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. A differential equations for 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).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 aplicable start-up laws with different parameters. This analysis method could provide a reference to the stable and optimum operation of hydro generator units.

Keywords

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

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INTRODUCTION

The operation of hydro generator is a complex process with hydraulic-mechanical-electric coupled. A copuled 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 study, 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 positon 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 stablity with small load variation by Hovey [1]. With taking into consideration the compress-ibility of water and elastic of penstock, Wozniak and Fett [2] establised 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] too has proposed low order models for above study.In papers [6][7], several hydropower plant models of linear and nonlinear were reported by IEEE group to research the effects of non-elastic and elastic water column on the plant.In recent years, many researchers give significant focus on the model....Over the past decades, many studies 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 establised general guideling for hydro-turbine control theory. The permanent droop and generator damping which are neglected by above studied, are considered into the governor models in the papers of Chaudhry [10] and others researchers [11]. The PID control strategy is developed and studied for hydro-turbine control by many literatures unitl recent years. And with the delvelopment 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 reseach, more control theory were deleloped such as optimal control, nonlinear control, adaptive control, robust control and so on [15][16][17][18][19].

The model of rotor-bearing system is the core component of hydropower generator unit. Mostly, the model is consisted of the shaft, the rotor, the turbine and the support structure. The dynamic characteristics of this model are the objective for reseachers to study,while the vibration of the rotor system is mainly affected by the source which copuled hydraulic,mechanical and electric factors. The self-excitation oscillation of water seal for turbine has discussed by many papers. The dynamic response of rotor system under the axial thrus from water is studied in paper [20]. The magnetic effect on the system commonly mannifested as a unblanced magnetic pull on the rotor centre. The eccentric force of rotor and turbine is the mechanical effect].

All of studies in the past of the transient (or coupled transient) and the rotor system are indepenednt. For the former the objective is mainly foucus on the stability of the control/power sytsem 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 loads effect on the rotor system is summarized form the vabration source system which are time-invariant. In these disscusion, the loads are changed with many factors except time. For the reason mentioned above, it is neccessory to carry out the research for the dynamic characteristic of rotor-bearing system coupled with the hydraulic system, mechanical system and electric system.

In this paper, a nonlinear copuled model of hydropower plant is development to study the structure's/rotor system dynamic characteristics during the coupeld transients process which are resulted in start-up laws. First, a elastic penstock model is establised on the basis of the continuity and momentum equations describing the general behaviours 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 represented as a third order differential equation in mathematic. 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-net water head of turbine
D,A -the cross section diameter and area of penstock
D_1-the diameter of hydro-turbine
H_{np}-the operating head of hydro-turbine
Q_p,Q_1'-hydroturbine's discharge and unit discharge
a-water hammer wave velocity
the superscript * represent the per-unit parameters
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
T_{yB}-pilot valve and servo motor time constant
y_d,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

1. MODEL

A complex and coupled whole nonlinear system for hydopower plant is established as illustrated in Fig.1. In order to develop the mathematical model, the system is decoupled into several modules and then dynamic nonlinear model is developed for each module. A new discussion can be carried out for the dynamic characteristics of the generator unit an palnt structure by using this numerical model.

1.1 Penstock Model

The the pressure conduit on the upstream of the plant is the connection between the hydro-turbine and reservoirs. The transition flow of the penstock can be described as Momentum Equation and Continuity Equation, as shown in Eq.(1)~(2),

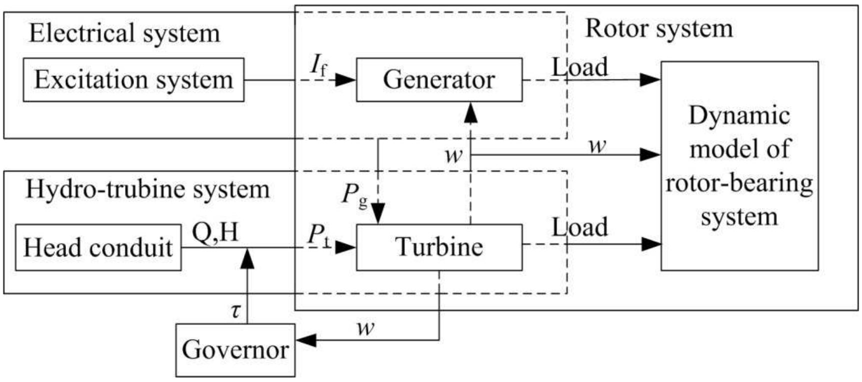

Figure 1. Sketch of Hydropower Plant System

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

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

and, a Explicit Finite Differnetial Method (EFDM) is applied to disvretize the Eq.(1) and Eq.(2) at the junction nodes,as

