Aerodynamic Modeling and Transient Performance Improvement of a Free Jet Altitude Test Facility

Feng Wu[1,2], Limin Gao[1], Xinyun Wu[3](✉), Xudong Feng[4], Lintao Leng[4], and Yaoyu Li[3]

[1] School of Power and Energy, Northwestern Polytechnical University, Xi'an 710072, China
wufeng_my@qq.com
[2] The National Key Laboratory of Aerodynamic Design and Research, Xi'an 710129, China
[3] School of Information and Software Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China
786465958@qq.com
[4] Key Laboratory of Science and Technology on Aero-Eigine Altitude Simulation, AECC Sichuan Gas Turbine Establishment, Chengdu 610000, China

Abstract. An inlet-engine altitude test facility for flight condition simulation is modeled for the system dynamic performance improvement. The system model equations are solved with an improved Euler integral method. To simulate the interaction between the tested engine and the test bench accurately, a turbojet engine module is introduced in the system model. By modeling and simulation, a linear temperature compensation control algorithm based on the control error is validated for feasibility; controller parameters optimization for cabin static pressure stabilizing is also carried out. In this paper, some issues like temperature transient performance and engine operate impact restraint on cabin static pressure are discussed efficiently and economically. With the characteristics of high efficiency and economy, the modeling and simulation tools are suitable for the optimization of such systems.

Keywords: ATF · Aerodynamic modeling · Transient performance improvement

1 Nomenclature

The symbol name in the article is shown in Table 1.

X. Sun et al. (Eds.): ICAIS 2020, CCIS 1254, pp. 618–630, 2020.
https://doi.org/10.1007/978-981-15-8101-4_55

Table 1. Nomenclature in article.

A = area	C_p = specific heat at constant pressure
C_V = specific heat at constant volume	C_t = response time factor
T = temperature	C = heat capacity
F = force	h = heat transfer factor
I = inertia	K_e = enhancement factor
K = specific heat ratio	Ma = Mach number
p = pressure	p_s = static pressure
Psch = test cabin pressure	Δp = pressure drop
PW = power	R = gas constant
t_s = simulation time step	T = time
V = volume	ν = velocity
Wa = mass flow	α = flow coefficient
ρ = density	λ = Velocity factor
ω = rotate speed	ATF = altitude test facility

2 Introduction

In the development of aircraft, airframe inlet and engine compatibility evaluation is an important issue. It has great advantages to make the compatibility evaluation in ground altitude test facility (ATF), such as no risk of flight crash, much more measurement probes allowed and wider flight envelope can be simulated than that in a real flight platform.

To make the compatibility evaluation, both the inflow condition (including the inflow total pressure, total temperature, inflow Mach, attack angle, slip angle) and the engine exhaust environment pressure should be represented the same as that at flight condition. The ATF is designed to implement this function by utilizing the air supply and exhaust components (such as compressors, valves, pipes, chambers, air supply nozzles, coolers, heaters etc.) and the control system for the whole facility [1].

The transient performance of ATF and engine can interact on each other. For example, when the engine is accelerating, the intake plenum pressure will drop because more mass flow is aspirated into the engine. Therefore, the lower density of intake plenum will change the air-fuel ratio of the engine and change the transient performance. The ATF and the propulsion system is dynamic coupled. It is detrimental for the test evaluation and will provide incorrect test results of the engine performance. It's necessary to decrease the interaction between ATF and engine [2].

The traditional direct-connect altitude test facility only simulate the total pressure and total temperature for the engine inlet, this is obviously different from that discussed in this paper which can simulate flight Mach, flight attack angle and slip angle additionally. Some old experience from the direct connect facility need assessment for applicability [3].

The modeling and simulation has been proved to be a useful tool to research the transient performance of system like ATF [4].

3 Solution Method

In this paper, we use the lumped parameter method to describe the model behaviors. Such control volumes have properties with no spatial dependence [4]. All the model components are divided into three kinds: potential component, flux component and function. Some components are listed in Table 2.

Table 2. Model component classification.

