Non-dimensional study on the start-up process of a centrifugal pump and its related pipe system

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Abstract. Hydraulic transient processes sometimes bring with it violent or dramatic unsteady phenomenon, which would interfere the normal operation or even damage the system. The start-up of a centrifugal pump with cavitation can lead to serious transient phenomenon. One dimensional calculation (Method of characteristics) was widely used to solve transient problems, but its drawback is lacking of details for the flow characteristics inside the pump, 3D simulation for transient process simulation needs huge computer resources. A simulation method that coupled MOC and 3D simulation (CFD) was frequently used for solving complex transient problems in these years. The results of the coupling simulation are usually complex when cavitation happens and disappears quickly during the short start-up period, a simplified method to describe the process is necessary. A centrifugal pump and its related system were simulated with a coupling method. Dimensionless mass flow rate, head and cavitation conditions of the pump was used to analyse the start-up process. It was proved that the non-dimensional study method can make the whole process more intuitive and easier to understand.

1. Introduction

Pumps are acting more and more important roles in daily life, economic production and firefighting. As a pump never works without the pipeline system, the study of pump cannot focus on the pump only. Hydraulic transient processes sometimes bring with it violent or dramatic unsteady phenomenon, which will interfere the normal operation or even damage the system. The situation will be more complex if cavitation is also considered. However, the hydraulic systems usually combine with kilometers pipelines and hydraulic facilities, between which, the mutual influence under transient processes cannot be ignored. However, this kind of interaction between the pump and the system cannot be well predicted when the pump or pipeline is simulated separately. Coupling of 1D (for the pipeline part) and 3D (for the hydraulic machines part) simulation thereby came to people’s eyes because of its efficiency and accuracy [1].

The startup process of a pump and its related system was simulated with the coupling simulation method, the coupling method and simulation results are introduced in earlier works [2-3]. After the simulation, the startup process was analyzed with dimensionless parameters. With this non-dimensional study method, the startup process of a centrifugal pump was no more a specific case but a case that shares common characteristics of similar pumps.

2. Models and simulation methods
The coupling simulation method was implemented in a pump and its related system. The layout of the pump system was shown in figure 1. The simulation results are compared to the results from the pump start up experiment carried out in LML laboratory (Lille, France) by Duplaa [4-6].

In this research, both cavitation and non-cavitation conditions during the startup process were studied. The pressure in the tank was set to $5 \times 10^5$ Pa for cavitation condition and $3.5 \times 10^5$ Pa for the non-cavitation condition, while the flow rate is $0.9 \bar{Q}$ ($\bar{Q}$ means the rated mass flow rate). The rotational speed increased from 0 to 3000 rpm in 0.5 seconds during the test.

In the coupling simulation, the pipeline portion (including the tank and the valves) was calculated with 1D MOC, while the hydraulic machine (including the suction chamber, the impeller and the volute) was simulated with 3D CFD. The boundary conditions (flow rate and pressure) at the interface were transferred back and forth between the two coding systems. In this process, an integration point (in 1D MOC) was coupled with a surface mesh (in 3D CFD), where the cross-section averaged quantities were transferred, either from the 1D to the 3D model or from the 3D to the 1D model. The fluxes conservation was ensured during data integration and redistributions.

![Figure 1. The layout of the pump and pipeline system](image)

After the simulation, flow rate coefficient $\delta$ (equation (1)), pressure coefficient $\psi$ (equation (2)), and cavitation coefficient $\sigma$ (equation (3)) were applied to study the startup process. Including with efficiency $\eta$, these dimensionless parameters were used to describe the transient process.

\[
\delta = \frac{Q}{u_2^2}, \\
\psi = \frac{\Delta P}{\rho u_2^2}, \\
\sigma = \frac{\left(P_s + \frac{1}{2} \rho v_i^2 - P_v\right)}{\frac{1}{2} \rho u_2^2}.
\]

In which, $Q$ is the mass flow rate, $u_2$ is the tip velocity at the pump outlet, $v_i$ is the velocity at the pump runner inlet, $v_2$ is the velocity at the pump runner outlet, $r_2$ is the impeller radius at the outlet of the pump, $\Delta P$ is the pump head, $P_s$ is the static pressure at the pump inlet, $P_v$ is vapor pressure.

3. Results and discussion
During the coupling simulation, the non-cavitation condition was firstly simulated for the pump to verify the simulation method. As shown in figure 2, the simulated and tested $\delta$-$\psi$ curves were compared to check the reliability of the simulation. It can be learnt that the curves under different working conditions (for conditions with rotational speed of 1000 r/min, 2000 r/min and 3000 r/min) coincided well. Which means that the simulation method was acceptable. It can be seen that the dimensionless curve is not influenced by the rotational speed. With this precondition, the pump running characteristics at other conditions (rotational speed of 500 r/min or lower) can be predicted and the results can be reasonably correct.
Figure 2. Comparison between the simulated and tested $\delta$-$\psi$ curves for the pump

The startup process of the pump under non-cavitation condition from 500 r/min to 3000 r/min can then be drawn like figure 3. The startup process of the pump was plotted with the black squared line. The line met the head-mass flow rate lines at different rotational speed successively. It can be seen that during the startup process, the pump was running at offset load conditions at early stages since the unsteady properties of the transient process. When the rotational speed reached 3000 r/min, the running characteristics moved to the rated zone.