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

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

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

The hydro-turbine model consist of the relationship between H, Q, τ and n. It is the downstream boundary condition for penstock, the positive characteristic equation at time n is,

$$Q_P=C_PA-C_aAH_P \tag{5}$$

Where,

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

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

The subsrcipts M and L denote the last two position nodes as shown in Fig.2.

1.2 Hydro-turbine model

The Hydro-turbine converts the hydraulic power to the mechanical power which can supply the motivity to drive (as M_t shown in Eq.(8)) the shaft of rotor system,the rotation equation is,

$$J\frac{d\omega_m}{dt}=J\frac{d^2\theta_m}{dt^2}=M_t-M_e \tag{8}$$

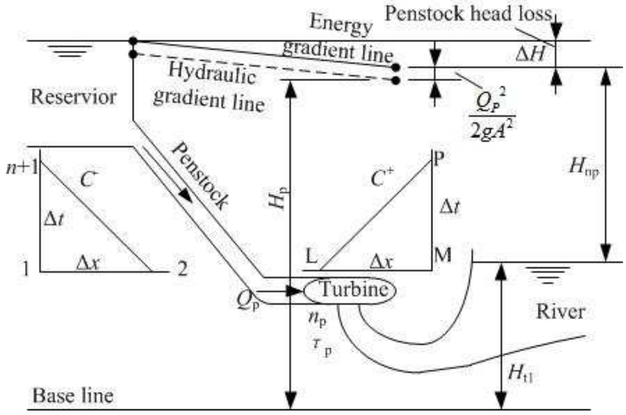

Figure 2. Boundary Conditon

The synthetic characteristic curves are applied into the numerical calculation which could consider the nonlinear variation sufficient during the ttransient process. The datas of the curves for whole operations can be obtained by fitting and interplation.

$$\tau=f\left(n_1',Q_1'\right) \tag{9}$$

$$\eta=g\left(n_1',Q_1'\right) \tag{10}$$

Eq.(9) to Eq.(10) express the nonlinear relationship of the synthetic characteristic curves, which reflect the turbine's dynamic behaviors. With combining the H_p, Q_p which are solved from the penstock model as shown in Eq.(3)~Eq.(5), the Eq.(9) and Eq.(10) and the law of hydraulic similitude, we can calculation the n, H_n, Q_p and M_t for hydro-turbine at any operation point.

1.3 Governor model

The hydraulic governor system provide a reliable rotate speed regualtion of turbine with load variation in the power system. In this paper, a classical PID control strategy is applied in the coupled system on the basis of the predecessors' studies.

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

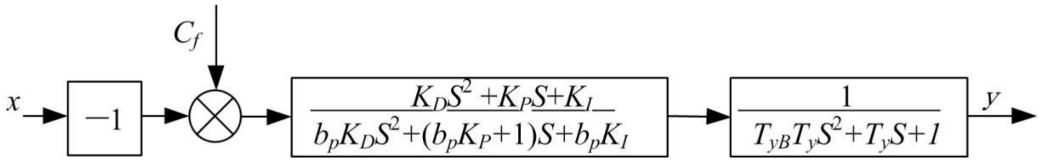

Figure 3. The Transfer Function of the Frequency Regulation Mode

$$G(s) = \frac{Y(s)}{X(s)}$$
$$= \frac{K_D S^2 + K_P S + K_I}{b_p K_D S^2 + (b_p K_P + 1)S + b_p K_I} \frac{1}{T_{yB} T_y{}^* S^2 + T_y{}^* S + 1} \quad (11)$$

Where x is the input variable and and y is the output variable. A third order differential equation can be derived from Eq.(11) by the Inverse Laplace Transformation, as

$$b_p K_D T_y{}^* y''' + (b_p K_P T_y{}^* + T_y{}^* + b_p K_D) y'' + (b_p K_I T_y{}^* + b_p K_P + 1) y' + b_p K_I y = K_D x'' + K_P x' + K_I x \quad (12)$$

Further,a equation of state is obtained from Eq.(12) according to the Modern Control System [09], which is a first-order differential equations. The y can be sloved from the equations by Multistage Runge-Kutta algorithm.The gate opening can be obtained finally.

