Numerical Simulation on Startup Transient Performance of a Centrifugal Pump

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Abstract

During the rapid startup transient of a centrifugal pump, in order to investigate its transient characteristics, the torque equations are deduced. Based on these equations, numerical simulation is carried out with the Large Eddy Simulation (LES) method and UDFs (User Defined Functions) are applied during the simulation. Comparison between simulation and experiment results of pump heads and rotational speed shows that they are in good agreement, indicating that the dynamic characteristics of this pump can be predicted accurate comparatively through simulation with LES method during its startup process.

Introduction

As we all known, centrifugal pump was applied widely in many filed, such as power engineering, petroleum & chemical, and water supply or other similar industries. As the significant advances are being steadily made in the understanding of the key technical phenomena relating to its running at constant rotating speed, more and more studies are concerned on the transient period of pump or other hydraulic machines. Because its design is not only has close relation with its constant speed also its startup and shutoff period, especially the vibration and hydraulics performance.

Tsukamoto and Ohashi[1] studied the transient outer character of centrifugal pump through experiment in the startup period, its startup time from 0 r/min to 1500r/min (the maximum rotate speed) is 0.15s. They got the idea that the flow rate and water head was lag behind the rotate speed, the experiment showed the obvious transient characteristic. Thanapandi and Prasad [2] investigate the centrifugal pump and its pipeline system at the startup period using the method of characteristics. Wang Leqin and Wu Dazhuan et al. [3~4]studied the hydraulic performance at different startup acceleration of centrifugal pump. The above experiments showed that the characteristic in the startup period is different from the steady state. And also Zhu Wencan[5] and Yu Yonghai [6] simulated the startup process by solving the one dimension models. Tuskamoto et al.[7] proposed a model based on nonviscous linear cascade calculations. The predictions from these models are qualitatively good; the results are far more from the experimental results. As the numerical simulation become a useful tool in the fluid area, there are some people investigate the startup and shutoff process of hydro turbine. In this paper we studied the startup period of centrifugal pump by 3D transient numerical simulation by commercial code FLUENT6.3, and in the computing process we added the volume force source and speed adjustment Marco, and used the Large Eddy Simulation (LES) method as the simulation code. We forecasted the transient development process of hydraulic torque, rotate speed and lift head, and compared the results with the experimental results.

The Toque Equations on the Startup Period

The driving torque is equated to the drag torque in the starting period of centrifugal pump, and the drag torque includes two parts, as equation (1).

$$M_a = M_{pz} + M_{\varpi} \qquad (1)$$

Where, M_a : driving torque of pump shaft;

M_{pz} : drag torque of pump;

M_{ϖ} : inertia drag torque from the pump.

and, $M_{\varpi} = J\,\mathrm{d}\varpi/\mathrm{d}t = C\,\mathrm{d}n/\mathrm{d}t$

where, $C = GD^2/375$, $GD^2 = \pi\left(D_2^4 - D_1^4\right)B\gamma/8$ is the flywheel torque of the pump.

In the starting up period, In order to start up the centrifugal pump form the 0 r/min to normal speed, the driving torque M_a should larger than the drag torque M_{pz}, that is $M_a > M_{pz}$. At the starting up time, the drag torque of the pump M_{pz}, represents the mechanical static friction drag M_{f1},and it has effect only at the starting up time. Once the pump has started, M_{f1} decreased very quickly and become part of the dynamical friction drag M_{f2}.The M_{f2} not only include the M_{f1}, also the friction drag of the bearing and airproof setting and the driving hydraulic torque M_p as in equation (2):

$$M_{pz} = M_{f1} + M_{f2} + M_p \qquad (2)$$

Static Friction Drag Torque

At the starting up time(n=0), the driving electromotor should overcome the mechanical static friction drag, and offer sufficient driving torque for its acceleration, in order to starting up the centrifugal pump. In the simulation, we used the formula (3) as the mechanical static friction drag M_{f1}:

$$M_{f1} = K_{f1} M_d \qquad (3)$$

where, $K_{f1} = 1.6\times10^5/n_d^2$,

n_d : the design rotating speed of the pump,

M_d : the normal torque of centrifugal pump

Dynamical Friction Drag Torque

After the starting up, the mechanical static friction drag M_{f1} decreased, and mechanical dynamical friction drag M_{f2} increased. There are some factors influenced the dynamical friction drag M_{f2},such as the bearing of pump shaft, the airproof setting of pump, the loss from the generator. But as we known, the total amount of the dynamical friction drag M_{f2} is constant, it does not change as the speed. The Loss of power from the mechanical dynamical friction drag M_{f2}, is represented by the mechanical efficiency. Experimented showed that the dynamical friction drag M_{f2} is so small, that is

$$M_{f2} = 1\sim3\% M_d \qquad (4)$$

so we used the dynamical friction drag at the normal speed instead of the mechanical dynamical friction drag in the starting up period,

$$M_{f2} = \left(1/\eta_r - 1\right) M_d \qquad (5)$$

Where, η_r —the normal efficiency of electromotor.

