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DEVELOPMENT AND VALIDATION OF A TWIN SHAFT INDUSTRIAL GAS TURBINE PERFORMANCE MODEL

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ABSTRACT

Gas turbine performance is very responsive to ambient and operational conditions. If the engine is not operating at its optimum conditions, there will be high energy consumption and environmental pollution. Hence, a precise simulation model of a gas turbine is needed for performance evaluation and fault detection and diagnostics. This paper presents a twin shaft industrial gas turbine modeling and validation. To develop the simulation model component maps are important, however they are property of the manufacturers and classified documents. In this case, known the compressor pressure ratio, speed, and flow rate, the missing design parameters, namely turbines inlet temperatures and pressure ratios were predicted using GasTurb simulation software. Once the design parameters are developed, the nearest compressor and turbine maps were selected from GasTurb map collection. Beta lines were introduced on each map so that the exact corresponding value can be picked for a given two parameters of a given map. After the completion of components model, a simulation model was developed in Matlab environment. The equations governing the operation of individual component were solved using iteration method. The simulation model has modular nature; it can be modified easily when a change is required. The parameters that the model can predict include terminal temperature and pressure, flow rate, specific fuel consumption, thermal efficiency and heat ratio. To demonstrate the validity of the developed model, the performance of GE LM2500 twin shaft gas turbine operating in a gas oil industry at Resak PETRONAS platform in Malaysia was predicted and compared with operational data. The results showed that an average of 5, 3.8 and 3.7 % discrepancies for compressor discharge temperature and pressure, and fuel flow rate, respectively. This comparison of results showed good agreement between the measured and predicted parameters. Thus, the developed model can be helpful in performance evaluation of twin shaft gas turbines and generation of data for training and validation of a fault detection and diagnostic model.

Keywords: gas turbine model, simulation, performance prediction, performance map, beta lines.

INTRODUCTION

Gas turbines have considerable share in power generation and propulsion units [1]. The operation of gas turbine depends on the characteristics of its main components such as the compressor, turbine and combustor. Among these, the turbine is known as one main components of the gas turbine. The main idea with a turbine is to extract work from the incoming airflow and convert it into mechanical work at a rotating axis [2].

There have been attempts to develop gas turbine simulation model. Al-Hamdan and Ebaid [3] developed a computer program that convinces the matching conditions between gas turbine components. The program can be used as a tool for performance evaluation of the gas turbine at off-design conditions. Also, it can be helpful in designing a control system for the engine. Haqlind and Elmegaard [4] presented two different design models for predicting off design performance of gas turbines. Asgari *et al*. [5] used two different methods to model and simulate the transient behavior of an Industrial Power Plant Gas Turbine. Experimental data collected during the start-up of a single-shaft turbine were used for model development and validation. A physical and a black-box models were developed by using the MATLAB tools, namely Simulink and Neural Network toolbox, respectively. The former was developed based on the thermodynamic and energy balance equations in MATLAB environment. The latter was set up by using the same data sets and subsequently applied to each of the data sets separately. Their results showed that both models are capable of acceptable prediction of transient behaviour. Recently, Emil Larsson [6] modified existing gas turbine performance simulation model and used this model to predict engine healthy parameters which are used to estimate performance deterioration. Silvio Simani [7] mentioned model-based techniques have been widely recognized as powerful approaches for fault diagnosis and require a realistic mathematical model of the monitored system. Therefore, the objective of this research is to develop a twine shaft gas turbine engine model for performance simulation and validate the model the model with operational data collected from a working gas turbine.

MATHEMATICAL MODELING OF A TWIN SHAFT GAS TURBINE

Design point condition

Figure-1 shows the schematic diagram of a twin shaft gas turbine. The main components are compressor, gas generator turbine, combustion chamber, gas generator turbine and power turbine.

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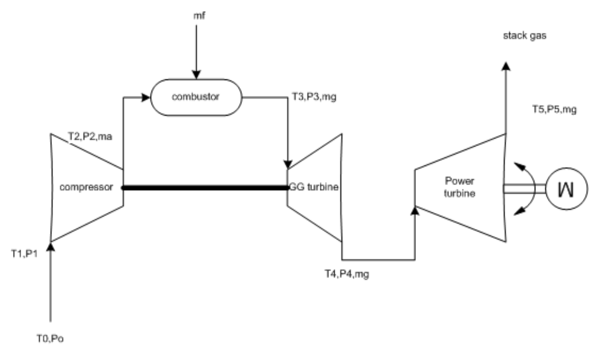

Figure-1. Schematic diagram of a twin shaft gas turbine.

