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Research on the Influence of Variable Geometry Power Turbine Speed Adjustable on the Overall Performance of Turboshaft Engine

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ABSTRACT

Turboshaft engine has been widely used in aviation, land and other fields, and its operating range is expanding day by day. The performance of turboshaft engine with fixed geometry and fixed speed power turbine is greatly restricted. In this paper, T700 turboshaft engine is taken as the research object to explore the influence of variable power turbine geometry and adjustable speed on its overall performance. Referring to the design parameters of the engine, the 0D calculation model of turboshaft engine is built by using Matlab/Simulink platform. The influence of power turbine speed change on the overall performance is analysed, and the influence law of speed change on the overall fuel consumption is obtained, and the optimal variable speed strategy is determined. The characteristic diagram of the power turbine under different guide vane openings is obtained by using the NUMECA three-dimensional numerical simulation. After modeling, the overall performance series analysis is carried out, and the influence law of the different guide vane openings on the overall fuel consumption rate of the power turbine is obtained. Based on the relevant calculation results, the performance change of variable geometry power turbine is determined when the speed changes.

KEYWORDS: Power turbine, Variable geometry, Variable speed, Overall performance

INTRODUCTION

Aero turboshaft engine has experienced four generations of development, which is widely used in helicopters, rotorcraft, heavy armored vehicles, mechanical drive, power generation and other fields. It is a typical representative of small and medium-sized gas turbine engine, and performance improvement is its consistent demand. The power turbine is the direct component of the power output of the turboshaft engine. For the sake of simplicity and easy handling, the existing power turbine of turboshaft engine mostly operates with the fixed speed strategy and fixed geometry, which limits the performance improvement of the turboshaft engine. At present, new helicopter rotorcraft （typical as A160） and tilt rotor aircraft （typical as Osprey V-22） have higher requirements for engine fuel economy, and they also begin to develop variable main rotor speed configuration, which provides development space for adjustable power turbine speed of turboshaft engine, Moreover, the relevant operation strategies have been adopted in the gas turbine of armored vehicles with much working hours under low load conditions （such as AGT1500， GDT1250， etc.）， showing its good performance improvement ability.

Takanori Iwata of Stanford University made relevant research and Analysis on the advantages of variable rotor speed in helicopter/engine integrated control in the 1990s. In their method, in the framework of Integrated Flight propulsion control, the flight control system generates an optimal variable rotor speed command in addition to the traditional control command[1]. Andrea Garavello of the University of Padua conducted a preliminary study on the helicopter rotor turboshaft engine system with large speed range, and explored the coupling performance with the connected turboshaft engine when the helicopter rotor changes in a wide speed range[2]. Gianluigi Alberto Misté et al. from the University of Padua has conducted related performance studies based on the helicopter/engine integrated variable speed, and studied the influence of the power turbine speed change on the overall engine performance[3].

According to the working characteristics of tilt rotor aircraft, NASA researchers discussed the design and performance of turboshaft engine power system, they believe that conventional turboshaft engines used in large tilt rotor aircraft can adjust rotor speed in two ways. One is that the speed of the power turbine of the turboshaft engine remains unchanged and the reduction gearbox is redesigned to adjust more transmission ratio gears; the other is to upgrade the turboshaft engine itself without changing the structure of the gearbox. The power turbine speed can be adjusted in a wide range to achieve variable speed output[4][5]. Based on the second way above, NASA researchers deeply studied the working characteristics and efficiency of the power turbine of the large civil tilt rotor aircraft during takeoff and cruise, and theoretically designed and verified that the scheme is basically feasible[6].

Huish Wang et al. studied the thermal cycle characteristics of a MW class surface gas turbine based on GDT1250 with variable power turbine geometry and adjustable speed[7]. W.D. Jone. an engineer of GE, has made relevant research and analysis on the electric drive system of Lv100 gas turbine. Based on the fact that the power system of Lv100 does not have a gearbox structure, and the starter /generator is directly connected with the engine shaft, this paper analyzes the matching problem between the gas turbine and the motor when the speed changes in the process of gas electric drive[8].

