"Two Step Simulation Method"
A General Method for Establishing Gas Turbine's Dynamic Model

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ABSTRACT
A new approach is suggested to establish gas turbine's dynamic model. The conventional approach of solving a nonlinear equation set is divided into the following two steps: 1) to establish a generalized steady-state model which is a set of explicit polynomial expressions; 2) to make the steady-state model applicable to the dynamic process by taking the major dynamic characteristics into account. Because all the parameters in the said model are explicitly expressed, the calculation load is cut by several hundred times, and can be estimated exactly. The model makes the real-time simulation become applicable on microcomputers. An example is discussed in detail to show the usage and advantages of this new method.

NOMENCLATURE
Gf the fuel flow
N rotating speed
P environmental pressure
Q the rate of heat transfer
T environmental temperature
TIT turbine inlet temperature
W power

INTRODUCTION
Simulation can provide a basis for the design of the control logic and a cost-effective way of evaluating the dynamic behavior of the engine and control combination prior to any full-scale engine testing. In addition, the simulation can also serve as aids in solving problems that arise after the control development is completed.

Conventionally, the gas turbine model is comprised of a set of nonlinear equations. The parameters of gas turbine are obtained by solving the equation set. This approach is rigorous in theory, and it can cover all complex factors including component volume, heat transfer, combustion delay and so on. It is well known that solving the nonlinear equation set is very difficult. The first problem encountered is the determining of
initial values. The second is that it is hard to guarantee the rapid convergence of reiteration, making it almost impossible to use the above method to the real-time simulation of gas turbine. Therefore, it is necessary to simplify the model.

Up till now, the approaches of dynamic simulation of gas turbine have long been in a dilemma, which can be roughly divided into three categories. The first is to simplify the model of gas turbine by ignoring some unimportant elements and simplifying component characteristics, which may result in inaccurate results. The second is to use high-speed equipment, which means a high cost has to be thrown in. The third approach is to spend quite a long time. To simulate real-timely, the hybrid computer is needed, and the software is difficult to transplant. The main reasons to this difficulty are due to the necessity of solving a nonlinear equation set and of component characteristics expressed by the function with two variables.

Moreover, the limited range of simulation cannot cover all the dynamic processes from 0 to 100% design rotating speed, and the startup of gas turbine is simulated scarcely. It should be noticed that the method with large time steps (Sellers, 1975), is sometimes unaccepted. Because the modern digital control system works in the frequency of 50-100 Hz.

The two-step simulation method (TSSM) proposed by the authors avoids the above problems. The basic idea of the TSSM is to put as great as possible calculation load before simulation, thus greatly reduces the calculation volume of the simulation period. The basic procedures of the TSSM are as follows:

1) The off-design state program is adopted to calculate all necessary states. The state mentioned here is called generalized steady state (GSS). Because it actually may not be possible for gas turbine to maintain steady operation in these states. By assuming the existing of the steady operation of machine in these states, it brings about a great advantage which can diminish many dynamic effects such as component volume and heat transfer. After obtaining these GSSs, regressing method is used to fit the GSSs. The parameters of the GSSs are expressed into explicit polynomial expressions. Because this part of work can be done in advance, the model in this step therefore can be accurately worked out. An accurate steady-state model provides a sound guarantee for the accuracy of the dynamic model of the machine.

2) Effects of component volume, heat transfer, and combustion delay are added to the model for dynamic simulation. Because the great amount of work has been done in advance, the calculation in this step is greatly simplified. The other important advantage is that the calculation volume can be estimated accurately thanks to the avoidance of reiteration. That is essential to simulate real-timely.

From the above narration, we can find out that the complexity of software is reduced. The dynamic model of a gas turbine is transferred from a complicated program
into several simplified programs, greatly reducing the work load of software programming and debugging. In the example cited in this paper, the major processes, including the starting, and load transition from 0 to full load of a gas turbine can be effectively simulated on an IBM-XT (4.77MHz) with the BASIC language, these are impossible by the conventional methods.