Hydraulic Driving Torque

Hydraulic driving torque concluded from the numerical unsteady simulation process.

Driving Torque of Pump Shaft,

We get the input driving torque of pump shaft, M_a from the starting up experiment.

Mathematic Description in the Starting up Period

From above, the equations in the starting up period can be described as follows:

$$\begin{cases} M_a - \left(M_f + M_p\right) = \dfrac{GD^2}{375}\dfrac{\mathrm{d}n}{\mathrm{d}t} \\ t \le t_1,\ M_f = M_{f1},\ M_p = 0 \\ t > t_1,\ M_f = M_{f2},\ M_p \ne 0 \end{cases} \qquad (6)$$

where , t_1 represents that at that moment $M_a > M_f$,and the centrifugal pump is starting up.

Numerical Simulation of the Starting Up Process

The Model Pump

The model pump in the experiments and simulations is a single stage centrifugal pump. The main specifications of the impeller are summarized in Table 1.

Table 1 Impeller specifications

Geometric specifications		Hydraulic specifications	
Inlet diameter	80mm	Nominal speed	2900r/min
Diameter of impeller	160mm	Nominal flow rate	90 m3/h
Number of vanes	9	Nominal total head	40m

Governing Equations at the Starting up Process

The unsteady governing equations at the starting up process in the rotational relative coordinate system are deduced from Reynolds-averaged continuity and Navier-Stokes equations in the Euler absolute coordinate system. While at the starting up period, the coordinate is being at an accelerated status. The governing equations are as follows:

$$\begin{cases} \dfrac{\partial\rho}{\partial t} + \nabla\bullet\left(\rho \boldsymbol{W}\right) = 0 \\ \dfrac{\partial \boldsymbol{W}}{\partial t} + \boldsymbol{W}\bullet\nabla\boldsymbol{W} = \boldsymbol{f} - \dfrac{1}{\rho}\nabla p + v\Delta\boldsymbol{W} - \dfrac{\partial\boldsymbol{\omega}}{\partial t}\times\boldsymbol{R} - 2\boldsymbol{\omega}\times\boldsymbol{W} - \boldsymbol{\omega}\times\left(\boldsymbol{\omega}\times\boldsymbol{R}\right) \end{cases} \qquad (7)$$

where: ρ is the density of water; W is the absolute velocity vector in the accelerated rotational relative coordinate; f is body force vector; ν is the kinetic viscosity coefficient of water; R is radius vector from the rotational axis to the mass particle; p is the pressure in the absolute coordinate; ω is the rotating speed.

Numerical Simulation Method

The flow passage of the centrifugal pump are divided into four parts for simulation: suction pipeline, impeller, outer chamber and outer pipeline(see fig.1). And the impeller zone should be defined at the rotating coordinate system. For the Moving zones the Moving Mesh technology for the solve of the governing equations are used. At the interface of different parts, the velocity vector should keep continuity and the flux of the physics quantum should be conserved.

Smagorinsky-Lilly model is adopted for Sub–Grid-scale stress in the LES simulation, where, the constant of Smagorinsky Cs＝0.1. The governing equations are discretized with Finite-Volume-Method (FVM). Second-order implicit format are used for time item, second-order central difference format for source and diffusion item, second-order upwind format for convection item, and SIMPLEC method for velocity-pressure coupling solution. The algebra equations after difference are solved by sub-relaxing, the relaxing factor of pressure is 0.3, density is 1.0; body force vector is 1.0, and velocity is 0.7. In the iterative process the time step is 0.01s.

Boundary Condition

Inlet condition: flow rate, turbulent kinematics energy and its dissipation rate should be given in pipeline inlet;

Outlet condition: free outflow condition, and the turbulent has fully development;

Boundary conditions: no-slip condition for the wall, and standard wall function for region near the wall;.

The adjustments of rotational speed and additional body force vector source

From the governing equations in the accelerated rotational relative coordinate, it is known that the following two aspects should be considered in order to realize the simulation of the startup transient:

1. Rotational speed of the impeller increases along with time based on equation (6).
2. Additional source forces should be added during the simulation process.

According to the above consideration, UDFS (User Defined Functions) are made and added into the Fluent code. The simulation process is depicted as Fig.1.

