Research on Calibration Device Using Plunger Metering Cylinder for Turbine Flowmeter

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# Abstract

Accurate fuel rate acquisition is one of the basic requirements to improve the reliability and confidence of testing results for aero-engines. Because of its high precision and good repeatability, turbine flowmeter is widely used in flow measurement of fuel or fuel system. However, due to the influence of wear and corrosion, the meter coefficient is bound to change. To accurately evaluate the current meter coefficient of turbine flowmeter, we developed a calibration device using a plunger metering cylinder for turbine flowmeter. Considering the mathematical model of turbine flowmeter, the stability of fuel pushing was researched through system modelling and simulation. As a result, the consistency between the calculated flow and the output flow rate of the calibrated meter was proved, which indicates the effectiveness of the device. The calibration experiments for a flowmeter were carried out under different strokes and speeds of fuel pushing. Besides, computational methods of average meter coefficient and repeatability of the calibrated flowmeter were also introduced. According to the testing data, the meter coefficient and the repeatability of the calibrated flowmeter were analyzed. The results show that the flow consistency of the calibration device can reach 0.002%, and the deviation between its average meter coefficient and factory inspection data is no more than 0.04%. Besides, pushing speed of its metering cylinder has little influence on the meter coefficient within the effective range of the calibrated meter..


# 1. Introduction

In aero-engines, fuel control system is an important part which has a great influence on the control system and even the whole engine. As a result, it affects the stability and security of aircraft flights [1-3]. Fuel system and actuators are the primary physical frames of engine control system. For example, HIL, Hardware-In-the-Loop, engine semi-physical or bench test should be built on the basis of accurate measurement about the fuel rate. As shown in Figure 1 for typical control circuit of the engine, in the system, the rotation speed of the engine is the expected regulating parameter, which is achieved by controlling the fuel rate in practice because the former can just be regulated by the later.



**Figure 1:** Typical main fuel control loop of aviation engine

Compared with others, turbine flowmeters are widely used for its high precision, wide range, good repeatability and dynamic characteristics. However, after longtime usage, the meter coefficient of turbine flowmeter is bound to change, making the results with larger error because of the impact of fluid medium and environment change, turbine blades corrosion, bearing wear and so on. Therefore, engine control system test is lack of a precise, simple and practical calibration device which is designed to regularly correct flowmeters, which has a serious influence on confidence level of the results and the development of test technology. Recently, specialists and scholars from different countries conducted deep and wide researches on related problems. In 1956, American J. Grey established dynamic equation of turbine flowmeter, although the following researchers make the correction and improvement for decades, the basic pattern to solve the problem does not essentially change [4]. Without considering the influence of fluid viscosity and static friction force of the meter, the dynamic equation of volume flow and the turbine rotating frequency, is achieved where Ks and Kd stand for static meter coefficient and dynamic meter coefficient respectively. Then a set of dual-rotor turbine meter is developed which is the first commercial testing instrument and the same as the recent flowmeters using the friction compensation [5]. To study characteristics of turbine flowmeter, it is necessary to firstly establish its mathematical model. For that, scholars from all over the world have made lots of researches since 1960s and during this time new studying ways based on numerical calculation were developed. For example, water medium experiments were used to verify the transient characteristic of the turbine flowmeter while a cathode ray oscilloscope was used to display steady-state frequency and amplitude of the rotor [6], both of which can give a certain reference to aviation fuel flowmeter calibration with low viscosity. Besides, pushing, immersion and multi-nozzle charging turbine flowmeter calibration [7] were investigated. Another case is establishing the dynamic model of gas flowmeter, which was compared with actual flowmeter calibration curve [8]. And the Extended Lee model of the rotor of turbine flowmeters was also presented to find the effects on the calibration accuracy according to the temperature on the influence of viscous force, but the specific experiment scheme and the studies on influence of the fluid medium were not given. In this paper, a calibration device using a plunger metering cylinder for turbine flowmeter is studied. Considering the mathematical model of turbine flowmeter, performance of the system calibration is studied and the calibration experiments for a flowmeter are carried out under different strokes and fuel pushing speeds.

# 2. System principle

The principle of the designed calibration device with the metering cylinder is shown in Figure 2.



