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Function Modelling and Simulation Analysis of Aero-engine VBV

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Variable Bleed Valve (VBV) as the core component of aero-engine compressor airflow control plays a vital role in eliminating the risk of booster stall during transient conditions and is an important foundation to ensure the stable operation of the engine and the flight safety of aircraft. In this paper, the VBV of a certain engine is studied to build its function model and carry out the system simulation analysis based on AMESIM. Secondly, the control system simulation model is established by using MATLAB and aircraft Quick Access Recorder (QAR) data. In combination with the function model and the control model, the working characteristic curve of VBV is analyzed and compared with the actual working characteristic curve of the engine. The results show that the variation trend of the simulation characteristic curve is consistent with the real characteristic curve, which fully verifies the accuracy and reliability of the VBV functional model.

Keywords: VBV, AMESIM, Electro-hydraulic Servo Valve (EHSV), Aero-engine

1 Introduction

A VBV system locates downstream from the booster to regulate the amount of air discharged from the booster into the inlet of the HPC. To eliminate the risk of booster stall during transient conditions, the VBV system bypasses air from the primary airflow into the secondary airflow [1-3]. The VBV system consists of the following components: a fuel gear motor, a stop mechanism, a master bleed valve, 11 variable bleed valves, flexible shafts, and a feedback sensor (RVDT) (Fig. 1).

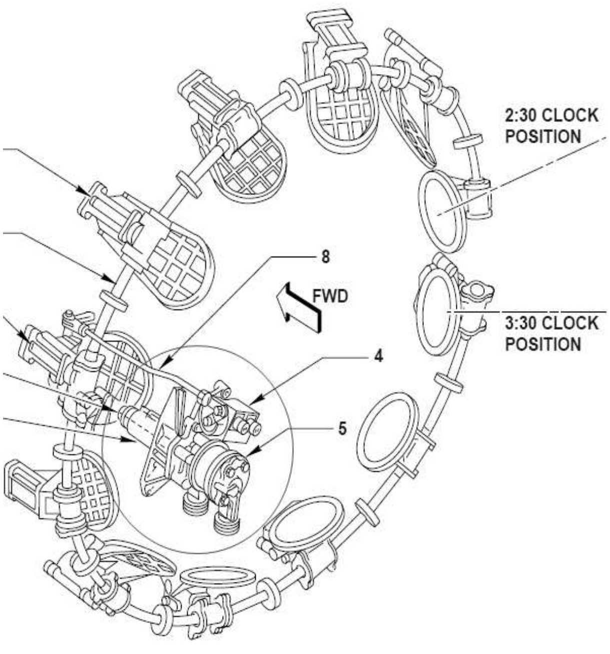


Fig. 1 *VBV system [1]*

Fuel pressure from the Hydro-mechanical Unit (HMU) is delivered to the gear motor. The gear motor transforms the fuel pressure into rotary torque to actuate the master bleed valve. The master bleed valve drives the 11 variable bleed valves, through a series of flexible shafts, which ensure that the VBV remain fully synchronized throughout their complete stroke [4, 5]. At low speed, they are fully open and reject part of the booster discharge air into the secondary airflow, preventing the LPC from stalling. At high speed, the VBV is closed. In addition, VBV can also prevent aliens from entering the engine when the engine thrust is opened to prevent engine damage. Therefore, VBV plays an important role in the smooth operation of the whole engine [6, 7].

2 Materials and Methods

2.1 The control principle of VBV

The control structure of the VBV system is shown in Fig. 2, which is a typical electronically controlled hydraulic mechanism. Using engine parameters, the Engine Control Unit (ECU) calculates the VBV position, according to internal control laws. An electrical signal is sent to the HMU, which provides the fuel pressure necessary to drive the gear motor. The gear motor transforms the fuel pressure into rotary torque to actuate the master bleed valve. The stop mechanism mechanically limits the opening and closing of the valve. The master bleed valve drives the 11 variable bleed valves, through a series of flexible shafts, which ensure that the VBV remain fully synchronized throughout their complete stroke [8].

