Simulation on Fuel Metering Unit Used for TurboShaft Engine Model

Bin Wang, Hengyu Ji, Zhifeng Ye

***Abstract*—**Fuel Metering Unit (FMU) in fuel system of an aeroengine sometimes has direct influence on the engine performance, which is neglected for the sake of easy access to mathematical model of the engine in most cases. In order to verify the influence of FMU on an engine model, this paper presents a co-simulation of a stepping motor driven FMU (digital FMU) in a turboshaft aeroengine, using AMESim and MATLAB to obtain the steady and dynamic characteristics of the FMU. For this method, mechanical and hydraulic section of the unit is modeled through AMESim, while the stepping motor is mathematically modeled through MATLAB/Simulink. Combining these two sub-models yields an AMESim/MATLAB co-model of the FMU. A simplified component level model for the turboshaft engine is established and connected with the FMU model. Simulation results on the full model show that the engine model considering FMU characteristics describes the engine more precisely especially in its transition state. An FMU dynamics will cut down the rotation speed of the high pressure shaft and the inlet pressure of the combustor during the step response. The work in this paper reveals the impact of FMU on engine operation characteristics and provides a reference to an engine model for ground tests.

***Keywords*—**Fuel metering unit, stepping motor, AMESim/MATLAB, full digital simulation.

I. Introduction

As is known to all, aircraft performance improvement mainly depends on high performance aero engines [1]. A multiple-variable control system allows an engine to have comprehensive performances [2]. It is quite difficult for traditional hydraulic mechanical control systems to meet the control requirements of modern engines due to its narrow control range, low precision, and complex structure [3], [4]. Since the 1970s, the full authority digital electronic control (FADEC) increasingly becomes a main trend for control system of aeroengines [5].

Complexity and performance requirements to a digital control system determine the difficulty in development [6], [7]. FMU is one of the main mechanisms in fuel system, enabling fuel to flow into a combustor at an expected rate [8]. And the metering flow is not affected by factors such as metering unit inlet and outlet pressures, fuel pump, and another external environment [8]. It is only related to the valve opening of the metering unit [9], that is, the pilot controls the throttle lever, as shown in Fig. 1. The working reliability of FMU plays a decisive role in the performance of the entire engine control system [10], [11]. Therefore, in order to further study the characteristics of the aero engine control system, mathematical model of the FMU is established to the engine model to discuss the research on its influence on the engine performance [10].

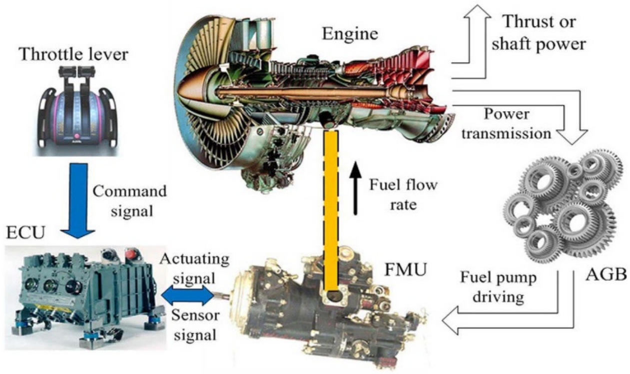

Fig. 1 An aeroengine control system

As a driving component of FMU, stepping motor has advantages of high reliability and precision [12]. The input pulse signal is linear with the rotation angle [13]. The output angular displacement has no cumulative error to easily interface with a computer or other digital electronic components [14], [15]. With its driving, FMU is more suitable for digital control system in engines [14]. As a stepping motor has increasingly become the key component of digital control fuel system, the model for a digital FMU should include the motor part [15]. Semi-physical test is implemented to verify the performance of components or control algorithms which will be used in engines [16]. Because of the economy and safety, an engine model is most of the time used to simulate a real one [17]. The model hardly involves FMU characteristics but rather the key components, for example, air inlet, compressor, combustor, turbine and nozzle [18]. Some ground tests show that results from engine models without the FMU characteristics reckoned cannot describe the engine operation very well especially during some transition processes. Therefore, in order to investigate how an FMU influence the operation parameters, it is necessary to model an FMU and combine it with an engine model for full model simulation and analysis.

