FEED FORWARD CONTROL OF PRESSURE AND FLOW-RATE IN PUMPING SYSTEM

Junichi KUROKAWA*, Kenji IDO**, Hiromichi TAKAHASHI***

* Professor of Yokohama National University, 156 Tokiwadai, Hodogaya, Japan
** Engineer of Hitachi Co. Ltd., 2860 Kousu, Odawara, Japan
*** Engineer of Toshiba Co. Ltd., 2-4 Suehirocho, Tsurumi, Yokohama, Japan

ABSTRACT

In order to produce a desired pulsation of the pressure and the flow-rate independently in a pipe flow, the method of controlling a pump speed and a valve opening simultaneously is proposed taking the inertia effect into account.

Here presented is the following two examples: One is the flow-rate pulsation along a sine-curve with the pressure kept constant and the other is the pressure pulsation along a sine-curve with the flow-rate kept constant. The possibility of the present control and the limit of the pulsatile period are determined by comparing the quasi-steady control with the non-steady control.

INTRODUCTION

The time dependent variation of the pressure and the flow-rate in pulsatile blood flow is illustrated in Fig.1, in which the pressure and the flow-rate are seen to vary almost independently. The laboratory study on the blood flow requires the same pulsatile flow in amplitude and period in a pipe flow, but it is still difficult to simulate the time dependent variation of these flow characteristics.

If the pressure and the flow-rate can be controlled independently and simultaneously in pulsatile or oscillatory pipe flow, it becomes possible to simulate the real pulsatile blood flow in a laboratory. Such control makes also possible in the emergency cooling system of an nuclear reactor to vary the pump operating point immediately according to the emergency status.

In order to produce a desired variation in both the pressure and the flow-rate, it is necessary to vary the operating point in pumping system by more than two variables, because the system operating point is determined by both the pump head curve and the pipe-line resistance curve.

In the present study the pump revolution speed and the opening angle of a ball valve set in the pipe-line are selected as the independent variables, and here is presented the method of producing the pressure and the flow-rate variation independently and simultaneously along the desired time-dependent curves.

In the non-steady pump operation, the inertia force working on the fluid column \( \rho \frac{dQ}{dt} \), where \( \rho \), \( l \), \( Q \) and \( t \) are fluid density, equivalent length, flow-rate and time respectively, becomes remarkably larger with a decrease in the period \( T \) of the variation, and the dynamic characteristics of the whole system also becomes larger.

As for the pump performances in pulsatile operation, the critical frequency of the quasi-steady pump operation is given as \( f_{cr} = \frac{n \cdot \phi}{4.1n} \), where \( n \), \( \phi \) and \( z \) are the pump revolution speed, flow coefficient and impeller vane number. This equation shows that the pump performance at the start-up or the stopping period of an ordinary pumping system can be treated as the quasi-steady state.

On the other hand, the pressure in a pipe-line is largely dependent on the inertia force of the fluid column and the inertia effect must be considered in order to control the valve opening.

In the present study the dynamic characteristics of a pump is not taken into account.

THEORY AND METHOD OF CONTROL

In the pump-pipe line system shown in Fig.3, the energy balance between \( 1 \) and \( 2 \), and \( 3 \) and \( 4 \) are expressed as follows in terms of the total head \( H \) and the flow velocity \( v \) in the suction pipe:

\[
H_1 - H_2 = \xi_1 \frac{v^2 \rho}{2g} + 1 \frac{1}{2} \left( \frac{d\rho}{dt} \right) \quad (1)
\]

\[
H_3 - H_4 = \xi_3 \frac{v^2 \rho}{2g} + 1 \frac{1}{2} \left( \frac{d\rho}{dt} \right) \quad (2)
\]

where \( \xi_1 \) and \( \xi_3 \) are the energy loss coefficient between \( 1 \) and \( 2 \) and \( 3 \) and \( 4 \), non-dimensionalized by \( v^2/2g \). \( \xi_2 \) and \( \xi_4 \) are the equivalent length of the pipe defined as follows:

\[
\xi_2 = \int \frac{A_s}{A_0} ds, \quad \xi_4 = \int \frac{A_s}{A_s} ds \quad (3)
\]

where, \( A \) and \( A_0 \) are the pipe sectional areas at the distance \( s \) and at the suction, respectively.

\( \xi_{2a} \) and \( \xi_{2b} \) in Eqs.(1) and (2) may be diffe-
Fig. 2 Quasi-steady control for pressure pulsation with constant flow-rate.

The instantaneous total head of the pump $H(t)$ can be expressed in terms of the quasi-steady pump head $H_p$ as follows with the inertia force taken into account:

$$H(t) = H_3 - H_2 = H_p - \frac{1}{2g}(dv/dt)$$

Fig. 3 Pumping system.

Experimental apparatus and method

Figure 3 shows the experimental apparatus. The pump used is a volute pump with $n=2820$ (rpm), $H_p=10.2$ (m) and $Q=75$ (l/min) at the rated point, and is driven by an AC servo-motor. The ball valve is driven by a pulse-motor. Both the revolution speed $n$ of the servo-motor and the setting angle of the pulse-motor are controlled by a personal computer.

In ordinary pipe flow the pressure varies in accordance with the flow-rate variation. But the aim of the present study is to vary the pressure and the flow-rate independently along the given time-dependent curves, and the following two extreme cases are selected as the target variations:

1. vary the flow-rate along the given curve with keeping the pressure $H_x$ constant.
2. vary the pressure $H_x$ at the point $X$ along the...
Flow-rate Pulsation with Constant Pressure

Figures 6 and 7 show the target values, controlled variables and the measured results for the case of relatively long period T=2s and relatively short period T=0.4s, respectively. In Fig.(a) of each figure is shown the case of steady-state control and in Fig.(b) the case of non-steady control taking the inertia force into account.