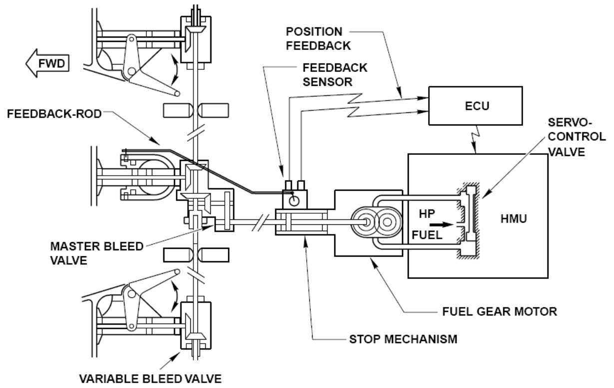


Fig. 2 *The basic control architecture of VBV*

The bleed valve position sensor transmits the angular position of the VBV doors to the ECU through an electrical feedback signal. The sensor is a Rotary Variable Differential Transducer (RVDT) and is mounted onto the stop mechanism. The adjustment is made through the feedback rod connecting the master bleed valve to the transducer's feedback lever. A complete closed-loop control system is formed, and the basic control principle is shown in Fig. 3.

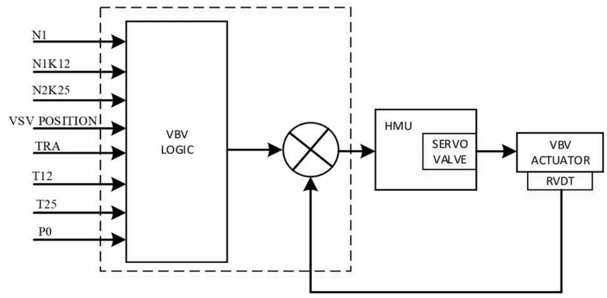


Fig. 3 *The schematic diagram of VBV closed loop control*

The ECU controls the position of the VBV according to engine operations. The VBV demand calculation is computed from different engine and aircraft parameters, including fan speed (N1), corrected fan speed (N1K12), corrected core speed (N2K25), ambient pressure (P0), fan inlet total temperature (T12), core inlet temperature (T25), VSV position and Thrust Reverser Angle (TRA). These input parameters are processed by the VBV logic through 7 logic blocks. The output parameter, called VBV demand, is sent to the actuator loop control. VBV demand is compared with RVDT feedback and gives a closed-loop control command signal. The electrical command signal is converted into a fuel pressure signal in HMU to drive the servo valve which is used to drive the VBV actuator [9, 10].

2.2 The function model of VBV based on AMESIM

The function model of VBV includes fuel actuating system and electronic control logic system, which architecture is shown in Fig. 4. The fuel actuating system mainly consists of an EHSV, a fuel gear motor, actuating cylinder, and a series of flexible shafts. The electronic control logic system mainly includes command signals and RVDT position feedback signals [11, 12].

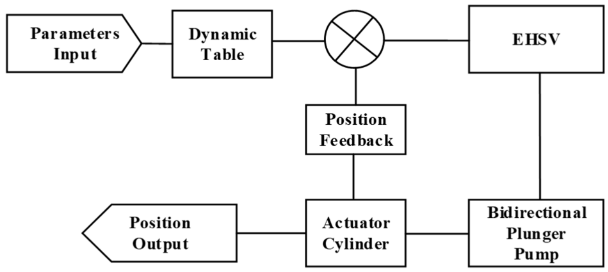


Fig. 4 *The function model architecture of VBV*

3 Discussion of results

3.1 Mathematical analysis

The fuel gear motor in VBV is the most important mechanism to drive the main valve actuator, and it is also the basis of the whole actuator system's stability and reliability. A Fuel gear motor is equipment that drives and controls load movement by adjusting hydraulic power with aviation kerosene as a transmission medium. In the analysis, the nonlinear differential equation is linearized because the parameters of the power element can describe the characteristics of the system in a wide working range [2-5]. In the process of modelling, it is first mathematically analyzed.

The linearized flow equation of the slide valve is:

$$Q_L = K_q x_v - K_C P_L \tag{1}$$

Where Q_L is the load flow, K_q is the flow gain coefficient, x_V is the displacement of the slide valve, K_C is the flow-pressure coefficient, and P_L is the load pressure.

$$K_q = \frac{\partial q_1}{\partial x_V} = C_d W \sqrt{\frac{1}{\rho}(p_S - p_L)} \tag{2}$$

$$K_C = \frac{\partial q_1}{\partial p_L} = \frac{C_d W \sqrt{\frac{1}{\rho}(p_S - p_L)}}{2(p_S - p_L)} \tag{3}$$

The continuity equation of the hydraulic motor is:

$$Q_L = D_m \frac{d\theta_m}{dt} \tag{4}$$

Where D_m is the average theoretical displacement of the hydraulic motor and θ_m is the turning angle of the fuel gear motor output shaft.