Potential component	Flux component	Functions
Such as:	Pneumatic valve	Controller
Pneumatic volume	Flow resistance	Ejector
Heat capacity	Air supply free jet nozzle	…
Inertia	Cooler	
…	Heat resistance	

The solver takes the following steps to calculate the whole system model. First, all the potential components listed in Table 1 are initialized, and Flux component states are calculated by formula (1), second, the potential component state derivative of time are calculated using formula (2), Third, potential component state is updated using integration formula (3) by improved Euler method. Then iteratively, the simulation is marching through formula (1–3).

$$F_s = f\left(\sum P\_s, Func, F\_p\right) \tag{1}$$

$$\frac{dP\_s}{dt} = f\left(\sum F\_s, Func, P\_p\right) \tag{2}$$

$$P\_s(t + \Delta t) = \int_t^{t+\Delta t} \frac{dP\_s}{dt} dt + P\_s(t) \tag{3}$$

P_p = potential component parameters, (such as volume size, mass, heat capacity…).
P_s = potential component states, (such as pressure, temperature, rotation speed…).
F_p = flux component parameters, (such as valve opening, pipe Roughness, resistance).
F_s = flux component states, (such as mass flow, heat flow, power output).
Func = functions, (define output/input relations).

An external engine model is introduced to represent the tested engine effect on facility by using a couple interface to transfer simulation data. In the facility and engine model interface, the facility model transfers the total pressure and total temperature to the engine model inlet, and the exhaust static pressure to the engine nozzle. Reversely the engine model transfers the intake mass flow, the total pressure and the total temperature after the low pressure turbine to the facility model to calculate the intake and exhaust performance.

4 Modeling Approach

In this paper, an object oriented modeling method is used to construct the model, which can provide better maintainability if physical equations of components need modification, and this technology also makes it easier to change the structure of the system model consisted of many components. Object oriented modeling method can make the physical description of the components independent form each other, and use the connection to transfer data between model components, similar to the physical connection in the real world.

The fidelity of the whole system depends on the descriptions of all components. This section will focus on the physical descriptions of the pneumatic components used in this paper.

4.1 Volume Modeling

In order to achieve the pressure and temperature change in pipes, chambers, cabin, an open system transient equation is introduced. Using Eq. (4), (5), the temperature gradient dT/dt and the pressure gradient dp/dt can be calculated. In Eq. (4), (5), subscript i represents different inflow or outflow ports connected with the volume. Q is the heat flow into or out of the system in heat source ways RT.

$$\frac{dT}{dt} = \frac{\sum_1^i \left(c_p T_i - c_V T\right) Wa_i + Q}{pV \times c_V} RT \tag{4}$$

$$\frac{dp}{dt} = \frac{\sum_1^i c_p T_i Wa_i}{V \times c_V} \tag{5}$$

When studying the temperature issue, the heat transfer between air flow and volume container (such as pipe and other metal structure container) cannot be ignored. The heat flow from air to steel can be calculated by Eq. (6) which will cause the steel temperature increase or decrease, the heat transfer coefficient h is simplified to a constant. The heat capacity Csteel is determined with steel mass and specified heat capacity as Eq. (7).

$$C_{steel} \frac{dT_{steel}}{dt} = Ah(T_{air} - T_{steel}) = -Q \tag{6}$$

$$C_{steel} = \rho_{steel} V c_{steel} \tag{7}$$

4.2 Air Valve Modeling

The air valve is used to control the mass flow passed which is interrelated with upstream pressure and the pressure ratio between upstream and downstream (Eq. (8)). The inlet air density is another influence factor, for a single valve the minimum flow area is determined by valve opening. α is the flow coefficient, generally a function of valve opening. In this paper, the minimum flow area is simplified to a liner function of opening and the flow coefficient is constant.

To meet the demands of huge airflow, the supply and exhaust valve should be very huge if just take one single valve in supply or exhaust leg. But the cost and weight will raise rapidly with the size increase. So several small valve parallel connection is a better choose. In the modeling, the valves in each parallel leg were simplified into one valve with a total area equal to the sum of the areas of the individual valves.

$$\mathrm{W}a = \alpha A_{min}\omega\sqrt{2p\rho\psi} \tag{8}$$

$$\psi = \begin{cases} \sqrt{\frac{k}{k+1}\left(\frac{2}{k+1}\right)^{\frac{2}{k-1}}} \; if\ critical \\ \sqrt{\frac{k}{k-1}\left(\left(\frac{p_{out}}{p_{int}}\right)^{\frac{2}{k}} - \left(\frac{p_{out}}{p_{int}}\right)^{\frac{k+1}{k}}\right)} \end{cases}$$

For the reasons of mechanic and hydraulic inertia, the valve action will lags behind the controller command which orders the valve to open or close. To represent this delay, a 1-order process with time delay is utilized.