At present, the special equipment represented by tilt rotor aircraft needs the engine to provide a wide range of power output. The conventional turboshaft engine can not guarantee the high performance of the engine when the working conditions change greatly. If it works at the position deviating from the design point for a long time, the actual fuel consumption rate will be much higher than the design fuel consumption rate. Therefore, the structure or speed of power turbine need to be adjusted and changed to adapt to different working conditions. In order to explore the influence of power turbine structure change and speed change on the performance of turboshaft engine, a turboshaft engine simulation model which can realize variable geometry and speed of power turbine is built in this paper and the influence of power turbine speed change and geometric adjustment on the performance of gas turbine is explored.

Research Objects

T700 is a typical representative of high performance turboshaft engine, which is used in UH-60 Black Hawk and Ah-64 Apache helicopter. T700 is a twin-shaft turboshaft engine with free turbines. It has a five-stage axial/single-stage centrifugal combined compressor with variable inlet guide vane angles; an annular combustion chamber with central fuel injection can improve combustion and reduce smoke; there is a two-stage free power turbine behind the high-pressure turbine, which performs external work through the output shaft.

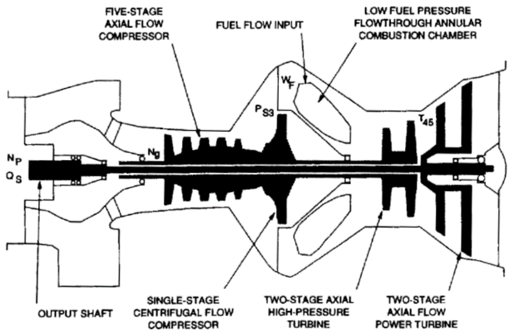

Figure 1 Cross section of a T700 turboshaft engine[9]

Research Method

In this paper, T-700 turboshaft engine is used as the template to build the model. Referring to its relevant performance parameters, its performance is simulated based on the improved open source T-MATS program. The influence of variable speed and variable geometry on the performance of the whole machine is calculated and analysed.

T-MATS is a set of open source tools for thermal system modeling, simulation and control published by NASA in 2014[10]. Some domestic scholars use this tool package to carry out research on aero-engine[11][12], but there is no previous research on variable geometry and variable speed of power turbine. The function of the original program relatively simple, and the complete engine performance calculation still needs to be built and implemented by ourselves. This paper improves the turbine in the open source tool adds and realizes the power turbine geometric variable function, and processes the calculation results of the model components, and draws them on the working characteristic diagram of the components.

Using the component modules in the program, the 0D calculation model of gas turbine can be built. Firstly, the external environment module needs to be set, and then the inlet, compressor, combustion chamber, HPT, FPT and nozzle are connected in turn. Each module has built -in thermodynamic calculation program, which can calculate and generate enthalpy, temperature, pressure power, thrust and other thermodynamic parameters based on the input parameters and thermodynamic formulas related to gas turbine thermodynamic cycle. In addition, a rotating shaft module is added to connect the high pressure turbine and the compressor. The Newton-Raphson-Jaccobi iterative solver used in steady-state solution is added, and the initial value, convergence accuracy iteration step size and times of steady-state operation of the model are set. The completed engine calculation model is shown in Figure 2. In the figure, COMP refers to compressor, HPT refers to high pressure turbine, and FPT refers to free power turbine.