1-servo motor; 2-retarder; 3-coupling; 4,9-stroke switches; 5-grating ruler head; 6-ball screw; 7-connecting rod; 8-worktable; 10-metering cylinder; 11,14,19-pressure sensors; 13,16,18-switch valves; 12,15-proportional flow valve; 17-calibrated flowmeter; 20-temperature sensor; 21-fuel tank

**Figure 2:** Principle diagram of the calibration device using metering cylinder.

The flowmeter calibration test procedure is as follows: when the device starts, switch valve 13, 16, 18 are opened. Take the plunger connecting rod of metering cylinder 10 back to leftmost position of scheduled metering stroke and open switch valve 13, fuel from the tank charges the metering cylinder. When the metering cylinder is full, shut off the switch valve 13. Then, open calibrated flowmeter 17 and the calibration test begins. PC sets the rotation speed of the motor 1, which pushes the plunger connecting rod of metering cylinder shifting right. And the fuel flows to fuel tank 21 through the upstream and downstream valves of calibrated flowmeter 17. Through controlling the speed of servo motor, several tests are conducted to measure the full range and fuel flow of multi measuring points. By comparing the theoretical calculation results and the actual output the current meter coefficient of the calibrated flow meter can be assessed.

# 3. Mathematical model

When turbine flowmeter works normally, the torque on the turbine mainly includes: T, the driving torque of the blade when the fluid flows through the turbine, Trm, mechanical friction torque between turbine shaft and support bearing, Trf, flow resistance torque of fluid passing through the turbine and Tre, electromagnetic torque of electromagnetic converter to the turbine. According to Newton's law of motion, motion equation of the turbine can be obtained:

 (1)

where *J* is rotation inertia of the turbine, *ω* is rotation angular velocity of the impeller, *T* is driving torque, *T*rm is mechanical friction torque, *T*rf is flow resistance torque and *T*re is electromagnetic torque.

For dynamic testing, the instantaneous velocity of fluid changes quickly, and by comparison the resistance torque is so small that it can be ignored. Therefore, the equation can be written as

 (2)

Expression of driving torque is

 (3)

Substitute T into Equation (3) with the consideration *q*v=A*v*, the equation is obtained as

 (4)

If , and ,

where *K* is meter coefficient of the flowmeter, *Z* is the number of impeller blades, *f* is pulse frequency, *Q*i(t) is input flow rate, *Q*o(t) is output flow rate of the meter. Substituting the above into Equation (4) obtains

 (5)

Rewriting Equation (5) by Laplace transform, the expression about the output flow rate and the input flow rate shows as

 (6)

Equation (6) is a simplified model of the turbine flowmeter, which can be used to study its general characteristics. Because B involves the input *v*(*t*), the turbine flowmeter can be regarded as a first-order nonlinear system, which is in agreement with the results derived before. However, if *v*(*t*) is unit-step function, *G*(*s*) can be considered as first-order inertial loop with the time constant τ=1/*Br*.

Parameters of the meter are shown as Table 1.

**Table 1:** Parameters of the turbine flowmeter.

|  |  |  |  |
| --- | --- | --- | --- |
| **Geometric parameter** | **Value** | **Geometric parameter** | **Value** |
| Effect radius *r*(m) | 7.5×10-3 | Rotation inertia *J*(kg·m2) | 2.025×10-7 |
| Density *ρ*(kg·m-3) | 800 | Blade angle *θ* | 45º |
| Flow area *A*(m2) | 225×10-6 | Number of blade *Z* | 4 |
| Speed *v*(m·s-1) | 1 | Meter coefficient *K*(P·L-1) | 377.4 |

Substituting the parameters in Table 1 into Equation (6) can obtain

 (7)

From Equation (7), the simplified model of the turbine flowmeter is considered as first-order inertial whose time constant τ=1/*Br* is about 0.02s and magnification factor is 1. If the flow area of the tested meter is 225×10-6 m2, volumetric flow rate related to step flow speed can reach 13.5L/min. According to the above, when the step flow rate is greater than 13.5L/min, the time constant τ is longer than 0.02s.

# 3. Simulation studies

In order to achieve a simple and practical simulation model to evaluate the performance of the calibration device designed in this paper, the following AMESim model is established and the simulation is carried out. Considering effects of the pipe layout on the fuel pushing flow of the device and the mathematical model of the turbine flowmeter, AMESim model is established as Figure 3.



