup process the field current began to increases and began to produce the unbalanced magnetic pull as shown in Fig.11. Then, the rotor displacements increased again because of the increased UMP. As shown in Fig.11, the UMP was balanced with small fluctuations, because the value of UMP is connected to the value of rotor's dis-placements, which the rotor's trajectories achieved a new stability again. As shown in Fig.13, the axis trajectories' change of upper and lower guide bearings are similar to the rotor's because they provide the directly supporting to the rotor.

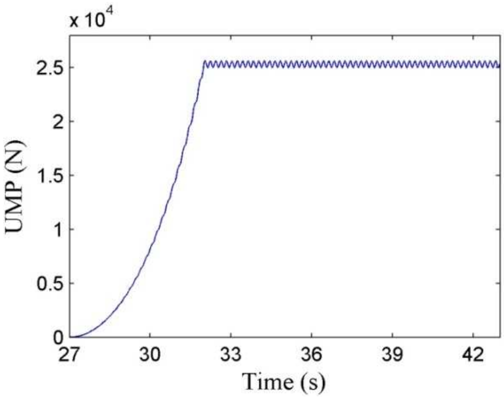

Figure 11 The change of UMP

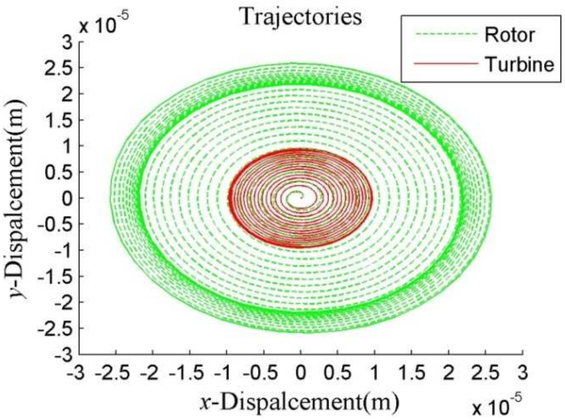

Figure 12 The trajectories of rotators

Comparing Fig.12 with Fig.9 & 10, the vibration of rotor system has no influence on the hydraulic transient process in the normal start-up process, because the head and discharge of the turbine were stable when the rotor's displacement increased with the UMP as shown in the figures.

Under the conditions of this paper, the hydraulic force has not been taken into consideration for the rotor system movement yet, but the hydraulic transient process show its great influence on it.

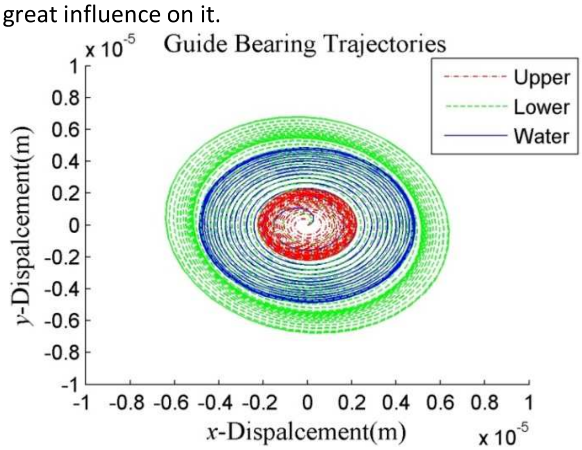

Figure 13 The trajectories of guide bearings' axis

4. Conclusions

In this paper, a whole numerical system model of the hydro-electric power station was established. The model of the system can be used to study the dynamic characteristics of the power station in different operations. The model is based on reliable mathematic and physical theories, and it demonstrates a perfect simulation of the process of start-up in the numerical calculation. The variation of parameters in the process of start-up that obtained in this paper are reasonable and with considerable regularity. The electric transient process was not involved in the study of the start-up, because the generator is open circuit.

The results indicate that the hydraulic transient influence the rotor system's rotation, which reflecting the inner connection between the subsystems. But the vibration of the rotators has no influence on the hydraulic transient in the normal process of start-up.

In the future studies, the hydraulic forces on the turbine and the impulse pressure on flow passage will be considered, a study of generator will be involved into the whole model, then, much more processes of station operation could be simulated to study for the dynamic characteristics of the coupled rotor system.

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