This paper focuses on a feasible co-modeling method for a stepping motor driven FMU, which can describe the steady-state and dynamic property of the unit. Combining the FMU model to a turboshaft engine model, a new engine model is obtained, and the difference from original model is analyzed based on simulations.

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II. Principle and Model

A. System Principle

1) FMU: As shown in Fig. 2, the digital control FMU is mainly composed of a metering valve, a stepping motor, a rack and pinion pair, a displacement sensor, a constant differential pressure valve (CDPV) and a constant pressure valve.

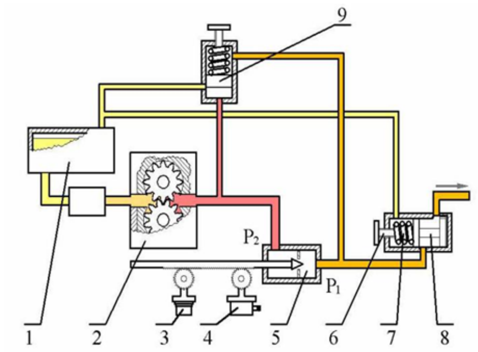


Fig. 2 Schematic diagram of FMU driven by stepping motor. 1. Tank; 2. Gear pump; 3. Rotary variable displacement transducer (RVDT); 4. Stepping motor; 5. Metering valve (MV); 6. Adjusting bolt; 7. Balancing spring; 8. Constant outlet pressure valve (COPV); 9. Constant differential pressure valve (CDPV)

The fuel delivered from the main fuel pump flows towards the metering valve, whose inlet and outlet connects two pressure chambers of the CDPV, respectively. The pressure difference between these two chambers balances the spring force. Because it just needs a very little deformation increment to adapt the change in inlet or outlet pressure of the metering valve, the CDPV can ensure the pressure difference across the MV constant in the certain range. The pressure difference can be set by adjusting the preload of the spring. With constant pressure difference, fuel flow rate through the metering valve is only proportional to its opening. The RVDT measures the actual displacement of the metering valve and feeds back the controller to drive the stepping motor for precise regulation of the fuel flow rate.

B. Mathematical Model

A mathematical model based on the working principle of FMU is built to evaluate its performance and will be used to establish the co-modeling interface.

1) Stepping motor: According to electromagnetic circuit of the four-phase reactive stepping motor and the relationship between the self-inductance of a phase winding and the rotor angle, the voltage balance equation of the one-phase winding is written as

$$U(t) = RI(t) + L_0 \frac{dI(t)}{dt} + L_1 \cos(N_r\theta)\frac{dI(t)}{dt} - L_1 N_r \sin(N_r\theta) I(t)\frac{d\theta}{dt} \tag{1}$$

where $U(t)$ is the rectangular pulse voltage applied to the phase, R is the resistance of the one-phase winding, $I(t)$ is the current of the one-phase winding, L_0 is the average inductance of the winding, L_1 is the fundamental component of winding inductance, N_r is the teeth number of the motor, θ is the angular displacement of the rotor. From (1), it can be seen that the voltage applied to the phase winding of the stepping motor minus voltage drop by the winding resistance yields the induced voltage u.

Induced current is expressed by

$$i = \int \frac{u\mathrm{d}t}{L_0 + L_1 \cos(N_r\theta)} \tag{2}$$

The electromagnetic torque for a phase in a reactive stepping motor is described as

$$T_{en} = -\frac{1}{2} N_r L_1 I(t)^2 \sin\left[N_r\theta - \frac{\pi}{2}(m-1)\right] \tag{3}$$

The motion equation for its mechanical system is

$$T_e = J\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2} + B\frac{\mathrm{d}\theta}{\mathrm{d}t} + T_1 \tag{4}$$

where J is the moment inertia of the rotor, B is the damping coefficient of the mechanical system, T_1 is the load torque. All above make a complete mathematical model of the stepping motor.

2) Gear pump: The FMU is equipped with a gear pump that pressurizes and delivers fuel at a flow rate greater than the engine requires. Considering internal leakage of the pump and compressibility of fuel in the chamber of the pump, the flow continuity equation of the pump is as follows:

$$Q_p = Q_{th} - \delta Q - \frac{V_p}{E}\frac{dp_s}{dt} \tag{5}$$

where Q_p is the output flow rate of the pump, Q_{th} is the theoretical flow of the pump, δQ is the leakage flow, V_p is working volume of the delivery chamber, E is bulk modulus of the fuel, and p_s is the outlet pressure of the pump.

