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Transient Characteristics in a Centrifugal Pump During Rapid Regulating Flowrate

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Abstract: The transient behavior of a centrifugal pump is theoretically analyzed for different transient processes. In the process of starting, stopping and frequency control, transient behavior in centrifugal pump must come into being. In the process of regulating flowrate, there is no transient behavior in centrifugal pump with radial straight vanes, while transient behavior in common centrifugal pump with back curved vanes is directly related to regulating rule of flowrate. The results of numerical simulation show that rotor-stator interaction is strongest when relative position between vane and volute tongue is nearest. The process of regulating flowrate is a coupling process brought by rotor-stator interaction and varying flowrate.

Key words: Centrifugal pump, regulating flowrate, transient behavior, theoretical analysis, sliding mesh, rotor-stator interaction

INTRODUCTION

Centrifugal pump is widely used but most of researches were carried out at stable state. With the development of application field, for example, underwater weapon launch, rapid starting of large pump station, it is more and more necessary to research transient behavior. At present, a little studies have shown that transient effect in centrifugal pump for transient operations is very obvious. The starting and stopping processes (Tsukamoto and Ohashi, 1982; Tsukamoto *et al*., 1986) have been studied the transient characteristics of a centrifugal pump by means of theoretical analysis and experimental study. The results show that the impulsive pressure and the lag in circulation formation around impeller vanes were the main reasons for the difference between dynamic and quasi-steady characteristics. Moreover, they (Tsukamoto *et al*., 1995) studied the dynamic characteristics of centrifugal pump subject to sinusoidal changes in rotational speed. A mixed-flow pump was tested for four transient cases during acceleration and deceleration period (Lefebvre and Barker, 1995). The results showed the quasi-steady hypothesis in predicting the pump performance is unreliable. A volute pump was tested at different valve openings to study the dynamic behavior of the pump during normal startup and stopping (Thanapandi and Prasad, 1995). A method was presented to predict the turbomachinery's transient behavior (Dazin *et al*., 2007). Based on the angular momentum and energy equations, the internal torque, power and head could be solved.

With the transformation of piping system and delivering demand, it is impossible for pump to work at a working condition forever, namely that switching process among different working conditions must occur. It is actually a process of regulating flowrate. At present, transient researches about switching process are few. In this paper, theoretical analysis and numerical calculation would be used to research switching process.

THEORETICAL ANALYSIS

Additional head: The additional head of centrifugal pump during transient operation is as below (Ping *et al*., 2007):

$$H_u = H_{u1}\text{-}H_{u2} \tag{1}$$

$$\left.\begin{aligned} H_{u1} &= \frac{\omega}{\rho g Q_d} \cdot \Omega_J \cdot D^5 \cdot \frac{d\omega}{dt} \\ H_{u2} &= \frac{\omega}{\rho g Q_d} \cdot \Omega_M \cdot D^2 \cdot \frac{dQ_d}{dt} \end{aligned}\right\} \tag{2}$$

where, the first item of Eq. 1 is additional head brought by varying rotational speed, the second item is the additional head brought by varying flowrate.

In the process of starting, stopping and frequency control, rotational speed and flowrate is sharply changed, so in common centrifugal pump with back curved vanes, transient behavior must be brought by two additional head. In centrifugal pump with radial straight vanes,

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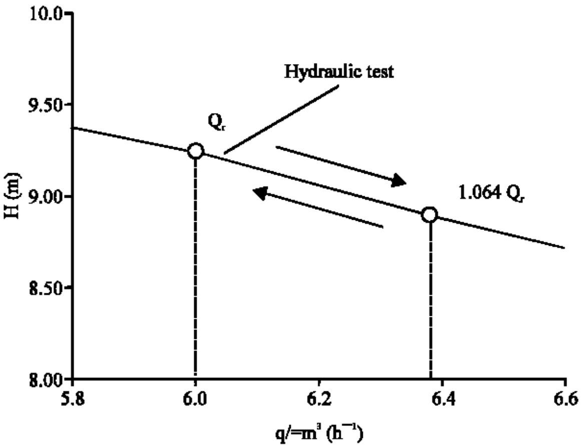