4.3 Free-Jet Nozzle Modeling

The free-jet air supply nozzle in the facility is used to generate supersonic or subsonic flow which can sink into the airframe inlet inside. The mass flow swallowed from the intake plenum by the nozzle can be calculated from Eq. (9), (10) in uncritical or critical situation respectively.

$$Wa = \sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \frac{p_{tot}A_t}{\sqrt{T_{tot}}}\left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \lambda\left(1-\frac{k-1}{k+1}\lambda^2\right)^{\frac{1}{k-1}} \tag{9}$$

$$Wa = \sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \frac{p_{tot}A_t}{\sqrt{T_{tot}}} if\ critical \tag{10}$$

The jet flow Mach number is another important attribute of free jet nozzle, which is identified as the simulated flight Mach number as the airframe inlet faces. Generally the airflow out from the nozzle will experience expansion or compression, only the area at the nozzle outlet is with uniform Mach number distribution, which is known as a diamond shape.

The uniform Mach number within the diamond area can be calculated by the algorithm (shown in Fig. 1) for different pressure ratio range. The pressure ratio range boundary PR1, PR2, PR3 can be acquired by Eq. (11), (12), (13). Obviously all the boundary is related to the ratio of nozzle throat area and outlet area. If the pressure ratio between nozzle inlet total pressure and exhaust static pressure is lower than PR3, the free jet nozzle will work at an uncritical status while the Ma all over the nozzle is less than 1.0.

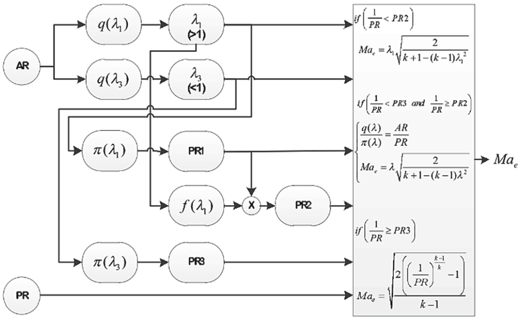

Fig. 1. Mach calculate algorithm.

$$q(\lambda) = \left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \lambda \left(1 - \frac{k-1}{k+1}\lambda^2\right)^{\frac{1}{k-1}} \tag{11}$$

$$\pi(\lambda) = \left(1 - \frac{k-1}{k+1}\lambda^2\right)^{\frac{k}{k-1}} \tag{12}$$

$$f(\lambda) = \frac{4k}{k+1}\left(\frac{\lambda^2}{k+1-(k-1)\lambda^2}\right) - \frac{k-1}{k+1} \tag{13}$$

4.4 Mixer Ejector Modeling

In the cabin, only a small part of airflow from the air supply nozzle will be sucked into the airframe inlet and into the engine. In this case, the spill flow of the rest with high speed will flow through the cabin and mix with the main flow escaped from engine nozzle in the gas collector, sometimes for cooling demand, some cold air from the atmosphere will mingle into the flows. Total pressure loss and heat exchange will occur during the mix process [5].

Therefore, the mass flow equation, momentum equation and energy equation is introduced to calculate the mixer outlet total pressure and temperature. For a given cabin static pressure, the mixer outlet total pressure is determined if other parameters keep constant. It should be noticed here that the mixer outlet pressure is affected by the exhaust system downstream, so the cabin static pressure, known as the simulated environment pressure, will be affected in the same way [6]. This model inputs and outputs are shown in Fig. 2.

In Eq. (14–17), some simplifications are made, no friction and no heat exchange between flow and mixer wall, mixer inlet static pressure is uniform, no pressure loss for the spill flow from air supply nozzle to mixer inlet. In the calculation, the mixed flow total temperature is obtain from Eq. (17), and then the mixed flow velocity can be calculated with Eq. (15), (16), finally the total pressure of mixed flow can be get from Eq. (14). After several iterations the correct cabin pressure corresponding to the existing exhaust downstream pressure is achieved.

