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Steady-State and Transient Performance Simulation of a Turboshaft Engine with a Free Power Turbine

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A program of steady-state and transient performance analysis for a 200kW-class small turboshaft engine with free power turbine was developed. An existing turbojet engine was used for the gas generator of the developed turboshaft engine, which was modified to satisfy performance requirements of this turboshaft engine. To verify the accuracy of steady-state performance program for this engine: the program was applied to the gas turbine test unit of the same type, and the analysis results were compared with experimental results. The developed transient performance analysis program using the CMF (Constant Mass Flow) method was utilized to analyze the cases of step increase and ramp increase of the fuel.

Key Words : Steady-State and Transient Performance Analysis Programs, Turboshaft Engine with Free Power Turbine, CMF (Constant Mass Flow) Method

Nomenclature

C_p : Coefficient of specific heat at constant pressure
ΔH : Enthalpy of reaction
I : Moment of inertia
N : Rotational speed
P_0 : Total pressure
R : Pressure ratio
T_0 : Total blade temperature
$\dot{m}$: Mass flow rate
η : Efficiency

Subscripts

$D.$: Design point values of scaled component
$M.$: Arbitrary map values
$M.D.$: Design point map values of original components
a : Air
c : Compressor
g : Combustion gas
t : Turbine

Station Number of Figure

1 : Compressor inlet
2 : Compressor exit
3 : Gas generator turbine inlet
4 : Power turbine inlet
5 : Power turbine exit

1. Introduction

Since Whittle introduced a gas turbine engine in 1930, it has played a role as not only the power source of aircraft due to advantages of light, compact, and high performance but also the power plant for the electric power generation. The accurate engine performance simulation is essential for accurate prediction of the performance, safe operation, and the life usage as well as diagnostics of the engine. It has been used as the best way to reduce the developing cost and risk of various experiments (Cohen, H., et al., 1996).

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In this study, steady-state performance analysis and dynamic simulation program was developed for small turboshaft engines with the free power turbine. An existing small turbojet engine of a RPV(Remotely Piloted Vehicle) was used for the gas generator. This engine could be widely applied, for example, as an emergency power source, pump, auxiliary power unit, educational test unit, and so on.

To satisfy the requirement of the lifetime, the materials of the turbine were changed, the maximum rotational speed was reduced, and the turbine inlet temperature was restricted. In order to perform steady-state and transient simulation, the components performance characteristics of the gas generator and power turbine were used to scale them of the turbojet engine.

For the transient performance analysis, the CMF (Constant Mass Flow) method was used. It was assumed that mass flow storage in duct between components was ignored, and therefore the mass flow at the inlet of each component was constant. In addition, the Euler integration method was applied to integrate the surplus torque produced by the work difference between the compressor and the turbine.

2. Engine Type, Design Point Performance and Modification

The engine used in this study was a small turboshaft engine whose desirable weight was between 55 to 70kg, so that it could be mobile and available in the narrow space. The engine could be used for various purposes, such as emergency pump motor, emergency power source, gas turbine for educational unit, auxiliary power unit, and so on. Station No. for performance simulation is shown in Fig. 1.

The design point performance summary of the original turbojet and the modified turboshaft engines is shown in Table 1.

The turbojet engine, which was used with a RPV(Remotely Piloted Vehicle) for the gas generator has the following characteristics. The maximum thrust is 1.42KN, the specific fuel consumption is 0.399kg/kW/hr, and lifetime is 10 hours.

The performance requirements of the modified turboshaft engine were as follows ; The maximum power was more than 250kW, the specific fuel consumption was less than 0.373kg/kW/hr and the lifetime was over 3,000 hours.