Fig. 1: Selection of transient process

setting angles of vanes at inlet and outlet are both 90°, so flow inertia coefficient of fluid in impeller is about zero, namely:

$$\Omega_M \approx 0 \tag{3}$$

Therefore, the additional head is only brought by the varying rotational speed. In conclusion, transient behavior in any centrifugal pump must come into being for above three transient operations.

In the process of regulating flowrate, rotation speed is nearly constant, therefore:

$$\frac{d\omega}{dt} \approx 0 \tag{4}$$

So, there is no additional head brought by the varying rotational speed, namely that $H_{u1} \approx 0$. And there possiblely is additional head brought by varying flowrate. In centrifugal pump with radial straight vanes, $\Omega_M \approx 0$, so no additional head will be brought, namely that there is no transient behavior. In common centrifugal pump:

$$\Omega_M \neq 0 \tag{5}$$

Therefore, transient behavior is existent. The expression (H_{u2}) shows that transient behavior is related to geometry parameters, rotational speed and regulating rule of flowrate. In the process of increasing flowrate, $dQ_d/dt = 0$, which manifests that additional head will be consumed. Otherwise additional head will be increased. The process is consistent with the tendency of head curve of centrifugal pump.

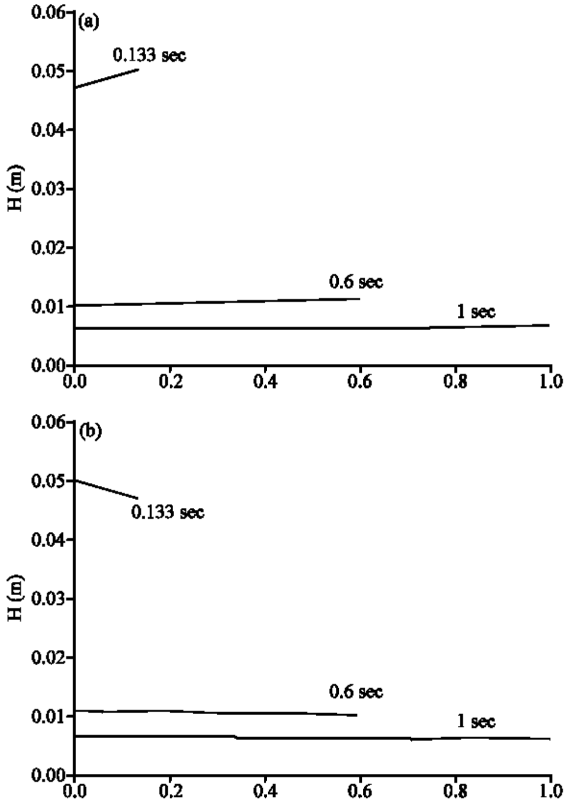

Fig. 2(a-b): Time history of additional head during regulating flowrate, (a) Flowrate decreasement and (b) Flowrate increasement

Table 1: Geometric parameters of centrifugal impeller

Parameter	Value	Parameter	Value
β_1	25°	D_1/m	0.048
β_2	25°	D_2/m	0.160
Z	5	b_1/m	0.0200
ψ_1	0.92	b_2/m	0.010
ψ_2	0.93	D/m	0.160

Results analysis: A low-specific-speed centrifugal pump is used to analyze transient behavior during regulating flowrate. Flowrate is switched between two working conditions and is uniform transformation. Main design parameters of centrifugal pump are as follows. Flowrate is 6 $m^3\ h^{-1}$, head is 8 m, rotational speed is 1450 r min^{-1}, other parameters are in Table1. The part test result and the selection of transient process is shown in Fig. 1.