The force balance equation of a hydraulic motor and its load is:

$$T = J\frac{d^2\theta_m}{dt^2} + B_p\frac{d\theta_m}{dt} + T_L \quad (5)$$

Where J is the total inertia at the output axis, B_p is the viscous damping coefficient and T_L is the external load torque.

3.2 Function model of VBV

The function model of VBV based on AMESIM is constructed based on mathematical analysis which is shown in Fig. 5.

According to the structure of VBV, the complete function model is constructed through the component library of AMESIM software and self-built supermodel blocks. The model mainly includes a servo fuel supply system, electro-hydraulic servo valve, main valve actuator cylinder, and connecting rod mechanism. The control signal is built through the sensor supermodel block, VSV RVDT supermodel block, ECU supermodel block, and RVDT supermodel block. The control parameters are derived from airborne QAR data, which is used to provide input parameters for the model through a data fitting algorithm in a MATLAB environment.

The key parameters obtained according to the maintenance manual and interface file of the engine are shown in Tab. 1.

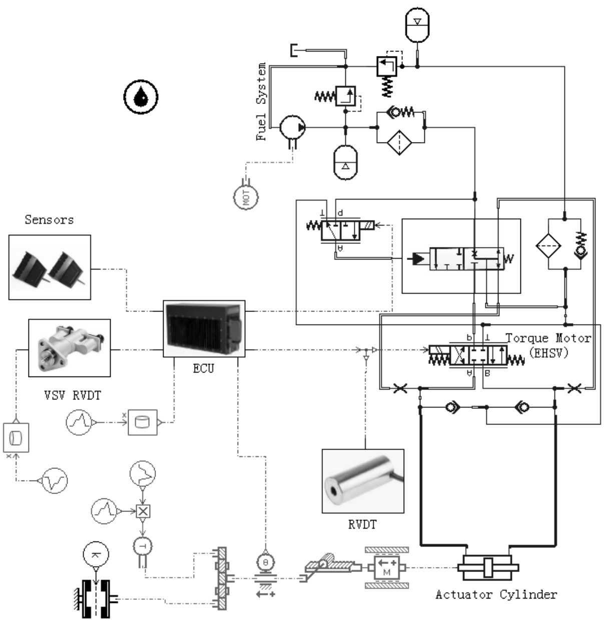


Fig. 5 *The function model of VBV based on AMESIM*

Tab. 1 *The related parameter setting of the model*

Physical Meaning	Numerical Value
hydraulic pump displacement（cc/rev）	100
speed of the torque motor shaft（rev/min）	2000
critical pressure of relief valve（bar）	150
rated current of solenoid directional valve（mA）	40
piston diameter（mm）	60
rod diameter port1 /port2（mm）	20/20
maximum displacement of the rod（m）	0.4
hydraulic cylinder dead zone capacity port1 /port2（cm^3）	50/50
opening pressure of reducing valve（psi）	3000

3.3 Control parameter fitting

The VBV control logic of a certain type of engine is shown in Fig. 6, which realizes the control function of each module under the unified scheduling of ECU software.