The design point was modified to satisfy the lifetime extension and the performance requirement, i. e., the turbine material was changed, the maximum rotational speed was restricted, and the turbine inlet temperature was limited. The modified components of the core engine were the intake, the shaft, the turbine exit, etc. and the

Table 1 Modified Design Point for Life Extension

Design Parameters	Existing Engine	Modified Engine
Mass Flow Rate (kg/sec)	2,276	1,882
Max.Gas Generator Speed (RPM)	40,500	35,000
Pressure Ratio of Compressor	4.5	3.2
Limit Turbine Inlet Temperature(K)	1,250	1,140
Combustor Pressure Loss (%)	4.5	4.5
Compressor Efficiency	0.765	0.765
Combustor Efficiency	0.99	0.99
Compressor Turbine Efficiency	0.875	0.91
Power Turbine Efficiency	-	0.91
Mechanical Efficiency	0.987	0.987
S.F.C.(kg/kW/hr)	0.399	0.297
Power Output	1.42 kN	265 kW
Turbine Material	IN713LC	IN792
Life (hr)	10	3,114

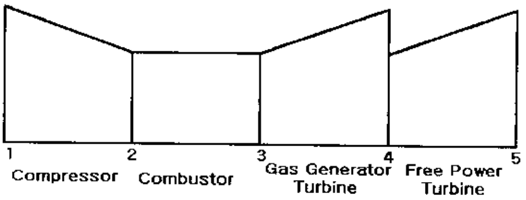
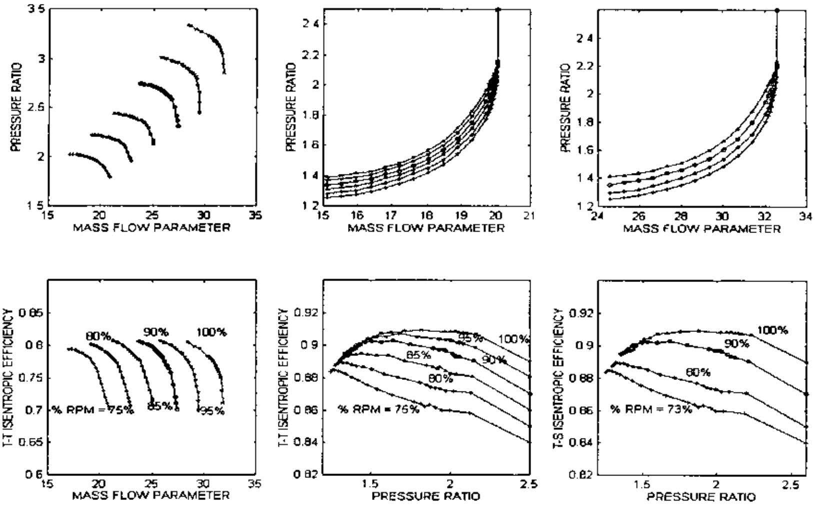


Fig. 1 Station No. s of Turboshaft Engin with Free Power Turbine



Compressor Compressor Turbine Power Turbine

Fig. 2 Components Characteristics for the Developing Engine

added components were the power turbine, the reduction gear, and so on. To extend the lifetime, the material of a compressor turbine was changed from IN713LC to IN792. The lost type Lubricating System was applied to bearings and the sump type Lubricating System was utilized to the reduction gear system.

2.1 Scaling of components characteristics

In order to simulate the performance of the steady-state and the transient, the performance characteristics obtained from the performance test results of each component are needed. A component map can be found which could be expected to perform in a scaling law to the actual map for the engine being studied.

In this study, the scaled turbojet engine component characteristics for the gas generator in turboshaft engine were found to be satisfied during the preliminary design process. The power turbine characteristics were utilized to scale by the performance map of the compressor turbine. The scaled equations used in this study are as follows (Sellers, J. F., and Daniele, C. J., 1975),