The transient switching process is between 6 and 6.38 $m^3 h^{-1}$. Regulating time are respectively 0.133, 0.6 and 1 sec. Theory calculation results are shown in Fig. 2. No matter what flowrate is regulated, more additional head will be brought in process of fast regulating. Fig. 2a is the time history of additional head during flowrate decrease. Decreasing flowrate makes additional head gradually increase but absolute value of additional head is still minor. Maximum additional head is only 0.049 m, relative to the difference value (0.35 m) of heads between two working conditions, it isn't very remarkable. So additional head brought by transient behavior isn't main component of increasing head during flowrate decreas, namely that transient behavior isn't very remarkable. The reason for head increase is still explained by interior flow theory of centrifugal pump. Figure 2b is time history of additional head during flowrate increase. With augment of flowrate, additional head will decrease. Absolute value of additional head is also minor, transient behavior isn't very remarkable as well.

NUMERICAL SIMULATION

Calculation method: Transient process from 6-6.38 m^3 h is selected as calculation process. The sliding mesh method and User Defined Functions (UDF) were applied to simulate the three-dimensional unsteady viscous flow during regulating flowrate. At inlet, boundary condition and initial condition are simultaneously gived by UDF:

$$Q(t) = \begin{cases} 6 & t < 0.0207 \\ 6 + 2.857(t - 0.0207) & 0.0207 \le t \le 0.1537 \\ 6.38 & t > 0.1537 \end{cases} \quad (6)$$

where, Q(t) is transient flowrate (m^3/h). At outlet, outflow condition is applied.

No slip boundary condition is adopted on wall. Standard wall function is also adopted to dispose low Reynolds number problem near wall region. SIMPLE algorithm is used to couple velocity and pressure. The relative differences of head are all less than 2%, which confirms that calculation results have nothing to do with grid quantity. Consequently, grid quantity is 974523 in later calculation, part grid result is shown in Fig. 3.

Fluctuation characteristics: Regulating flowrate process is a coupling process brought by rotor-stator interaction and varying flowrate. Initial position of impeller is shown in Fig. 4.

For volute tongue, every revolution has 5 motion periods. The marked channel in Fig. 4 is the first motion period during regulating flowrate. The flow character can be embodied by external performance. After simulation, head will be obtained by the following expression:

$$H = \left\{ \sum_{i=1}^{N} \left(\frac{P}{\rho g} \right)_i \Big/ N + \sum_{i=1}^{N} \left(\frac{v^2}{2_g} \right)_i \Big/ N \right\}_{outlet} - \left\{ \sum_{i=1}^{M} \left(\frac{P}{\rho g} \right)_i \Big/ M + \sum_{i=1}^{M} \left(\frac{v^2}{2_g} \right)_i \Big/ M \right\}_{inlet} + \Delta h \quad (7)$$

In this study, $\Delta h = 0.2$ m. The result is shown in Fig. 5.

In any period, transformation tendency of head is similar. Rotor-stator interaction brings fluctuate character, while varying flowrate makes head decrease as a whole. When the distance between impeller and volute tongue is