1.4 Rotor_bearing model

A FEM model of rotor system is establised in this paper by Ansys, which is a mature software for FEM methods. The beam188 element is employed to simulate the shaft of the rotor system. The rotor and the turbine are simplifed as mass21 element in the model. The combine14 element is used into 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 is mounted on a FEM model of powerhouse, as shown in Fig.4.

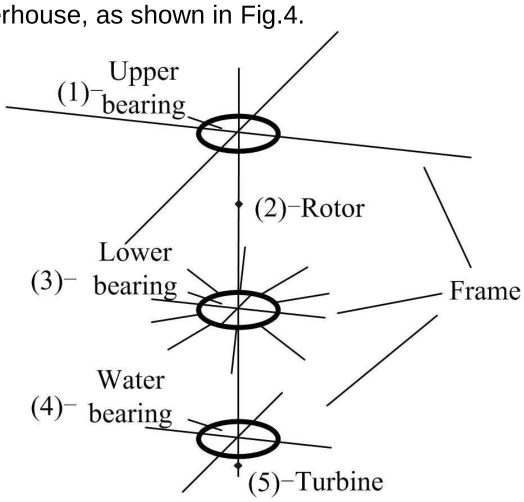

Figure 4. Rotor-bearing model

A tilting pad guide bearing model is used in 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 small.

$$\frac{\partial}{\partial x}\frac{h^3}{\mu}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\frac{h^3}{\mu}\frac{\partial p}{\partial y} = 6U\frac{\partial h}{\partial x} \quad (13)$$

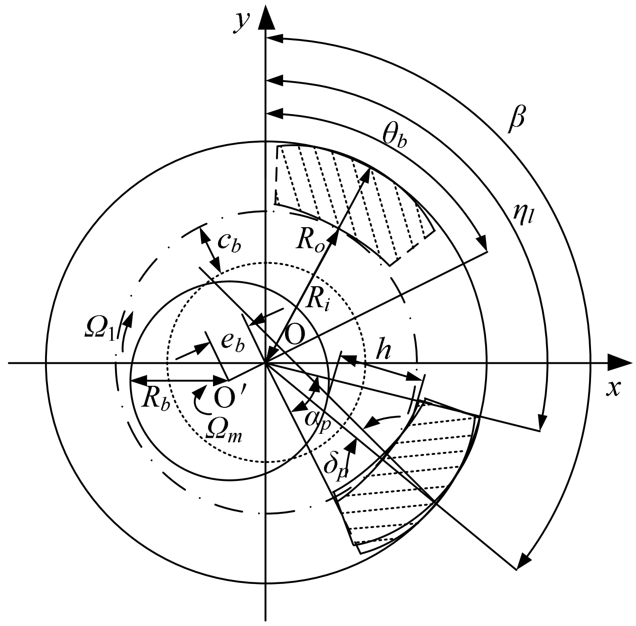

Figure 5. Tilting pad guide bearing

p is the pressure of oil film. The equation in nondimension can be written as

$$\frac{\partial \bar{h}}{\partial \eta_l}\bar{h}^3\frac{\partial \bar{p}}{\partial \eta_l} + \gamma^2 \bar{h}^3 \frac{\partial \bar{p}}{\partial \lambda} = 6\frac{\partial \bar{h}}{\partial \eta_l} \quad (14)$$

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

$$\bar{h} = 1 + \varepsilon\cos(\eta_l - \theta_p) - (1 - c'/c_b)\cos(\beta - \eta_l) + \delta_p / b \sin(\beta - \eta_l) \quad (15)$$

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 is the circumferential velocity and radia velocity speed of the oil film, the Dynamic Reynolds Equation can be expressed as,

$$\frac{\partial \bar{h}}{\partial \eta_l}\bar{h}^3\frac{\partial \bar{p}}{\partial \eta_l} + \gamma^2 \bar{h}^3 \frac{\partial \bar{p}}{\partial \lambda} = 6\frac{\partial \bar{h}}{\partial \eta_l} + 6(u\sin\eta_l + v\cos\eta_l) \quad (16)$$

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 interation of element solution [21]. The loads' partial derivatives respect to the displacement and velocity are(i,s=x,y),

$$K_{is} = \frac{\partial f_i}{\partial s}, C_{is} = \frac{\partial f_i}{\partial \dot{s}} \quad (17)$$

Which is the coefficents of the stiffness and damping for each pad.Then, the total coefficients (k_{ij},c_{ij}) of the bearing can be generated by combining the coefficients of pads[11].