3) Metering valve: The spool displacement of the metering valve is L, and when L=0, the spool profile can be expressed based on the relationship between the displacement L and the diameter Φ in Table I.

TABLE I
Spool Profile of the Metering Valve

L (mm)	Φ (mm)
1	3.014
2	2.857
3	2.686
4	2.490
5	2.276
6	2.406
7	1.725
8	1.496
9	1.089
9.5	0.800

Using Q_0, L_0, P_{20} and P_{10} as the steady-state operating parameters of the metering valve, the linearized incremental equation near the operating point is

$$\Delta Q = K_1 \Delta f(L) + K_2(\Delta P_2 - \Delta P_1) \tag{6}$$

here

$$K_1 = \left.\frac{\partial Q}{\partial f(L)}\right|_{\substack{L=L_0\\P_1=P_{10}\\P_2=P_{20}}} = -\frac{\pi}{2}C_d f(L_0)\sqrt{\frac{2}{\rho}(P_{20}-P_{10})}$$

and

$$K_2 = \left.\frac{\partial Q}{\partial P_2}\right|_{\substack{L=L_0\\P_1=P_{10}\\P_2=P_{20}}} = \left.\frac{\partial Q}{\partial P_1}\right|_{\substack{L=L_0\\P_1=P_{10}\\P_2=P_{20}}} = \frac{\pi}{4}C_d\left[d^2 - f^2(L_0)\right]\sqrt{\frac{P_{20}-P_{10}}{2\rho}}$$

4) Constant differential pressure valve: As a key component of FMU, it uses a spring-typed valve. It balances the pressure change and keeps a constant pressure difference across the metering valve by prolonging or shortening the spring, which gives an essential prerequisite of linear relationship between the flow rate and the opening of the metering valve in FMU. The force balance equation of the CDPV is given as

$$P_2 A_2 - P_1 A_1 = F_0 + kx \tag{7}$$

where A_1 and A_2 are the effective working area of the inlet chamber and the spring chamber respectively. F_0, k and x are the preloading force, the spring stiffness, and deformation amount of the spring, respectively.

The object of this paper is a free-turbine single-rotor turboshaft aeroengine, which has five main components including inlet, compressor, combustor, gas turbine, power turbine and exhaust nozzle, ignoring the air guiding and bleeding parts, accessories and other additional systems. The following gives the structure models for each component above.

i. Atmospheric Environment: The effects of atmospheric pressure and temperature on flight conditions are considered here.

Atmospheric temperature is designed as

$$T_{s0} = \begin{cases} 288.15 - 0.0065H, H \le 11000 \\ 216.5, H > 11000 \end{cases} \tag{8}$$

Atmospheric pressure is defined as

$$P_{s0} = \begin{cases} 101325(1 - 0.225577 \times 10^{-4} H)^{5.25588}, H \le 11000 \\ 222632 e^{\frac{11000-H}{6328}}, H > 11000 \end{cases} \tag{9}$$

ii. Inlet: Total temperature of inlet airflow is

$$T_1 = T_{s0}(1 + \frac{k-1}{2}M_a^2) \tag{10}$$

Total pressure of inlet airflow is described as

$$P_1 = P_{s0}(1 + \frac{k-1}{2}M_a^2)^{\frac{k}{k-1}} \tag{11}$$

Total temperature and total pressure of the outlet gas is expressed as

$$\begin{cases} T_2 = T_1 \\ P_2 = P_1 \cdot \sigma_i \end{cases} \tag{12}$$

here σ_i is the inlet pressure recovery coefficient.

$$\begin{cases} \sigma_i = 1, M_a \le 1.0 \\ \sigma_i = 1 - 0.075(M_a - 1)^{1.35}, M_a > 1.0 \end{cases} \tag{13}$$

iii. Compressor: Total pressure, total temperature and air flow at the compressor outlet are written as

$$\begin{cases} P_3 = P_{21} \cdot \pi_c \\ T_3 = T_{21} \cdot \left[\dfrac{\pi_c^{\left(\frac{k-1}{k} - 1\right)}}{\eta_c} + 1 \right] \\ W_{a3} = W_{a21} \end{cases} \tag{14}$$