$$R = \frac{R_{D.} - 1}{R_{M.D.} - 1}(R_{M.} - 1) + 1 \tag{1}$$

$$\dot{m} = \frac{\dot{m}_{D.}}{\dot{m}_{M.D.}}\dot{m}_{M.} \tag{2}$$

$$\eta = \frac{\eta_{D.}}{\eta_{M.D.}}\eta_{M.} \tag{3}$$

The closer scaling factors $\left(\frac{R_{D.} - 1}{R_{M.D.} - 1}\right)$, $\left(\frac{\dot{m}_{D.}}{\dot{m}_{M.D.}}\right)$, and $\left(\frac{\eta_{D.}}{\eta_{M.D.}}\right)$ values are to 1.0, the more reasonable are the simulated maps of the engine. However, not being close to 1.0 does not necessarily mean that the simulation is poor since many maps have been shown typically over quite large ranges in the variables.

In this study, because scaling factors were 0.83 to 1.01, it could be considered that the scaling components characteristics would be valid.

The performance characteristics of the compressor, compressor turbine, and power turbine were shown in Fig. 2.

3. Steady-State Performance Simulation

The steady-state performance analysis is mainly classified as the design point and the off-design point performance analyses. For steady-state performance analysis, performance matching between components based on flow and energy conservation laws is required. Therefore, there are the following conditions (Cohen, H. et al., 1996).

(1) The rotational speed of the compressor and the turbine connected with the same shaft must be the same.

(2) The airflow passed through the intake, the compressor, the compressor turbine, and the power turbine must be constant.

(3) The work done by the compressor and the turbine connected with the same shaft must be the same.

The performance of each component follows the scaled performance characteristics from the original characteristics.

3.1 Component matching

In the steady-state operation the performance values to be matched include the rotational speed, the airflow, and the work between the compressor and the turbine. In order to match these components, some performance characteristics such as the pressure ratio and the mass flow parameter as the function of the rotational speed of components which is connected with the same shaft are required. The performance values are calculated by matching equation for whole components.

In the turboshaft engine with free power turbine, the following equations should be satisfied for component matching. The flow and the work matching equations between the compressor and the compressor turbine, and between the gas generator and the power turbine are needed. The following illustrates the matching equations applied in this study (Cohen, H. et al., 1996).

The flow compatibility equation of the gas generator is

$$\frac{\dot{m}\sqrt{T_{03}}}{P_{03}}=\frac{\dot{m}\sqrt{T_{01}}}{P_{01}}\times\frac{P_{01}}{P_{02}}\times\frac{P_{02}}{P_{03}}\times\sqrt{\frac{T_{03}}{T_{01}}} \quad (4)$$

The work compatibility equation of the gas generator is

$$\frac{\Delta T_{034}}{T_{03}}=\frac{\Delta T_{012}}{T_{01}}\times\frac{T_{01}}{T_{03}}\times\frac{C_{pa}}{C_{pg}\eta_m} \quad (5)$$

$$\eta_m C_{pg}\Delta T_{034}=C_{pa}\Delta T_{012} \quad (6)$$

The flow compatibility equation between the gas generator and the power turbine is

$$\frac{\dot{m}\sqrt{T_{04}}}{P_{04}}=\frac{\dot{m}\sqrt{T_{03}}}{P_{03}}\times\frac{P_{03}}{P_{04}}\times\sqrt{\frac{T_{04}}{T_{03}}} \quad (7)$$

In this program, component matching was performed by the iteration method with error margin within 10^{-2} by comparing the performance values obtained from the above equations and the component performance characteristics. The flow chart for the steady-state performance is shown in Fig. 3.