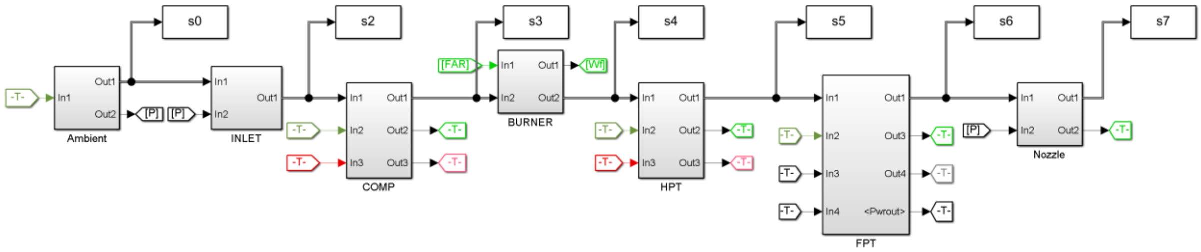

Figure 2 T-700 engine model

After the model is built, the parameters of each module are set. The design parameters of the model which are based on the T-700 engine performance data recorded in document[3] are shown in Table 1. Assuming that the engine is at sea level, the inlet temperature is 15℃ and the inlet mach number is zero, the turboshaft engine under the design parameters is simulated and calculated. The performance parameters of the design point are obtained as shown in Table 2. The design point performance parameters obtained are basically consistent with the T-700 parameters in reference[3]. The design point position of the turboshaft engine is taken as the rated working condition position, that is, the rated output power is 1343kW, the fuel consumption SFC is 0.2708kg/kWh, and the total thermal efficiency is 0.3084.

Table 1 Design parameters of engine model

Model design parameters	
Air flow	4.612kg/s
Intake total pressure recovery coefficient	0.988
Compressor pressure ratio	17.5
Compressor efficiency	0.821
Compressor/ HPT speed	44700
Total pressure loss of combustion chamber	0.04
Combustor efficiency	0.985
Fuel flow	0.101kg/s
HPT efficiency	0.85
Pressure ratio of HPT	4.283
Design speed of FPT	20900
FPT efficiency	0.85
Pressure ratio of FPT	3.3897

Table 2 Design point calculation parameters

设计点	S2	S3	S4	S5	S6	S7
Enthalpy[kJ/kg]	288.18	735.31	1624.71	1187.10	903.80	903.80
Total temperature[K]	288.17	721.11	1454.44	1098.33	857.22	857.22
Total pressure[bar]	1.001	17.644	16.940	3.953	1.160	1.144
FPT output[kW]	1343					
SFC[kg/kWh]	0.2708					
Total thermal efficiency	0.3084					

In order to verify the calculation accuracy of the model, the fuel consumption rate of the model under different power is calculated and compared with the off design experimental data in reference[3]. The comparison of the component modeling characteristic diagram used in the steady-state operation calculation and the off design calculation data is shown in Figure 3 and Figure 4. It can be seen that the fuel consumption rate of the model in the off design calculation is basically consistent with the data in the references, especially in the middle and high power section, the accuracy is different in the low power section because it is far away from the design point, but the change trend is basically consistent. Generally speaking, the model built on the simulink platform has the ability of simulation calculation and research.

