

Investigation on complete characteristics and hydraulic transient of centrifugal pump[†]

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Abstract

An improved method was developed to obtain the complete characteristic of centrifugal pump. The conversion formula of complete characteristics is established based on the normal performance curve. An example was presented to illuminate the new method, and the complete characteristic curves of 14SA-10 centrifugal pump were obtained by the new method. The hydraulic transient of the centrifugal pump failure and start-up was simulated by method of characteristics (MOC), which quote the complete characteristics data. The results show that the inversion method is available to obtain the complete pump characteristic curves provided the normal performance curve. For hydraulic transient simulation, more accurate numerical result can be obtained, if the new model is adopted to convert the experimental normal performance curve to complete characteristics curve of centrifugal pump.

Keywords: Centrifugal pump; Hydraulic transient; Complete characteristics; Performance curve

1. Introduction

Hydraulic transient usually happen during the pump failure and start-up. The simulation and control of hydraulic pressure is significant to the stability and safety of the pipeline system. There are some methods to simulate the hydraulic transient of pump failure and start-up, including graphic method, analytic method and method of characteristics. Method of characteristics is used widely to compute the hydraulic transient of pump failure and start-up [1, 2]. Many cases of pump hydraulic transient were simulated by such numerical method. Spence [3] computed the hydraulic oscillation in the pipeline with pump. Chen [4] simulated the hydraulic transient of pump start-up. Rao [5] simulated the hydraulic transient of pump failure. Sridharan [6] researched the hydraulic transient of interlinked pumping mains. Rizwan [7] researched the steady characteristic of pump by the transient numerical model. These studies have shown that the MOC is convenient to compute the hydraulic transient of pump failure or start-up. However, the complete characteristics of the pump are necessary when the MOC is applied to the hydraulic transient simulation. According to the dimensional similarity principle, Marchal, Flesh and

Suter [8] developed the complete characteristic curves of pump, which includes only two curves and can represent the pump's complete characteristics at various rotate speed. However, complex experiments are usually required to gain the complete characteristic curves [9, 10]. In fact, manufactory can only supply normal performance curve which can also be predicted by some numerical methods [11, 12]. However, it is difficult to gain the complete characteristic curves by experiments or numerical simulations. In order to avoid the expensive experiments, researchers developed many fitting methods to gain the complete characteristic curves. Zhang [13] developed the complete characteristic curves by B-spine interpolation. Shao [14] gained the curves by surface fitting and least square method. Liu [15] developed the neural network model to compute the complete characteristic curves. Berndt [16] investigates the complete characteristic curves of large scroll pumps. These literatures present methods to get complete characteristic curves based on the specific speed. However, these methods strongly depend on other known complete characteristic curves, and can gain the approximate data. The fitting curves may give some inaccurate results when they are applied to the fluid transient simulations. A new inversion method was presented in this paper, based on the experimental normal performance curve from the manufactory. The method gives a formula to transform the normal performance curve into the complete characteristic curves. An example is pre-

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sented to illustrate the method. Considering the available experimental data was limited, an extension method was also established to obtain the whole complete characteristic curves data.

2. Operation zones analysis

2.1 Complete characteristic curves and normal performance curve

Pump’s complete characteristic curves represents the unstable characteristics of pump, which include the complex relationship among the flow rate, pumping head and torque at the varying rotation speeds. It is the foundation of pump’s hydraulic transient simulation. The performance curve of pump represents only the stable characteristic of pump at the rated rotation speed. It consists of flow-head curve $Q-H$, flow-energy curve $Q-P$ and flow-efficiency curve $Q-\eta$. Because performance curves are the characteristics at the constant speed, it can’t be directly applied to simulation of pump’s hydraulic transients.

2.2 Operation zones and digital complete characteristic curves

Pump characteristics consist mainly of pump head H , flow rate Q , speed N and torque T . There are only two independent variables and other two variables are correlative with them. In dimensionless scheme, all these variables can be expressed as:

$$\alpha = \frac{N}{N_R}, \quad v = \frac{Q}{Q_R}, \quad h = \frac{H}{H_R}, \quad \beta = \frac{T}{T_R}$$

where α is the dimensionless speed; v is the dimensionless flow rate; h is the dimensionless pumping head; β is the dimensionless torque; Q_R is the rated flow; N_R is the rated speed; H_R is the rated head and T_R is the rated torque. Given α , v/α and h/α^2 represent the pump head curve, as well as v/α and β/α^2 represent the torque curve of pump. In fact, there are different curve for different speed α . The complete characteristics of pump can be expressed only by curves system. It is difficult to apply directly these curves to hydraulic transient numerical simulation, since these relationships consist of many curves.