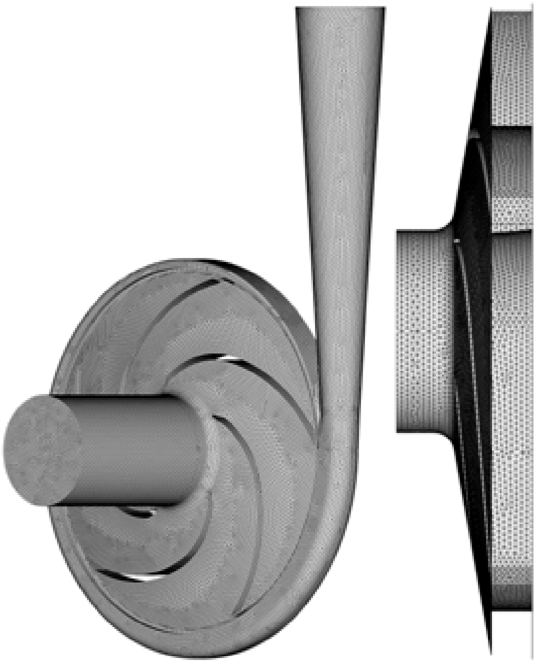

Fig. 3: Grid of calculation region

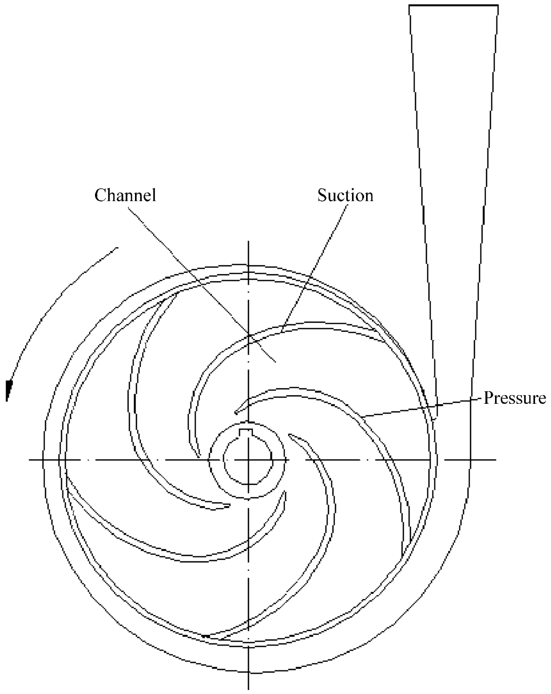

Fig. 4: Initial position diagram

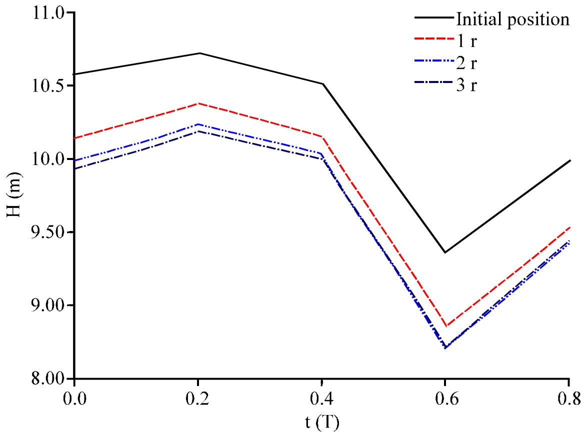

Fig. 5: Head characteristics

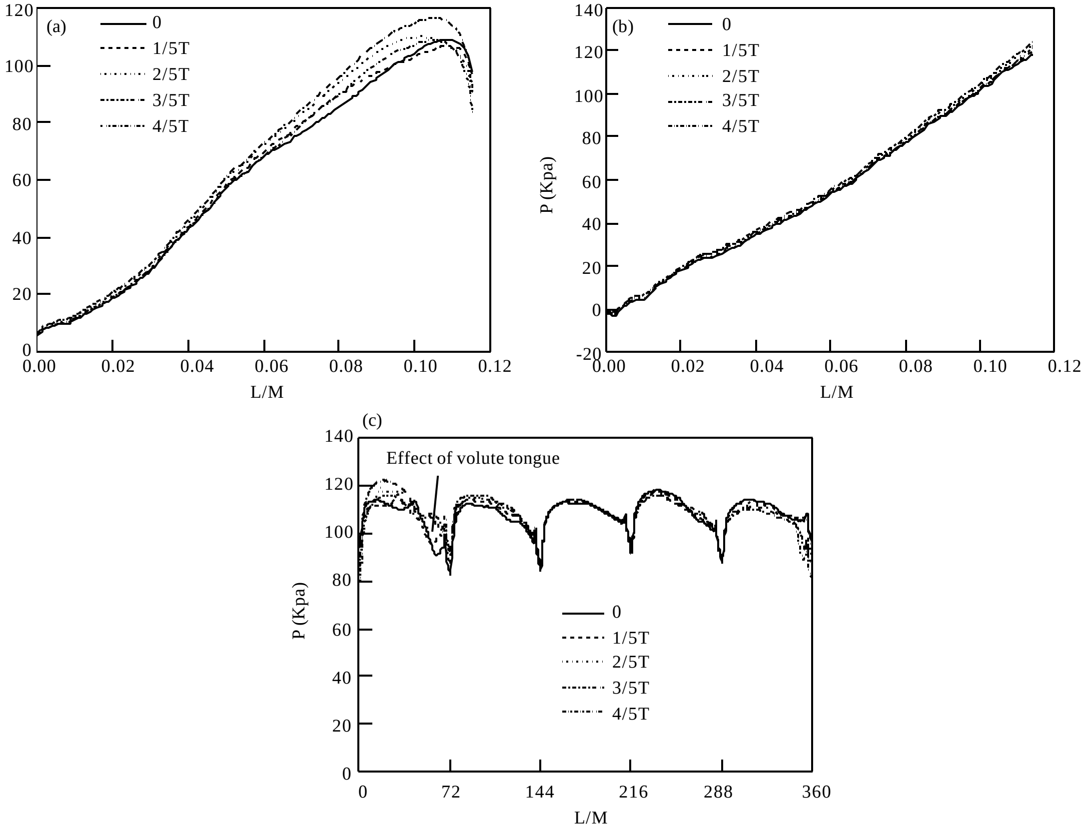

Fig. 6(a-c): Pressure distribution at different moments, (a) Pressure surface, (b) Suction surface and (c) Impeller outlet

minimum (in this paper, the moment is 3/5T), heads will reach minimum, which manifests that rotor-stator interaction is strongest. Rotor-stator interaction is common and inherent in fluid machinery. It isn't completely eliminated and only make it reach minimum by optimization design.

Pressure distribution: In the first motion period during regulating flowrate, pressure distributions of pressure surface, suction surface and impeller outlet on middle section are shown in Fig. 6. When motion moments are all 3/5T in four periods, pressure distributions are shown in Fig. 7. The results show that very strong distinction don't

