Experimental Research of Crosscorrelation-Based Virtual Dynamic Flowmeter

W L Jiang¹, H M Sun², H F Niu¹ and M Gao³

¹ Heavy Machinery Fluid Power Transmission and Control Key Laboratory, Yanshan University, 438 West Hebei Avenue, Qinhuangdao 066004, Hebei, China
² Beijing Polytechnic of Second Light Industry, 9 Liangshuihe One Street, Yizhuang Economics and Technology Development Zone 100176, Beijing, China
³ BeiJing Beizhong Steam Turbine Generator Co Ltd, Wujiacun Street, Shijingshan District 100040, Beijing, China

E-mail: wljiang@ysu.edu.cn

Abstract. An innovated method for measuring dynamic flow is put forward, and a virtual dynamic flowmeter is established. Basing on the principle of pressure pulse containing the flow information, for the dynamic laminar flow, by means of collecting the pressure signals at two points at interval of $L$ and processing them with crosscorrelation calculation, then the transit time is gained, consequently the average flow rate can be got. This calculation is prosecuted repeatedly according to a certain time step length, thus the average flow rates in each time slice can be acquired. If the step length is decreased to zero, the piecewise average flow rate is approximate to the instant dynamic flow. In order to calibrate the virtual dynamic flowmeter, the unloaded servo cylinder was used for the contrasting experiment. The accuracy and validity of this approach has been proved.

1. Introduction

In the field of condition monitoring and fault diagnosis of hydraulic systems and in the experimental investigations of hydraulic components and systems, flow is one of the main parameters to be measured and controlled. In the condition monitoring and fault diagnosis of hydraulic systems, dynamic flow signals contain abundant fault characteristic information. Likewise, in the area of performance test of hydraulic components and systems, the measurement of dynamic flows is important for assessing dynamic characteristics of hydraulic valves and systems [1-3].

Along with the development of modern hydraulic control technology, the requirements for dynamic characteristics of hydraulic systems and components are higher and higher. Then the transient dynamic flow measurement technology must be improved synchronously. Due to the complexity of fluid, not only viscous shear force and inertia force exist in variable-speed fluid medium, but other complicated flow phenomena such as unstable spiral vortex and secondary flow appear exist also. Therefore the measurement of dynamic flow is very difficult. The on-line measurement of dynamic flow is an unsolved puzzle in condition monitoring and fault diagnosis of hydraulic systems at present [4].

In the flow measurement filed, the cumulative flow and the static flow can be measured, but the measurement of instant dynamic flow is still a puzzle needs to be solved urgently now [5]. A new measuring approach for dynamic flow under laminar flow pattern based on calculating the
crosscorrelation of two pressure signals at two different points is advanced in this paper. According to this approach, a virtual measuring system for the dynamic flow has been constructed. The calculation error in model-based approaches is well avoided by this method. The validity of this approach has been verified through the contrast test by use of the unloaded servo-cylinder on the testing bench of servo valve static and dynamic performances.

2. Measurement principle of dynamic flow

2.1. Correlation

In dynamic measurements, the correlation is a function reflecting the associative relation between waveforms of two time variable signals. The cross-correlation function of random signals \( x(t) \) and \( y(t) \) can be presented as follows

\[
R_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T}^{T} x(t)y(t+\tau)\,dt
\]

The off-origin distance \( \tau_0 \) of peak value reflects that two signals have the highest correlative degree when their shift is \( \tau_0 \). The crosscorrelation of the two signals is shown in figure 1.

The amplitudes of \( x(t) \) and \( y(t) \) will influence the amplitude of \( R_{xy}(\tau) \). Thus it is not accurate when comparing the correlative degrees of different couple signals only by using of their crosscorrelation function amplitudes. For avoiding the amplitude influence to the correlative degree, correlation function must be normalized. Then a dimensionless correlation coefficient function \( \rho_{xy}(\tau) \) is introduced as follows

\[
\rho_{xy}(\tau) = \frac{R_{xy}(\tau)}{\sqrt{R_{xx}(0)R_{yy}(0)}}
\]

Where \( \rho_{xy}(\tau) \) varies from 0 to 1. If \( \rho_{xy}(\tau)=1 \), then \( x(t) \) and \( y(t) \) are complete correlation. If \( \rho_{xy}(\tau)=0 \), \( x(t) \) and \( y(t) \) are complete noncorrelation. If \( 0<|\rho_{xy}(\tau)|<1 \), then \( x(t) \) and \( y(t) \) are partial correlation.

2.2. Measurement principle

Dynamic flow measurement under laminar flow pattern is researched in this paper. Generally, dynamic flow of laminar fluid has definite pulsating. Through the correlation processing of pressure waveforms of points A and B at interval of \( L \) along the pipe, the time \( \tau_0 \) corresponding the peak value of correlation function can be obtained. Namely, \( \tau_0 \) is the transit time between points A and B. It represents the time spent by certain fluid micelle traveling from A to B. The liquid average flow rate in time \( \tau_0 \) can be obtained through the equation of \( V=L/\tau_0 \). This calculation is prosecuted repeatedly according to a certain time step length, thus the average flow rates in each time slice can be acquired. If the step length is decreased to zero, the piecewise average flow rate \( V \) is approximate to the instant dynamic flow.
In order to implement the measuring process, some old sampling points of pressure signals at A and B are truncated out continuously and new sampling points are added in simultaneously. In this way, the total sampling points are fixed. Namely the data length for correlation calculation is fixed.

