Transient Analysis of a Simple Cycle Gas Turbine Engine

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Abstract

A method to simulate the gas turbine transient behavior is developed. The basic principles of the method and main input data required are described. Calculation results are presented in terms of whole operating regime of the engine. The influence of initial parameters such as starting engine power, moment of inertia of the rotor, fuel schedule on performance characteristics of gas turbine during transient operation is shown. In addition, the effect of bleeding air on transient behavior is also considered. For validation of the developed computer code, a comparative analysis with experimental data obtained from a heavy duty gas turbine is made. Calculation results agree well with the experimental data for the range of operating regime studied and proved applicability of the developed technique to initial design stage of control system.

Key Word : Transient, Design point, Off-design, Part-load, Control system, Surge

NORMENCLATURE

CC	Combustion chamber		*Subscripts*
DCR	Cry crank regime	a	Air
G	Flow rate	c	Compressor, consumer
GTI	Gas turbine installation	cc	Combustion chamber
J	Dynamic moment of inertia	f	Friction
P	Power	i	Time index
QLHV	Low heating value	o	Nominal condition
RS	Rotational speed	r	Reduced
TIT	Turbine inlet temperature	R	Rotor
Cp	Isobaric heat capacity	sh	Shaft
n	Rotor speed	t	Turbine
ε	Pressure ratio	T	Torque
δ	Expansion ratio	1	Starting position
τ	Time	2	End position
η	Efficiency factor		
ξ	Nondimensional pressure loses		
ω	Rotational angular velocity		

Introduction

Reliable operation of a modern gas turbine unit (GTU) substantially depends on the control system and its ability to predict emergency situation during operation. With increase in complexity of gas turbine control, the system for accurate manipulation of gas turbine engine operation are

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getting more sophisticated. A full understanding of transient behavior of the engine is especially important for the development of a suitable control system at design stage [1]. However the information on dynamic behavior of the engine is not available at initial design stage. Therefore the development of a simulation technique which enables prediction of transient behavior of the gas turbine cycle is very important [2]. Using the developed method to simulate transient regime it is possible to investigate the effect of components characteristic on dynamic behavior of gas turbine unit and thereby increases the effectiveness of the control algorithm. The control system design and transient performance analysis are inseparable, as the engine responds to the schedule of fuel flow rate, variable geometry, etc. [3]. In order to obtain the accurate information on dynamic behavior of the gas turbine it is required to have complete characteristic data of components. The performance characteristics of the individual components may be estimated on the basis of previous experience or data obtained from actual test [4]. Performance data of a nominal point has to be known as well. Thus, for a given engine, if all component characteristics and engine layout are known, then its dynamic behavior can be analyzed mathematically. This approach has many advantages: the simulation over the entire running range and effects such as bleed, blow-off, and variable geometry can be predicted.

Basic Equations

The underlying concepts in calculating the transient behavior is the unbalance between energy generated and its consumption. The unbalanced power produced between the components will result in spool acceleration or deceleration. Air flow rates, pressure, temperature, power and efficiency of the components will change with spool speed variations. The relationship between the components can be expressed as,

$$2\pi J\frac{dn}{d\tau} = M_s + M_t - M_c - M_f \tag{1}$$

where,

M_t = N_t/ω - torque of turbine engine , N-m;
P_t : turbine power, W;
M_s : starter torque;
M_f : resistance torque of friction;
M_c : resistance torque of gas turbine unit during dry crank regime (DCR).

And M_c can be determined using the following formula [5].

$$M_c = \zeta_f W_R d_{sh} / 2 \tag{2}$$

where, ζ_f = 0.2−0.35 Is the friction factor, W_R is the rotor mass, and d_{sh} is the diameter of shaft. During acceleration, the moment due to friction and auxiliary equipment can be taken as 3-5% of compressor torque. J is the moment of inertia of all rotating mass in kg-m^2; $dn/d\tau$ is the accelerating rate in 1/s^2.