In order to apply these curves to simulation of hydraulic transients, Marchal et al. [8] used only two curves to represent the complete characteristics of pump. The Suter’s scheme can be written as:

$$\left. \begin{aligned} Wh(x) &= \frac{h}{\alpha^2 + v^2} \\ Wb(x) &= \frac{\beta}{\alpha^2 + v^2} \\ x &= \pi + \arctan \frac{v}{\alpha} \end{aligned} \right\} \quad (1)$$

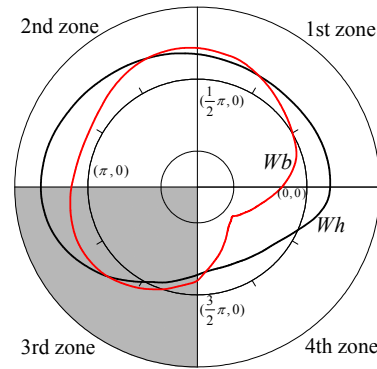


Fig. 1. Operation zones in polar coordinate system.

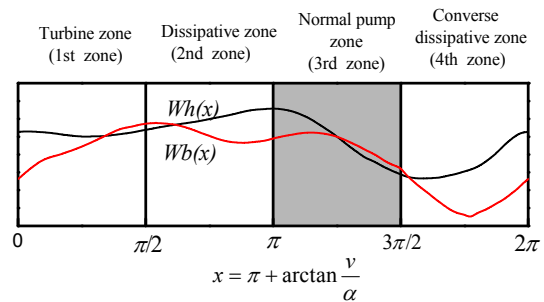


Fig. 2. Operation zones in rectangular coordinate system.

In this equation, $Wh(x)$ is the head curve; $Wb(x)$ is the torque curve. $x = \pi + \arctan \frac{v}{\alpha}$ is the independent variable in the domain $(0, 2\pi)$. The two curves established by this equation represent all unstable characteristics of pump, so it named complete characteristic curves of pump. According to the α and v , pump’s operation is divided into four pattern zones [1]. As shown in Fig. 1, the area $0 < x < \pi/2$ ($\alpha < 0, v \leq 0$) is the turbine zone (1st zone); the area $\pi/2 < x < \pi$ ($\alpha \geq 0, v < 0$) is the dissipative zone (2nd zone); the area $\pi < x < 3\pi/2$ ($\alpha \geq 0, v \geq 0$) is the normal zone (3rd zone); the area $3\pi/2 < x < 2\pi$ ($\alpha < 0, v > 0$) is the converse dissipative zone (4th zone). These zones can be also expressed in rectangular coordinate system. As shown in Fig. 2, the 3rd zone (shadow area) is the pump normal operation area, which is the focus of the research.

Pump’s complete characteristics consist of head curve Wh and torque curve Wb , both of which can’t be represented by continuous regular functions for computer use. In order to use the curves for the computer, the curves will be stored as data arrays in computer. The complete characteristic curves are equally divided into 88 segments and 89 data points. The segment between two adjacent points is used to substitute for the correlative practical curve shown in Fig. 3. Since reverse speed and flow is possible, the independent variables v and α include the real number field. It is difficult to get the complete characteristic curves by experiments. In order to gain the complete characteristic curves based on the manufactory’s experimental normal performance curve, the inversion model of the complete characteristic curves was established.

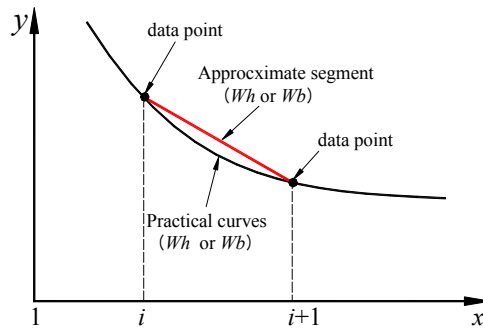


Fig. 3. Approximate substitute for complete characteristic curves.