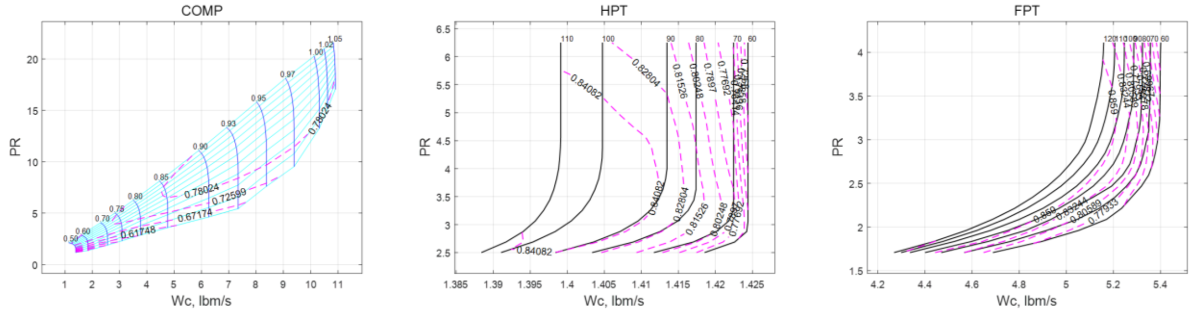

Figure 3 Component characteristic diagram

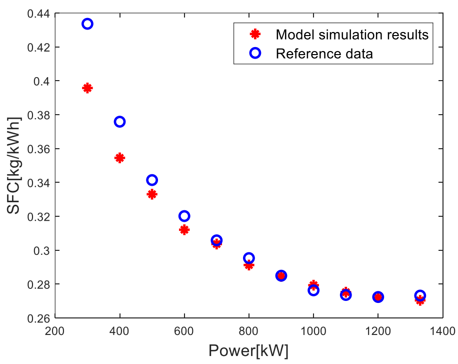

Figure 4 Comparison of off design calculation

Influence of FPT Speed Variation

The purpose of realizing the adjustable speed of power turbine is to meet the relatively low fuel consumption of engine under different power output, so as to achieve better thermal efficiency. Since the engine structure has not been changed, the variation of power turbine speed of turboshaft engine reflects the change of main rotor speed. The change of the power turbine speed changes its inlet and outlet pressure ratio and flow rate, which leads to the same result of the high-pressure turbine, then causes changes in the working status of the whole machine, and affects the fuel consumption rate of the whole machine.Due to the limitation of material and structure on rotor, the variation range of speed can not be too large, so the upper limit of the designed maximum speed change is only 1.1 times of the rated speed.

Using this model, the influence of speed on fuel consumption rate is calculated for every 100kW of output power within 300-1400kw and the speed variation range is 80%-110%. The influence of power turbine speed variation on fuel consumption rate under various working conditions is analyzed, as shown in Figure 5. Under different working conditions, the fuel consumption rate of the whole machine is calculated when the speed of the power turbine changes. From 900 kW to 1400 kW, the relative speed fuel consumption curve of each working condition is the lowest when the speed is 110%; from 600kW to 800kW, the minimum fuel consumption rate is between 105% and 110% of the speed; in the low power range of 300kW to 500kW, the fuel consumption rate will have a relatively low value when the speed drops to 90%-95%.(There is no need to compare the difference in fuel consumption between different output powers. The speed at which the fuel consumption is the lowest at each power output is what matters.)

The above characteristics are mainly due to the fact that the distance between each speed line and efficiency circle in the map of power turbine is getting closer and closer when the output power is reduced. Therefore, there is a big difference between the pressure ratio and efficiency values before and after the speed change of the matching point, so the fluctuation of the influence of the speed change on the fuel consumption rate in the above figure will appear. Therefore, the speed change strategy can be determined according to the law in Figure 5, and the distribution of output power and speed is shown in Table 3.