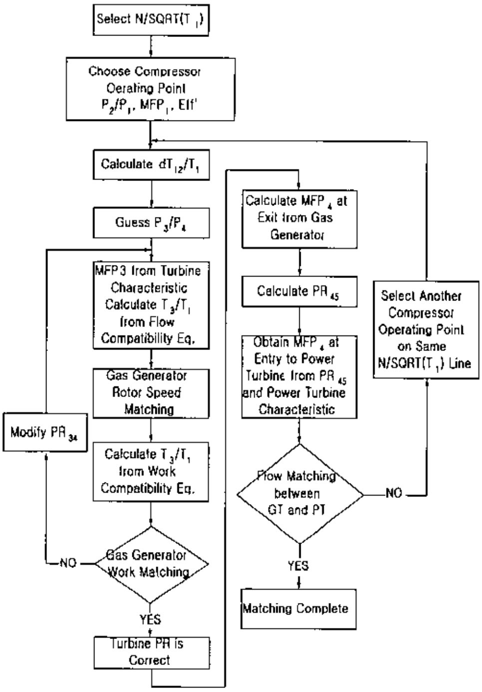


Fig. 3 Flow chart of Steady-State Matching Program

3.2 Verification of program

To verify the steady-state performance analysis program, the calculated results of the performance analysis program were compared with experimental results of the same type gas turbine test unit. The test unit was composed of a one-stage centrifugal compressor, the can-type combustor, a one-stage radial compressor turbine, a radial power turbine and accessories. The propane gas is used as the fuel, and the output of power turbine is converted for the electrical power by the alternator. The major performance data are shown in Table 2 (Cussons Technology, 1993).

In the test unit, the normal rotational speed range of the gas generator was between 1,000 to 2,000RPS, and the normal rotational speed range of the power turbine are between 100 to 600RPS. However, the rotational speed of the gas generator had an operational limit of 1,350RPS in this

Table 2 Major Performance Data of the Test Unit @ Sea Level,Standard

Performance Parameters	Performance Values
Max.Speed of Gas Generator (RPM)	120,000
Max.Speed of Power Turbine (RPM)	36,000
Compressor Pressure Ratio	2
Compressor Efficiency	0.65
Limit Turbine Inlet Temperature (K)	1,170
Turbine Efficiency	0.91
Air Mass Flow Rate (kg/sec)	0.15
Fuel Flow Rate (kg/sec)	0.003
Max.Power Output (kW)	4

study.

The test unit with a data logging system can gather both experimental and operational measurement parameters. All seven temperatures are measured using type K NiCr/NiAl thermocouples, for example, T1 air temperature, T2 compressor exit temperature, T3 turbine inlet temperature, T4 power turbine inlet temperature, T5 power turbine exit temperature, Tg fuel temperature, and To oil temperature. Seven pressures are measured by using both wet gages and pressure transducers, for example, P1-P2 differential pressure, P2 compressor exit pressure, P3 combustion chamber pressure, P4 turbine exit pressure, Pg-P3 supply gas differential pressure, Pg gas pressure and Po oil pressure. Moreover two rotational speeds, such as the gas generator speed and the power turbine speed, were measured by the magnetic pick-up and FVC, and the DC voltage and current for the power turbine output were measured by the alternator with the rectifier, ammeter, voltmeter, and the resistive load bank.

Therefore, the performance curve of the component used in the steady-state performance simulation was modified after completing the test. In aforementioned performance analysis, the efficiencies of the combustor, and the power turbine were assumed to be constant because of the lack of efficiency characteristics maps. The values of the fixed parameters are shown in Table 3.

Table 3 Experimental Atmospheric Condition,Fuel Property,and Components Characteristics of the Test Unit

Parameters	Considering Values
Atmospheric Temperature (K)	292
Atmospheric Pressure (bar)	1.01
Compressor Turbine Efficiency	0.735
Combustor Efficiency	0.98
Combustor Pressure Loss	0.019
Efficiency of Alternator	0.4 to 0.65
Power Turbine Efficiency	0.91
Mechanical Efficiency	0.98
Fuel Property	Propane Gas
Low Heating Value (kJ/kg-K)	516,000