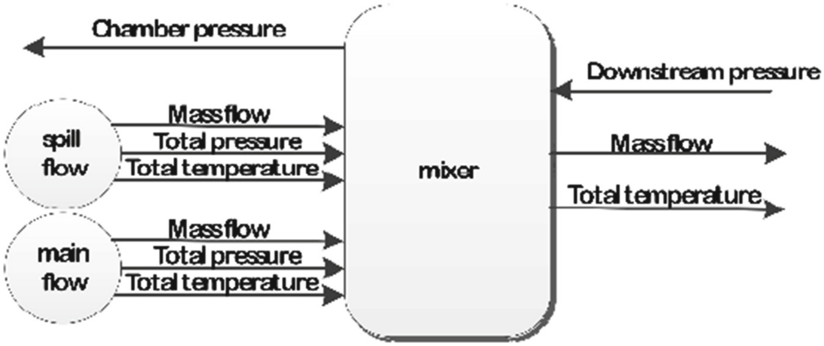

Fig. 2. Mixer model inputs and outputs.

Mass continuity

$$Wa_{main\,flow} + Wa_{spill\,flow} = Wa_{mix\,flow} \tag{14}$$

Momentum conservation

$$F_{A1} + F_{A2} + F_{A3} - F_{mix} - F_{wall\,fric} = (Wa \cdot v)_{mix} - (Wa \cdot v)_{main\,flow} - (Wa \cdot v)_{spill\,flow} \tag{15}$$

$$(Wa \cdot v) + pA = Wa\left(v + \frac{p}{\rho v}\right) = \frac{k+1}{2k} Wa \cdot \sqrt{\frac{2k}{k+1} RT^*} \cdot \left(\lambda + \frac{1}{\lambda}\right) \tag{16}$$

Energy conservation

$$\left(Wa \cdot cp \cdot T^*\right)_{main\,flow} + \left(Wa \cdot cp \cdot T^*\right)_{spill\,flow} = \left(Wa \cdot cp \cdot T^*\right)_{mixed\,flow} \tag{17}$$

4.5 Engine Modeling

The transient engine model is adopted from Gasturb [7, 8], the engine inlet pressure and temperature is coupled with the air supply nozzle outlet parameters, and the engine exhaust static pressure is coupled with the cabin static pressure. On the contrary, the engine calculated intake mass flow, exhaust pressure, exhaust temperature and total exhaust mass flow is transferred to the facility model. So the interaction between the facility and engine can be simulated in this way.

In the model, the volume effect of engine component is ignored. And power balance between turbine and compressor is list as Eq. (18). The control system is active which employ PID type controller as well [7]. Other detailed thermodynamic descriptions of the gas engine will not be discussed here.

$$PW_{compressor} = PW_{turbine} - \frac{dn}{dt} nI_{spool} \tag{18}$$

4.6 Other Components Modeling

Some other components used in the simulation such as Cooler, Controller are simplified and will be briefly introduced here. As a function of inlet temperature and mass flow, the cooler pressure drop is modeled with flow resistance which is fitted with test data. The heat transfer is not involved in the calculation and the cooler outlet temperature is set to a constant value. The controller used in this paper is a standard feedback circuit, firstly the difference between the target and the measured parameter is transformed to range − 1~1, then a standard PID function transformed the signal, after another transform block the signal is rectified to range 0~1 [9].

5 Transient Performance Improvement

In this paper, a free jet ATF system concept is presented in Fig. 3 and is modeled. The cold flow and hot flow is supplied into volume PA1, PA2, and valve VA1, VA2 handle the pressure control of PA1 and PA2. Valve VB1 and VB2 handle the mass flow control of that flow into the volume PI. The free jet nozzle inlet total pressure is control with valve VS1 and the test cabin static pressure is controlled by valve VC. The PC and PE represent the volume after the test cabin and volume before the exhaust pressure. Valve VE make the exhaust compressor working at suitable pressure ratio condition. With this model concept, the test transient operation and the corresponding requirement for both the facility configuration and control algorithm are evaluated to simulate the flight condition as accuracy as possible [10].