To determine the design point of the gas turbine, partially known design parameters were used with GasTurb simulation software [8]. Known the compressor pressure ratio, speed, and flow rate, the missing design parameters namely, turbines inlet temperatures and pressure ratios were predicted using GasTurb simulation software. In order to insure an accurate prediction of the off-design performance using component characteristic maps, it is essential to use suitable maps. The best choice is to use the component characteristic maps which reflect the actual components of the engine under consideration. However, manufacturers rarely distribute such information. Thus, once the design parameters are estimated, the nearest compressor and turbine maps were selected from GasTurb map collection [9]. Table-1 shows the design condition of a twin shaft gas turbine that is considered for this study.

Table-1. Design parameters of twin shaft gas turbine.

Design parameter	Value
power rating	20087 kW
compressor isentropic efficiency	0.82
compressor pressure ratio	15.9
turbine inlet temperature	1500K
inlet air mass flow rate	66.91
combustion efficiency	0.99
gas generator turbine isentropic efficiency	0.85
power turbine isentropic efficiency	0.89

The selected maps were scaled to match the actual component performance. Figures-2 and 3 show the compressor performance maps for different relative speeds varying from 0.7 to 1.05.

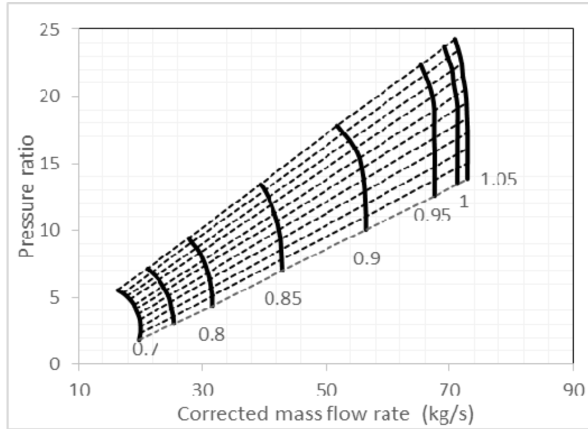

Figure-2. Compressor pressure ratio versus corrected mass flow performance map with auxiliary Beta lines for LM2500.

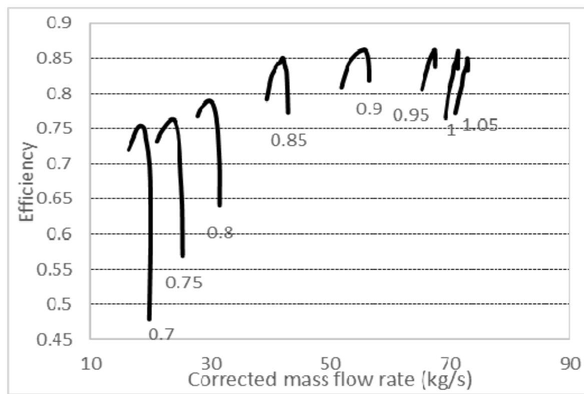

Figure-3. Compressor isentropic efficiency versus corrected mass flow performance map for LM2500.

Figures-4 and 5 show the scaled gas generator turbine performance maps for different relative speeds from 0.4 to 1.2. In these maps beta lines have been introduced in order to find exact value of a third parameter for known two other parameters for a given relative speed curve.

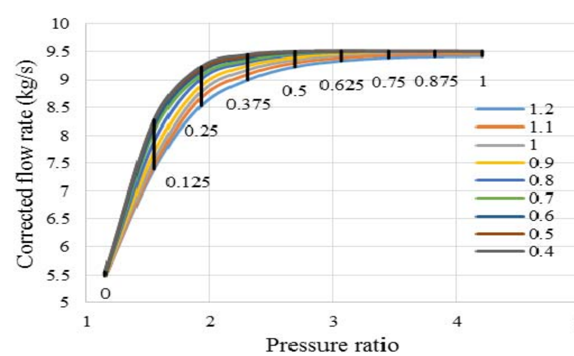

Figure-4. Gas generator turbine corrected mass flow versus pressure ratio for LM2500 with auxiliary beta lines.