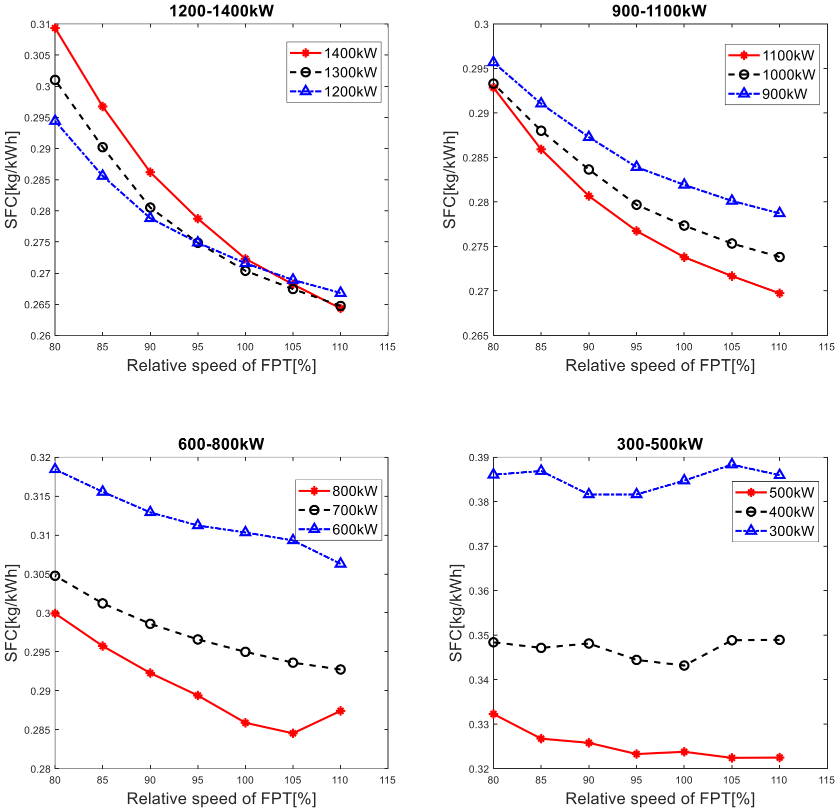

Figure 5 Influence of variable speed on SFC under different working conditions

Table 3 Corresponding speed under each working condition

Output[kW]	Variable speed strategy [rpm]
1400	22990
1300	22948
1200	22886
1100	22781
1000	22635
900	22447
800	21945
700	21527
600	21109
500	20900
400	20482
300	19855

Based on the above model and speed change strategy, the fuel consumption rate of the fixed geometry is compared with that of the power turbine with constant speed. In the Simulink platform, the steady-state and off design conditions of the gas turbine model are calculated, and the corresponding fuel consumption rate under different power is output. By interpolating and fitting the data of power with corresponding variable speed and constant speed, the relationship curve between power and fuel consumption can be obtained when the speed of the model changes or not, as shown in Figure 6. It can be seen that when the power turbine geometry is fixed, using the variable speed strategy, the fuel consumption rate can be significantly reduced compared with the constant speed operation at medium and high power output (600kW-

1400kW). When the output power is reduced to less than two fifths of the rated power (Below 600kW), the influence of the speed change on the fuel consumption rate of the whole machine is not obvious.

Figure 7 shows the comparison of off design operating characteristics of components under constant speed and variable speed. When the speed of power turbine changes the distribution of operating characteristic points of compressor basically keeps the same working line with constant speed, the flow rate, pressure ratio and efficiency of high power output section of compressor will decrease, and the low power section is basically consistent with constant speed; in the high and middle power output section, the pressure ratio of HPT is slightly lower, the flow rate is slightly larger, and the efficiency is basically the same； when the FPT works at medium and high power output, the working point falls at the position where the pressure ratio is equal, the flow rate is reduced and the efficiency is increased, and the low power working point is close to the constant speed.