**Figure 3:** Principle diagram of the calibration device using metering cylinder.

**Table 2:** Main parameters used in the model.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Value | Parameter | Value |
| Density *ρ*(kg·m-3) | 800 | Leakage gap *l*c (mm) | 0.1 |
| Motor speed *n* (rev/min) | 2000 | Connecting pipe diameter *d* (mm) | 20 |
| Reduction ratio *i* | 10 | Ball-Screw Travel *h* (mm) | 10 |
| Plunger cylinder diameter *D* (mm) | 120 | Torsion stiffness *K* (N·m/deg) | 10 |
| Plunger rod diameter *d*1 (mm) | 50 | Damping ratio *C* [N·m/(rev/min)] | 1 |
| Plunger width *b* (mm) | 30 | Moment of inertia *I* (kg·m2) | 0.1 |

With 16s running time in simulation, the pushing flow rate and the plunger displacement of the metering cylinder are illustrated in Figure 4.

According to Figure 4(a), the metering cylinder has a step flow rate at the beginning and then deliver steady flow rate. Besides, the flow rate keeps steady throughout the stroke and has small fluctuation at the end of the stroke. The theoretical flow rate is about 22.608L/min while the steady value of simulation is about 22.620L/min, so the deviation is about 0.05%. From Figure 4(b), the plunger of the metering cylinder performs uniform motion. The expected stroke is 400mm while the actual data is 400.02mm, which produces 0.005%travel deviation. In general, the tracking performance of this system is good and the expected displacement can be achieved



Figure 4: Flow rate and displacement of the metering cylinder.



Figure 5: Flow rate and displacement of the metering cylinder.

Figure 5 clearly shows the leakage rate with fuel pushing velocity at different command speeds of the servo motor. As the fuel pushing velocity increases, the leakage rate increases quite slowly and remains steady at about 0.4% variation. Considering the magnitude of the leakage rate, it has a small effect on the output flow rate. As a result, the system can realize the command output flow.

With effects of the flowmeter, the output response of the system lags behind. Within simulation time of 1 second, the relationship between the input and the output fuel rate of the calibrated flowmeter is shown as Figure 6.



Figure 6: The measured flow simulation curve of calibration flowmeter.

To study dynamic performance of the system, the motor speed is supposed to have a step change. Specifically, a step is made on the speed after reaching the steady running speed. When the motor starts at 2000 rev/min and accelerates to 1500 rev/min in the 3 seconds, the simulation results in Figure 7 indicate that the pushing flow rate of the metering cylinder is fluctuant and the overshoot reaches up to 4.2%. The system responses fast and have a short equilibration time. Except for the response lagging, the pushing flow rate is steady and consistent with the input.



Figure 7: The measured flow simulation curve of calibration flowmeter.

# 4. Experimental studies

The calibration device based on Figure 2 is developed as Figure 8, which is activated and controlled by a PC (not shown in Figure 8). In Figure 8, a large plunger stretches out for the large flow rate calibration. The arrangement of the ball screw and the plunger cylinder should guarantee good straightness and low friction. The tank is fixed higher than the metering cylinder for easy fuel filling into the calibrating pipeline and returning without a pump.



Figure 8: The real calibration device.

Experimental data acquisition under the same running condition should be done more than three times as soon as the fuel flows steady in accordance with calibration rules. The average meter coefficient, linearity and repeatability of the turbine are calculated by utilizing the experimental results.

The meter coefficient K[10] of the flowmeter can be calculated as depicted by

 (8)

where *K* is meter coefficient of flowmeter; (*Ki*)max is maximum value of *K*i of all measuring cases and (*Ki*)min is minimum value of *K*i of all measuring cases.

The repeatability *E*r of the flowmeter can be calculated by

 (9)

 (10)

where, (*Er*)*i* is repeatability of testing point *i*; *Ki* is average meter coefficient of testing point *i*, *n* is test times of testing point *i*; *Kij* is meter coefficient at *j* testing time for testing point *i*, *K* is meter coefficient of flowmeter; *Er* is repeatability of flowmeter.

The experimental data of the above cases on a calibrated turbine flowmeter are listed as Table 2.