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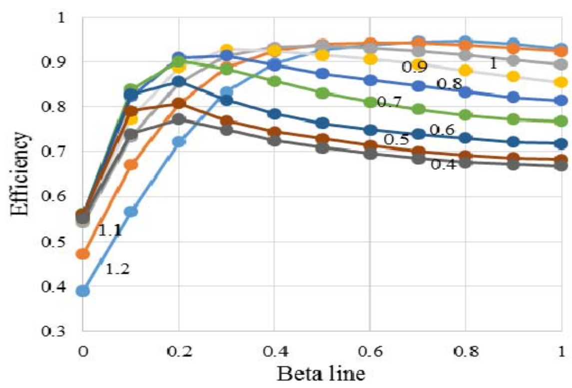

Figure-5. Gas generator turbine isentropic efficiency versus auxiliary Beta lines performance map for LM2500.

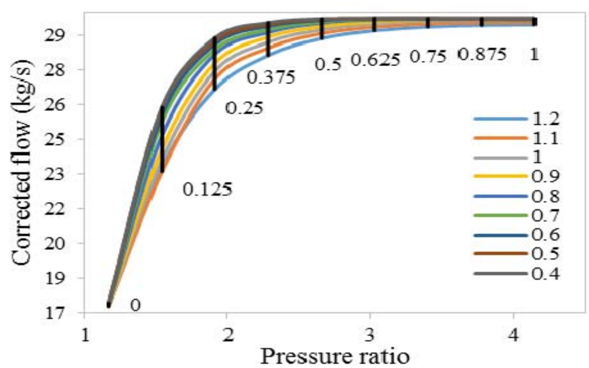

Figure-6. Power turbine corrected flow rate versus pressure ratio performance map for LM2500 with auxiliary beta lines.

Figures-6 and 7 are the scaled maps for power generating turbine and the relative speeds curves runs from 0.4 to 1.2. Similarly, Beta lines have been introduced for reading exact value of a third parameter given two other parameters on a horizontal or vertical portion of a given relative speed curve.

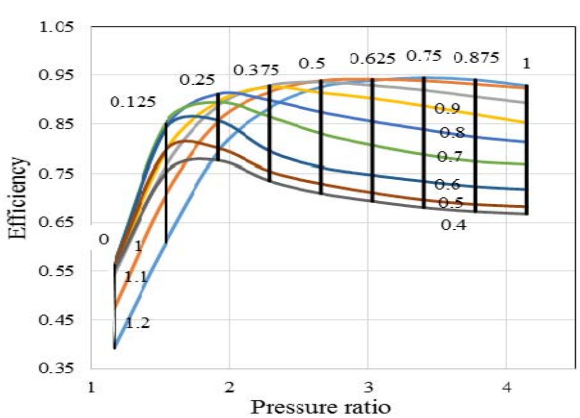

Figure-7. Power turbine isentropic efficiency versus pressure ratio performance map for LM2500 with auxiliary Beta lines.

Compressor modelling

The performance characteristic map and energy balance are used to model the compressor. The air enters the compressor at ambient conditions and leaves with high pressure at compressor outlet. The governing equations of the compressor are as follows:

$$Wc = \dot{m}\,(h_2 - h_1) \tag{1}$$

$$T_2 = T_1 + \frac{T_1}{\eta_c}\left(Pr_c^{\frac{(\gamma-1)}{\gamma}} - 1\right) \tag{2}$$

$$Pr_c = \frac{P_2}{P_1} \tag{3}$$

The simulation started with the following input ambient conditions, namely temperature and pressure, power output of the power turbine, gas generator and power turbines speeds, and the initial inlet temperature to gas generator turbine.

In the compressor, the compressor corrected relative speed and random Beta line are the input parameters to the compressor model, from compressor scaled map using corrected speed and selected Beta line the corrected flow rated is determined. Then an interpolation function programmed as subroutine is used to calculate the pressure ratio and efficiency of the compressor.

The predicted parameters are used to determine the exit temperature and pressure of the compressor using equations (2,3), and then the compressor work is calculated.

Combustion chamber modeling

The performance of the combustor is evaluated by the quantity of heat generated and the pressure loss across the chamber. The outlet temperature, pressure and gas flow rate are calculated according to the following equations:

$$T_3 = \frac{\dot{m}_f \times LHV}{\eta_b \times \dot{m}_a \times Cp_g} + T_2 \tag{4}$$

$$P_3 = P_2\left(1 - \Delta P_b\right) \tag{5}$$

$$\dot{m}_3 = \dot{m}_2 + \dot{m}_f \tag{6}$$

The compressor exit temperature and pressure, air mass flow rate and fuel properties are used as input to the combustion chamber.