2. Methods

The process of elecro-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 rotor-bearing FEM model is built by Ansys, and other models are compiled in Fortran. With the UPFs of the Ansys, the programs of Fortran can be compiled into some commands from users, then, the operation process of hydro-turbine and generator's rotor can be simulated by the dynamic time-history analysis method with Ansys. On this basis, dynamic characteristics of the rotor system can be studied at any process during the operation of hydropower station.

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

The mechanical eccentric forces of rotators and the unbalanced magnetic pull of rotor are considered for the kinetic rotor-bearing system[22].

3. Result analysis

The datas of the whole model are listed in the Tab.1.

During the process of start-up, the speed rised up smoothly with good dynamic response, short response time, small overshoot and fast attenuation. The gate

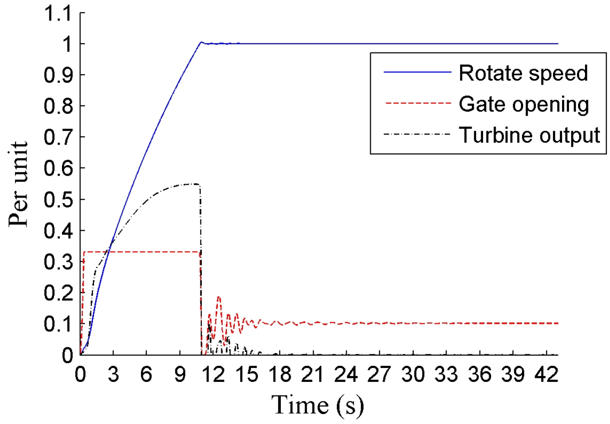

Figure 6. Simulation result of start-up transient

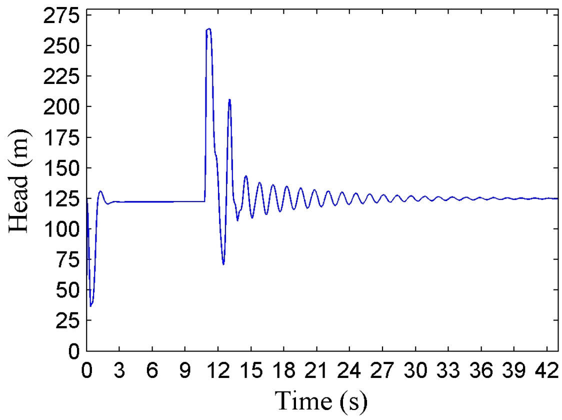

Figure 7. The head change during start-up

opening fast reached the start opening at first, when the speed arrived at the rated point, the opening begins to attenuate with fluctuation 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 output is reduced to 0 with a short fluctuation process.

When the gate is quickly opened at first, the head decreased and the flow increased quickly for the hydro-turbine.Near the 12 seconds, the flow suddenly arrived

Table 1. Datas 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 governorn 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

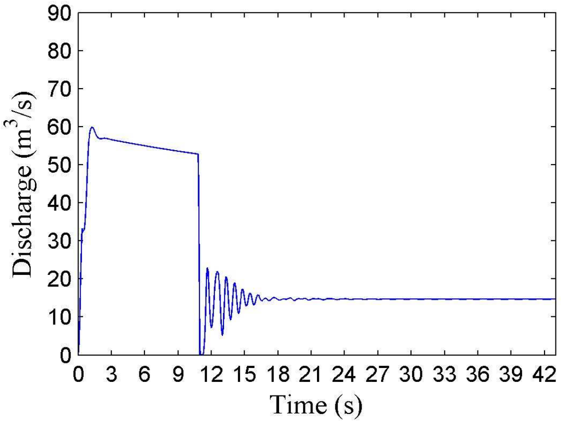

Figure 8. The discharge change during start-up

at $0m^3$/s because of the closed gate, it caused a high head for the turbine, this phenomenon may create a great impulse pressure on the spiral case.

