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A Study on the Dynamics of a Turbine-Meter-Type Flowmeter for Hydraulic Systems

Shinichi YOKOTA*, Do-Tae KIM** and Kenji SUZUKI*

* Precision and Intelligence Laboratory, Tokyo Institute of Technology
4259 Nagatsuta, Midori-ku, Yokohama 227, JAPAN

** Dept. of Mechanical Engineering, Kyungpook Sanup University
33 Buho-ri, Hayang-up, Kyungsan, Kyungpook, KOREA

ABSTRACT

In this study, the dynamic characteristics of a turbine-meter-type flowmeter is investigated by making use of the remote instantaneous flow rate measurement method (RIFM). The results of the frequency response test indicated that the gain of the flow rate of the turbine-meter-type flowmeter relative to the flow rate of the RIFM was nearly unity up to 40Hz and the phase lag of the flow rate became 90 degrees at 70Hz.

1. INTRODUCTION

A real time measurement of unsteady flow rate through pipes and equipments is one of the most important theme in hydraulic control systems under high pressure. Up to now, turbine-meter-type flowmeters have been widely used to measure steady and unsteady flow rate in oil hydraulic and other industrial applications because of the distinct advantages of simplicity, accuracy and fast response.

However, the dynamic characteristics of turbine meters are yet to be investigated in detail, since it is difficult to procure a flowmeter having improved high-accuracy, fast response, also the calibration methods have not been established in the current state of unsteady flow rate measurement technology.

A cylindrical-choke-type instantaneous flowmeter (abbreviated as CCFM) has been experimentally confirmed to be measured the change of unsteady flow rate in high frequencies up to 400Hz under high pressure hydraulic system(1). Recently, a new type instantaneous flow rate measurement method by making use of hydraulic pipe line dynamics called as "a remote instantaneous flow rate measurement method (abbreviated as RIFM)" has been proposed and developed by the authors previous works(2),(3). The RIFM has been shown to respond to change in the flow rate at high frequencies above 400Hz in comparison with CCFM. This method has an advantage convenient to install a flow rate sensing system. In this study, the dynamic characteristics of turbine-meter-type flowmeter is investigated by making use of RIFM. Under unsteady laminar oil flow conditions, flow rate waveforms measured by the turbine meter are compared with results measured by RIFM. Also simple mathematical model described as dynamics of the turbine meter is proposed and compared with experimental results.

Figure 1 shows a schematic diagram of turbine-meter-type flowmeter (flow rate range 7.8～76.3 cm^3/s) manufactured by DODWEL Co. LTD. The turbine meter consists basically of a bladed rotor mounted on bearings inside a pipe. The rotor is equipped with four blades. As the fluid moves through the turbine meter, it causes a rotation of rotor. The rotor is driven by fluid impinging on the blades; the rotor's angular velocity is proportional to fluid velocity, in turn, is proportional to the volumetric flow rate. A magnetic pick-up-coil attached on the casing detects rotor motion. The pick-up-coil has a magnet, magnetic field and the rotor blades are made from ferrous material; as each rotor blade passes the pick-up it cuts the magnetic field and produces a pulse. The output signal is a continuous sinusoidal wave voltage pulse train with each pulse representing a discrete volume of fluid.