Gas generator turbine modeling

The gas generator turbine is modelled by employing component characteristic map similar to compressor modeling. The high temperature gas from combustor is expanded through the turbine generating the power required to drive the compressor. The following equations are governing the turbine operation:

$$W_T = \dot{m}_3 \ (h_3 - h_4) \tag{7}$$

$$T_4 = T_3 - T_3 \times \eta_T \left(1 - \left(\frac{1}{Pr_T} \right)^{\frac{(\gamma-1)}{\gamma}} \right) \tag{8}$$

$$Pr_T = \frac{P_4}{P_3} \tag{9}$$

Based on combustor exit parameters and reference ambient conditions, the corrected relative speed and flow rate are calculated. Using the performance characteristics map of gas generator turbine, a subroutine interpolation function is used to determine the position of Beta line corresponding to the calculated corrected mas flow rate and corrected speed. Doing so will insure accurate determination of the value of pressure ratio and efficiency and overcome the problem of the map data that are not in ascending order.

Power turbine modeling

The free power turbine is modelled by employing component characteristic map similar to gas generator turbine modelling. The high temperature gases from gas generator turbine is expanded through the free power turbine generating the required mechanical power. The following equations are governing the turbine operation:

$$W_{PT} = \dot{m}_4 \ (h_4 - h_5) \tag{10}$$

$$T_5 = T_4 - T_4 \times \eta_{PT} \left(1 - \left(\frac{1}{Pr_{PT}} \right)^{\frac{(\gamma-1)}{\gamma}} \right) \tag{11}$$

$$Pr_{PT} = \frac{P_5}{P_4} \tag{12}$$

Similar to the gas generator turbine, the outlet of the previous component is used as input to the power turbine, same interpolation function subroutine is used to calculate the exhaust pressure and temperature and the power output.

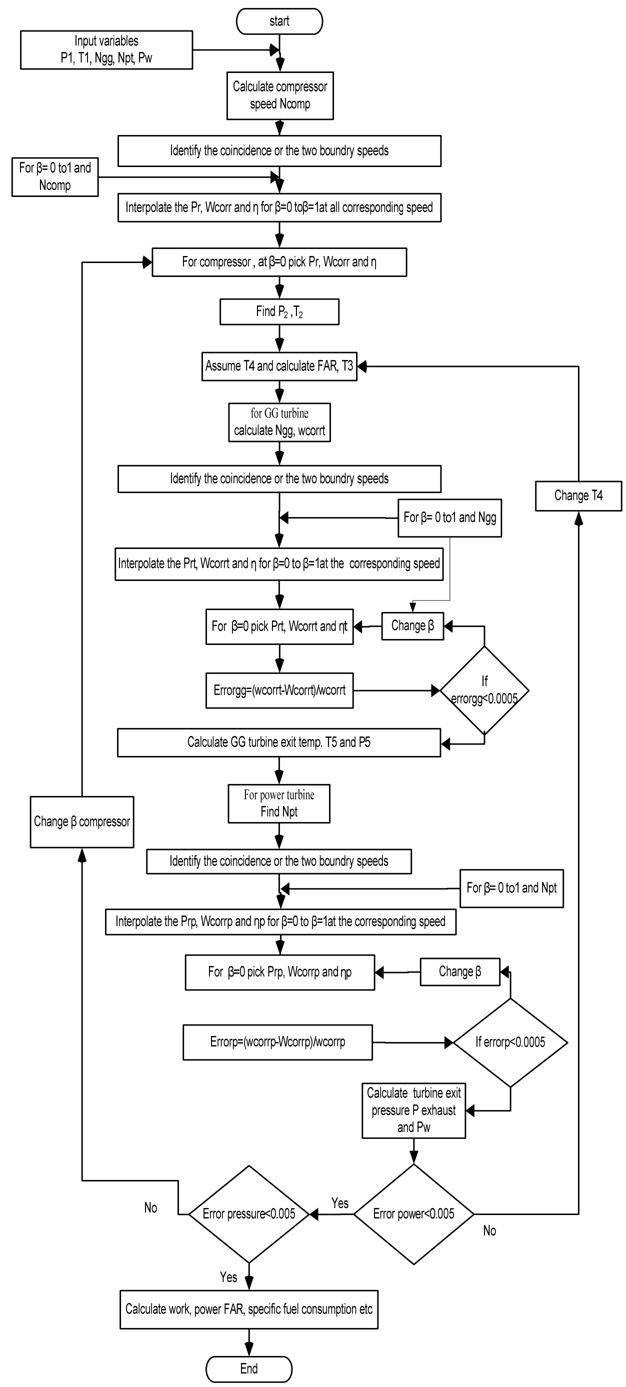

Figure-8. Overall simulation flow chart.