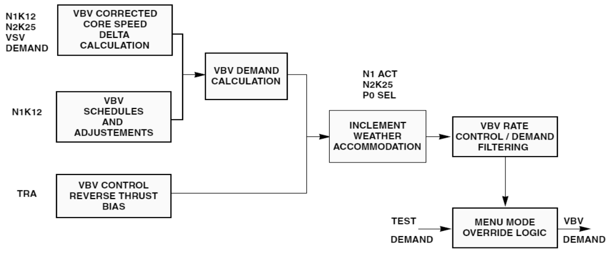
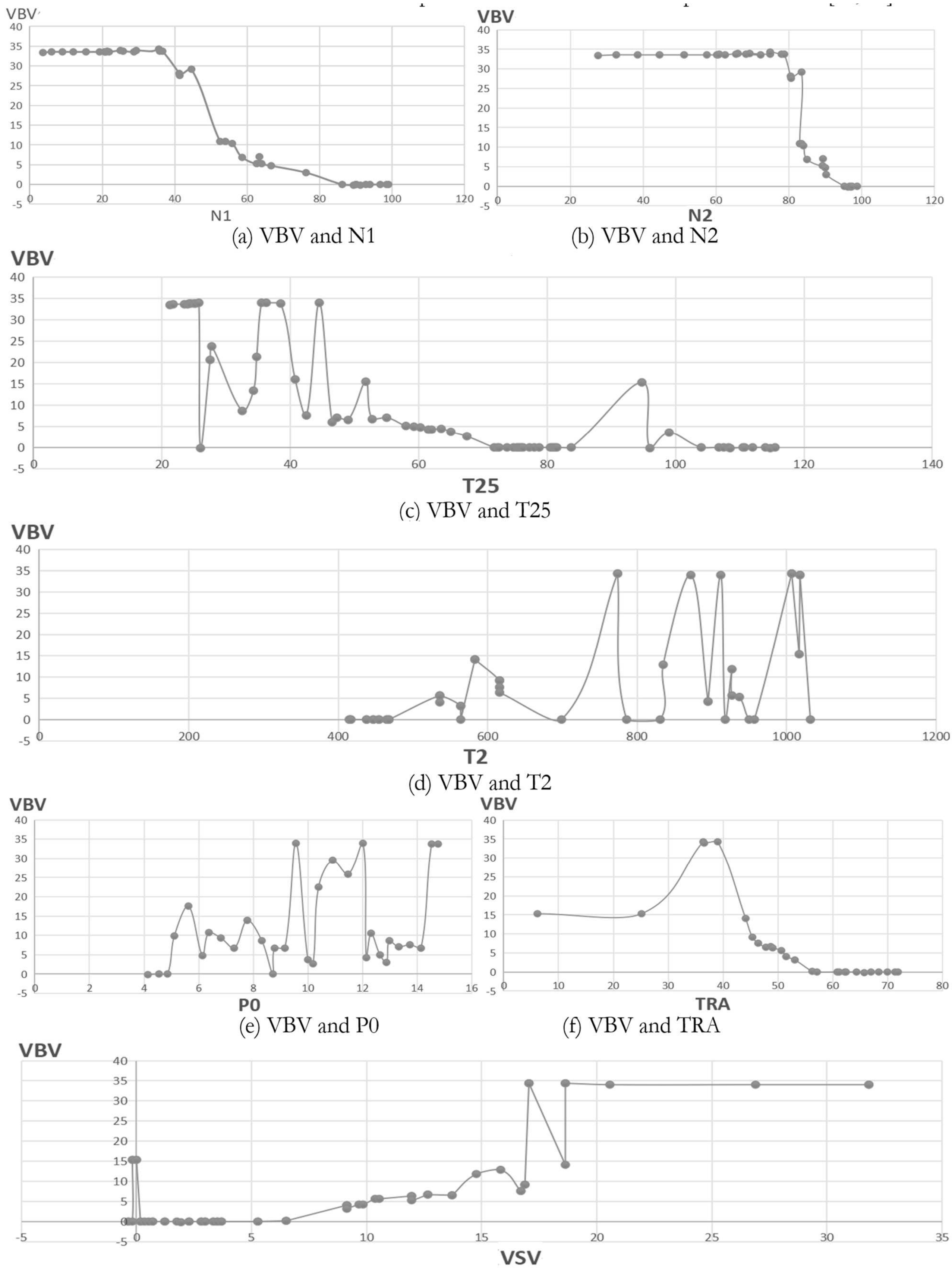


Fig. 6 *The control logic of VBV system*

The logic includes 7 blocks. The Schedules and adjustments block includes three baseline laws which are used to compute the VBV demand. These laws are a function of the corrected fan speed N1K12. The Corrected core speed delta calculation block is to calculate a term, which is representative of their current matching. This term is computed from N1K12, T2, and T25, which are representative of the booster flow, and also, from N2K25 and VSV position, which indicate the high-pressure compressor situation. The VBV baselines are mixed to calculate one opening value in the demand calculation block.



(a) VBV and N1 (b) VBV and N2

(c) VBV and T25

(d) VBV and T2

(e) VBV and P0 (f) VBV and TRA

(g) VBV and VSV

Fig. 7 *The fitting curve of VBV with correlation parameters*

Control reverse thrust bias block checks the throttle position and, when the TRA reaches the upper limit of the reverse idle, an order is sent to increase the opening of the VBV doors. According to the ambient pressure P0 and the fan rotational speed N1, the VBV is set in a more open position to prevent the engine from flaming out in an inclement weather accommodation block. The rate limiter logic limits the rate at which the VBV opens or closes to reduce mechanical wear. The menu mode motor test override function logic block sets the VBV in the fully open or closed position according to the motoring test demand, during a FADEC ground test. This checks the whole motion range of the VBV.