The power of compressor is rewritten as:

$$N_c = W_{a21} \cdot C_p' (T_3 - T_{21})' \tag{15}$$

iv. Combustor: Total pressure, total temperature and flow rate of airflow at the combustor inlet are expressed as

$$\begin{cases} P_{31} = P_3 \\ T_{31} = T_3 \\ W_{a31} = W_{a3} \end{cases} \tag{16}$$

These variables at the combustor outlet are expressed as

$$\begin{cases} P_4 = P_{31} \cdot \sigma_B \\ T_4 = \dfrac{W_{a31} \cdot C_p \cdot T_{31} + H_u \cdot \eta_b \cdot W_f}{W_{g4} \cdot C_p'} \approx T_{31} + \dfrac{H_u \cdot \eta_b \cdot W_f}{W_{g4} \cdot C_p'} \\ W_{g4} = W_{a31} + W_f \end{cases} \tag{17}$$

where σ_B is the total pressure recovery coefficient of the combustor, H_u is low heating value of fuel, η_b is the efficiency of combustor, and W_f is the fuel flow rate injected.

v. Gas turbine: Gas total pressure, total temperature, and flow rate of gas turbine are expressed as

$$\begin{cases} T_{44} = T_4 \cdot \left[1 - \left(1 - \left(\pi_{gt} \right)^{(1-k)/k} \right) \eta_{gt} \right] \\ P_{44} = P_{41} / \pi_{gt} \\ W_{g44} = \dfrac{P_4}{101325} \sqrt{\dfrac{288.15}{T_4}} \cdot W_{g41cor} \end{cases} \tag{18}$$

The power the turbine generates is

$$N_T = W_{g4} \cdot C_p^{'} \left(T_4 - T_{44} \right) \tag{19}$$

C. AMESim Model

Fig. 3 shows the AMESim model of the FMU. The input is the displacement command of the metering valve, and the stepping motor drives the metering valve through the rack and pinion pair to control the opening for adjustment of fuel flow rate. An ideal motor model is adopted to describe the stepping motor. When the command is fed into the unit, the motor receives the pulse signal for output angle to make rack and pinion pair move, as a result of controlling the opening of the metering valve.

D. MATLAB/Simulink Model

1) Stepping motor: Fig. 4 shows a MATLAB/Simulink model of the stepping motor based on its mathematical equations.

Input of the pulse signal (voltage U), exerting the load torque T_1, setting the rotor teeth number N_r, system damping B, resistance R, etc. yields the motor output angle θ.

2) Component Level Model: The components and modules above form a complete system model of the turboshaft engine as shown in Fig. 5.

