Simulation of an Advanced Twin-Spool Industrial Gas Turbine

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Abstract

A full range mathematical model of the LM-1600 gas turbine has been developed, for future use in EHM studies. No data was available from the manufacturer other than sales brochures giving some design and off-design performance. The model was developed using generalized component characteristics and shows excellent agreement with field data from a pipeline operator.

A new method has been developed for doing the matching calculations, starting from the turbine (hot) end rather than from the compressor operating point. This method permits solution on a PC, and can be used for studying the full range of operating conditions and the development of fault matrices.

Nomenclature

\begin{align*}
P & \quad \text{total pressure} \\
T & \quad \text{total temperature} \\
M & \quad \text{mass flow} \\
\eta & \quad \text{efficiency} \\
C_p & \quad \text{specific heat} \\
\gamma & \quad \text{specific heat ratio} \\
\epsilon_a & = \left( \frac{\gamma - 1}{\gamma} \right)_\text{air} \\
\epsilon_f & = \left( \frac{\gamma - 1}{\gamma} \right)_\text{gas}
\end{align*}

Subscripts

\begin{align*}
a & \quad \text{air} \\
g & \quad \text{gas}
\end{align*}

Abbreviations

EHM — Engine Health Monitoring
PR — Pressure Ratio
OPR — Overall Pressure Ratio
TIT — Turbine Inlet Temperature
LP — Low Pressure
HP — High Pressure
IGV — Inlet Guide Vanes
VSV — Variable Stator Vanes
VBV — Variable Bleed Valve
ISO — International Standards Organization

Introduction

When a new model of gas turbine is introduced, the user has no background of operational experience and in-service faults or deterioration may be difficult to identify. Mathematical modelling of the engine's thermodynamic performance is a powerful tool, permitting the user to predict fault matrices which can be used for fault identification. A major problem, however, is the lack of information required to construct such a model. This paper discusses the work required to create a model of the recently introduced General Electric LM-1600,
which has been ordered by a number of major pipelines. This work represents a form of "reverse" engineering, using publicly available data. The first step required is to define the thermodynamic design point, specifying temperatures and pressures through the engine, knowing the overall specified performance. The next step is to estimate compressor and turbine characteristics to provide a model capable of operating over the entire running range. An alternative method which does not need compressor characteristics has also been developed, based on gas dynamic relationships between the three turbines. The predictions compare very favourably with results from the field. Once this stage has been reached it is possible to implant faults in the model and produce fault matrices. It will become increasingly important, for modern engines of modular construction, to be able to detect faults to the module level. The model developed can be run on a PC which is compatible with installations on pipeline compressor stations.

**Design Point Calculation**

The initial step in developing the computational engine model is to re-establish the design point conditions from available data. Since this information will be incorporated into the off-design model, it is very important to ensure that an accurate design point is obtained.

As an advanced high temperature gas turbine, the LM-1600 has cooled HP and LP turbine blades. The coolant is extracted from the middle stage and exit of the HP compressor. The simplified flow pattern is shown in Fig. 1. Variable geometry is required because of the high overall pressure ratio, and IGV, VSV and VBV are all used. At the design point, the IGV and VSV are fully open and the VBV fully closed.

A design point mathematical model containing basic thermodynamic equations and compatibility equations is set up first, to solve the unknown design point parameters. The problem here is lack of information. Most design point parameters of the LM-1600 have not been published. The major sources of information are the manufacturer's sales brochure and Gas Turbine World (1988). The most reliable design point parameters specify engine overall performance. To solve the design point model, it is necessary to make empirical assumptions for two parameters, and the assumptions are validated by the following analysis.

It is known that if a mathematical model has two freely specified variables, the solution point is any point within a two-dimensional domain; all the other calculated parameters will have different values corresponding to every different solution point. In real gas turbine operation, every parameter has a valid range of value; out of the range, the parameter would be meaningless. To establish the validity of the assumed parameters, the model initially locates the solution point within a limited 2-D domain. Further, even in this domain, inaccurate assumptions could cause some other calculated parameters to be out of their value range. This later consideration would shrink the 2-D solution domain again.