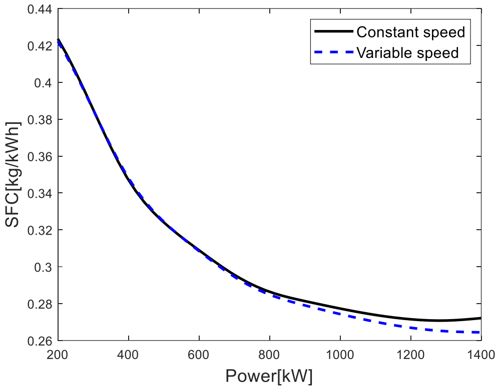

Figure 6 Influence of FPT speed change on fuel consumption

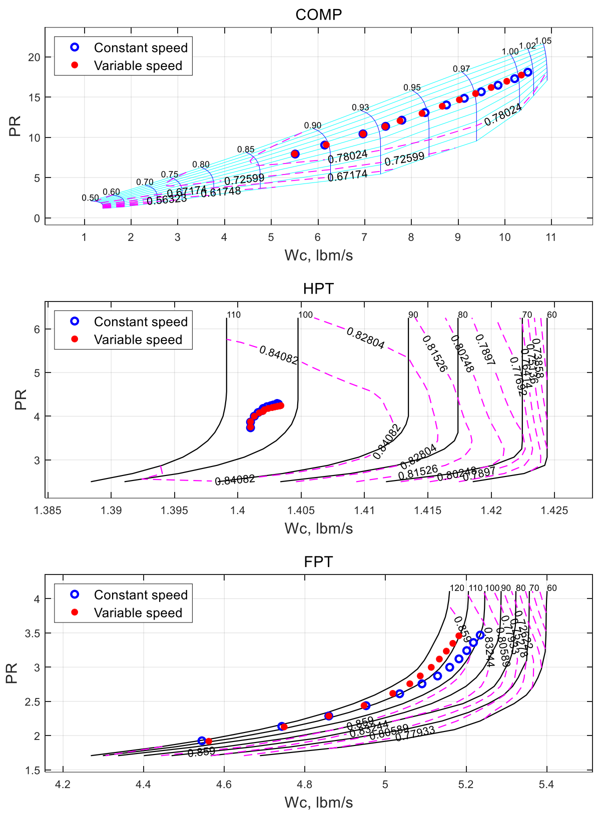

Figure 7 Comparison of working characteristics of components

Influence of FPT Geometry Change

In this paper, the variable geometry turbine module used in the model built in simulink platform can call the map parameters when the power turbine is in different guide vane openings, which can simulate the influence of variable geometry on the performance of the power turbine in real operation state. The map parameters with different opening are obtained by NUMECA when the guide vanes of two-stage power turbine are switched to different angles, as shown in Figure 8. When the output is the same, the flow and efficiency of the power turbine operating point will change under different inlet guide vane openings, which will affect the performance of the whole machine.

The variable geometry power turbine module is used to call the map parameters corresponding to different guide vane opening and the power turbine characteristic diagram is shown in Figure 9 when the guide vane opening is increased or decreased by 5 degrees or 2 degrees, when the opening decreases, the efficiency corresponding to the same speed and pressure ratio position will decrease and the flow rate will increase. As a contrast, calculate the fuel consumption rate parameters generated by each power output under each guide vane opening at constant speed of power turbine, and draw the curves of several openings in the same graph as a comparison, as shown in Figure 10. Then calculate the relationship between power and fuel consumption rate under different guide vane opening when the power turbine changes speed. The data obtained through simulation calculation are processed and plotted as shown in Figure 11.