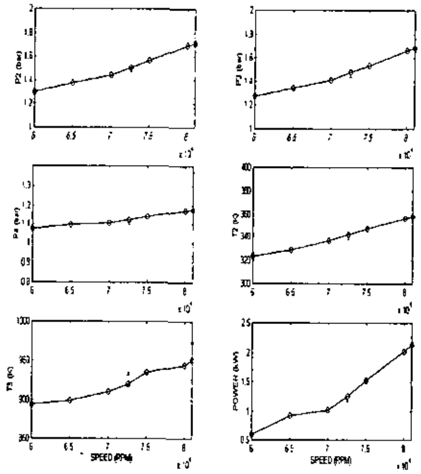


Fig. 4 Comparison of Simulation and Test Result for the Test Unit(○ ○ ○SIMULATION× × ×TEST)

Where, the alternator efficiency refers to the alternator calibration chart of Cussons, Ltd. (Cussons Technology, 1993).

To verify the program, the inlet and exit temperatures and pressures of each component, and the output powers in the gas generator rotational speeds of 1,000RPS, 1,210RPS and 1,350RPS were compared. In these cases, the experimental data were obtained by using the specific data

Table 4 Comparison of Simulation and Experimental Results for Test Unit

	1,000 RPS			1,210 RPS			1,350 RPS		
	Test	Simulation	Error (%)	Test	Simulation	Error (%)	Test	Simulation	Error (%)
P2(bar)	1.30	1.30	0.00	1.48	1.51	1.99	1.70	1.71	0.58
P3(bar)	1.28	1.28	0.00	1.45	1.48	2.03	1.66	1.68	1.19
P4(bar)	1.07	1.07	0.00	1.10	1.12	1.78	1.18	1.18	0.00
T2(K)	325.00	322.78	0.69	338.00	341.83	1.12	355.00	357.73	0.76
T3(K)	893.00	894.33	0.15	933.00	920.71	1.33	973.00	950.47	2.37
T4(K)	843.00	866.84	2.75	853.00	876.20	2.65	878.00	891.76	1.54
Power (kW)	0.58	0.60	3.33	1.19	1.26	5.56	2.16	2.13	1.41

Table 5 Standard Atmospheric Condition and Components Characteristics of a Developing Engine

Parameters	Considering Values
Atmospheric Temperature (K)	288
Atmospheric Pressure (bar)	1.013
Combustor Efficiency	0.98
Combustor Pressure Loss	0.05
Mechanical Efficiency	0.98
Bleed Air	0
Low Heating Value (LHV) (kJ/kg)	43,210

acquisition system and the rotational speed range of the power turbine was 120 to 490RPS.

A comparison between the program analysis data and the test results was shown in Fig. 4 and Table 4.

According to the comparison, the pressures and the temperatures of each station were all within the margin of error of 2.75% and the outputs were within the 5.56% error range at each RPM. Therefore, the accuracy of the steady-state simulation program was verified.

3.3 Steady-state performance analysis of developing engine

The off-design point performance analysis of the developing engine, which was explained in Table 1, was carried out. When the rotational speeds of the power turbine were 73%, 80%, 90%, and 100%, respectively, the rotational speed at each value of gas generator between 75%RPM (26, 250RPM) and 100%RPM (35, 000RPM) for each 5% increment. Standard sea level was assumed for the atmospheric condition.

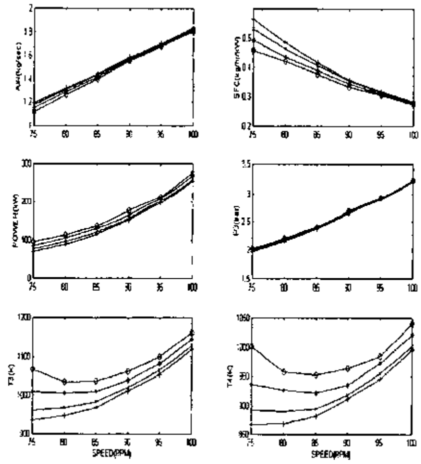


Fig. 5 Results of Steady-State Performance Analysis for the Developing Engine(PT Speed : ooo 100% ∗∗∗ 90% xxx 80% +++ 73%)

The constant parameters including the combustor efficiency are shown in Table 5.