THE GENERALIZED STEADY-STATE MODEL

The major variables of a normal three-shaft gas turbine (Fig.1) are as follows:

\[ W_1 = W_1(N_1,N_2,N_3,G_f,T,P) \]
\[ W_2 = W_2(N_1,N_2,N_3,G_f) \]
\[ W_3 = W_3(N_1,N_2,N_3,G_f) \]

The procedure of establishing a generalized steady-state model is as follows:

1) the calculation of GSSs

The calculation of GSSs is simpler than that of normal off-design states, mostly due to the simpler balance technique. In the calculation of the GSSs, a certain point on the characteristics of the compressor is given, the reiteration can be carried out between the combustion chamber and the turbine. The power balance turns out to be unnecessary. Only one variable (Gf or TIT) needs to find its value by reiteration. Consequently, the number of times of reiteration is greatly reduced and the program is accordingly simplified. In the conventional off-design performance calculation, because the operating point of the compressor is not given before the calculation, it is necessary to couple the compressor, combustor and turbine. The compressor's characteristic is the most complex and important one among all the components. Without the compressor's calculation in reiteration, the whole calculation load is reduced greatly. The calculation procedures of the GSS referred in Fig.1 are as follows:

Supposing each shaft is jointed by a device which can generate as well as absorb power, then each shaft can operate steadily at any rotating speed and at any fuel flow. Accordingly, the power of the three shafts can be respectively expressed as

\[ W_1 = W_1(N_1,N_2,N_3,G_f,T,P) \]
\[ W_2 = W_2(N_1,N_2,N_3,G_f) \]
\[ W_3 = W_3(N_1,N_2,N_3,G_f) \]

The above is the mathematical expressions of the generalized steady-state model (GSSM). If \( W_1 = 0, W_2 = 0 \), then the GSSM becomes the normal steady-state model.

After applying the dimensionless parameters, the above three equations become
To input \( N_1, N_2, N_3 \) and the operating point of the low pressure compressor.

To calculate the low-pressure compressor outlet parameters.

To calculate the high-pressure compressor outlet parameters.

To guess a \( Gf \) or TIT.

To calculate the combustor's parameters.

To calculate the parameters of the high-pressure turbine, the low-pressure turbine and the power turbine.

To check the balance of the energy, the mass flow and the pressure ratio.

To modify \( Gf \) or TIT.

![Fig.2 The block diagram for calculating GSS](image)

The details are described by Weng (1987) and Koenig (1972).

According to the complexity of gas turbines, the number of GSSs needed is varied from several score to nearly one thousand.

2) GSSM establishment by using the regression analysis.

A set of polynomial expressions is assumed and the unimportant terms are ignored by using the regression analysis (Weng, 1987). If the accuracy cannot satisfy the demand, the technique of zoned fitting can be used. On the interface between two zones, some simple methods may be used to continue the parameters. If this step is ignored, which means the GSSM is expressed by many discrete points, the calculation of the performance of gas turbine with interpolation will be very troublesome due to the multiple dimensions.

So far, a complicated model of gas turbine has been transferred into a set of explicit polynomial expressions.

**THE DYNAMIC MODEL**

The dynamic model of gas turbine can be expressed as

\[
J \cdot \frac{dN}{dt} = W(N_1, N_2, N_3, Gf)
\]

The right term of the above equation is the GSSM that is discussed in the preceding paragraphs. Though it is impossible, also unnecessary, to cover all dynamic effects, some principal elements must be considered. Through some simplification, several rather simple approaches are suggested to deal with the component volume, heat transfer, and combustion-delay. Although these approaches are very simple, they do can simulate the major characteristics of the dynamic process of gas turbine.

1) Heat transfer

The gas in gas turbine transfers heat with components, the most which is turbine. Therefore, other components can be ignored. Using the concentrated heat capacity model, the rate of heat transfer is expressed as

\[
Q = K'(T_{TIT} - T_t)
\]

where \( T_t \) is the temperature of turbine and \( K' \) is a coefficient.

Converting the rate of heat transfer into fuel flow, the dynamic model of gas turbine is expressed as

\[
W_1 = W_1(N_1, N_2, N_3, Gf - Gf_1)
\]

\[
W_2 = W_2(N_1, N_2, N_3, Gf - Gf_1 - Gf_2)
\]

\[
W_3 = W_3(N_1, N_2, N_3, Gf - Gf_1 - Gf_2 - Gf_3)
\]

\[
Gf_1 = Q_1/H_u
\]

\[
Gf_2 = Q_2/H_u
\]

\[
Gf_3 = Q_3/H_u
\]

Where \( H_u \) is the calorific value of the fuel,
the Q1, Q2, Q3 represent the rates of heat transfer in each turbine respectively.