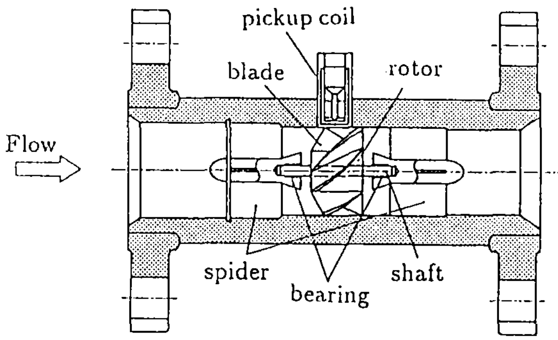

Fig.1 Schematic diagram of turbine meter

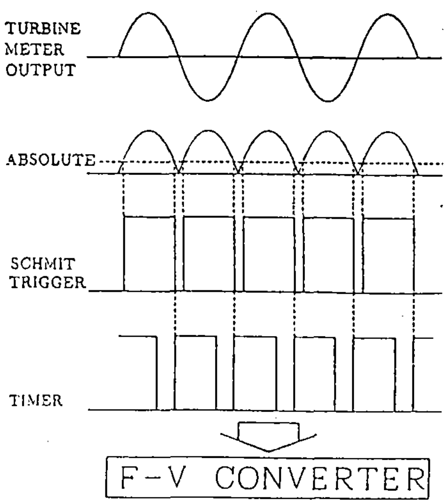

Fig.2 Signal processing procedure

2. TURBINE-METER-TYPE FLOWMETER AND SIGNAL PROCESSING

Figure 2 shows output signal processing procedure generated from turbine meter. In order to maintain the accuracy of measurement, after sinusoidal wave pulse train from the pick-up-coil in the turbine meter is rectified in full-wave, its signal is made rectangular wave pulse through a Schmidt trigger circuit, and made double frequencies of output pulse. At the decreasing in pulse wave forms, pulse with constant time interval is made to become duty ratio 100%. Also, the frequency-voltage(F/V) conversion is achieved by the 2nd-order low pass filter to obtain an analog voltage signal proportional to angular velocity.

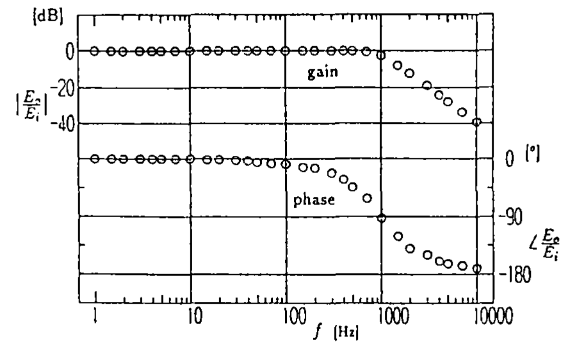

Fig.3 Frequency characteristics of 2nd order low pass filter

Figure 3 shows the frequency characteristics of the 2nd order low-pass filter used F/V converter. The cut-off frequency of filter is 1kHz to take off the time lag due to the filter characteristics. For this reason, pulse is not sufficiently smoothing and is fed into a microcomputer. As data are averaging at serial points using digital filtering in a microcomputer, a proper smoothing is carried out without phase lag and gain decreasing of frequency components in the flow rate ripple.

3. MATHEMATICAL MODEL DESCRIBED AS THE TURBINE METER

Several mathematical models for the turbine meter are proposed under steady flow conditions. Here, we consider a simple mathematical model described as the dynamic characteristics of the turbine meter.

When rotor is rotated with angular velocity ω the driving torque T_f can be expressed as

$$T_f = C_1 n r_e \rho \tan\zeta\, q^2 A^{-1} - C_2 n \rho r_e^{\,2} q\, \omega \quad (1)$$

where, A is the cross-sectional area of rotor of annular flow passage at the rotor blades, C_1, C_2 are drag coefficients in the axial direction, n is number of blades (=4), r_s is equivalent mean rotational radius, ζ is blade angle measured in the axial direction of the turbine meter, q is volumetric flow rate passing through the turbine meter, ω is angular velocity of rotor.

Also, the retarding torque T_r is exerted on the rotor hub when fluid is passed through the rotor blades.

$$T_r = C_3 \pi d^3 (\rho\mu l)^{0.5} A^{-1.5} \sin\zeta\, q^{1.5} \quad (2)$$

where C_3 is constant, d is outer diameter of rotor hub, l is rotor length (=0.7cm), μ is absolute oil viscosity.

Neglecting the relatively small friction torque due to the bearing in comparison with the driving torque T_f and the retarding torque T_n, the equation of motion for the rotor system is

$$J\, d\omega/dt = D_1 q^2 - D_2 q\, \omega - D_3 q^{1.5} \quad (3)$$

where, J is moment of inertia of the rotor system about the rotor axis

$$D_1 = C_1 \rho n r_e \tan\zeta A^{-1}, \quad D_2 = C_2 \rho n r_e^{\,2}$$
$$D_3 = C_3 \pi d^3 (\rho\mu l)^{0.5} A^{-1.5} \sin\zeta \quad (4)$$

Next, consider a linearization for the mathematical model in equation (3) near an operating point q_0, ω_0. When the mean flow rate q_0 is passing through the turbine meter, ω_0 is output pulse generated from the turbine meter. The flow rate and output pulse are

$$q = q_0 + \Delta q, \quad \omega = \omega_0 + \Delta\omega \quad (5)$$

where, Δq, $\Delta\omega$ are indicated small deviations of the flow rate and the output pulse, respectively.