The relevant parameters of the control logic are stored in the QAR module. QAR is a quick access recorder of aircraft parameters in all stages from engine starting to engine closing, which contains all environmental parameters related to VBV control, engine sensor parameters, VBV angle, and other necessary correlation parameters[4][5]. It is the key to realizing the data driving of the function model. The correlation parameters of VBV control are selected from the QAR data to draw the scatter diagrams was drawn. Then, the control curve is fitted, which is input to the ECU supermodel block to calculate the control instructions.

The multivariate nonlinear fitting algorithm is designed by using MATLAB and QAR data to analyze the nonlinear relationship between VBV-related parameters and VBV angle. Through data preprocessing and fitting parameter optimization, the fitting curves of the VBV position instruction signal with the related parameters are shown in Fig. 7.

According to the multi-group fitting curves, the angle of VBV remains unchanged before the N1 speed reaches about 38%. When the N1 speed continues to increase, the angle of VBV changes rapidly. When the speed reaches about 60%, the rate slows down until the angle is 0. The VBV angle is unchanged before the N2 speed reaches 80%. With the increase of N2 speed, the VBV angle changes dramatically until the position is 0. Before the T25 temperature reaches 50℃, the angle of VBV changes greatly between 0 and 1. After 50℃, the angle of VBV maintains at 0, and there is an obvious jump at 95℃. The angle of VBV changes greatly and repeatedly with the increase of T2 temperature, which has no obvious trend. When the temperature is below 400℃ and above 1000℃, the angle of VBV remains 0. VBV has no obvious change trend when P0 changes and its angle is greatly affected by other factors. With the increase of TRA, the angle of VBV increases and then decreases, this reaches the maximum near 38° and almost 0 after 56°. When the VSV position reaches 6%, the VBV angle begins to grow slowly. When the VSV position reaches 17%, the VBV angle increases rapidly. Before the VSV increases to 18%, the VBV angle remains at the maximum position.

By comparing the variation trend of VBV theory in the engine maintenance manual, the curve obtained by data fitting is consistent with it. However, due to the large amount of QAR data and the influence of environmental factors, the process is complicated and has a lot of interference, and the data has obvious changes. Therefore, before providing input parameters for the model, the fitting data is preprocessed to remove the data with a large jump and the mutation caused by special flight phenomena. Part of the data is taken at appropriate intervals, and the table editor of AMESIM software is used to input the data to the relevant supermodel block [14, 17].

3.4 Simulation analysis of the VBV function model

The angle of VBV is affected by a variety of parameters including environmental pressure, engine inlet pressures, engine temperature, and engine speed. During the operation of the engine, the ECU will calculate the VBV angle instruction based on the comprehensive parameters to control the valve opening at a certain Angle. In the Compartment Maintenance Manual (CMM) of the engine, the manufacturer gives the theoretical trend of the VBV angle with the related parameters according to the design parameters. In this paper, the corresponding VBV change trend is obtained by modelling in AMESIM. Through comparing and analyzing, the function model is reliable. By running the VBV function model, the characteristic curves of the VBV angle and the associated parameters are obtained, as shown in Fig. 8.

As shown in Fig. 8(a) and (b), the variation curves of the VBV angle with engine fan speed and core speed are stable. When the engine runs at low speed, VBV opens to release a part of airflow to ensure smooth flow of compressor airflow and prevent stall caused by poor airflow at low speed. The VBV control rate curve of a certain type of engine is shown in Fig. 9. When the speed is lower than 10000RPM, VBV is fully on, and when the speed is greater than 12000RPM, VBV is fully closed. When the N2KVBV speed is between 10000 and 12000 RPM, the valve moves towards the closed direction. The simulation results are consistent with the real trend which can confirm that the accuracy of the function model is high [15,17,19].