For steady-state condition (n = const), the right side of the equation becomes zero. However at transient state the right side can be both negative and positive, and, hence, acceleration or deceleration will result, respectively. During acceleration phase, the fuel flow rate will be an independent parameter. The whole process is divided into short increments of time $\Delta\tau$. The fuel flow increase causes turbine inlet temperature rise that can be determined from the following equation:

$$TIT = T_t = T_c + \frac{fQ_{lhv}\eta_{cc}}{c_p G} \tag{3}$$

where, T_c is the compressor exit temperature and f is the fuel flow rate. In this calculation it is assumed that the turbine torque changes with small time increment but the compressor torque remains the same. Then it is possible to find power P_t and torque M_t which exceeds those for steady state. As a result, the right side of equation (1) is different from zero, and the rotation speed increases during the time of increment $\Delta\tau$, which can be expressed as,

$$\Delta n = \frac{\Delta\tau(M_t - M_c)}{2\pi J} \tag{4}$$

After time increases to a new step of rotation speed $n+\Delta n$, changes of power and torque of the turbine and energy that are consumed can be calculated. During this process, compressor map data, through progressive approximation, will be utilized and a new operating point that provides a new gas flow rate passing through the turbine for higher TIT can be determined [7]. The equation of Stodola-Flugel was used to satisfy this process as,

$$\varepsilon = \frac{1}{1-\xi_0\overline{G}_r^2}\sqrt{1+(\delta_0^2-1)\overline{G}_r^2\overline{T}_t[1+2\xi_{d0}(1-\overline{G}_r^2)]} \tag{5}$$

where $\overline{T}_t$ = TIT/TIT$_0$, and assumptions are made that non-dimensional pressure losses, ξ, will change proportionately to the square of the reduced flow rate $\overline{G}_t$, and $\overline{G}_t \approx \overline{G}_c$. Heat flux from the metal components and volume dynamics for ducts and combustor have been neglected. Influence of unsteady aerodynamics on the performance maps has also been neglected in the present study. If all these characteristics have been defined correctly, then they are used for next short time step of calculation to find next addition of Δn and so on. As the speed of rotor increases, a larger amount of air enters the combustor, and the gas temperature will decrease till a new steady state operating condition is reached at increased resistance of the consumed power. In most cases, it is known that incorporation of polar moment of inert alone into the transient calculation provides fairly good performance estimation.

Simulation model

The simulation of a physical system involves two processes such as setting up of a model of system and investigation of the behavior of this model. The model of the present study consists of several parts. First, initial data which include a stream of main information, such as nominal performance data, starter motor's data, and values of time and fuel flow increment for principal stages of engine operating conditions must be prepared. Second, thermodynamic calculation of the cycle, where the detailed information of a nominal point is given and further excess power on every step of time increment must be evaluated. And in third, dynamic analysis to calculate the addition with rotation speed variation must be made. All these parts are interconnected and influences each other. The consecutive simulation of operating time consists of four principal periods of engine running, namely, starting (dry crank regime), ignition, acceleration (accel. to idle), loading. Every stage has its own feature and was taken into account in the developed method. In the first stage, a starter is the main driving source to accelerate a turbine. The value of M_t in eq. (1) equals zero, especially when $\overline{n}$, rotational speed normalized by design point speed, corresponding to moment of ignition is less than 0.2. The second stage is considered to be the first few seconds after ignition where the gas temperature increase is high and therefore an extremely short time of increment is necessary to achieve the accuracy of calculation. Third period is acceleration stage till idle (nominal rotation speed for generator turbine). It should be noticed that within this period the starter power will be terminated and rotor acceleration will be realized only by the turbine power. As indicated in eq. (1) the time for dry crank regime substantially depends on the value of starter power and low limit of its change. In general, the starter torque varies linearly with rotational speed, i.e. $M_s = M_0 - bn$ and the following equation was used for speed calculation:

$$N_i = N_o(2 - \frac{n_i}{n_0})\frac{n_i}{n_0} \tag{6}$$

where, N_0 and n_0 are rotational speeds at nominal powers of gas turbine and starter, respectively. For a shorter time of acceleration it is needed to have a surplus torque moment ΔM as much as possible as shown in the equation below,

$$\Delta\tau = J\int_{\varpi_1}^{\varpi_2} d\varpi / \Delta M \tag{7}$$

The greater the starter power N_s, the faster and more reliable is the dry crank step calculation [5].