Substituting equation (5) into equation (3) and higher order terms are neglected, the deviation between the flow rate measured by the turbine meter Δq_t and $\Delta\omega$ is then given by

$$\Delta\omega = \Delta q_t\, 2\pi\, \alpha\, n^{-1} = \Delta q_t C_0 \quad (6)$$

where constant α is determined from steady state characteristics of the turbine meter in Fig.5. From equation (6) and equation (3), the linearized mathematical model is given by

$$J C_0 d\Delta q_t/dt = (2 D_1 q_0 - D_2 \omega_0 - 1.5 D_3 \times q_0^{0.5})\Delta q - C_0 (D_2 q_0) \Delta q_t \quad (7)$$

For the calculation, the flow rate and the output pulse at an operating point are $q_0=q_t=55\text{cm}^3/\text{s}$, $\omega_0=1.4\times10^3$ rad/s, the moment of inertia of the rotor system about rotor axis, $J=3.0\times10^{-5}$ kg·cm^2. From the experimental results, the parameters are determined that constants α = 17.8 cm^3/s, $D_1=4.1\times10^{-3}$ kg/cm^4, $D_2=1.4\times10^{-4}$ kg/cm, $D_3=4.6\times10^{-3}$ kg/cm^{5}s$^{1/2}$.

4. EXPERIMENT

4.1 Experimental apparatus

Figure 4 shows a schematically overall experimental apparatus. Overall experimental apparatus consists of the turbine meter, hydraulic pipeline system which is included a long straight copper pipe (inner radius=0.7cm, length L=125cm) installed the cylindrical choke type instantaneous flowmeter (CCFM) at the downstream section, data acquisition and numerical operating system.

In the experiment, an instantaneous flow rate wave forms q_t measured by the turbine meter at upstream section of the pipe line is compared with the results estimated by a remote instantaneous flow rate measurement method (RIFM). In RIFM, the upstream flow rate $q_u(t)$ is estimated by using the measured downstream pressure $p_d(t)$ and flow rate $q_d(t)$ and dynamic characteristics between upstream and downstream section. It has been experimentally confirmed that steady CCFM and RIFM can be measured the change of unsteady flow rate in high frequencies about 400Hz under laminar oil flow conditions. Also, pressure drops pd_t across turbine meter is measured by the semi-conductor-type pressure transducer (the resonant frequency 100Hz). Every sample data are fed into a microcomputer system through the 12bit A/D converter at the sampling frequency of 3.5kHz.

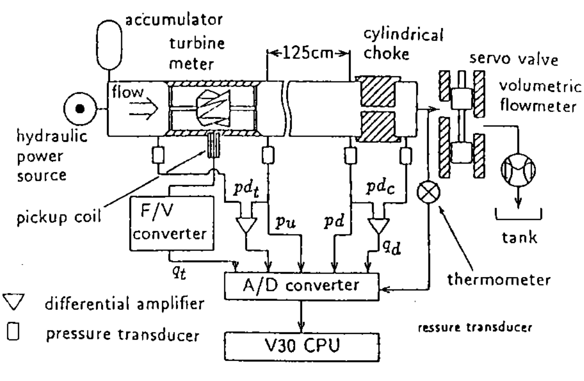

Fig.4 Schematic diagram of overall experimental apparatus

An accumulator (10l) is installed at the upstream manifold to take off the influence of flow disturbance in front of the turbine meter. An electro-hydraulic servo valve is installed at the downstream manifold to generate a change of flow rate in hydraulic pipe line system. Oil temperature is measured by a thermistor-type thermometer.