**Table 2:**Testing data for a calibrated turbine flowmeter.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Flow rate/ (L/min) | Actual flow/ (L/min) | Meter coefficient/ L-1 | Average meter coefficient/ 1/L | Repeatability/ % |
| 0.20 | 0.158 | 5289.8309 | 5289.8387 | 0.0020 |
| 0.158 | 5289.9307 |
| 0.159 | 5289.7544 |
| 3.39 | 3.316 | 6502.0929 | 6502.0928 | 0.0011 |
| 3.325 | 6502.0331 |
| 3.307 | 6502.1525 |
| 8.14 | 7.867 | 6482.3321 | 6482.3778 | 0.0008 |
| 7.923 | 6482.3802 |
| 7.971 | 6482.4212 |
| 13.56 | 13.251 | 6491.4370 | 6491.3221 | 0.0018 |
| 13.211 | 6491.2911 |
| 13.197 | 6491.2383 |
| 18.31 | 17.865 | 6504.1272 | 6504.1152 | 0.0009 |
| 17.878 | 6504.1554 |
| 17.833 | 6504.0630 |

The above data show that the calibration accuracy is out of acceptable range at 0.20 L/min flow rate, which can be avoided. The meter coefficient K, linearity E and repeatability Er are respectively calculated by using these data.

(L-1)



**Table 2** indicates that the meter coefficient of the flowmeter almost keeps constant, within the effective measuring range and discordance of the flow rate among different tests, which just reaches 0.02%. Calibration testing under the flow rate less than the minimum rang should be avoided because of larger error.

Table 3 and Table 4 are the testing data for different speeds at 100 and 400mm fuel pushing speed respectively.

Analysis on the above implies calibration testing under these speeds and strokes can obtain nearly consistent results due to the minor deviation between the 6492.699 L-1 and 6492.613L-1 meter coefficient. The testing repeatability is 0.0903% and 0.0871%, which fuel pushing speed has the little influence on the meter coefficient within the effective measuring range and under the fixed plunger stroke.

**Table 3:** Testing data for different speeds at 100mm fuel pushing stroke.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Speed/ (mm/s) | Actual flow/ (L/min) | Meter coefficient/ (1/L) | Average meter coefficient1/L | Repeatability% |
| 2 | 1.286 | 6490.7953 | 6491.8502 | 0.0153 |
| 1.303 | 6492.3531 |
| 1.320 | 6492.4021 |
| 5 | 3.316 | 6502.0929 | 6502.0965 | 0.0010 |
| 3.325 | 6502.0441 |
| 3.307 | 6502.1525 |
| 8 | 5.304 | 6488.7150 | 6488.9251 | 0.0069 |
| 5.258 | 6489.3958 |
| 5.279 | 6488.6645 |
| 11 | 7.867 | 6482.5321 | 6482.4471 | 0.0012 |
| 7.923 | 6482.3882 |
| 7.971 | 6482.4212 |
| 18 | 11.910 | 6494.7644 | 6488.5231 | 0.0903 |
| 11.863 | 6485.4881 |
| 11.754 | 6485.3168 |
| 26 | 17.081 | 6501.3032 | 6502.7783 | 0.0210 |
| 17.131 | 6503.9439 |
| 17.091 | 6503.0878 |

**Table 4:** Testing data for different speeds at 400mm fuel pushing stroke.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Speed/ (mm/s) | Actual flow/ (L/min) | Meter coefficient/ (1/L) | Average metercoefficient1/L | Repeatability% |
| 2 | 1.294 | 6492.3981 | 6495.2096 | 0.0871 |
| 1.283 | 6492.9680 |
| 1.301 | 6500.2628 |
| 5 | 3.316 | 6503.9024 | 6503.3014 | 0.0184 |
| 3.325 | 6502.0349 |
| 3.307 | 6503.9669 |
| 8 | 5.304 | 6488.7150 | 6489.2388 | 0.0127 |
| 5.258 | 6490.1369 |
| 5.279 | 6488.8645 |
| 11 | 7.332 | 6481.8344 | 6482.0966 | 0.0083 |
| 7.345 | 6482.6644 |
| 7.289 | 6481.7910 |
| 18 | 11.873 | 6485.7385 | 6486.1070 | 0.0118 |
| 11.910 | 6486.9147 |
| 11.858 | 6485.6677 |
| 26 | 17.082 | 6502.8100 | 6502.6204 | 0.0029 |

# 7. Conclusion

Simulation and experimental study for the designed double-plunger metering cylinder flow calibration device is presented and studied in this paper. Results indicate that discordance of the flow rate is not more than 0.002%. Deviation from the average meter coefficient of a new flowmeter to that on factory specification is 0.04%. Besides, within effective flow rate range, the fuel pushing speed has negligible influence on the meter coefficient of the turbine flowmeter. The work of this paper provides calibration method references for flow meters covering wide service range.

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