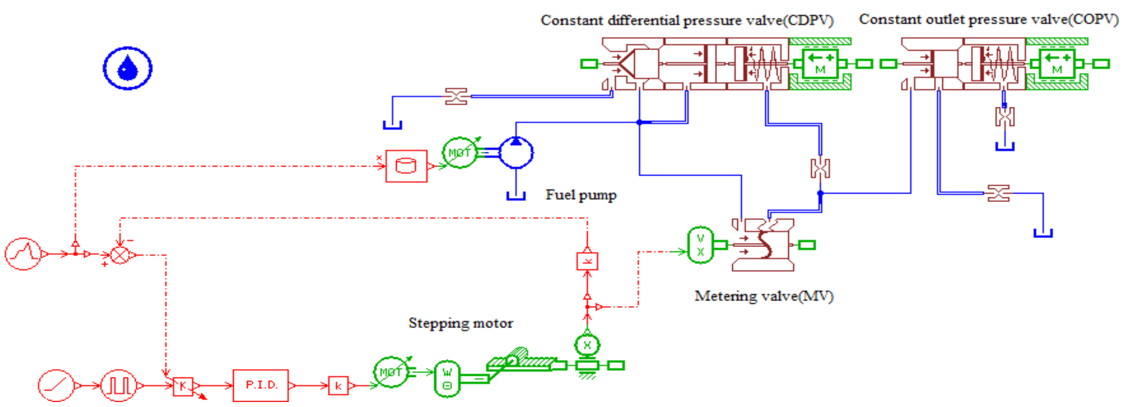


Fig. 3 AMESim model of the FMU

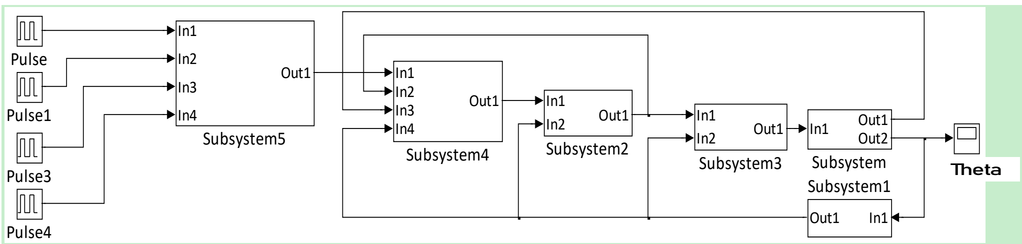


Fig. 4 MATLAB/Simulink model of the stepping motor

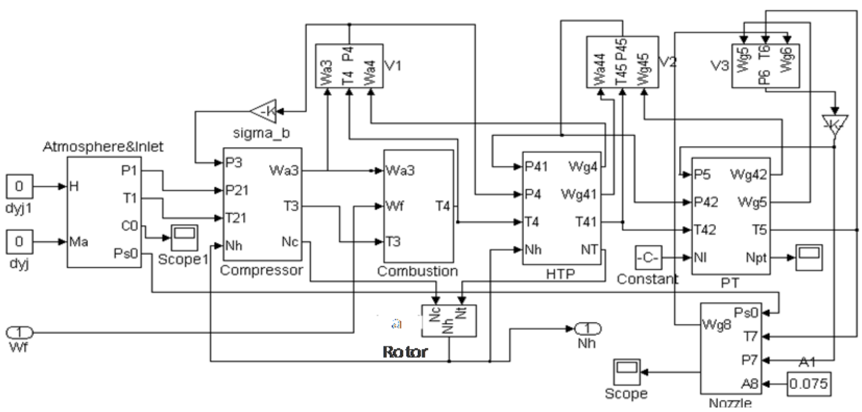
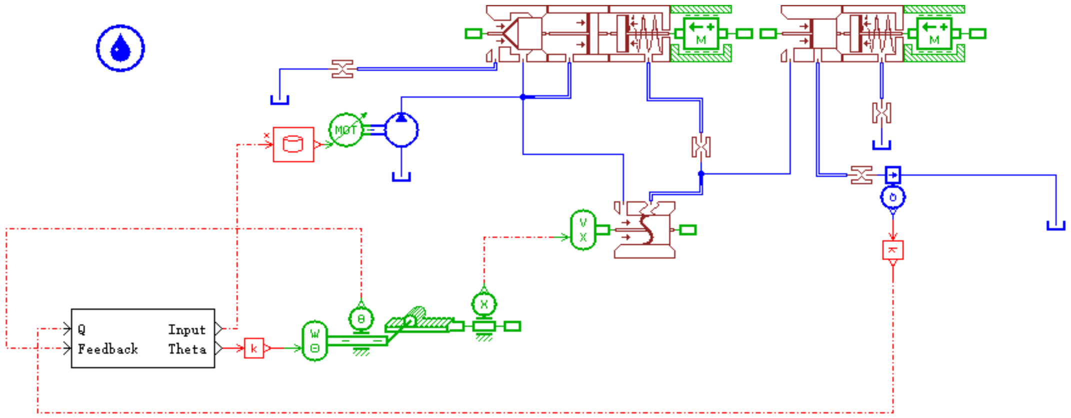