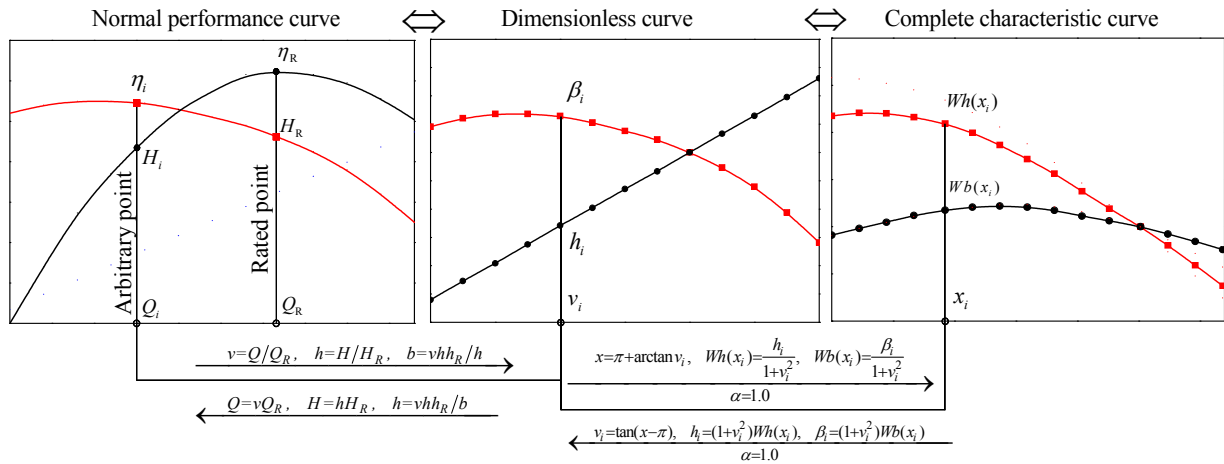


Fig. 4. The flow chart and basic principle of inverse method.

3. Inverse model for complete characteristic curves

3.1 Mapping analysis of characteristics curve

Complete characteristic curves stand for the unstable flow characteristics and performance curve stand for stable flow characteristics of pump. The normal performance curve can be considered as the curve Wh and Wb at the rated speed ($\alpha = 1.0$). The $Wh(x)$ and the $Wb(x)$ are only dependent on the x , though x is dependent on α and v , which meet the equation $\pi + \arctan(v/\alpha) = x$, the Wh and Wb can just be obtained. If there are a known condition point α_0, v_0, h_0 and β_0 , the $Wh(x) = \frac{h_0}{\alpha_0^2 + v_0^2}$ and the $Wb(x) = \frac{\beta_0}{\alpha_0^2 + v_0^2}$ can be obtained, in this formula $x = x_0 = \pi + \arctan(v_0/\alpha_0)$.

As shown, for $\exists(\alpha, v) \in \left\{ (\alpha, v) \mid \pi + \arctan \frac{v}{\alpha} = x_0 \right\}$ in the normal performance curve, the condition point can give the value of $Wh(x) = \frac{h_0}{\alpha_0^2 + v_0^2}$ and $Wb(x) = \frac{\beta_0}{\alpha_0^2 + v_0^2}$. In other words, any point at the normal performance curve can always deduce a point in complete characteristic curves. For $\forall x_0 \in (\pi, \frac{3}{2}\pi)$, $\exists(\alpha_0, v_0)$ in the performance curve can meet $\pi + \arctan \frac{v_0}{\alpha_0} = x_0$. The complete characteristic curves at the 3rd zone can be obtained, since point x_0 can be established

according to the performance curve. The speed $\alpha = 1.0$ is specific constant when pump work at the stable conditions.

3.2 Inversion model

Above analysis shown that the 3rd zone complete characteristic curves can be obtained based on the performance curve of pump. The inversion principle and the solutions process of the curve can be illustrated by Fig. 4. The performance curves often include the pump head curve and efficient curve at the rated speed. However, the torque curve isn't directly included in the performance curves, which needs to be computed by other variables. After all variables is transformed into dimensionless variables, the complete characteristic curves Wh and Wb can be obtained by the dimensionless variables.