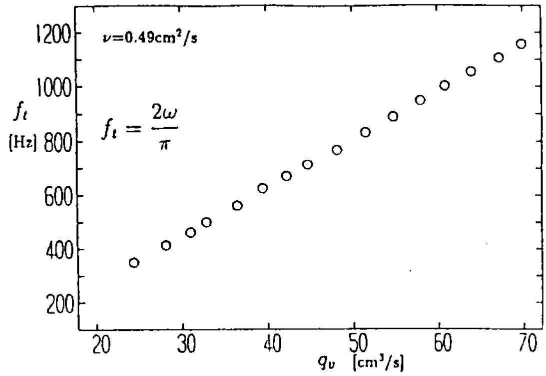

Fig.5 Steady flow rate characteristics of turbine meter

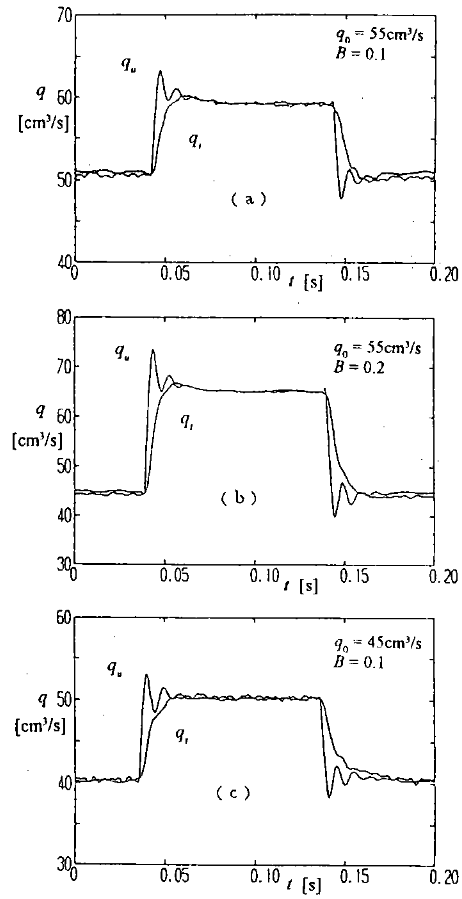

Fig.6 Comparison of the measured flow rate wave forms for rectangular wave input 5Hz

5. EXPERIMENTAL RESULTS AND COMPARISONS

In the experiment, oil temperature is maintained 31±1℃ during the testing, the kinematics viscosity of the working fluid (ISO VG32) is 0.49cm²/s at 31℃ under the line pressure 3.0MPa.

5.1 Steady state characteristics

For steady flow, flow rate passing through turbine meter is directly measured by a volumetric flowmeter. The experimental result is shown in Fig.5. In Fig.5, pulse output frequencies generated from the turbine meter are proportional to the volumetric flow rate. It is shown that steady flow rate is accurately measured by the turbine meter.

5.2 Transient Characteristics

Next, a step wise current input is applied to a servo valve located a the downstream manifold to generate unsteady flow conditions in the hydraulic pipe line system.

Figure 6 shows the example of recorded wave forms of flow rate q_t measured by the turbine meter and q_u estimated by RIFM, respectively. In Fig.6(a), a mean flow rate q_0 =55cm³/s and one-side amplitude ratio B=0.1, In Fig.6(b), q_0=55cm³/s, B=0.2 and in Fig.6(c), q_0=45cm³/s, B=0.1, respectively. In Fig.6, the dependence of the amplitude ratio and mean flow rate at the operating point are shown. In comparison with q_t measured by the turbine meter and q_u by RIFM, the delay in the time of rising scarcely existed between q_t and q_u, q_t is relatively shown up a gentle slope at the rising and decreasing in flow rate wave forms. Although there are a large overshoot and a large undershoot in the wave form of q_u, there are not existed in q_t . Also, from these results, as for the feature, it can not be seen dependence of amplitude ratio and amount of flow rate at operating points. We can conclude the blades of the turbine meter can not be responded to suddenly change of momentum in the fluid.

5.3 Frequency response characteristics

A sinusoidal wave inputs are applied to a servo valve to obtain frequency response characteristics of the turbine meter. Here, mean flow rate q_0 = 55cm³/s, one-side amplitude ratio B = 0.1 during the frequency response test.