5.1 Transient Air Supply Temperature and Pressure

Transient pressure and temperature control is applied with valve VB1, VB2, VS1, of which VB1 handle the air supply hot leg, VB2 handle the cold leg, VS1 handle the pressure of chamber PI. The VB1 and VB2 control the hot/cold airflow ratio that supplied into the chamber PI, by changing the airflow ratio the temperature of PI is changed. The mass flow control target of VB1 and VB2 is calculated with the free jet air supply nozzle mass flow requirement. VS1 is a leak valve so the pressure of chamber PI can be hold constant or changed as expected while the inflow changing. The VB1 and VB2 valve is used to keep the supply pressure of each leg constant, so as to the mass flow control by VB1 and VB2 is only related to valve minimum flow area. This is a basic concept of air supply system.

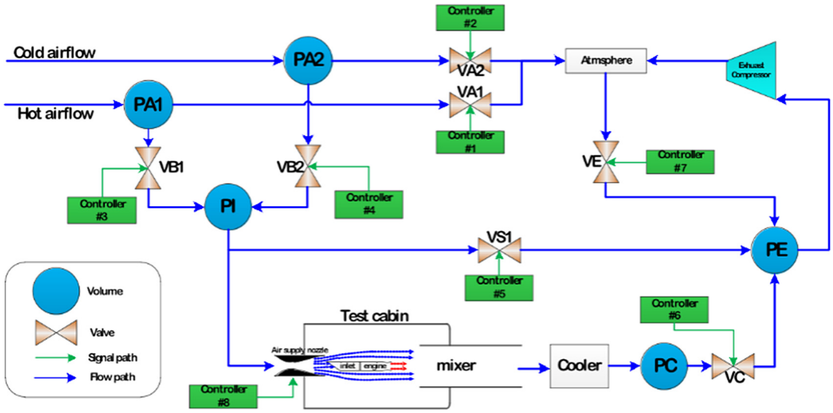

Fig. 3. Free jet test facility concept.

To control the intake plenum temperature, the former temperature control algorithm is to control the VB1 and VB2 mass flow following energy equation, Wa_{VC1}, Wa_{VC2} is the mass flow through valve VB1 and VB2, T_{VC2}, T_{VC2} is the supply air temperature of different leg. Wa_{ASN} is the needed air flow of air supply nozzle. For demand of intake plenum pressure control, the total supplied air flow from two legs $Wa_{VC1} + Wa_{VC2}$ must be more than the air supply nozzle needed, so a factor Kair (less than 1.0) is introduced to scale the mass flow ratio.

$$Wa_{VC1}T_{VC1} + Wa_{VC2}T_{VC2} = (Wa_{VC1} + Wa_{VC2})T_{target} \tag{19}$$

$$Wa_{VC1} + Wa_{VC2} = Wa_{ASN}/Kair \tag{20}$$

Because of heat transfer between steel structure(pipe, valve, plenum chamber) and air flow when their temperature is different, when the simulated temperature need a shift, the real temperature transient will slow than expected. To evaluate how worse this problem will be, a transient test process which represents flight acceleration from Mach 0.8 to 1.2 at altitude 11 km is simulated as shown in Fig. 4. The difference is big in temperature raise slope, for the model with heat transfer, obvious lag in temperature can be observed. The heat capacity of steel structure and heat transfer coefficient used here is in normal range by existing altitude facility [11].

To improve the transient performance of temperature control, a linear temperature target fixed method is used in the temperature algorithm, the basic concept is to change the temperature control target in Eq. (21) based on the existing temperature lag, shown in Fig. 5.

$$T_{target} = T_{expect} + K_{fix}\left(T_{expect} - T_{real}\right) \tag{21}$$

Using the improved algorithm, the same simulation is carried on. As can be seen in Fig. 6, the temperature transient control error is reduced to 1°. Here the Kair is set as 4.0 which means four times of the temperature error is compensated into new fixed target.