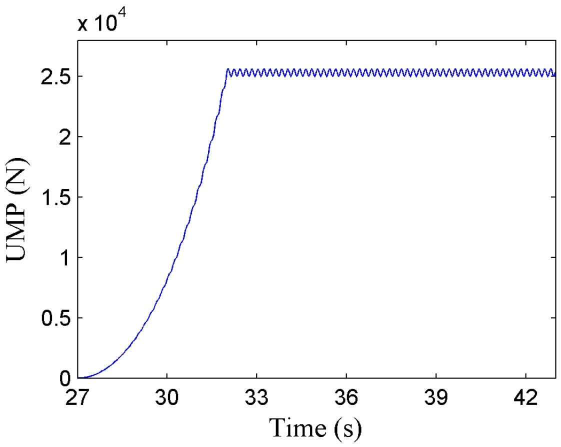

Figure 9. The change of UMP

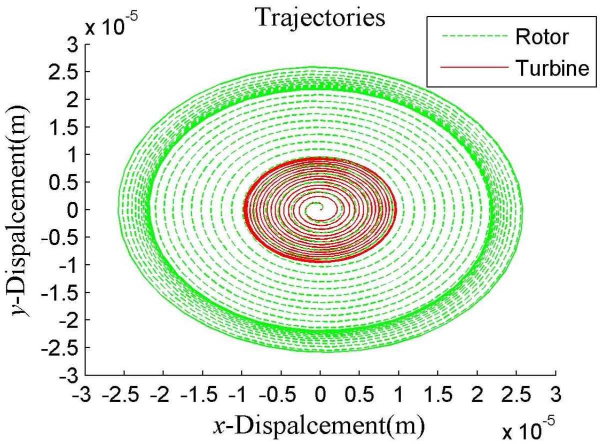

Figure 10. The trajectories of rotators

As the fig.10 shown, the displacements of rotor and turbine are growing with the rotate speed. The trajectories are stable when the rotate speed at the rated point. When the process of voltage build up is started, the field current is increased. The rotor displace-ment is growing because of UMP's increasing as shown in Fig.9, and with the UMP is balanced in fluctuation which is because the value of UMP is concerned with the rotor's displacement, the rotor's trajectories achieved a new stability again. As shown in Fig.11, the axis trajectories' change of upper and lower guide bearings are similar to the rotor's because they provide the directly surpporting to the rotor.

Comparing Fig.10 and Fig.7 & 8, the vibration of rotor system has no influence on the hydraulic transient, because the head and discharge of turbine are stable when the rotor's displacement increased with the UMP.

Under the condition of this paper, the hydraulic force has not taken into consideration for the rotor system movement yet, but the hydraulic transient show its great influence on it. The generator power is zero during the process, so, when the turbine output is increased, the torque for the turbine is increased too, then the eccentric forces become larger with the higher rotate speed, finally, the rotor system vibrate with its ratotion.

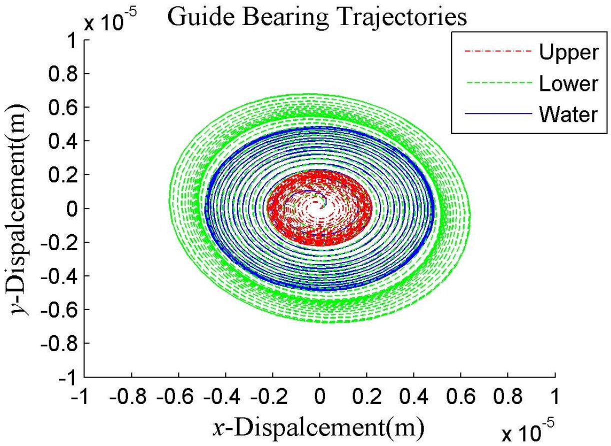

Figure 11. The trajectories of guide bearings' axis

4. Conclusions

In this paper, a whole model of the hydraulic power system was established. The model is used to studying the dynamic characteristics of rotor system when the coupled hydraulic-mechanical-electric factors is considered. The rotor-bearing system is the most important component in the model, meanwhile, the hydraulic, mechanical and electrical subsystems' are built and coupled together. The model is based on reliable mathematic and physical theories, and it gives a good simulation of the process of start-up as shown above.

On the basis of simulation, the results indicate that the hydraulic transient influence the rotor system 's rotation, it reflects the inner connection between the subsystems.

In the furture, the hdyraulic forces on the trubine and the impluse pressure on volute will be considered, a detial generator model will be coupled into the whole model, then, the more process of station operation can be simulated to study on the dynamic characteristics of rotor system.

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