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Simulation and experimental verification of a fuel calibration system based on metering cylinder

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ABSTRACT

Simulation and experimental verification of a fuel calibration system based on hydraulic metering cylinder has been carried out in this paper. A novel hydraulic metering cylinder is designed for more accurate flow rate measurement. The calibration workbench with this cylinder is presented and mathematically modeled. Also, the calibration system is numerically simulated in AMESim. The simulation results show that the calibration system can work smoothly. In addition, the impact of given plunger speeds and calibration strokes on the accuracy of the calibration results is experimentally verified. It can be found that stroke of approximate 600 mm and a medium given speed are the most effective ways to reduce the measuring error under the experimental condition provided in this paper. Moreover, a calibration error less than 0.5% is achieved in the fuel calibration system.

1. Introduction

As a common sensor used to measure flowrate, turbine flowmeters (TFMs) are widely used in military and industrial areas as well as many other fields [1]. It is necessary, or at least desirable, to deeply understand the characteristics and their influencing factors before we put the flowmeters into practice. Guo et al. analyzed the viscosity effect on TFM performance based on experiments and CFD simulations [2]. Zhang and Tao in [3] reported the computational study of the tangential type TFM. In [4], Tang et al. studied TFMs precision through the variable-cycle frequency measurement. Gray et al. established the TFM performance model in [5]. With ignorance of fluid viscosity and static friction, the Gray model was transformed into the dynamic equation below by the author of [6].

$$KQ^2 - Q\omega = K_d\dot{\omega} \tag{1}$$

where, K is the static meter coefficient, Q is the flowrate, K_d is the dynamic meter coefficient, and ω is the rotational frequency of the turbine blades inside the TFM. As shown in Eq. (1), the TFMs are a kind of first-order nonlinear system. Here, in this paper, only the static meter coefficient under stable flow condition is considered. The K factor refers to the ratio of the rotational frequency to the flowrate [7]. In most situations, the rotational frequency is attained by an electromagnetic pick-up which generates a signal each time a turbine blade passes [8].

However, after being used for a long time, the meter coefficient, K, would surely fluctuate due to corrosion of the turbine blades, abrasion of the bearings and change of both the ambient environment and the measured fluid itself, which may introduce terrible measuring errors [9]. Accordingly, every flowmeter needs to be calibrated regularly in the whole course of usage [10].

As is well known, the general principle of calibrating a TFM is to choose a standardized device and let the measured fluid flow through the calibrated flowmeter and the device respectively, and then compare their indicating values. On account of different demands, different calibration methods are employed. Stevens et al. [11] recommended a high-accuracy differential pressure flowmeter as the standardized device. However, one cause of variability into the calibration system is the wild measurement uncertainty of the differential pressure flowmeter, which can lead to an indentified change of the calibrated meter and relatively imprecise calibration. In [12], an institute in Germany adopted the so-called mass method into the calibration. The author of [13] addressed the use of soap film calibrator to calibrate the rotameter. Aguilera in [14–16] presented the dynamic weighing calibration method for liquid flowmeters. This method relies on a thorough analysis of the interaction between the acting flow-induced forces presented in the measurement process, and the dynamics of the weighing system. Engel and Baade in [17] discussed the impact of water density on uncertainties in the measurement process of flowmeter calibration.

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Nomenclature

TFM	turbine flowmeter
K	static meter coefficient
$Q(q)$	flowrate
ω	rotational frequency
K_d	dynamic meter coefficient
P	power of the motor
F_d	driving force of the motor
v	the actual plunger speed
d_p	diameter of the plunger
T	torque on ball screw
T'	torque of ball screw acting on coupler
θ	rotor angle of motor
x	displacement of plunger
F_t	force received by connecting rod
F_t'	reactive force acting on slider
J_1	rotational inertia of reducer and screw
m	mass of slider and connecting rod
h	helical pitch of ball screw
μ	damping coefficient of slide way
K_s	torsional stiffness of ball screw
J_2	rotational inertia of motor shaft
i	reduction ratio of reducer
d	nominal diameter of ball screw
G	shear modulus
A	active area of plunger
C_{tp}	external leakage coefficient
p	internal pressure of cylinder cavity
V	working volume of the cylinder
β_e	elastic modulus of effective volume
η	transmission efficiency of ball screw
B_p	viscous dam stroke ping coefficient
Q_m	TFM indicating flowrate
Q_c	calculating flowrate
Δ	absolute error
ε	relative error