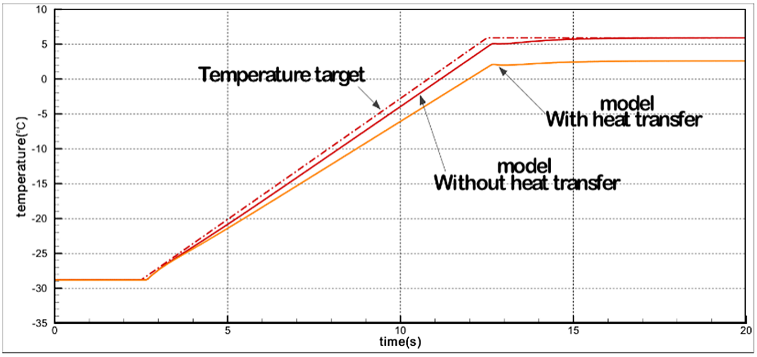

Fig. 4. Comparison between models with or without heat transfer

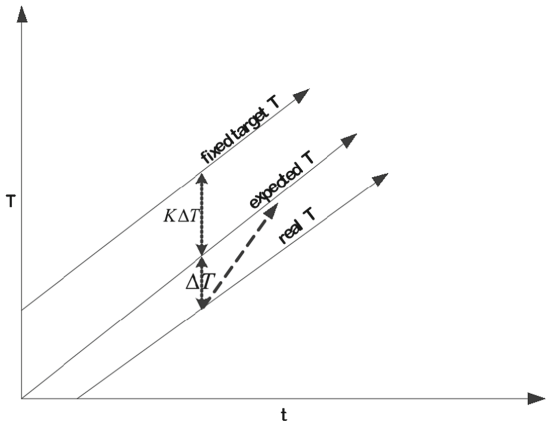

Fig. 5. Linear temperature target fixed method

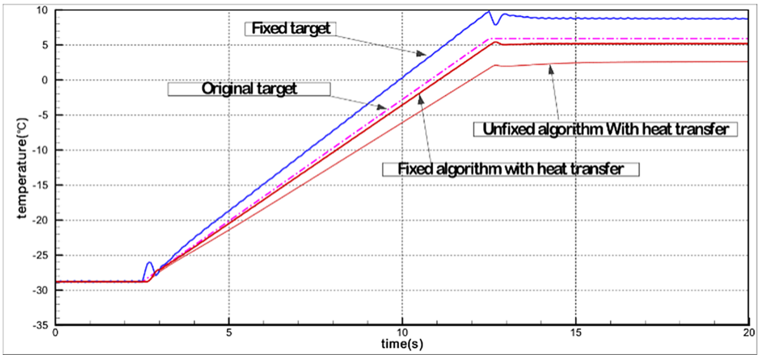

Fig. 6. Transient temperature performance

If the error between target temperature and real one is big at initial time, the vibration may happen due to too much disturbance to the inflow mass, in this case, the algorithm should be disabled temporarily.

5.2 Engine Exhaust Static Pressure Stabilizing

Exhaust system is consist of mixer, cooler, exhaust valve, exhaust pressure stabilize system, exhaust compressor. The exhaust valve VC controls the airflow go through, so the pressure downstream of the cooler will be affected, as the distribution spread upstream the cabin static pressure is affected too, just as described in mixer modeling. The final result is the VC can control the cabin static pressure. From the cabin to valve VC, the system transient performance is complicated because of mixer-cooler-volume feature is linked together that will inevitably bring in time delay in system dynamic response.

When the engine is operating (accelerate or decelerate) in the free jet altitude test [12], the engine mass flow, pressure and temperature leaving the turbine (p6 and T6) will change rapidly. The momentum and energy of engine exhaust flow and spill flow from the ASN will change accordingly, which will result in test cabin static pressure wave. And the exhaust control system should recover the pressure as soon as possible, and no oscillation occurs [13].

To evaluate how bad will the cabin static pressure diverge from the target, a facility simulation is carried out with engine model. The simulated altitude is 9 km. After the system is stable, the engine power level is pulled up and down, the main engine parameters in the acceleration and deceleration is shown in Fig. 7. The mass flow varies from 70 kg/s to 106 kg/s.

With higher power level, the total momentum and heat into the mixer will raise and as a result the cabin static pressure will drop to fill more spill flow into the cabin for balancing the ejection effect. The change of cabin static pressure (Psch) is shown in Fig. 10, and the deviation is about 5% with the configuration in use. The valve VC opening and VC inlet pressure is also shown in Fig. 10. With higher engine power level, the ram effect of entire exhaust is higher and valve VC will close to reduce the mass flow passed by to keep the Psch stable.

In the real altitude engine test, the Psch deviation should be as lower as possible and recover to initial target as soon as possible. This can be achieved by optimizing the PID controller for a certain facility setup [14].