Model Application

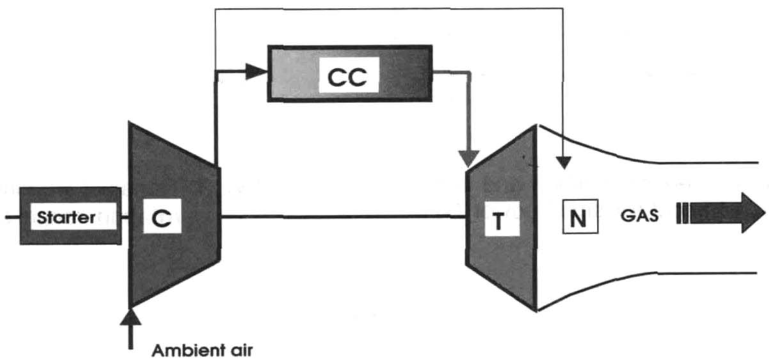

Fig. 1. Simple cycle turbo-jet engine

Table 1 Basic information of the simple cycle model

Compressor pressure ratio	3.098	-
Compressor mass flow	1.663	kg/s
Compressor efficiency	0.8	-
Turbine inlet temperature.	1024	K
Bleeding air	0.440	Kg/s
Turbine efficiency	0.86	-
Rotational speed	36750	rpm

Fig. 1 shows the scheme of the engine used in the present analysis. It is a turbojet engine usually used as an auxiliary power unit for starting of the helicopter/airplane main engines or to provide compressed air to the cabin. It can also serve as a stand-by DC power source for the main engine, should the main generators of the airplane fail in flight, or a ground power source to be used for checking the electrical equipment. Some of basic engine data are shown in the Table 1. The compressor characteristics have to be known for starting range (before ignition) calculation and approximate equation used for this analysis is as following,

$$P_c = P_{co} \cdot (\bar{n})^m \tag{8}$$

where, P_c is the compressor power, P_{co} is nominal compressor power, $m \approx 2.7$, for $\bar{n}(= n/n_0) = 0.1 \sim 0.2$, and $m \approx 3 \sim 3.2$, for $\bar{n} > 0.2$.

The turbine torque has been neglected during DCRs and it will be positive only after ignition. For the considered gas turbine, the variation of major parameters during starting condition are presented in Fig. 2. The primary function of the starting system is to accelerate the gas generator from rest to a speed level beyond self-sustaining speed of the gas turbine engine. To accomplish this, the starter must develop a torque enough to overcome the drag torque of the gas generator's compressor and turbine, and other associated accessory loads

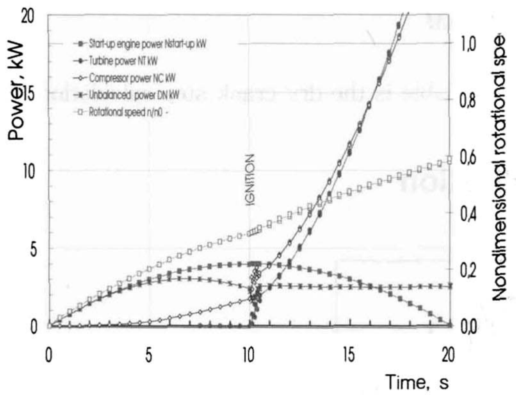

Fig. 2. Dry crank regime, ignition and initial Phase of accel for small power GTI.

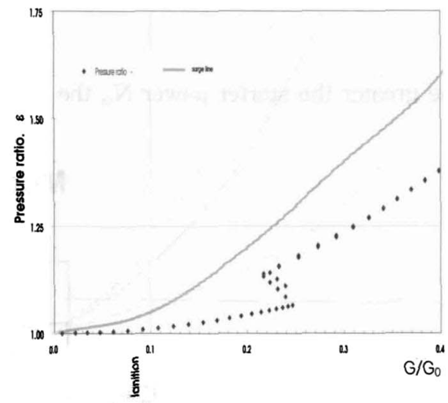

Fig. 3. Transient working line in the low rotating range speed.

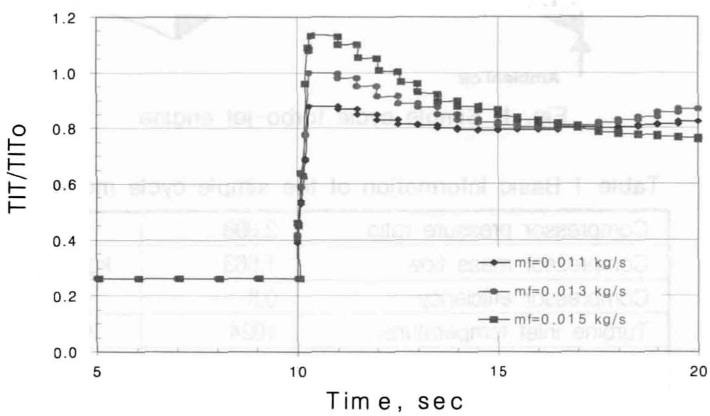

Fig. 4. Turbine inlet temperature rising for first few seconds after ignition.