All the methods above that have been used are the traditional ones. Among them, the mass method and the volumetric method contain the means of both static and dynamic calibration. Although these methods are easy to implement and could meet the accuracy requirement in a certain range, the defects could not be neglected, namely, bulkiness, the possibility that the measured fluid would evaporate or be polluted, low-accuracy dynamic calibration and so on. To meet the requirements for calibration accuracy, dynamic performance, convenient operation and easy adjusting, a calibration installation based on the servo motor-metering hydraulic cylinder is established for the fuel flowmeter, which can be automatically controlled by an upper monitor. In addition, the calibration bench presented in this paper has its design advantage of diminishing metering error.

The paper is organized as follows. In Section 2, the structure and parameters of the experimental system are briefly explained. The mathematical model of the experimental system is presented in Section 3. Section 4 describes the numerical simulation of the system in AMESim. In the next section, the experimental results are analyzed and compared with the numerical simulation data. The final section, Section 6, provides some concluding remarks.

2. Experimental system

The system is driven by a servo motor, which can precisely control the displacement and the speed of the plunger in the cylinder barrel. The cylinder can not only implement continuous motion, but also activate emergency stop which expands the usable range. Principle sketch of the system is presented in Fig. 1.

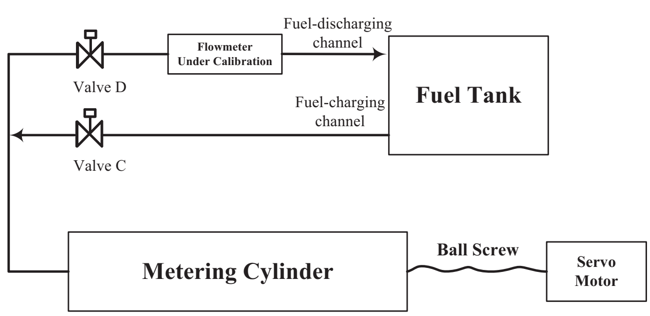

Fig. 1. Schematic of the calibration system.

The structure of the hydraulic metering cylinder is shown in Fig. 2. Moving part in the cylinder is the plunger. The ball screw transforms the motor rotation into the linear motion in order to actuate the plunger to conduct reciprocating motion in the cylinder barrel. The guiding sleeve installed at the cylinder barrel guarantees the plunger to move smoothly. Not shown in Fig. 2, there are stern seals at both ends of the guiding sleeve to prevent the exchange of substances between inside and outside of the barrel. The plunger moves rightwards to begin the fuel-charging process with the valve D closed and the valve C open; correspondingly, the plunger moves leftwards to start the fuel-discharging process with the valve C closed and the valve D open.

One picture of the calibration workbench is shown in Fig. 3. This system is composed of 14 major components. As proposed, the system is driven by a servo motor. The servo motor is of high rotary speed and low output torque, as a result of which, it is not appropriate for the motor to drive the ball screw directly. Based on Eq. (2)

$$P = F_d v \tag{2}$$

as power of the motor is fixed, in order to enhance the driving force F_d, the planetary reducer is adopted, hence, the output torque increases with the reduction of the rotary speed. The driving torque is then transmitted by a coupler to the ball screw, which actuates the slider for linear movement. The reducer is fixed on the workbench. The slider and the plunger are connected rigidly. In calibration, the plunger pushes the fuel out of the cylinder from the outlet at the end of the cylinder barrel. Then the fuel passes through the calibrated flowmeter which is placed downstream of the cylinder. The valves switch the fuel-circuit in

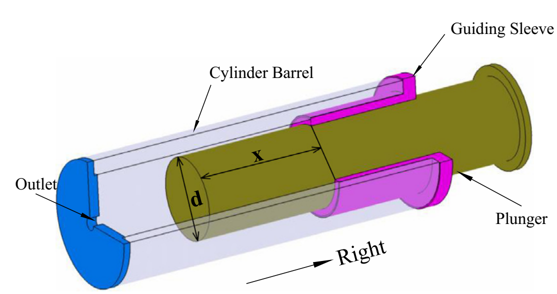

Fig. 2. Structure diagram of the metering cylinder.