By decreasing the integrate time factor, the pressure deviation is suppressed obviously. But too small integration time will lead to vibration when the $\Delta Psch / \Delta m$ is big, such as when a small diameter mixer is used. So a carefully look should be taken into the control system configuration for compatibility with facility. On the other hand, the modeling and simulation ways in this paper are good tools to do that.

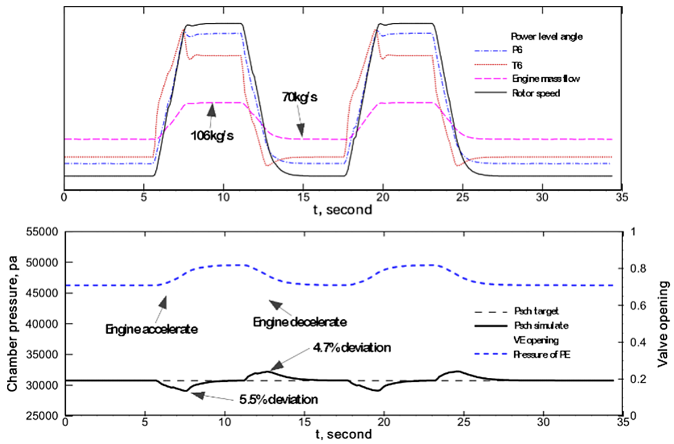

Fig. 7. Engine operation and the corresponding cabin static pressure history

6 Conclusion

With the modeling and simulation, more detailed information about the free jet altitude test facility can be get from the analysis. Some existing problem can be exposed, solutions can be evaluated before the real one is built. Even some concepts can be simulated with no harm. In this paper, some issues like temperature transient performance and engine operate impact restrain on cabin static pressure are discussed in an efficient and economical way. More transient performance improvement will be gained with further work in the near future.

There are also lots of test facility issues can be analyzed, this paper cannot cover all these issues, but it's shown as a useful tool to evaluate different concept designs. Not only for control system design and optimization, but also for facility component improvement.

Acknowledgement. Great thanks to the support of National Natural Science Foundation of China (51506108) and Aviation Science Fund (20141024002).

References

1. Li, X.Y., Zhu, Q.S., Zhu, M.Z., Wu, H., Wu, S.Y., Zhu, M.C.: The freezing Rènyi quantum discord. Sci. Rep. **9**(1), 1–10 (2019). https://doi.org/10.1038/s41598-019-51206-9
2. Bierkamp, J., Köcke, S., Staudacher, S., Fiola, R.: Influence of ATF dynamics and controls on jet engine performance. In: ASME Turbo Expo 2007, GT2007-27586 (2007)
3. Montgomery, P., Burdette, R., Klepper, J., Mihoan, A.: Evolution of a turbine engine test facility to meet the test need of future aircraft system. In: Proceeding of ASME TURBO EXPO GT-2002-30605 (2002)
4. Montgomery, P., Burdette, R., Krupp, B.: A real-time turbine engine facility model and simulation for test operation modernization and integration. In: Proceeding of ASME TURBO EXPO 2000-GT-0576. (2000)

5. Maurice, J., Hoffman, J.: Gas Dynamics. Wiley, Hoboken (1976)
6. Kebe, S., McCormick, D.: Parameter effects on mixer-ejector pumping performance. In: AIAA 88–0188 (1988)
7. Gasturb12 user manual. (2012). www.gasturb.de
8. Kurzke, J.: Gasturb computer deck. www.gasturb.de
9. Gold, B., Rader, C.: Digital Processing of Signals. McGraw-Hill Book Co., New York (1969)
10. Kurzke, J.: Transient simulations during preliminary conceptual engine design. ISABE 2011-1321. (2011)
11. Montgomery, P., Garrard, D.: Test and evaluation of hypersonic aeropropulsion systems along flight trajectories in a time-varying flight environment. In: AIAA-2005-3900 (2005)
12. Huffman, B.C., Lavelle, T.M., Owen, A.K.: An NPSS model of a proposed altitude test facility. In: AIAA 2011-312 (2011)
13. Takeshi, T., Masaharu, K., Nanahisa, S.: Dynamic characteristic tests of single spool turbojet engine using altitude test facility. In: AIAA-2007-5012 (2007)
14. Braig, W.: Transient aero engine testing at stuttgart altitude test facility. In: ISABE 99-7074. (1999)