According to Fig.6(a) the pressure Hx does not become constant and the time-lag in the flow-rate

RESULTS AND DISCUSSION

Here presented is some examples of the controlled results under quasi-steady condition and non-steady condition. The target variation is the following two extreme cases:

1. vary the flow-rate Q along a sine-curve with keeping the pressure Hx constant
2. vary the pressure Hx along a sine-curve with keeping the flow-rate Q constant

In every figures the time variations of Q and Hx are plotted in the lower half and that of the controlled variables (n, θ) are also plotted in the upper half together with the target curves of (n, θ, Q, Hx).

Flow-rate Pulsation with Constant Pressure

Figures 6 and 7 show the target values, controlled variables and the measured results for the case of relatively long period T=2s and relatively short period T=0.4s, respectively. In Fig.(a) of each figure is shown the case of steady-state control and in Fig.(b) the case of non-steady control taking the inertia force into account.

According to Fig.6(a) the pressure Hx does not become constant and the time-lag in the flow-rate

RESULTS AND DISCUSSION

Here presented is some examples of the controlled results under quasi-steady condition and non-steady condition. The target variation is the following two extreme cases:

1. vary the flow-rate Q along a sine-curve with keeping the pressure Hx constant
2. vary the pressure Hx along a sine-curve with keeping the flow-rate Q constant

In every figures the time variations of Q and Hx are plotted in the lower half and that of the controlled variables (n, θ) are also plotted in the upper half together with the target curves of (n, θ, Q, Hx).

Flow-rate Pulsation with Constant Pressure

Figures 6 and 7 show the target values, controlled variables and the measured results for the case of relatively long period T=2s and relatively short period T=0.4s, respectively. In Fig.(a) of each figure is shown the case of steady-state control and in Fig.(b) the case of non-steady control taking the inertia force into account.

According to Fig.6(a) the pressure Hx does not become constant and the time-lag in the flow-rate
Pressure Pulsation with Constant Flow-Rate

In this case the inertia effect does not exist, because there is no flow acceleration or deceleration, $\frac{dQ}{dt}=0$. Accordingly, there must be no time lag in pressure pulsation, as the pressure wave propagates much faster than the pulsation period.

Figures 9(a) and (b) show the comparison of the results for the cases of relatively long period ($T=4.0$ s) and short period ($T=0.48$ s). These figures reveal that there exists the phase lag and that it becomes larger with the shorter period. And moreover, the shorter the period of pulsation is, the more difficult it becomes to control the pump speed $n$ along the target curve as shown in Fig. 9(b).

From the above results, the phase lag of the pulsation might be mainly due to the delay in formation of the circulation around the impeller vanes and also due to the time lag in separation occurrence at the ball valve. Here, it is to be remarked that the steady valve drag is larger in the opening procedure from that in the closing procedure, even if the valve opening is the same. This phenomena might be due to the hysteresis in the separation occurrence, and this results that the time lag is larger in the period of decreasing pressure than in the period of increasing pressure.

Lastly, the pressure and the flow-rate pulsation are measured when a convergent pipe or a sudden expansion pipe of the area ratio 4:25 is inserted at the upstream of the point $\Theta$ in order to examine the influence of the delay in occurrence of flow separation. The results show slight change from those in Figs. 8 and 9, which reveals that the head loss caused by friction and flow separation is much smaller than that by the ball valve.

After all, more rapid pulsation of the pressure and the flow-rate requires the consideration of the dynamic characteristics of the pump and the ball valve. However, for the pulsatile flow such as blood flow the present method can simulate the phenomena with sufficient accuracy.
CONCLUSIONS

The method of producing a desired variations in pressure and flow-rate in a pumping system independently is presented by controlling simultaneously a pump speed and a valve opening angle. The conclusions obtained are summarized as follows:

(1) It is experimentally confirmed that the pressure and the flow-rate can be independently controlled in a pulsatile flow of the period longer than 0.5 sec.

(2) The pulsatile flow of the period longer than 4 sec. can be produced by a quasi-steady control, but the shorter pulsation requires the consideration of the inertia effect (non-steady control). For the period shorter than 0.5 sec. is necessary the consideration of the dynamic characteristics of the system.

NOMENCLATURE

\[ A \] = sectional area of a pipe, \( \text{m}^2 \n \]
\[ H \] = total head at each point, \( \text{m} \)
\[ H_p \] = quasi-steady pump head, \( \text{m} \)
\[ H(t) \] = instantaneous pump head, \( \text{m} \)
\[ H_x, H_d, H_{cin} \] = pressure head at \( x \), pump discharge and flow-meter inlet, \( \text{m} \)

\[ l \] = equivalent length of pipe-line, \( \text{m} \)
\[ l_{eq} \] = equivalent length of volute pump, \( \text{m} \)
\[ q \] = flow-rate, \( \text{m}^3/\text{s} \)
\[ s \] = distance, \( \text{m} \)
\[ t \] = time, \( \text{s} \)
\[ v \] = velocity in suction pipe, \( \text{m/s} \)
\[ \zeta \] = total loss coefficient of pipe line including velocity head, non-dimensionalized by \( v^2/2g \)

Subscripts

1~4 = at the point 1~4
12,34 = between 1 and 2, 3 and 4

REFERENCES