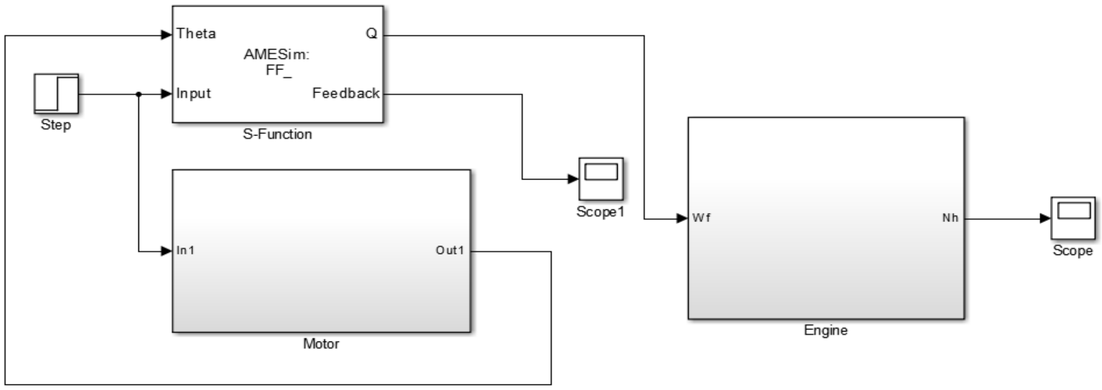
Fig. 5 Component level model of the turboshaft engine

E. AMESim/MATLAB Model

FMU model with co-model interface: Full simulation model of the FMU adopts AMESim for hydromechanical part and MATLAB/Simulink for the component level engine with the stepping motor respectively, which achieves the co-model of the turboshaft engine with digital FMU. Fig. 6 (a) shows the AMESim model of the digital FMU, which includes a co-simulation interface with MATLAB/Simulink. Fig. 6 (b) shows MATLAB/Simulink model of full turboshaft engine, which sends the output angle of the motor to AMESim model of the digital FMU and uses the fuel rate from the AMESim model.



(a) AMESim model of FMU with a co-simulation interface

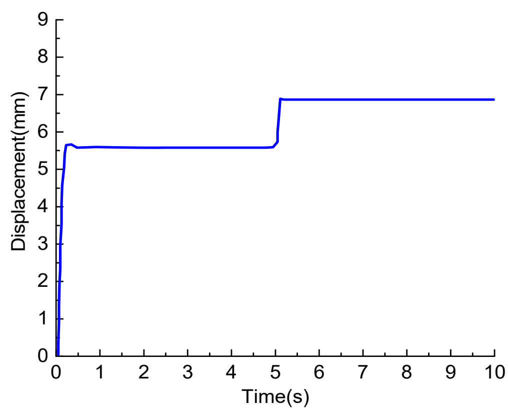


(b) MATLAB/Simulink model for co-simulation

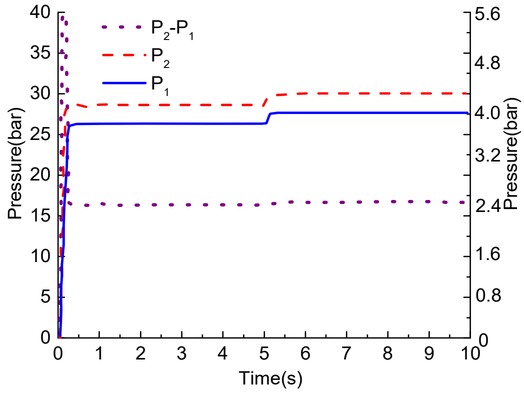
Fig. 6 Full co-simulation model for the engine

III. Co-Simulation Analysis

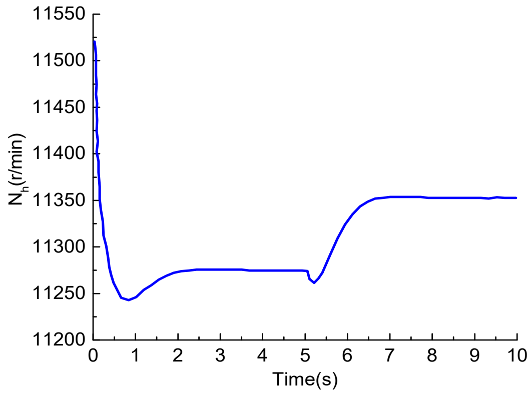
1) Co-simulation of the FMU: Fig. 7 (a) illustrates the response of the metering valve to the control signal transmitted from MATLAB/Simulink. It can be seen that the valve responds fast and the adjustment time lasts within 20 ms. Fig. 7 (b) shows the inlet/outlet pressure and their difference across the metering valve. It can be seen that the CDPV can make the pressure difference remain almost constant and around 2.4 bar but has rather high jitter at 10 ms due to the sudden opening increase of the metering valve under the larger step signal as a result of a sharp increase in inlet/outlet pressure with a 10 ms delay. Fig. 7 (c) shows the rotation speed of the power turbine, decelerated to drive the gear pump. The adjustment lasts about 1.5 s, which accords with the results by the component level of the engine. Fig. 7 (d) is the output flow rate from the FMU. The jitter of the flow rate at 10 ms can attribute to the fluctuation of the differential pressure across the metering valve here. It also verifies co-simulation model enabling better description to dynamic performance of the FMU.