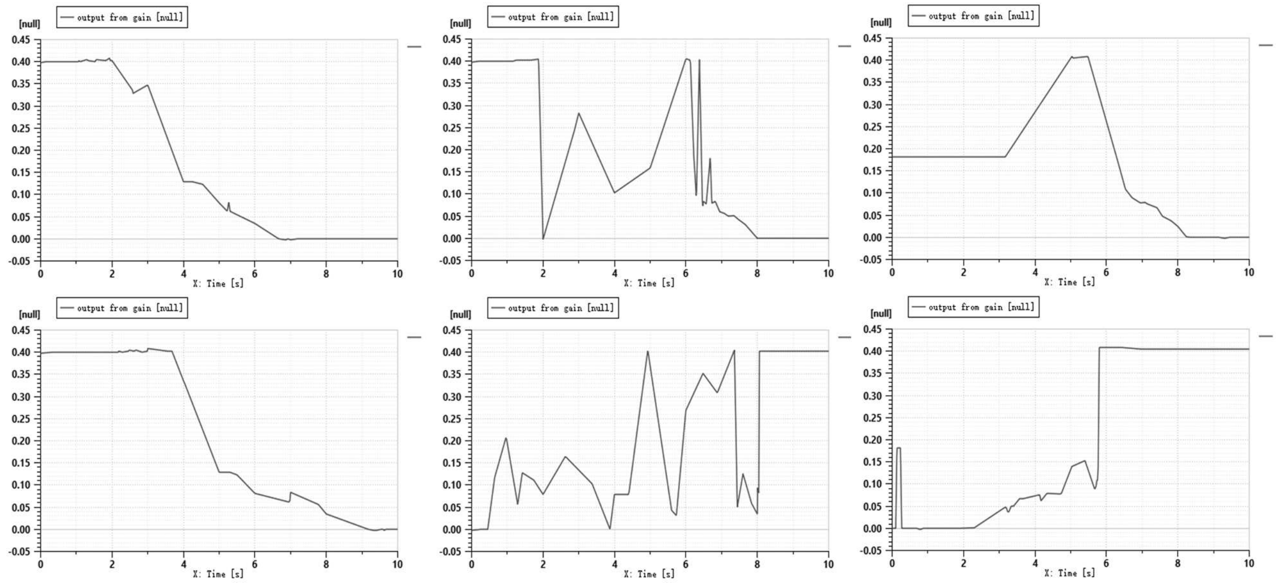
As shown in Fig. 8(c) and (d), the aircraft flight process is complicated, so the atmospheric pressure and air pressure change bigger in the same flight segment of different phases due to external influences, and the probability of irregular wave motion of the pressure is bigger. According to the theory change trend of VBV, the angle may fluctuate frequently, but the model of the output fluctuation is greatly improved compared with actual QAR data. The function model is optimized much better [16].

As shown in Fig. 8(e), TRA is the Throttle Resolver Angle of the aircraft, which is directly related to the throttle lever control in the cockpit.

The variation curve of VBV under TRA is smooth, which is consistent with the actual engine control.

As shown in Fig. 8(f), VSV is another important component of compressor stall control. The direction and size of the airflow are adjusted by adjusting the VSV angle, to adjust the angle of the flow attack. The control of VBV and VSV are synchronized, which can prevent stalls through cooperating. The curve of the VBV angle and VSV angle is smooth, which is consistent with the theoretical trend.

In conclusion, with the changes of N1 speed, N2 speed, TRA angle, and VSV position, the curve of VBV angle is smooth and consistent with the theoretical VBV position changing trend. However, with the change of T25, T2, and P0, a serious jump may appear in the curve of the VBV position. Because the three input parameters' change is focused on the stage when the engine operating environment changes dramatically, such as climbing, landing, etc. In these phases, the jump of the curve is a normal phenomenon. Subsequently, optimization will be carried out in the model [18].



(a) VBV and N1 (b) VBV and N2 (c) VBV and T25 (d) VBV and P0 (e) VBV and TRA (f) VBV and VSV

Fig. 8 *Simulation results of VBV function model*

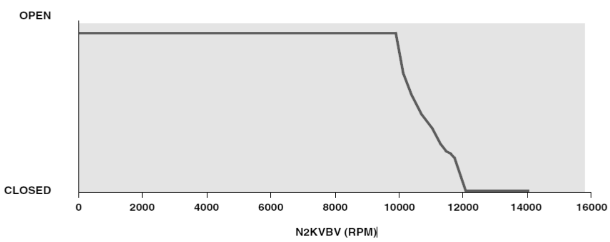


Fig. 9 *The VBV control rate curve of a certain engine*

4 Conclusions

In this paper, a function model of aero-engine VBV is built based on AMESIM, and a simulation method is proposed to input QAR data as control parameters into the model for simulation. Through the simulation analysis and verification of the model, the simulation curve is consistent with the variation trend of engine VBV theory, and the model has high reliability. Through continuous optimization and improvement, the model can be used to realize the fault analysis of the VBV actuation system. The comparison between actual engine VBV actuation and model actuation can be realized by using the operation data of the same engine, which provides strong support for VBV troubleshooting.

Acknowledgement

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