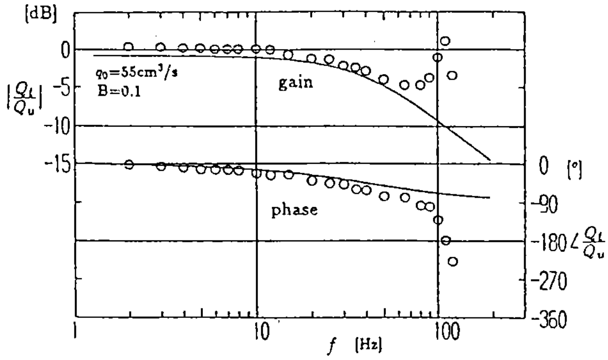

Fig.7 Frequency response characteristics $Q_t(j\omega)/Q_u(j\omega)$

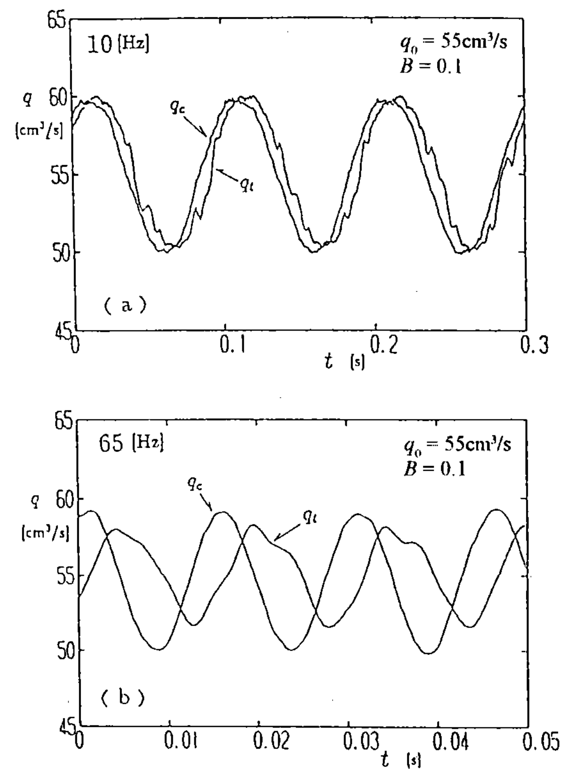

Fig.8 Typical example of recorded flow rate wave forms for frequency response test

Figure 7 shows the frequency response results of $Q_t(j\omega)/Q_u(j\omega)$. In Fig.7, ○ is indicated by the symbol of the experimental results. From Fig.7, it can be seen the gain of q_t with respect to q_u is decreased as the characteristics of the 1st-order delay system (cut-off frequency 40Hz) up to about 70Hz. In Fig.7, gain and phase lag are in good agreement with the calculated and the experimental results up to about 70Hz, which indicates the validity of the mathematical model proposed here.

Figure 8 shows an example of the recorded wave forms in the frequency response testing.

5.4 Pressure drop characteristics

During the frequency response measurement, the pressure drops pd_t, pd_c caused by the turbine meter and CCFM respectively are simultaneously measured by semi-conductor-type pressure transducers and ultra low-drift differential amplifiers.

Figure 9 shows the frequency response results of pressure drops. The gain of pressure drop pd_c across the CCFM is flat up to frequency 100Hz but the gain of pressure drop pd_t caused by the turbine meter is increased with frequencies. This is considered due to inertia of rotor and fluid. Because the gain of pressure drop pd_t for the turbine meter is very smaller than that of CCFM at low frequencies region, it is known that the turbine meter has appropriate characteristics at the low frequency region. Also, it is confirmed that the pressure drop pd_t by the turbine in comparison with that of the gear-motor-type flowmeter (KRACHT CO. W.G) is extremely smaller in the considering flow rate range in Fig.9[4].

CONCLUSIONS

The dynamic characteristics of a turbine-meter-type flowmeter is experimentally investigated by making use of RIFM. In addition, a simple mathematical model described as the dynamics of turbine meter is proposed, and the dynamics is investigated in the high frequency region. It is known that the turbine meter has a appropriate characteristics at the low frequencies region from the frequency response results of pressure drop caused by the turbine meter.

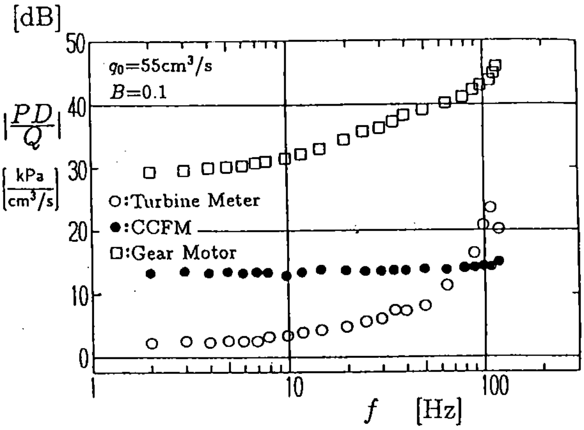

Fig.9 Frequency response characteristics of pressure drops

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