THE SIMULATION PROGRAM

Figure-8 shows the overall simulation flow. The simulation started with the input variables including ambient condition, spools speed and power output. The compressor relative speed is calculated based on ambient temperature and compressor speed. To calculate the pressure ratio and efficiency Beta line is used by selecting

Beta line 0 with suitable incremental amount delta Beat with a known compressor relative speed. The compressor outlet temperature, pressure and compressor work were calculated.

For combustion chamber the outlet temperature and pressure were calculated based on the inlet condition and the initial value of the firing temperature. The values of the specific heat at constant pressure, specific heat ratio and characteristics gas constant at a particular temperature were calculated using polynomial expressions and programmed as a subroutine.

The corrected speed and mass flow rate of gas generator turbine were calculated using ambient condition and inlet condition to the component. From the gas generator turbine map the corrected mass flow rate was calculated based on corrected speed and Beta line then, compared with the calculated one, if the difference is less than convergence criteria the value will be accepted else Beta value will be increased by a certain incremental amount. The same procedure was used with the power turbine. Matching point concept is applied to examine the produced power and exhaust pressure. If the calculated power output is different from the input the value of the firing temperature will change by a suitable incremental amount, same for the pressure balance, if the different between the calculated exhaust pressure and the prescribed one greater than minimum prescribed error, the Beta value for compressor will be increased by a suitable incremental amount.

RESULTS AND DISCUSSION

Validation of the model

The purpose of the validation effort is to demonstrate that the developed mathematical model simulation results can match actual running engine data over a wide range of operational conditions. Furthermore, performance simulation was done for GE LM2500 twin shaft gas turbine because operational data are available from PETRONAS Resak platform in Malaysia for validation purpose. As the measurable data are limited, a complete validation of the various components and parameters are not made. However, sufficient data are collected to demonstrate the process of validation. A change in the gas turbine operation was done by varying the turbine power output, which in actual operation of the gas turbine causes a reduction in the fuel flow rate to the combustor. Hence, the power output and ambient temperature are used as input for simulation.

Compressor exit pressure

The simulation model results were compared with operational data collected from the plant. As shown in

Figure-**9** the compressor exit pressure is increasing with the power output. The comparison between the simulation and operational data shows same trend and good agreement. The mean percentage error between the simulation and operational data is around 3.8%.

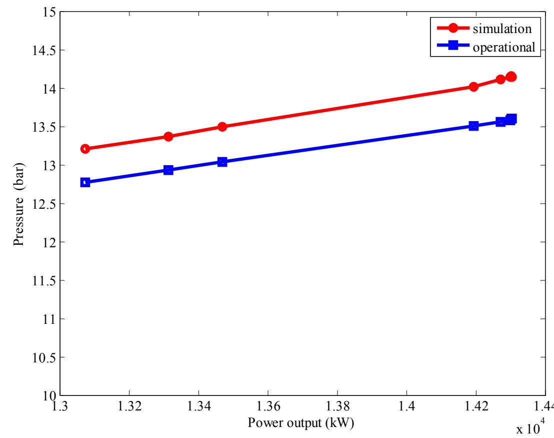

Figure-9. Comparison of simulation and operational data for compressor exit pressure.

Compressor exit temperature

Figure-10 shows comparison of simulation and operational data for compressor exit temperature. The compressor exit temperature is increasing with the power output. The comparison between the simulation and operational data shows good agreement. The average percentage error between the simulation and operational data is around 5%.

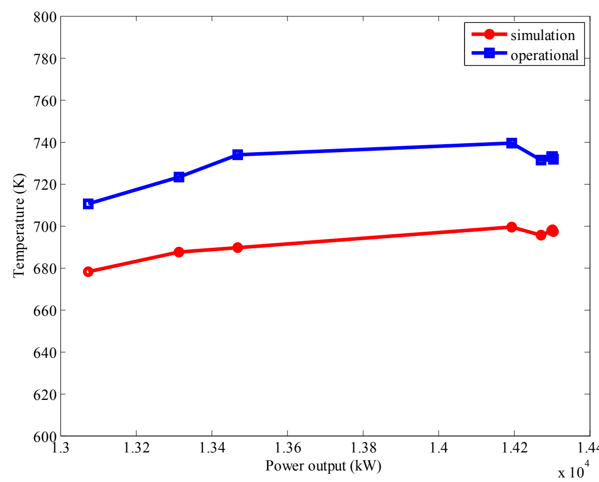

Figure-10. Comparison of simulation and operational data for compressor exit temperature.