Some parameter values, for example, temperature, pressure of each component, airflow, output, and specific fuel consumption were obtained. In these cases, when the rotational speed of the gas generator was increased, the airflow, the output and the pressure were also increased. Also, both of the gas generator and the power turbine were at maximum power and minimum specific fuel consumption at 100%RPM.

However, the inlet temperature of the compressor turbine and the power turbine was slowly decreased up to that at 85%RPM of the compressor turbine rotational speed, and then the turbine temperature gradually increased to that at 100% RPM. This tendency coincided with generally accepted turbine characteristics. The analysis result is shown in Fig. 5.

4. Transient State Performance Simulation

When fuel input is rapidly increased or decreased, the engine is in the transient state. In the transient state, the power output of the rotor shaft is surpassed or insufficient. Therefore, it would not be suitable for the required work balance between the compressor and compressor turbine. Consequently, the engine is frequently beyond the operational range, which may damage the engine or shorten its lifetime. Above all, when the engine is operated during rapid acceleration, the overshoot of the compressor turbine inlet temperature exceeds the limit temperature. It can cause structural damage by excessive thermal stress produced in the turbine blade.

Therefore, it is very important that the dynamic characteristics of the engine should be correctly simulated for improving the reliability of the engine.

4.1 CMF (Constant Mass Flow) method

The CMF (Constant Mass Flow) method and ICV (Intercomponent Volume) method are primarily used in dynamic simulations.

In this study the CMF method was utilized under the condition that the mass stored between components of the engine were ignored and the flow compatibility equation was satisfied. The CMF method calculates the surplus quantities of the rotor rotational speed as the work difference between the compressor and the turbine by the fuel increase. The CMF method can reduce calculation time, and perform the calculation for the variety of rotational speeds when comparisons are made to the ICV method (Pilidis, P. 1996).

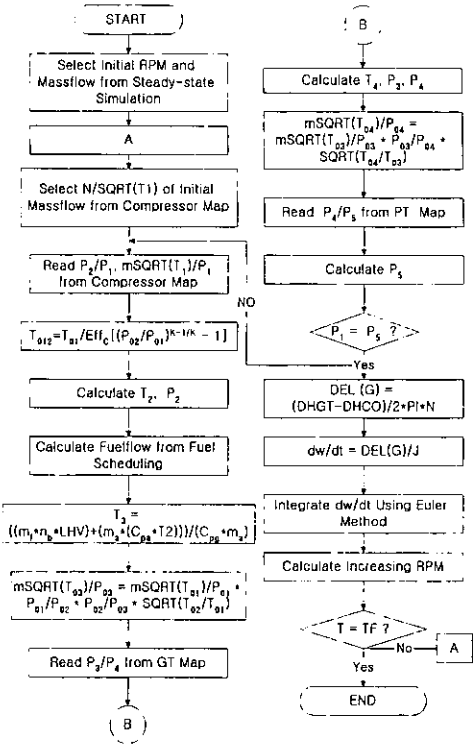


Fig. 6 Flow chart of Dynamic Simulation Program

The work difference between the compressor and the turbine in the transient state can be expressed in the following equation (Sellers, J. F., and Daniele, C. J., 1975).

$$\dot{m}\Delta H_{34}=\dot{m}_{12}\Delta H_{12}+\left(\frac{2\pi}{60}\right)^2 I\cdot N\cdot\frac{dN}{dt} \quad (8)$$

For performance analysis of the transient state, increase or decrease of the rotational speed is calculated by integrating the surplus torque of the second term of the right hand side equation. In this study, the Euler method was used for integration (William, H., 1992).

Figure 6 shows the flowchart of the dynamic simulation program by CMF method, where [A] of Fig. 6 indicates the flow chart of the steady-state matching program of Fig. 3.