According to the dependent relationship, the dimensionless torque can be expressed as:

$$\beta = \frac{T}{T_R} = \frac{QH\gamma/\eta\omega}{Q_R H_R \gamma / \eta_R \omega_R} = v h \eta_R / \eta. \tag{2}$$

In this equation, ω is the speed, ω_R is the rated speed, η is the efficiency; η_R is the rated efficiency at the best efficiency point (BEP).

As shown in Fig. 4, the dimensionless performance curves

can be obtained according to these origin variables of performance curves, which include the head curve and torque curve. Provided $\alpha = 1.0$, the $\forall(v_i, h_i, \beta_i)$ in the curve can give the point $(x_i, Wh(x_i))$ and $(x_i, Wb(x_i))$ of the complete characteristic curves. The 3rd zone complete characteristic curves Wh can be expressed as

$$\left. \begin{aligned} x_i &= \pi + \arctan v_i \\ Wh(x) &= \frac{h_i}{1 + v_i^2} \end{aligned} \right\} v \in [0, \infty), \quad x \in [\pi, \frac{3}{2}\pi]. \quad (3)$$

Analogously, the 3rd zone complete characteristic curves Wb can be expressed as:

$$\left. \begin{aligned} x_i &= \pi + \arctan v_i \\ Wb(x) &= \frac{\beta_i}{1 + v_i^2} \end{aligned} \right\} v \in [0, \infty), \quad x \in [\pi, \frac{3}{2}\pi]. \quad (4)$$

According to the equations, provided $\alpha = 1.0$, the $Wh(x_i)$ and $Wb(x_i)$ can be computed by applying the v_i , h_i and β_i to the Eqs. (3) and (4). Above analysis show that every experimental data point of normal performance curve can be used to deduce a data point of complete characteristic curves. For a whole normal performance curve, the 3rd zone's complete characteristic curves can be gained by the inversion method.

As shown in this paper, the inversion method was established without any approximate assumptions. Its reliability is dependent on the performance curve which is the observed data from the experiment. Because the approximate error is avoided in this computation, the method has more theoretical foundation than the traditional fitting method. However, considering the condition $v \in [0, \infty)$, only 3rd zone's curve can be obtained by the method.

4. The application procedure and discussion

4.1 Application procedure of inversion method

A case was presented following to illustrate the application procedure of inversion method. Fig. 5 shows the normal performance curve of 14SA-10 centrifugal pump, in which only head curve and efficiency curve are shown. The pump characteristic curve can be supplied by manufactory. All rated variables can be gained according to the BEP, $Q_R = 0.32 \text{ m}^3/\text{s}$, $H_R = 66 \text{ m}$, $P_R = 240 \text{ Kw}$, $\eta_R = 89\%$. The flow rate, head and efficiency can be expressed as dimensionless number according to the performance curve. The dimensionless torque can be established by the Eq. (2). Fig. 6 showed the dimensionless performance curve.

The area $(\pi, \frac{3}{2}\pi)$ includes 23 data points according to Suter's digital scheme. In order to meet the storage scheme, the sequence was defined as $v_i = \tan(\frac{i\pi}{44})$, $i = 0, 1, 2, 3, \dots$, $x_i = \pi + \arctan v_i = \pi + \frac{i\pi}{44}$. The $Wh(x_i) = \frac{h_i}{1 + v_i^2}$ and

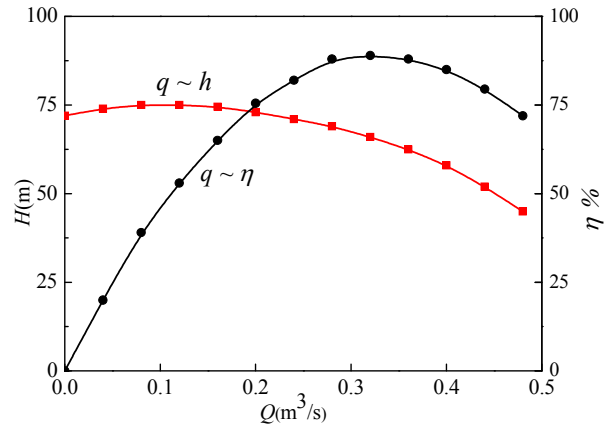


Fig. 5. Centrifugal pump performance curve.