Figure-11 shows comparison of the simulated and operational fuel consumption. The mean percentage error between the simulation and the operational data is around 3.5%. The cause for the discrepancy could be the possible differences in the specific heat capacity used in the calculation of the combustion chamber and turbine or compressor.

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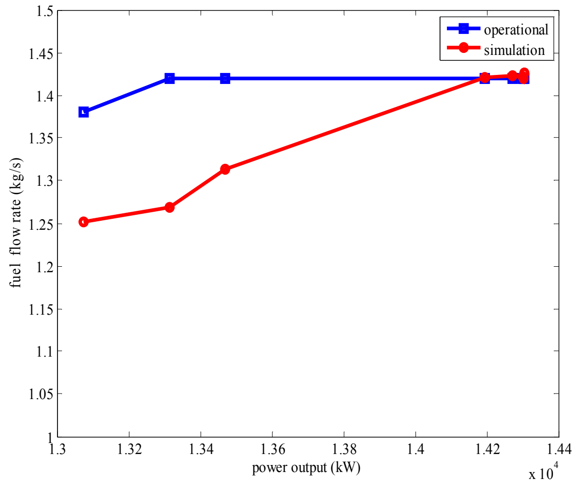

Figure-11. Comparison of simulation and operational data for fuel flow rate.

The gas turbine efficiency increases with respect to turbine power output as shown in Figure-12. This is expected and the maximum efficiency is approximately 0.292. Since the specific fuel consumption (sfc) is inversely proportional to efficiency, it decreases as the turbine power output increases.

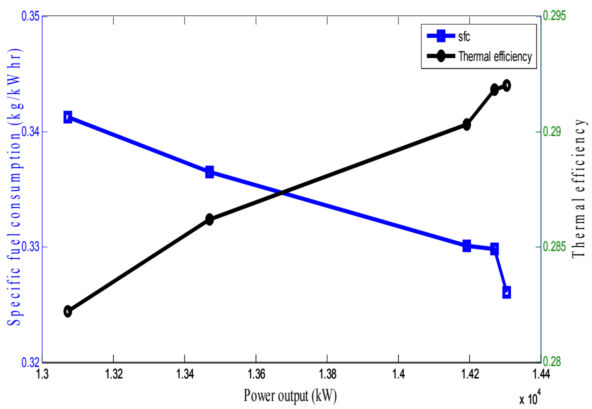

Figure-12. Variation of specific fuel consumption and thermal efficiency.

CONCLUSIONS

A twin shaft gas turbine model for simulation purpose was developed. Physical modeling was used to model the turbine and this method requires performance map of each component. However, component maps are proprietary of the manufacturers'. To overcome this, in this study the unknown design point data were determined using GasTurb simulation software. Once the design point data are obtained, performance maps of the compressor and the two turbines were generated by scaling method from performance maps that are obtained from GasTurb map collection. Then the maps, thermodynamic relationships and continuity equation were used to find the gas turbine performance matching point iteratively. Simulation model was developed in MATLAB environment. To validate the model, simulation was done for GE LM2500 twin shaft gas turbine and it was compared with operational data. The discrepancies are within acceptable error range. Thus, the simulation model can be helpful in performance evaluation of twin shaft gas turbines and generation of data for training and validation of a fault detection and diagnostic model.
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NOMENCLATURE

Wc	Compressor work (kW)
$\dot{m}$	Mass flow rate (kg/s)
h	Specific enthalpy (kJ/kg)
η_c	Compressor isentropic efficiency
Pr_c	Compressor pressure ratio
T	Temperature (K)
γ	Ratio of specific heat
P	Pressure (kPa)
$\dot{m}_f$	Fuel mass flow rate (kg/s)
LHV	Lower heating value (MJ/kg)
η_b	Combustion efficiency
$\dot{m}_a$	Air mass flow rate (kg/s)
Cp_g	Specific heat at constant pressure (kJ/kg)
ΔP_b	Pressure loss at combustion chamber (%)
W_T	Gas generator turbine work (kW)
η_T	Gas generator turbine efficiency
Pr_T	Gas generator turbine pressure ratio
W_{PT}	Power turbine work (kW)
η_{PT}	Power turbine efficiency
Pr_{PT}	Power turbine pressure ratio
1,2,3..	Engine component state points

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