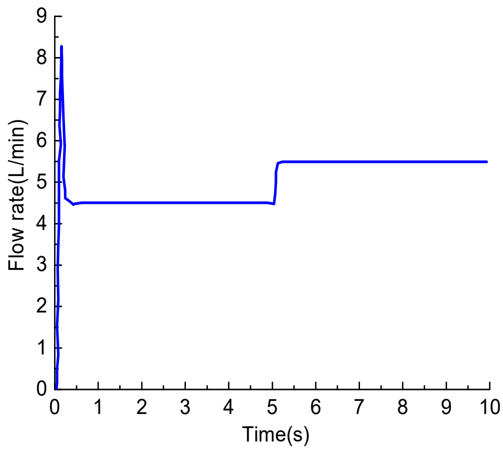
(a) Opening of the metering valve



(b) Pressures of the metering valve



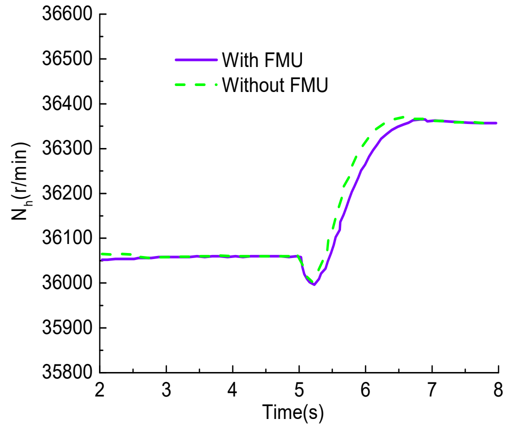
(c) Rotation speed of power turbine



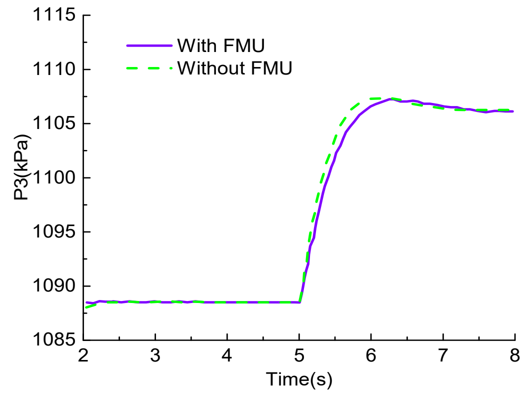
(d) Output flow rate of the FMU

Fig. 7 Co-simulation results

3) Full engine simulation with metering unit: The fuel flow rate into the full engine model is provided by the FMU model. The comparison of engine models with and without FMU is shown in Fig. 8. The power turbine speed and the step response time of P3 by the full simulation of the engine with FMU is about 80 ms longer than those by the engine model without FMU, while the flow rate in the engine model without FMU is the ideal step for the input signal. Additionally, under a step command, the FMU substantially decreases the rotation speed of the high pressure shaft and the inlet pressure of the combustor. The different dynamic responses of the two simulations at the same step show that the full simulation with FMU is necessary especially for dynamic performance analysis.



(a) Rotation Speed of the power turbine



(b) Compressor outlet pressure

Fig. 8 Comparison of engine models with/without FMU

IV. Conclusion

An aeroengine model with high-confidence is of great importance to control system or component research and development. In this paper, a co-modeling on a turboshaft engine with the FMU driven by the stepping motor is carried out, simulation on which indicates that the co-model built has higher steady-state accuracy by comparison in some aspects and allows more precise dynamic description of the engine. It is necessary to conduct semi-physical verification using a full engine model with FMU considered for FMU's influence on the virtual engine and tested objects in future.

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