2) time delay

The time delay is caused by executive unit of control system and the combustion delay. The effect of the component volume is included in the time delay. Because time delay affects the stability of the control system, it must be considered in the designing of the control system. The range of time delay is between 0.01 to 0.1 second. Up till now, there has been no method to estimate the value of time delay effectively. It can be roughly estimated according to the type and size of the gas turbine.

The time delay is expressed by the fuel flow's delay. If the value of time delay is given, however, it will be very simple to simulate the time delay. By using the method given in the following example, only few than ten statements of program are needed.

AN EXAMPLE

This is a small gas turbine that is being designed by the authors' department. Its structure is shown in Fig.3. The shaft is jointed to a load by a gear box. The gas turbine is required to be started instantly and keep rotating speed stable under any load changes. The fuel flow is the only variable controlled.

1) establishing the GSSM

The calculation is quite precise thanks to the careful consideration of the thermodynamic properties of gas (Zhang, 1980; Wu, 1959), the characterisitics of compressor, turbine and combustor, the performance of the starter, and the mechanical losses. The process of the GSS's calculation is as follows:

- To input a compressor operating point
- To calculate the compressor’s outlet pressure and temperature, the mass flow
- To guess a Gf or TIT
- To calculate the combustor's outlet pressure and temperature
- To calculate the mass flow in turbine according to the expansion ratio
- To modify the Gf or TIT
- To check the mass balance
- To output the results

Fig.4 The procedure for calculating GSS of the example

After calculating about 80 GSS including the different rotating speeds from 17% to 117% design rotating speed, and applying regression method, the GSSM is obtained, which is shown in Fig.8. The mean fit error is less than 1% and the biggest error is 2%. There are only eight in about 80 GSSs whose fit errors are more than 1%, and all the eight GSSs are in the region where the engine runs scarcely. The performance within the range of the rotating speed from 0 to 17% design rotating speed is fitted by a three times power function of rotating speed, with the fuel cut off at this
time.

According to the area of the turbine, the coefficient of K is obtained. Then the Q is calculated.

The time delay is about 0.02 and is realized by using a data structure of a queue.

2) the control system

The all-digital control system is selected and the fuel flow is controlled by a valve driven by a pecking motor. Because this paper is concentrated on gas turbine simulation, the control system is simulated by a simple formula, i.e. a PID algorithm with a pre-estimated time-delay. The dead band is ±0.2% design rotating speed.

3) the result of the simulation

The starting process is shown in Fig.5. It can be found that the effect of heat transfer is significant. Fig.6 shows transient process of loading suddenly to full capacity. The value of time-delay must be pre-estimated precisely, otherwise, the rotating speed will vibrate (Fig.7).

Fig.5 The Simulation Results of Starting Process

![Fig.5 The Simulation Results of Starting Process](image)

![Fig.6 The Transient Process](image)

Fig.6 The Transient Process

![Fig.7 The Effect of the Time-delay](image)

Fig.7 The Effect of the Time-delay

![Fig.8 The GSSM of a small gas turbine](image)

Fig.8 The GSSM of a small gas turbine

Note: The percentages in this figure are the relative quantities of the power
All above is calculated on an IBM PC-XT and programmed by BASIC language. The calculation time is about one hour for simulating a starting process of 20 seconds (there are 100 steps in a second). If compilable language is applied, the speed can be increased by about ten times, that means an advanced microcomputer (e.g. a 80486 microcomputer) can simulate real-timely the whole engine, including its control system.

CONCLUDING REMARKS

The two-step simulation method is simple, accurate, and reliable. Moreover, it opens up an applicable way to simulate real-timely on a microcomputer. With the increasing complexity of the gas turbine, more and more elements of engine have to be taken into consideration in a bid for accurate simulation. The current method of simulation is either costly or time-consuming. By using the TSSM, however, it will help to overcome those problems.

REFERENCES