For the LM-1600, if we assume compressor efficiency and HP turbine exit temperature, the validity analysis can be carried out by calculating the cooling air flow rates. Since all the cooling air flows must be positive, the possible solution domain indicated by this analysis is actually quite small. This means the assumed values are close to the correct ones.

It is important to choose the correct mathematical model and clearly define the flow pattern in the model design point calculation. An over-simplified flow pattern, which often ignores the cooling flow and fuel flow, would cause major errors for a high temperature gas turbine. An over-complicated pattern would increase the difficulty of model solving and programming, but would not necessarily increase the modelling accuracy.

The results of the design point calculation are listed in Table 1, which is an optional output of the engine model and provides basic information to the user.
Generalized Component Characteristics

The generalized compressor map can represent only the overall performance; incorporating the effects of variable geometry would require a more complex model using stage stacking methods.

The major impediment in developing a component-based gas turbine model is the lack of component characteristic maps. For most engines on the market, the full scale component maps are normally proprietary to the manufacturers and are seldom published. Although some simplified methods, which will be discussed later, have been introduced to avoid this difficulty, some important performance information such as rotor speeds, compressor running line, surge margin etc would not be predictable without the maps.

The LM-1600 is the industrial version of the F404, a widely used military engine, with the three stage fan of the aero engine cropped to match the flow requirement of the HP compressor. The major components of the two engines are almost identical. No component characteristics are available. To overcome the problem, a generalized compressor map developed by Saravananmuttoo and Maclsaac (1983), has been used. The map is derived from several gas turbine compressors by relative scaling of the available maps. The resulting map has been found valid for low and mid pressure ratio compressors up to PR 8:1. This is shown in Fig. 2. By slightly modifying the efficiency contours and scaling up the speed lines to meet the designed pressure ratio and non-dimensional mass flow of the LM-1600, this generalized compressor map functions very well in the engine model.

A generalized speed-independent turbine characteristic curve is used to model the turbine performance. The curve can be expressed either by a polynomial or a modified nozzle equation. The method has been widely used and proven accurate. The significance of this turbine curve is not only its simplicity, but also it reduces the location domain of the turbine working point from a 2-D area to a 1-D curve.

The comparisons of model predicted results with field measurements are shown in Fig 3 and 4. It indicates that provided a generalized map is the representation of a component in the same class, simulation of overall performance by a component-based engine model can be done fairly well. Absolute accuracy of the map, which implies the requirement of the real component characteristic map, is not possible; using the generalized map, further improvement of modelling accuracy by slightly modifying the map is quite simple.

The use of the compressor map allows the model to give a complete picture of engine operation to the user. The maps and the running lines can actually be shown on a screen or copied through a plotter. This will help inexperienced gas turbine operators to gain some knowledge by operating the model engine and comparing the results with that of the real one.
The LM-1600 has variable geometry components. The generalized compressor map can represent only the overall performance, so it incorporates the effects of the variable geometries.

Hot End Method

A steady state gas turbine model is based on compatibility relations of flow and work. The model can be mathematically and/or graphically expressed. The solution process is often described as component matching.

The normal component matching procedure is introduced by Cohen, Rogers and Saravanamutto (1987). Because of the difficulty of obtaining the maps, some simplified methods have been developed. One of them is by Wittenberg (1976); in this method, a generalized turbine curve and estimated component efficiencies are used instead of real component maps. The calculation is restricted to thermodynamic relationships. For a twin-spool gas generator, choking of the LP turbine is assumed; hence the operating point of the HP turbine is fixed. Then the component matching is simplified to the solving of the LP-spool work compatibility relation, which is graphically expressed as a cross point of two curves for the LP compressor and the LP turbine. If compressor maps are available, Wittenberg’s method can be applied with greater accuracy by correcting for the variation of efficiency.

Wittenberg’s method can be further modified for computer application. When the generalized turbine model and estimated component efficiencies are used, a mathematical engine model which consists of flow compatibility, work compatibility and pressure equilibrium relations can be expressed as a set of N equations with N+1 unknowns ( This may also be true if the relationship between the efficiencies and component operating parameters are found from valid characteristic maps. ).