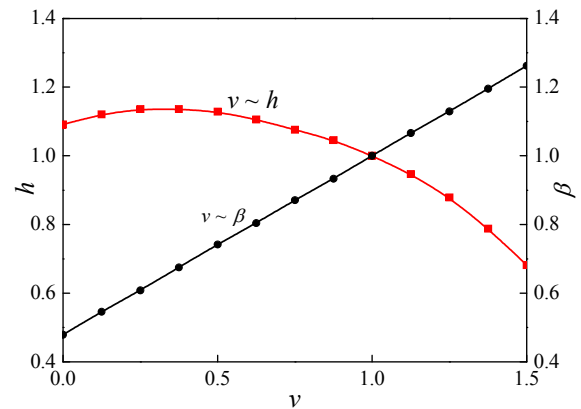


Fig. 6. Dimensionless performance curve.

$Wb(x_i) = \frac{\beta_i}{1 + v_i^2}$ can be obtained according to the correlative (α_i, h_i, β_i) . The value was full in the 5-6 column of Table 1 and the correlative curve was drawn according to these data. Fig. 7 showed the complete characteristic curves Wh and Wb . Specially, only 17 of 23 data points were predicted by the inversion method because the experimental data was limited. However these data points can represent almost all complete characteristic curves of 3rd zone.

In order to compare the proposed method with traditional method, the traditional fitting method is presented here. The specific speed of the centrifugal pump is computed as:

$$N_s = N \sqrt{Q_R} / H_R^{\frac{3}{4}} = 35.42. \quad (5)$$

According to Hollander's experimental data [1] for $N_s = 35$, 147 and 261, the fitting data was shown in column 7-8 of Table 1. Fig. 7 showed the complete characteristic curves based on the traditional fitting method.

Fig. 7 includes 17 data points in 3rd zone by different methods. Comparing with the fitting model, the inversion method gave the same trend in the complete characteristic curves. The figure shows that complete characteristic curves can be predicted by reverse tracking the pump's performance curve. The

Table 1. complete characteristic data.

v_i	x_i	h_i	β_i	Inversion		Fitting	
				$Wh(x_i)$	$Wb(x_i)$	$Wh(x_i)$	$Wb(x_i)$
0.00	3.14	1.087	0.479	1.087	0.479	1.291	0.457
0.07	3.21	1.109	0.516	1.104	0.513	1.284	0.492
0.14	3.28	1.122	0.552	1.100	0.541	1.262	0.524
0.22	3.35	1.133	0.594	1.081	0.567	1.226	0.555
0.29	3.43	1.135	0.630	1.047	0.581	1.172	0.581
0.37	3.50	1.135	0.672	0.998	0.591	1.106	0.604
0.46	3.57	1.131	0.719	0.933	0.593	1.030	0.617
0.55	3.64	1.118	0.766	0.858	0.588	0.941	0.618
0.64	3.71	1.102	0.813	0.782	0.577	0.841	0.606
0.75	3.78	1.075	0.870	0.688	0.557	0.733	0.582
0.87	3.85	1.046	0.932	0.595	0.530	0.617	0.546
1.00	3.93	1.000	1.000	0.500	0.500	0.500	0.500
1.15	4.00	0.932	1.078	0.401	0.464	0.368	0.432
1.33	4.07	0.819	1.172	0.296	0.423	0.240	0.360
1.55	4.14	0.637	1.286	0.187	0.378	0.124	0.287

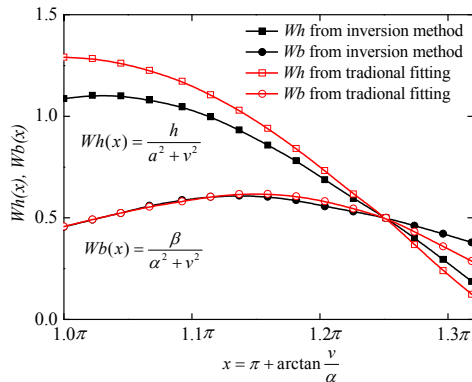


Fig. 7. Comparison of different method (17 data points in 3rd zone).

predictions from inversion method and the traditional fitting have similar tendency, but there are different value between two results. The reliability comparison will be presented in next section.