such as bearing resistance. If assistance from the starter were cut off below the self sustaining point, the engine would fail to accelerate to idle speed or would start to decelerate because it could not produce sufficient energy to sustain rotation or to accelerate. A 4kW starter power will be enough to accelerate the gas turbine till the moment of ignition. Having a less starter power, for instance, 3KW, will lead to increases of dry crank regime (DCR) almost 50%. From fig. 2 one can clearly notice that starter can provide power well above the ignition point and even higher level where turbine power exceeds that of compressor. Usually the limiting factor for acceleration is the proximity of the surge line to the equilibrium running line, and this is particularly critical during starting period. Decreasing the start-up engine power for economic reason will bring earlier self-sustaining condition but this will cause the surge margin decreased. Surge margin is already very small during low speed range compared with higher ones. As shown in the figure 3, there is a small kink close to the ignition point. Very close to this point, operating characteristic migrates toward the surge line resulting in a very high turbine inlet temperature that could destroy the turbine. In order to secure the safe engine operation, it is necessary to reduce this migration either by reducing the fuel flow rate or speed up quickly to pass over this dangerous operating regime. This can be fixed with engine testing eventually. Particular attention should be made that control system must be designed to predict such a sudden increase of turbine inlet temperature during the start-up process. Fig. 4 shows turbine inlet temperature overshoot as a result of engine light up for three different fuel flow rates. A small disparity in the fuel flow rate leads to big difference in TIT. This is a very important moment of gas turbine operation, because the amount of fuel injected will strongly affects the combustion stability, and not enough fuel flow for starting period can result in a flame failure that generally leads to emergency shut-down. On the other hand, a too large amount of fuel supply will cause a slam increase of TIT that makes negative effect on service life of the engine. Therefore, the necessity for accurate tuning of fuel flow rate delivered to the ignition equipment can not be overemphasized. Fig. 5 shows the acceleration and loading characteristics of the gas turbine engine after ignition. It is shown in the figure that there is a surplus torque as result of higher turbine power, but 45s after starting, power between the components become balanced which means idle. It should be noted that fuel flow was stabilized three seconds before entering the nominal rotation speed to avoid its exceeding. After a short period on the no-load-state, a mass flow rate through turbine is lowered gradually due to bleeding. Approximately 25% of bleed air is extracted from the last stage of compressor to be forwarded to the turbine end. This causes the fuel flow increased to keep rotational speed stable. For this regime the developed computer code determines sign (plus or minus) of unbalanced power and uses this information to change the fuel flow rate to return the rotor

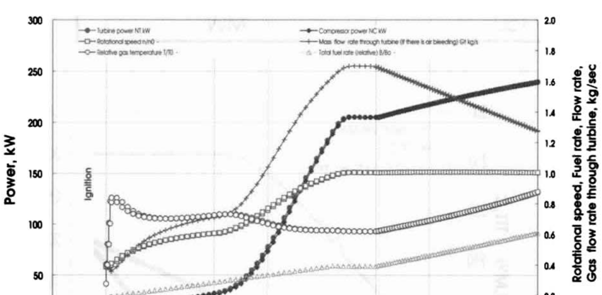

Fig. 5. Acceleration and stage of lowering of gas flow rate through turbine after idle.

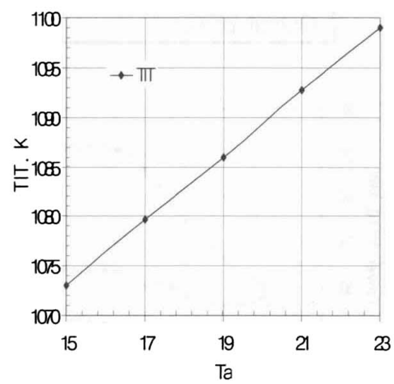

Fig. 6. Growth of TIT to keep the rotational speed stable.