The input torque of pump shaft is got from the experiments and as show in Fig.2. As we all known, the body force vector is $\mathrm{d}(\varpi r e_\theta)/\mathrm{d}t$, and was divided in the X and Y direction. They are all put into the UDFs.

Simulation Results

The starting up process of the centrifugal pump was conducted in the test rig [8], Based on the test results we started the numerical simulation. And we compared the results of the experiments and simulation, Fig 3 showed that the rotate speed change with the time increase. From the result , we can find that the change trends of experimental and numerical simulation are similar, so we thought that the numerical simulation can reflect the starting-up process.

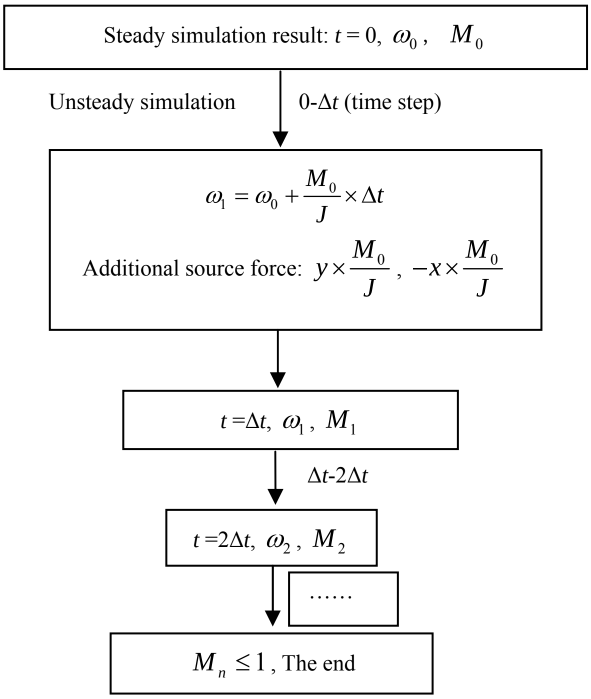


Fig.1 Unsteady simulation process in Fluent6.3 code

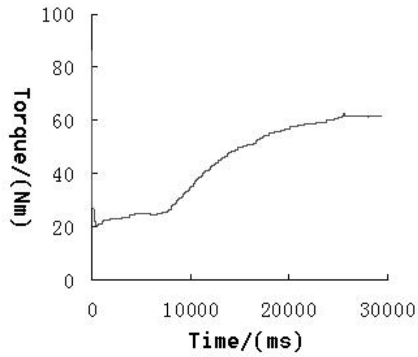


Fig.2 The input torque of pump shaft got from experiment

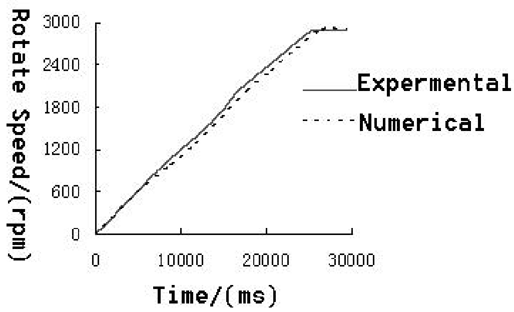


Fig.3 The rotate speed change as time change in the startup process

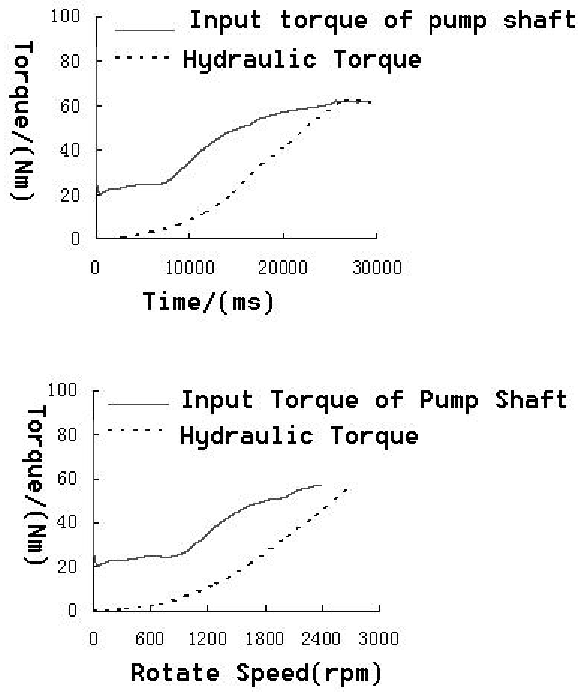


Fig.4 Toque change with the time and rotating speed

From the starting up moment, the input torque of pump shaft dropped from the maximum to the minimum, as the time increased, the torque decreased, the hydraulic torque increased with the time, and the total torque for the acceleration decreased slowly, until zero. At that time, the hydraulic torque equals the input torque of the pump shaft, and the centrifugal pump runs at the normal speed. Fig.4 showed the torque change as time and rotating speed change.