4.2 Model verification and discussions of model limitations

In fact, no assumption was made during the derivation process, so the inverse model has good theoretic foundation and avoids unnecessary errors from approximate assumptions. In order to corroborate the model, the comparison of experiment and computation will be presented. Head curve of pump is available from manufactory, which was obtained from experimental observation in the stable conditions. Since complete characteristic curves represent all unstable conditions as well as stable conditions, head curve can be gained by numerical method according to the known complete characteristic curves. Two kinds of complete characteristic curves data

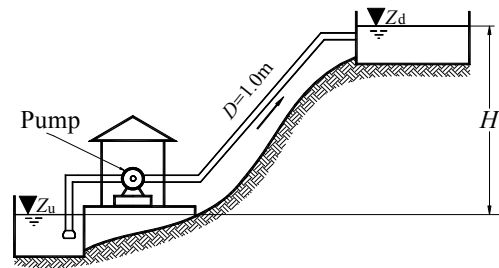


Fig. 8. Pump pipeline system.

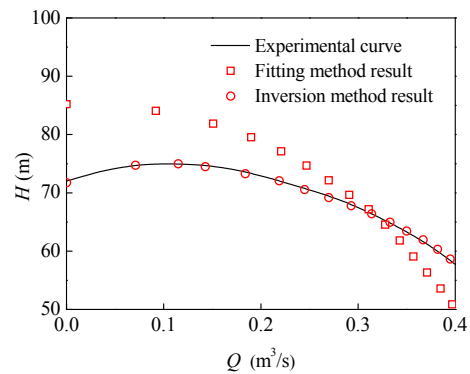


Fig. 9. Comparison of numerical result.

were applied to the MOC numerical model to compute the gradually unsteady process in 3rd zone with different hydraulic pressure. The computation is completed by transient simulation with two different complete characteristic curves data, one of them is inversion data and the other is traditional fitting data.

The pump system shown in Fig. 8 was computed by different complete characteristic data. Fig. 9 include results from two transient simulation and experiment data from manufactory, the example prove the inversion curve based on the performance curve is more close to the experiment data. In this figure, different points with symbols (\square and \circ) are the predictions of complete characteristic curves obtained separately from traditional fitting method and inversion method, and the line is the experimental result. As shown in the figure, the results obtained by the inversion method are more close to the experimental curve than those by the fitting method. Comparison between simulations and experimental curve showed that the inversion complete characteristic curves are more reasonable. Since it was established based on the experimental data, the inversion method can give more reasonable results in pump's transient simulations. In fact, the fitting complete characteristics curve brings on some approximate error. As demonstrated in Fig. 9, the result based on inversion method match well with the experimental curve. Especially, the process also proved that normal performance curve can be computed by numerical simulation based complete characteristics curve.

In order to analyze the application scope of inversion

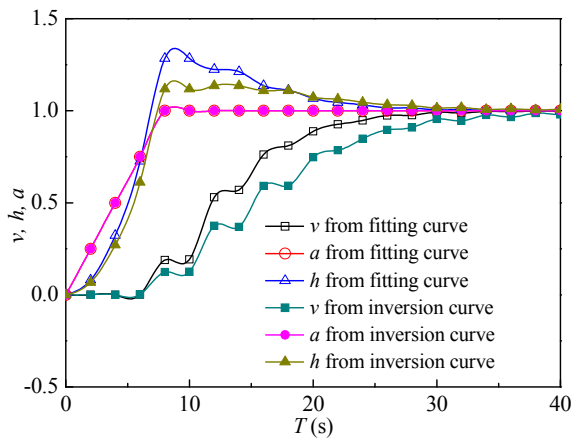


Fig. 10. 14SA-10 pump start-up transient.

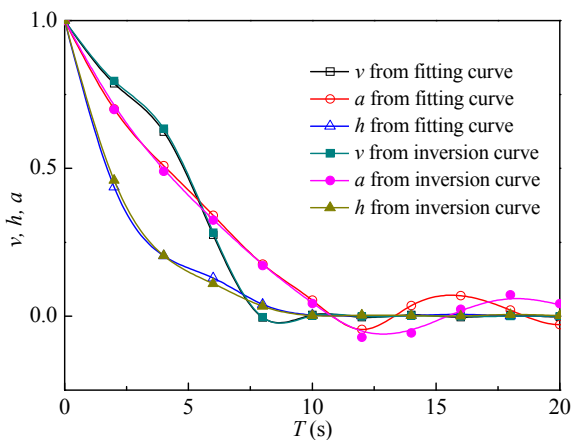


Fig. 11. Pump failure transient with one way valve.