For a land-based twin-spool gas generator turbine with negligible cooling flow and fuel flow, N equals 10. Theoretically, if one of the unknowns is specified, the model can be uniquely solved. This mathematical uniqueness reflects the steady state operation of gas turbines; i.e. corresponding to each steady state operating point, there is a unique set of gas turbine parameters which are thermodynamically coupled. If one of the parameters varies independently, the others will follow and vary dependently. This causes the change of engine operating point. At every operating point, each parameter takes a unique value.

Since these N model equations are highly nonlinear and highly coupled, the key to the equation solving is to specify a suitable parameter to make the solution process simple. Analysis shows that most of the parameters are not suitable to be the specified one, since solving of a nonlinear equation set will be required. This is difficult numerically, and also takes more computing time and memory. Analysis also shows that the proper solution process should start from the engine hot end. If the power turbine pressure ratio is initially specified, the operating conditions of the power turbine, the HP turbine and the HP turbine can easily be fixed by the generalized turbine characteristic and flow compatibility. Considering the thermodynamic relations and pressure equilibrium, the LP and HP-spool work compatibility equations can be simplified by the following steps.

1. The original equations can be written as:
   - Work compatibility between LP compressor and LP turbine:
     \[ M_a C_p (T_2 - T_1) = \frac{\eta_m M_g C_p}{\eta_{fcp}} (T_3 - T_4) \] (1)
   - Work compatibility between HP compressor and HP turbine:
     \[ M_a C_p (T_3 - T_2) = \frac{\eta_m M_g C_p}{\eta_{fcp}} (T_4 - T_3) \] (2)

2. Substituting the thermodynamic relationship between pressure ratio and total temperature into Equation (1) and (2), we can re-write them as:
   \[
   \frac{M_a C_p}{\eta_m M_g C_p \eta_{fcp}} \frac{T_1}{\left(\frac{P_2}{P_1}\right)^{\alpha_a} - 1} = \frac{\eta_{fcp} T_4}{1 - \left(\frac{1}{P_4/P_5}\right)^{\gamma_a}} \\
   \left(1 - \eta_{fcp}[1 - \left(\frac{1}{P_4/P_5}\right)^{\gamma_a}]\right) \left[1 - \left(\frac{1}{P_3/P_6}\right)^{\gamma_a}\right]
   \]
   \[
   \frac{M_a C_p}{\eta_m M_g C_p \eta_{fcp}} \frac{T_1}{\left(\frac{P_2}{P_1}\right)^{\alpha_a} - 1} = \frac{\eta_{fcp} T_4}{1 - \left(\frac{1}{P_4/P_5}\right)^{\gamma_a}}
   \]

3. From the previous assumption and solved turbine pressure ratios, Equation (1) now contains only two unknowns which are \(P_4/P_1\) and \(T_4\), and can be simplified as:
   \[
   \left[\left(\frac{P_2}{P_1}\right)^{\alpha_a} - 1\right] = A \cdot T_4 \] (1-1)

Equation (2) contains three unknowns \(P_3/P_2\), \(P_2/P_1\) and \(T_4\). To use the pressure equilibrium relation, we can write \(P_3/P_2\) as a function of \(P_2/P_1\) and pre-solved turbine pressure ratios. Again if we substitute Equation (1-1) into (2), then (2) can be simplified as a second order equation which contains only one unknown:

\[
B \cdot T_4^2 + C \cdot T_4 + D = 0 \] (2-1)

where A, B, C and D are coefficients derived from the known and the pre-solved turbine parameters.

One of the two roots of Equation (2-1) would be the
solution of T4. The other root is negative and of no importance. Finding $P_2/P_1$ from Equation (1-1) and fixing the conditions of the LP compressor and HP compressor by the solved variables and flow compatibilities is then quite straightforward.

The advantages of this hot end method are:

(1) The whole process contains only simple calculations which do not require any unnecessary computerized graphic work or matrix calculations that are needed in many currently used engine models. The process is very suitable for computation because the program is relatively short and the solution takes much less time than either graphic or matrix calculations. This method is especially useful when a portable PC model is required by the user in the field.