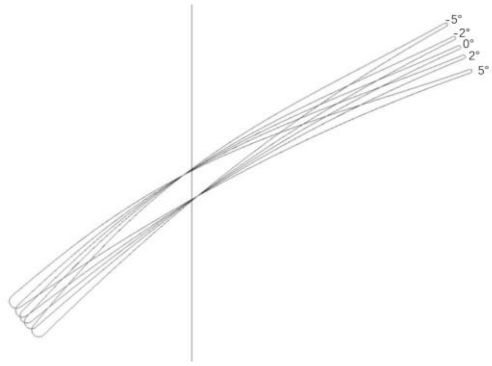

Figure 8 Changes in the opening of the inlet guide vane of the power turbine

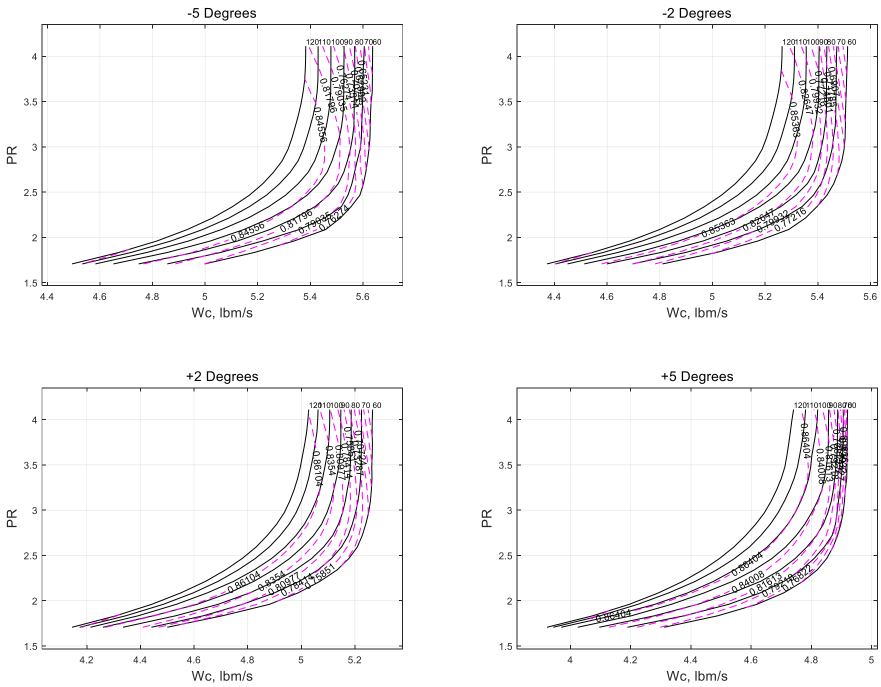

Figure 9 Characteristic diagram of FPT with different guide vane opening

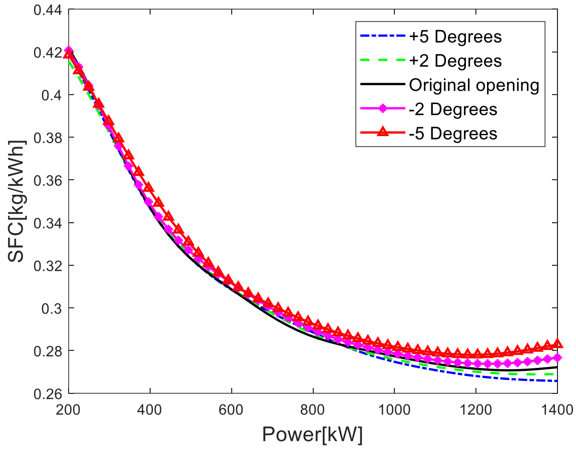

Figure 10 Influence of inlet guide vane opening of FPT on fuel consumption rate at constant speed

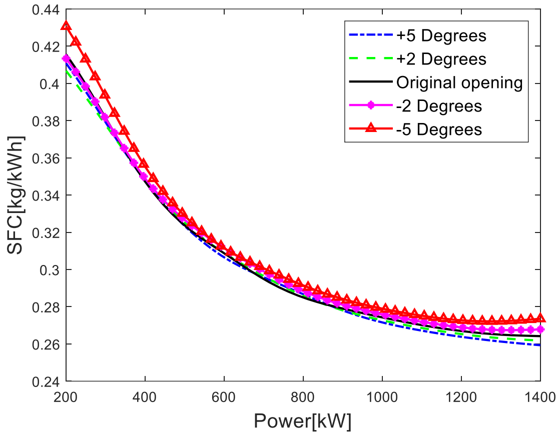

Figure 11 Influence of inlet guide vane opening of FPT on fuel consumption at variable speed

By comparing the curves of the relationship between power and fuel consumption rate obtained from the simulation results, it can be seen that no matter whether the speed changes or not, there will be a similar rule when changing the opening of the power turbine inlet guide vane, that is, increasing the opening of the guide vane can significantly reduce the fuel consumption rate in the middle and high power section. When the output power is less than two fifths of the rated power, the influence of the guide vane opening on the reduction of the fuel consumption rate is not obvious except that the guide vane opening decreases by 5 degrees and the fuel consumption rate increases at variable speed.

CONCLUSIONS

In this paper, a turboshaft engine model with variable power turbine geometry and adjustable speed is built in Simulink, and the influence of power turbine speed and inlet guide vane opening on engine performance is studied. Firstly, under the condition of constant power turbine geometry, the corresponding fuel consumption curve is obtained by changing the power turbine speed under different conditions so as to obtain the optimal speed change strategy under different power output.

Then, the influence of the speed change on the fuel consumption of the whole machine is compared, it is found that when the variable speed strategy is adopted, the fuel consumption of turboshaft engine in the middle and high power range is significantly lower than that in the constant speed range. However, with the output power reduced to less than two fifths of the rated power, the influence of speed change on the fuel consumption rate is not significant.

At last, the fuel consumption curves of different inlet guide vane opening are compared under constant speed and variable speed of power turbine, it is found that no matter whether the speed changes or not, increasing the opening of the power turbine inlet guide vane in the middle and high power section can effectively reduce the fuel consumption rate, while in the low power output section the change of the opening of the guide vane has little effect on the fuel consumption rate except that the guide vane opening decreases by 5 degrees in which the fuel consumption rate increases in the low power output range when power turbine is working at variable speed.

The focus of this paper is to explore the influence of power turbine geometry and speed change on the performance of turboshaft engine. The follow-up work will be further optimized by constructing the strategy of power turbine speed change cooperating with inlet guide vane opening change.

ACKNOWLEDGMENTS

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