4.2 Result of transient state performance analysis

Performance analysis of the transient state was

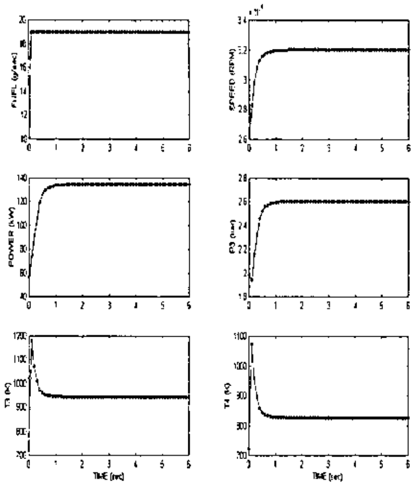


Fig. 7 Transient Behavior in Fuel Step Increase Case for the Developing Engine

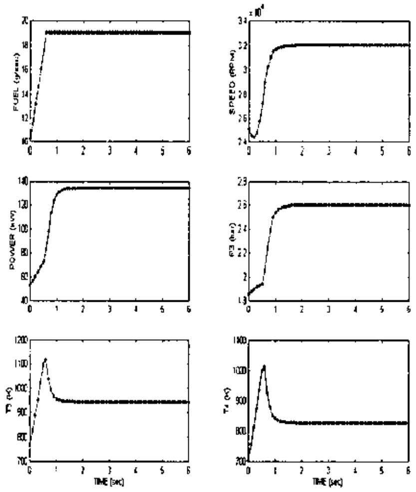


Fig. 8 Transient Behavior in Fuel Ramp Increase Case for the Developing Engine

performed by the following two methods. First, the step increase of the fuel in the worst case was considered. Second, the ramp increase of the fuel, which could be prevented from exceeding the turbine inlet temperature limit, was considered.

When the rotational speed of the power turbine was fixed at 80% rpm, the step increase of the fuel required to increase from 75%RPM to 91%RPM of the compressor turbine was considered. The results of the performance analysis are shown in Fig. 7. According to the results of the simulation, the rotational speed of the gas generator reached to the steady-state within approximately one second. However, the inlet temperature of the compressor turbine had the overshoot for a short period. The overshoot of the compressor turbine and the power turbine inlet temperature followed as each fuel step increase. As the result, the compressor turbine inlet temperature exceeded its limit temperature of 1,140K.

Therefore, in order to prevent from exceeding the limit temperature, the fuel flow should be scheduled again to be increased slowly. From this change, the fact that the same fuel flow increased over 0.6second was found. When the ramp increases of the fuel were done, the results of the performance were presented to Fig. 8.

5. Conclusions

Using an existing aircraft turbojet engine as a gas generator, a simulation program of its steady and transient state performances was developed in an effort to design the multi purpose small turboshaft engine from an existing aircraft turbojet engine.

After developing the program for performance analysis of the off-design points, the results were compared to experimental results of the turboshaft engine test unit in order to verify the program. It was found that the maximum range of error was within 5.56% of the experimental results. Steady-state performance analysis of the developing engine was performed in the following cases. When the rotational speed of the power turbine was at 73%, 80%, 90% and 100% rpm, respectively, the engine rotational speeds of the gas generator were between 75% (24,500RPM) to 100% (35,000RPM) at 5% intervals. The results show that the engine was at maximum power output and minimum specific fuel consumption at 100%RPM in both the gas generator and the power turbine. The dynamic simulation based on the CMF (Constant Mass Flow) method was then carried out. In this simulation, fuel was regulated by both step and ramp increases. The results of simulation indicated that following the step increase of the fuel, the overshoot of the turbine inlet temperature exceeded the limit temperature for the duration of 0.3 seconds. In order to prevent the overshoot of the compressor turbine inlet temperature, the ramp increase of the fuel with 0.6 second was the effective case.

To verify the dynamic simulation program, the dynamic performance test has been carried out. In the near future, comparison between the analysis and the test will be presented. In order to optimize engine performance, the study of optimal control should be followed by various performance simulations in the transient state.

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