(2) The physical meaning of the process, which is based on the concept of steady state operation, is clear.

(3) Since all points along the power turbine characteristic line are possible operating points, the solved turbine working points would always be valid. The solved compressor working points would be along the running line if the efficiency is accurately assumed, or very close to the line if a compressor map is available for further accuracy correction. The correction is made by the work compatibility equations, (1-1) and (2-1). It does not need to go back to the beginning of the calculation, so convergence occurs very rapidly.

(4) Though in most cases of interest, the LP turbines are choked, the assumption of LP turbine choking is not needed in the hot end method. This is still true even if the LP turbine is largely unchoked at very low output. The solution process is valid for the full range of engine operation.

(5) Since the hot end method is not initiated from the compressor end, any variation of compressor running lines would not affect component matching. For a deteriorated engine or an engine with variable geometry, the running line moves as engine condition and/or inlet conditions change. In this type of engine model, using the hot end method would facilitate the programming, increase the modelling flexibility, and save memory space as well as computing time.

If an engine has a complicated flow pattern and fuel flow or bleed flows can not be neglected, the number of unknowns in the mathematical engine model will increase. It is then necessary to include new modelling equations, which are related to the new unknowns, into the engine model. For example, if blow off through the VBV is required, a VBV model should be incorporated, adding another equation to the engine model; then the hot end method can still be applied.

The application of the hot end matching process can be enhanced by a numerical method of one-dimensional searching. It is known that all the important gas turbine operating parameters increase monotonically with power turbine pressure ratio. This means that any one of the parameters can be specified, and the 1-D searching subroutine will find the corresponding operating point by searching the related power turbine pressure ratio along the characteristic line. For the LM-1600 model, eleven parameters, as shown in Table 2, are provided to the user. Any one of them can be used as the engine model independent parameter. Since the generalized compressor map is built into the model, mechanical speeds of the rotors can also be selected as the independent parameter. Thus the model is similar to the real engine, making it easier to relate to field operation.

Model Results

1. Model Design and Output

The model can simulate the nominal engine and five deteriorated engine conditions, and can run at any inlet conditions. A window of design point calculation, Table 1, is left to the user for information and possible modification in future. According to its modelling purpose, the user can choose engine condition (nominal or deteriorated), inlet conditions and then specify the independent modelling parameter to run the model; two types of output are available.

(a). Table output: shown in Table 3, provides thermodynamic gas parameters at each engine station, component performance, cooling flow and bleed flow as well as overall engine performance at the user specified operating condition. This is a detailed description of engine working status. Taking the parameters of interest from several operating points, the user can plot curves of parameter variation for further analysis.

<table>
<thead>
<tr>
<th>No.</th>
<th>Selectable Parameters</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Work Output</td>
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<tr>
<td>2</td>
<td>Turbine Inlet Temp</td>
</tr>
<tr>
<td>3</td>
<td>Gas Generator Exh Temp</td>
</tr>
<tr>
<td>4</td>
<td>Power Turbine Exh Temp</td>
</tr>
<tr>
<td>5</td>
<td>Inlet Mass Flow Rate</td>
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<tr>
<td>6</td>
<td>Fuel Flow Rate</td>
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<tr>
<td>7</td>
<td>LP Compressor Press Ratio</td>
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<tr>
<td>8</td>
<td>HP Compressor Press Ratio</td>
</tr>
<tr>
<td>9</td>
<td>Overall Pressure Ratio</td>
</tr>
<tr>
<td>10</td>
<td>Power Turbine Press Ratio</td>
</tr>
<tr>
<td>11</td>
<td>LP-spool Speed</td>
</tr>
</tbody>
</table>

Table 2. Selection of Independent Parameter
tained from the design point. No additional restrictions are added to the engine model. The graphic output gives the user a visible concept of engine operation and deterioration. Two of the original component maps and engine parameters obtained are shown as examples, Fig. 5 and 6.