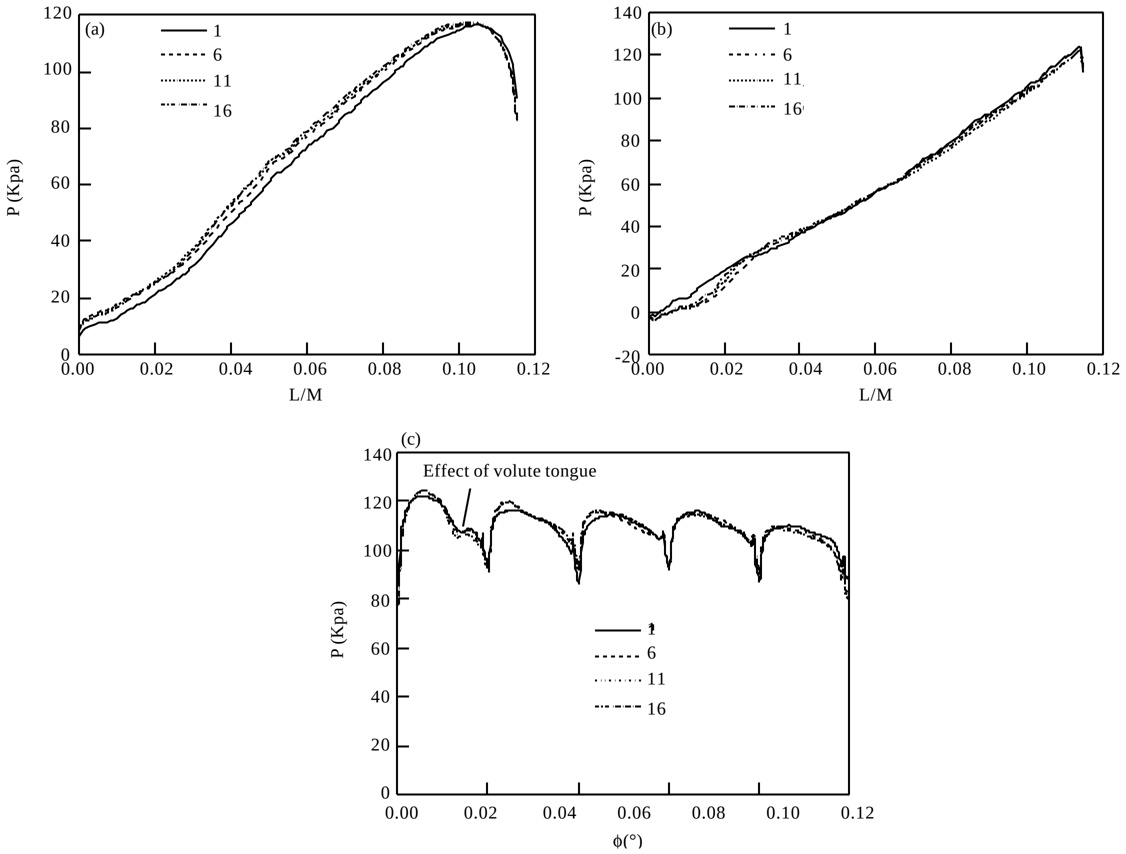

Fig. 7(a-c): Pressure distributionat at different periods (3/5T), (a) Pressure surface, (b) Suction surface and (c) Impeller outlet

appear, the reasons maybe are as follows. Too short time makes interior and external performances appear unobvious distinction. Strong rotor-stator interaction makes inherent fluctuation appear. Increasing flowrate restrains boundary layer and weakens flow separation phenomenon. Rossby dimensionless number can reflect the influence of vane curvature and rotation on backflow in impeller. Increasing flowrate makes relative velocity in channel gradually augment, Rossby dimensionless number simultaneously augment, so inertial force will gradually enhance. With the augment of radius, pressures on pressure surface and suction surface will gradually augment. At the same radius, pressure on pressure surface is greater than pressure on suction surface. Some vacuum degree appears at inlet of suction surface and the place easy appears cavitation phenomena. Low pressure regions appear at outlet of pressure surface and suction surface but decrease value of former more than latter. In this paper, volute is spiral. Space distribution of vanes will theoretically bring periodic distributions and is proportional to vane numbers. For rotor-stator interaction and model tolerance, parameter distribution at impeller outlet appears tiny tolerance at any period.

Flow field analysis: In the first motion period, the distributions of flow field parameters are in Fig. 8. Pressure gradually decrease from pressure surface to suction surface, while regularly increase from inlet to outlet. Action force and centrifugal force formed by pressure difference between pressure surface and suction surface are consistent with rotation direction of centrifugal pump, which completely accords with reality of centrifugal pump. Combination action of rotor-stator interaction and varying flowrate makes pressure distribution in volute variation. High pressure region is widest when the moment is 1/5 T and is straitest when the moment is 3/5 T.

Fig. 8(a-d): Pressure distribution, (a)0, (b)1/5T, (c)2/5T, (d)3/5T and (e) 4/5T

CONCLUSIONS

In the process of regulating flowrate, there is no transient behavior in centrifugal pump with radial straight vanes. Transient behavior in common centrifugal pump with back curved vanes is directly related to regulating rule of flowrate. The rotor-stator interaction is strongest when relative position between vane and volute tongue is nearest. The process of regulating flowrate is a coupling process brought by rotor-stator interaction and varying flowrate.

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