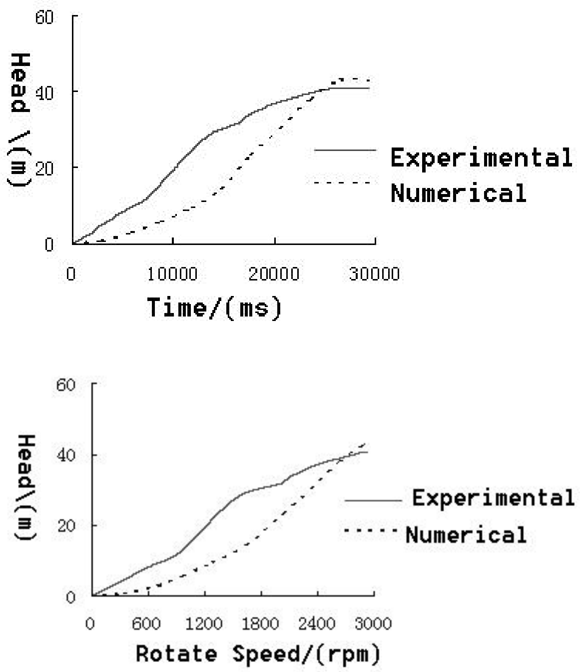
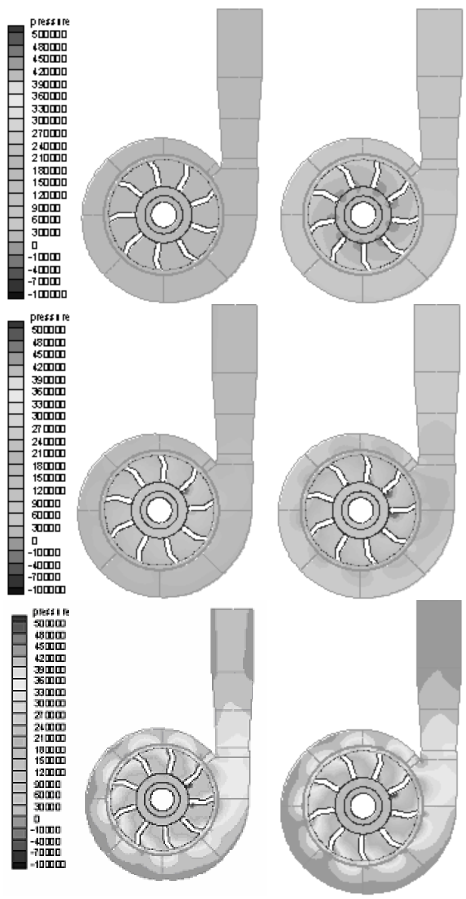


Fig. 5 Head change with the time and rotating speed in startup period

Fig.5 showed the change of the lift head as the time and rotating speed. We can find that the head increased with the time and rotating speed increased, when it reached the normal speed, the centrifugal pump runs smoothly, and the rotate speed and head keeps constant.



(a) t=0s (b) t=6.6s (c) t=13.2s
(d) t=19.8s (e) t=26.4s (f) t=29.7s

Fig.6 Static pressure distribution at different time of the startup period (half length of the vane)

Fig. 6 showed the static pressure distribution of half height of vane at the cross section at different time, we can seen from the chart that the static pressure increased with the time increased .The reason is the absolute velocity of the inlet of impeller is increased with the increased of the rotate speed, From the Bernoulli equation, the absolute velocity increased with the rotate speed, the total energy also increased with the rotate speed, but the outer chamber recovered the kinetic energy, and so the static pressure decreased with the speed.

Conclusion

In a word, there are two main conclusions we can get from above:
1) Comparison between simulation and experiment results shows that thay are in good agreement, indicating that variation of all the main parameters

(rotating speed, lift head and torque) with respect to time can be forecast accurately with the LES method.
2) Solving the transient performance at the starting up period with the adjustments of rotational speed and additional body force vector source has gained a convinced conclusion. The UDFs in Fluent6.3 code is very useful for more deeply investigate the performance of centrifugal pump.
From above, we can investigate the inner flow of pump at the starting up process, and more results will be drawn from the numerical simulation, such as the vibration, and other phenomenon.

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