Figure 3. The startup process of the pump under non-cavitation condition

For the startup process under cavitation condition, the simulation was more complex. First of all, the cavitation characteristics of the pump were analyzed. As shown in figure 4, the head drop under different working conditions were plotted. It can be seen that, the higher the $\delta$ is, the earlier the head drop. The lower the $\sigma$ is, the smaller the differences between $\sigma$ of 3% head drop and $\sigma$ of 10% head drop is. Which means that, for small mass flow rate conditions, small disturbance of cavitation coefficient would lead to violent changes in pump performance.

According to figure 4, head-mass flow rate relationship with cavitation considered can be drawn, like figure 5. The $\psi$-$\delta$ can be plotted under different cavitation coefficient. It can be seen from figure 5 that, the smaller the $\sigma$ is, the lower the $\psi$ is at same $\delta$. These curves were important for the startup co-simulation under cavitation condition. The Suter curve of this pump was adjusted according to figure 5.
With the co-simulation method, the startup process under cavitation of the centrifugal pump and its related system was simulated. The dimensionless parameters were plotted in figure 6 and figure 7 to describe the process. The dotted red curve was the $\psi - \delta$ curve obtained from steady state simulation. The squared black curve was the $\psi - \delta$ curve from the transient process. The blue arrow showed the evolution sequence. At the beginning of the startup, the pump was running under conditions that off the rated conditions. The head was higher than its rated head. As the pump speeded up, the running characteristics of the pump became closer and closer to its steady state performance. At $\delta=0.0145$, the pump was running around the trajectory. From $\delta=0.0145$ to $\delta=0.020$, the pump got off the track again. That was because cavitation occurred at this stage, and the pump head dropped. As the rotational speed increased to 3000r/min, the cavities became stable, the pump finally returned to its track.

In figure 7, the dimensionless parameters were plotted with the abscissa of time. It can be seen that the mass flow rate increased as time went. From 0.1s to 0.4s, $\sigma$ decreased quickly. From 0.4s to 1.0s, $\sigma$ was relatively stable. At time=0.45s, $\sigma=0.04$, $\delta=0.0143$, it can be learnt from figure 4 that, the head drop under this working condition was at least 10% of its rated head. That explained the drop of $\psi$ in figure 7.
With the help of the dimensionless analysis, the whole startup process can be displayed on the \( \psi - \sigma \) chart (figure 8). In figure 8, the \( \psi - \sigma \) curves under three flow rates are shown as a reference for the dimensionless startup process. The cavitation coefficient decreases from 5 to 0.45 from the very beginning of the startup process to \( T = 0.3s \). From \( T = 0.3s \) to \( T = 0.4s \), the pressure at the blade inlet is continually decreasing (the \( \sigma \) drops from 0.45 to 0.09) but the head coefficient is only slightly affected. From \( T = 0.4s \) to \( T = 0.55s \), the flow rate coefficient gets closer to 0.0147, so the curve coincides with the curve of \( \delta_1 (0.0147) \) in this period. For \( \delta_1 \), the incipient cavitation point is at \( \sigma = 0.075 \) and the head coefficient of the pump drops quickly after \( T = 0.45s \). At \( T = 0.55s \), \( \sigma = 0.029 \), for \( \delta_1 (0.0147) \), it was the severe cavitation zone. From \( T = 0.55s \) to \( T = 0.8s \), \( \sigma \) slightly increases to 0.05, but the flow rate coefficient of the pump keeps growing. The flow rate coefficient at \( T = 0.8s \) is 0.0189. For \( \delta_3 (0.0189) \), \( \sigma = 0.05 \) is no more the severe cavitation zone, as the volume of cavitation bubbles quickly shrink after \( T = 0.7s \).

It can be seen from figure 8 that the cavitation conditions during the startup process change greatly from incipient cavitation to severe cavitation in a short time. For traditional 1-D calculation, the pump boundary condition is given by a Suter curve, which comes from the non-cavitation \( \psi - \delta \) curve. The results in figure 8 imply that for 1D transient process simulation under cavitation condition, the non-cavitation Suter curve must be modified in order to consider the steep head coefficient drops, when cavitation number is low.

**Figure 7.** Dimensionless parameters evolution during the startup process

**Figure 8.** The startup process under cavitation condition in dimensionless form
4. Conclusions
In this paper, a coupling simulation method for closed-loop pipe system including a pump under cavitation condition has been introduced. This method has been implemented to simulate an existing reduced scale model test rig with available experimental results. In this way, numerical and experimental results have been compared. The following conclusions can be made.

The co-simulation method was appropriate for the transient process simulation. Dimensionless parameters can be used to describe the startup process for a centrifugal pump. The evolution of the parameters can help to understand the transient process with cavitation.

During the startup process under cavitation condition, the evolution of the startup operation points indicates that the pump passes through different conditions with low cavitation number, where sudden drop of head coefficient occur. When the rotational speed reached the rated value, the performance of the pump was around its rated performance.

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