The calculating formula [6] for instantaneous flow $Q$ is

$$Q = KAV$$

Where $K$ is the calibrated coefficient, $A$ is the cross-section area of pipeline.

2.3. Structure of measuring pipeline

The main body structure of flowmeter is shown in figure 2. A piece of horizontal steel pipeline having smooth inner wall is used as measuring pipe whose inside diameter is 10mm and total length is 500mm. Two pressure cross sections 300mm apart are set on the pipe. On each cross section, four small holes of diameter 5mm are opened symmetrically along circumference. A hollow pressure ring communicates with the 4 holes on each cross section. The pressure rings are traversed by the measuring pipe. They are welded together. There is a tap hole on each pressure ring for installing a pressure sensor. The measured pressures of hydraulic liquid are transferred from the pressure rings, and measured by the pressure sensors.

This structure can guarantee that the pressuring rings and the transducers do not influence to the flow pattern and flow rate in the pipe. Because this approach belongs to the non-contact measurement essentially, the influences of inserting measuring element or orifice of traditional flowmeters to the measured flow are avoided. Therefore, no pressure loss is produced. Higher measurement accuracy will be gained undoubtedly.

2.4. Functions of testing software

The testing software of this flowmeter is developed on the virtual instrument development tool LabVIEW. The new notion of “the software is the instrument” has been implemented.

The testing program of the flowmeter mainly includes modules as follows. Exciting module which generates sinusoidal signal to control servo valve; Pressure signal acquisition module; Crosscorrelation function-based instantaneous flow calculation module; Comparison and calibration module by means of unloaded hydraulic servo cylinder; Data saving and result display module and etc.

3. Experiments

3.1. Contrast testing and calibration

In equation (3), coefficient $K$ should be obtained through calibration test. Actually the amplitude of dynamic flow must be calibrated by special calibrating system. But the dynamic flow calibration is still a puzzle in measurement field at present.

Having no choice, the virtual dynamic flowmeter is calibrated roughly by a contrast test. The contrast testing has been executed by use of the unloaded servo-cylinder under the same experimental conditions. The system schematic diagram of contrast calibration test is shown in figure 3.

In the contrast test, exciting the servo valve by using of sinusoidal signal, then the dynamic flow is simulated by reciprocating motion of servo-cylinder which has little frictional resistance and fast frequency response [7]. The piston velocity is measured by speed sensor mounted on it. The structure of the speed sensor includes a permanent magnet and a moving coil. During the piston moves reciprocally, the coil cuts the magnetic lines, the electromotive force is generated which is proportional to the piston velocity. In this way, waveform of flow rate can be attained. The dynamic flow is equal to the piston velocity multiplying the piston area.
3.2. Experiment results and analysis
Under the system pressure of 5MPa, the servo valve on the experimental bench of servo valve dynamic performances is excited by means of a sinusoidal signal of 10Hz. The results of contrast test are show in figure 4-7. They show the pressure signals at point A and B, the correlation coefficient curve, the flow signal measured on unloaded servo-cylinder and the flow signal calculated by using of correlation approach respectively.

In the fields of condition monitoring and dynamic measurement of hydraulic components and system, frequency information of dynamic flow is most concerned. From the test results, the waveform and its frequency obtained from the correlation method are the same as from the servo calibration. The rough calibrating coefficient $K$ of flow amplitude is about 0.3.

4. Conclusion
Nowadays, the mechanics of dynamic flow variation and flow field distribution can not be described clearly in theory. Many factors such as the variation of temperature, viscosity and compressibility should not be ignored. So the accuracy soft measurement model of dynamic flow can not be established.

In this paper, a novel measurement approach for dynamic flow based on crosscorrelation is put forward, and a virtual dynamic flowmeter has been developed. The derivation error from the inaccuracy dynamic flow model is well avoided in the correlation-based measurement method. Furthermore, because this approach belongs to the non-contact measurement essentially, the influences of inserting measuring element or orifice of traditional flowmeters to the measured flow are avoided. Therefore, no pressure loss is produced. Higher measurement accuracy will be gained undoubtedly.

As a matter of fact, the accuracy calibration of dynamic flow is still a puzzle in engineering nowadays. The contrast test and the rough calibration have been executed by means of the unloaded servo-cylinder under the same experimental conditions. The results indicate they can get the same flow waveform and frequency. The validity of this approach is verified. A rough calibrating coefficient of flow amplitude is obtained.
Figure 4. Pressure signals at point A and B.

Figure 5. Correlation coefficient curve.

Figure 6. Dynamic flow measured on servo-cylinder.

Figure 7. Dynamic flow calculated by correlation approach.

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