method, different conditions were discussed in this section. The instantaneous characteristics ($x = \pi + \arctan \frac{v}{\alpha}$) were trailed during the transient simulation process. The scope of application was analyzed by comparing the tracked characteristic data with the inversion data. For the example, the pump system shown in the Fig. 8 is the 14SA-10 centrifugal pump. The pipe is 2000 m in length and 1.0 m in diameter. Considering the one way valve, the common start-up and failure process were simulated by MOC with different complete characteristic curves data. Fig. 10 showed the course of speed, flow and head during the start-up. It showed there are no reverse speed or flow in the transient process. The complete characteristic data have some influence on the transient process, though the trend was similar. Fig. 11 shows the trail of variables during the pump failure process. It indicates that the complete characteristic data has insignificant influence on the course of the transient process. Both of complete characteristic data were used in the example and the results have some difference. Fig. 12 is important to illustrate the scope of application, which showed the tracked data $x = \pi + \arctan \frac{v}{\alpha}$ during the transient process. In fact, only part 3rd zone's data ($1\pi,$

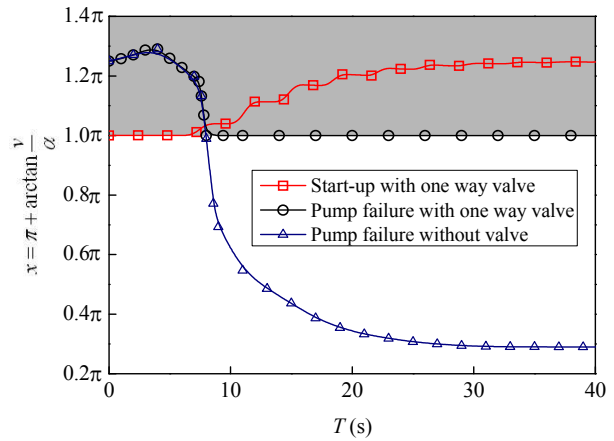


Fig. 12. The tracked data process during the transient process.

1.5π) was used in the simulation. Moreover, all data used are located in the shadow area, which is within the range covered by the complete characteristic data from inversion method based on the performance curve. The result showed that the complete characteristic data of inversion model is capable of simulating the common pump failure and start-up transient process.

4.3 Extension of the curve to other zones

Only in 3rd zone, the complete characteristic curves can be obtained by the inversion model. It is available for the condition without reverse speed and flow. However, reverse speed and flow will also happen in some special conditions, such as pump's runaway speed without one way valve.

Pump's runaway transient process needs to be simulated if there is no one way valve to prevent reverse speed or flow. Other zones' complete characteristic data may be necessary, because the reverse speed and flow may happen in this kind of special transient process. However, because only the 3rd zone's complete characteristic data can be obtained by the inversion model, it's difficult to simulate the runaway transient process of pump. The extension method was presented below to extend the limited data area of the inversion model.

For the pump failure transient process without one way valve, the trail in the Fig. 12 shows the tracked data $x = \pi + \arctan \frac{v}{\alpha}$ during the transient process. As shown in the figure, the tracked point falls into the 2nd zone at the time t_1 . It shows that the inversion data (shadow area) can't cover the whole transient process. In order to meet the need, the inversion curves need to be extended to other zones. A method is presented, and the other zone's data is substituted by the correlative data of fitting method. Fig. 13 showed the extended curve by substituting the fitting data for the necessary data in other zones. Fig. 14 showed the pattern variables process during the pump failure transient process. The result showed that the hydraulic variables is slight different in the 3rd zone in which different complete characteristic data was adopted. There is almost same variables process in 1st and 2nd

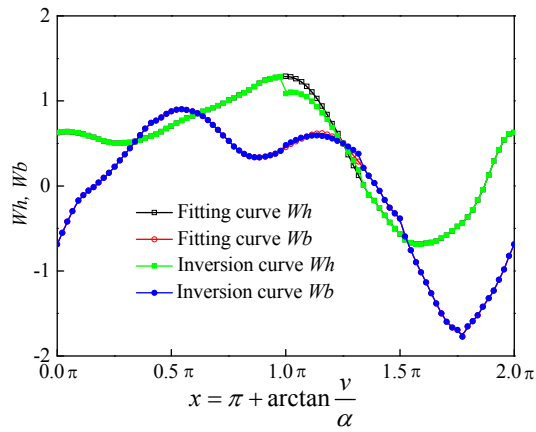


Fig. 13. The extended complete characteristic curves.