speed back to the nominal rotational speed. In this case, the fuel flow increase is demanded and it leads to TIT increase as shown in Fig. 6. In the considered example, TIT's growth for this period is too fast (400-600°C/min) and hence the duration of this period should be decreased less than 1/3 times to reduce harmful effect on the service life of the turbine. Generally, the temperature of TIT raised 220 - 250°C/min is considered as extreme and except special cases the TIT rise should be less than 100°C. It is well known that an ambient temperature (t_a) affects on the useful power on the shaft. If the gas turbine unit is used near the fire area, special attention should be given to this to prevent some failures. If a single spool turbojet is operating in a steady state and t_a is raised suddenly, but the fuel flow rate doesn't change much, then the power on the shaft will be reduced, even though there can be a small rise of TIT. This leads to lowering of revolution speed. To keep rotational speed constant, as calculation shows, TIT should be raised by increasing the fuel flow rate (fig.6).

Validity of the calculation method

To evaluate the developed computer code, calculated result were compared with those of experimental data obtained from performance test of heavy-duty gas turbine (Fig. 7,a) of NPO CKTI Russia. It can stated that rotation speed prediction curves agree well between the two, power and TIT prediction also show good agreement except a small disparity in TIT during acceleration period of time between 4 to 10 minutes. The overprediction of calculation result is considered to be because of difference that the fuel control is made and some uncertainty of TIT measurement during the test. Evaluating the result, it can be stated that the proposed method is useful for gas turbine transient performance prediction during initial design stage. Table 2 shows basic engine data of the heavy duty gas turbine engine used for comparison.

Table 2 Basic design data of heavy duty gas turbine engine used for comparison.

Compressor Pressure ratio	14	
Compressor mass flow	630	Kg/sec
Compressor efficiency	0.85	
Turbine inlet temperature	1373	K
Bleed air		
Turbine efficiency	0.86	
Rotational speed	3000	rpm
Output power	150	MW

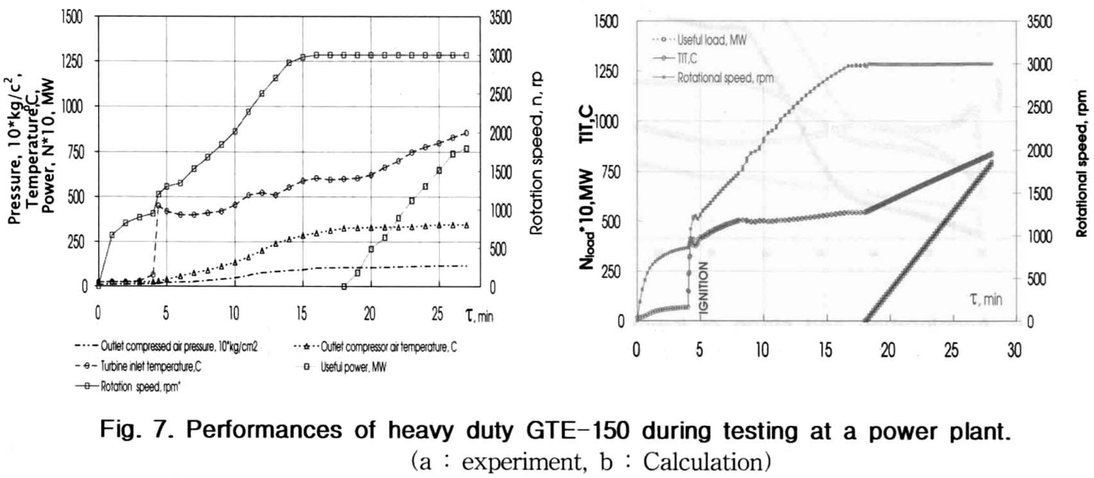

Fig. 7. Performances of heavy duty GTE-150 during testing at a power plant.
(a : experiment, b : Calculation)

Conclusions

A computer code is developed to analyze transient phenomena of a simple cycle gas turbine engine and is certain to shed some light to prepare the input data for control system.

Calculation result was compared with the existing experimental data of heavy duty gas turbine engine and the result showed good agreement. Proposed computer code can be useful for optimization of dry crank and ignition regimes and for prediction of operating characteristics as a whole. Investigations also showed that a time step small enough to prevent abrupt increase in TIT must be determined considering both surge margin and material confinement. Inclusion of the effect of heat transfer and volume dynamics into the present code will be necessary for further enhancing the effectiveness of the developed scheme. Capability to incorporate the detailed components characteristic data rather than approximate equations will further increase the versatility of the program.

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