2. Engine Performance Simulation
(a) Nominal Engine Simulation: This is based on the original component maps and engine parameters obtained from the design point. No additional restrictions are added to the engine model.
(b) Deteriorated Engine Simulation: Williams (1981) has listed eight common deteriorated conditions in pipeline gas turbine application. Five of them are incorporated in the model as follows:
1) LP compressor mechanical damage: by 5% drop of LPC efficiency.
2) Compressor excessive leakage: by 3% over-board leakage flow at the HP compressor exit.
3) HP turbine mechanical damage: by 5% drop of HP turbine efficiency.
4) HP turbine erosion: by 2% increase of HP turbine flow area.
5) LP turbine erosion: by 2% increase of LP turbine flow area.

(c) Comparisons: Some deteriorated performance parameters, OPR, TIT and HP-speed versus LP-speed, plotted with those of the nominal engine, are shown in Figure 7, 8 and 9. Detailed analysis and a fault matrix, that will be discussed later, shows that at a specified LP-speed:
1) Deterioration 1), 3) and 5) will increase OPR and deterioration 2) and 4) will decrease OPR.
2) All the deteriorations will result in higher TIT except deterioration 4).
3) Deterioration 1), 2) and 5) will raise the HP-speed and deterioration 3) and 4) will lower the speed.
4) Except for deterioration 2), most deteriorations will raise fuel flow and work output. The increase in work output is caused by the increase of fuel flow and hence TIT. If, however, the maximum allowable TIT is taken as the control parameter, this will result in reduced rotor speed and decreased work output.

Here the HP turbine erosion may appear to improve...
performance. If erosion causes the HP turbine flow area to increase, the work load of the HP-spool decreases and the load of the LP-spool increases. For fixed TIT or work output, the LP rotor has to run at a higher speed, which may not be permissible for mechanical reasons. For actual erosion, it would also be expected there would be some drop of the efficiency; so the erosion may be the combination of deterioration 3) and 4) that more likely will depress the performance rather than improve it.

As examples of graphic output, Fig. 5 shows the LP compressor map and the comparison of running lines; Fig. 6 shows the relationship between the two rotor speeds. As HP turbine mechanical damage is specified in these maps, it appears that the deterioration will raise the LP compressor running line toward surge and lower the HP-speed for a specified LP-speed.

3. Development of Fault Matrix

A fault matrix is a common tool used for field diagnostic analysis. By evaluating the trends of parameter variation, the operator can roughly locate the engine problem for further investigation.

Since only a few faults might be found in service, the complete fault matrix cannot be developed by real engine operation. It has to be produced by a diagnostic model with simulated faults implanted. A fault matrix produced by the LM-1600 model is shown in Table 4. The LP-spool speed is taken as the independent variable in the matrix, where the LP-speed varies from 100% design speed to 95% and 90%. The sign of "↑" or "↓" indicates parameter increase or decrease compared with the nominal engine; "↑↑" or "↑↓" indicates slight increase or decrease; and "—" means almost no change. It can be seen that the magnitude of the independent parameters has some effect on the various trends; for this reason, a restricted operating range should be specified for use with the fault matrices.

The model has been verified against field results from a pipeline. Because of the short time the engine has been in service, no extensive information on faults is available; thus, the fault matrix presented is developed from the mathematical model and has still to be proven. If either the VSV's or IGV's are out of tolerance, considerable shift in the parameters will result if LP speed is used as the independent variable; the fault matrix may, therefore, be a useful tool for checking errors in the variable geometry settings. Alternatively, HP speed could be used as the independent variable, and another fault matrix developed.

The fault matrix is a useful tool, because the effect of specific deteriorations can be implanted; not all of these may occur in service, and some may only be experienced at very high running hours, so the mathematical model offers a significant predictive capability.
Conclusions

A mathematical model representing the performance of the LM-1600 has been generated, showing excellent agreement with field results. The model is flexible in use and can generate fault matrices which can be used for diagnostic purposes, a feature which is particularly useful when little operating experience has been built up. The model has modest computing requirements and can be run on a PC compatible with those installed at pipeline compressor stations.

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References