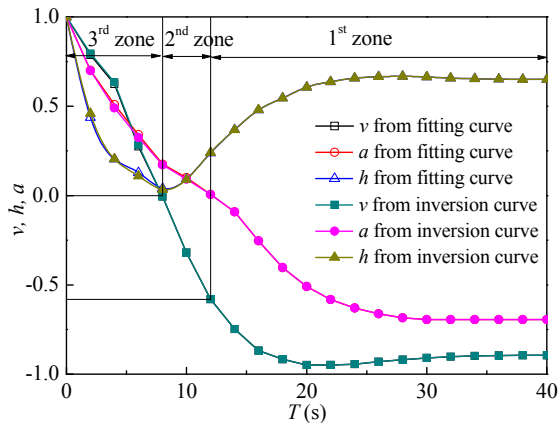


Fig. 14. The transient simulation without valve.

zones because only the same fitting complete characteristic data is available in these zones (turbine zone and reverse zone).

The results also show that the valves preventing reverse flow and speed have great influence on the transient process. For pump system with one way valve, inversion model is capable of simulating the transient process. For the computation of runaway speed, the extension of complete characteristic curves is needed to simulate the pump failure transient process. The extension method is to substitute the fitting data for the undetermined in the 1st, 2nd and 4th zones' data. Then the final complete characteristic curves are available to all kinds of pump transient processes.

5. Conclusions

There are some inevitable relationship between complete characteristic curves and normal performance curve of centrifugal pump. By analyzing the characteristic of these curves, the inversion model of pump's complete characteristic curves was established in this paper. It sets up the transformation formula from normal performance curve to complete characteristic curves of pump. The inversion model can be used as an effective tool to obtain the complete characteristic curves

based on the experimental data of normal performance curve for centrifugal pump. With more theoretical foundation and experimental data, the inversion method can give more reasonable results to describe the pump's transient process. As shown in the comparison figure, the results from the inversion method can math well with experimental result. Based on the performance curve, only 3rd zone's data can be obtained, which is the limitation of this method. However, the method is good enough to simulate common pump failure and start-up transient process without reverse speed and flow. For the simulation of runaway transient process with reverse speed and flow, the extension method was presented to extend the inversion complete characteristic data. By substituting the fitting data for the inversion curve in other zones, the whole complete characteristic curves of pump can be obtained. This method is convenient for applications to all kind of pump's transient process. Using the performance curve supplied by the manufactory, the inversion method can be used to derive the complete curve.

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Nomenclature

- Q : Instantaneous discharge of pump (m^3/s)
- H : Piezometric head, dynamic head (m)
- P : Power produced by a turbine (w)
- η : Pump efficiency
- N : Rotational speed of pump (rpm)
- T : Instantaneous torque of pump (Nm)
- N_R : Rated rotational speed of pump (rpm)
- Q_R : Rated discharge of pump (m^3/s)
- H_R : Rated pressure head (m)
- T_R : Rated torque of pump (Nm)
- η_R : Rated efficiency
- α : Dimensionless speed ratio
- v : Dimensionless velocity
- h : Dimensionless pressure head
- β : Dimensionless torque ratio
- Wh : Dimensionless head characteristics of pump
- Wb : Dimensionless torque characteristics of pump
- x : Instantaneous position of pump operation
- x_0 : Known point of pump operation
- a_0 : Known dimensionless speed
- v_0 : Known dimensionless velocity
- H_0 : Known dimensionless pressure head
- β_0 : Known dimensionless torque ratio
- i : Subscript for an operation point

- γ : Unit weight of water (N/m³)
 ω : Angular velocity of turbine (rad/s)
 ω_R : Rated angular velocity (rad/s)
 Z_u : Upstream water level (m)
 Z_d : Downstream water level (m)
 D : Diameter of pipe (m)

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