A New Methodology for Advanced Gas Turbine Engine Simulation

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Abstract

Gas turbine engine simulation in terms of transient, steady state performance and operational characteristics is complex work at the various engineering functions of aero engine manufacturers. Especially, efficiency of control system design and development in terms of cost, development period and technical relevance implies controlling diverse simulation and identification activities. The previous engine simulation has been accomplished within a limited analysis area such as fan, compressor, combustor, turbine, controller, etc. and this has resulted in improper engine performance and control characteristics because of limited interaction between analysis areas.
In this paper, we propose a new simulation methodology for gas turbine engine performance analysis as well as its digital controller to solve difficulties as mentioned above. The novel method has particularities of (i) resulting in the integrated control simulation using almost every component/module analysis, (ii) providing automated math model generation process of engine itself, various engine subsystems and control compensators/regulators, (iii) presenting total sophisticated output results and easy understandable graphic display for a final user. We call this simulation system GT3GS *(Gas Turbine 3D Graphic Simulator)*. GT3GS was built on both software and hardware technology for total simulation capable of high calculation flexibility as well as interface with real engine controller. All components in the simulator were implemented using COTS (Commercial Off the Shelf) modules. In addition, described here includes GT3GS main features and future works for better gas turbine engine simulation.

1. Introduction

Gas turbine engine is a very complex system that includes a variety of specialized engineering areas. Therefore, to predict the operational or control characteristics of an engine requires wide comprehension about component itself as well as its interactions. As a result, it is not possible to obtain exact behavior without real engine test that sometimes involves unwanted economical loss, time consuming, and even dangerous situations[1]. This fact is the reason why engine simulation methods are essential in developing gas turbine engine and designing its control system. The previous engine simulation was done within a limited component such as fan, compressor, combustor, turbine, etc. Consequently, a developer as well as a final user cannot estimate exact engine performance and control results because of limited interaction effect between components. This incorrect simulation has resulted in an increase in development budget, an unpredictable accident, a number of engine tests and changes of mechanical design and manufacturing. Hence, a need has arisen for the integration of separate simulation areas. We developed a powerful simulation software GT3GS applicable to the above purposes. GT3GS has been successfully used to support engine component design, integration, control logic design and verification on an engine as well as for future engine development plan.

GT3GS configuration is provided in Section 2. Section 3 explains the brief mathematical modeling method of gas turbine engine and its basic principles. In section 4, the controller design strategy and their dynamic simulation methods are explained. Section 5 shows special features of GT3GS that provide users with easy understandable and recognizable simulation results. In section 6, the implementation issues are mentioned with simulation results.

2. Configuration

GT3GS is composed of main 2 simulation categories (Fig. 1)

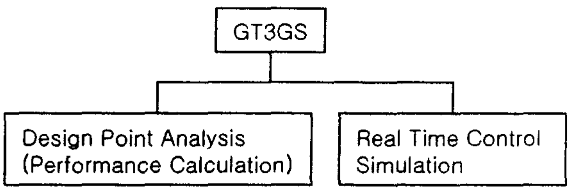

Fig. 1 GT3GS Simulation Categories

The first simulation category is on and off design point analysis for calculation of transient & steady state engine performance. From these results, the second category is to derive engine mathematical models in the form of state variable and uses them for achieving real time simulation. The detail simulation flow is shown in Fig 2.

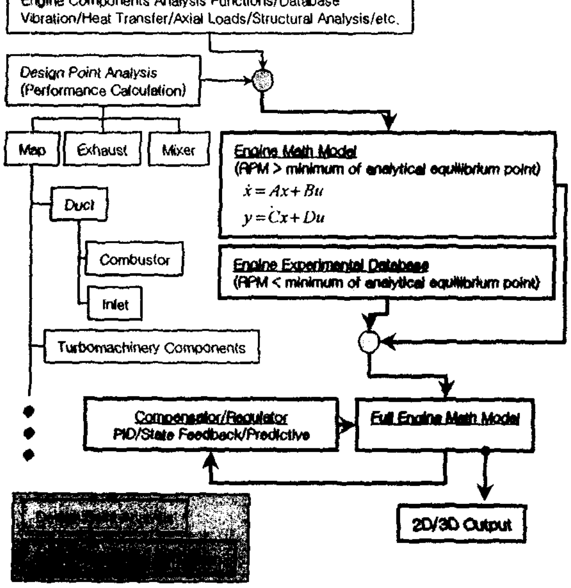

Fig. 2 Simulation Flow

We assumed that specific information of an engine such as the number of spool, compressor/turbine stages and the type of combustion chamber is given. Under this information, GT3GS creates analysis functions or database. A function or database is used as fundamental resources to calculate engine performance at on/off design points. Engine mathematical model is in the domain of state space whose variables can be rotor RPM, compressor pressure, turbine temperature and so on. However, this model is valid only in a range of rotor RPM over the minimum of engine analytical equilibrium point. In general, a calculation of engine performance is only possible when engine inside gas condition is balanced mechanically and thermodynamically. Therefore, engine mathematical model can be used only on this range. On the other hand, when the RPM is lower than minimum of analytical equilibrium point, the database is applied to make possible low RPM range simulation. In this range, engine state space model cannot be created because of analysis constraints. On these two different models, a control logic designer attaches control system including fuel supply systems, variable geometry actuators, PID or modern control codes. As a result, they form a full closed loop control system that makes desired transient and steady state responses while remaining engine within safe margins of engine thermal, aerodynamic and mechanical limits. Finally, the simulation results are shown at 2D plot as well as 3D drawings. As shown earlier in Fig. 1, GT3GS is composed of main two functions (i) on/off design analysis, and (ii) real time simulation. The step until generation of two different models mentioned above is called on/off design analysis. After that, the real time simulation considering transient effect and control scheme will be performed.

3. Mathematical Model of Engine

As mentioned before, engine mathematical model means a state space model on a range over thermodynamic equilibrium point. On this range, engine state matrices can be expressed as following form[2)-3)].

$$\begin{aligned} \Delta\dot{x} &= A\Delta x + B\Delta u \\ \Delta y &= C\Delta x + D\Delta u \end{aligned} \tag{1}$$

Simply, engine state variables can be engine rotor RPM and output variables can be vital parameters that are used for engine operation directly. However, it is highly dependent on engine configuration, flight profile and ambient condition. This ABCD description is a linearized form of nonlinear transient and steady state physical relationship of engine. Most of the analytical design approaches used by control designers require linear description for transient and steady state characteristics of the engine. A linear approximation to a nonlinear system can be obtained at a particular operating point (a particular equilibrium condition of power setting and flight condition) for small excursions about that particular point. For example, if the state vectors x and input vector u are assumed to be single elements, the state equation can be expressed as follows:

$$\dot{x}_0 = f(x_0, u_0) \tag{2}$$

Where, subscript 0 means at an operating point. The Taylor series expansion about operation point x_0, u_0 is

$$\begin{aligned} \dot{x} = f(x_0,u_0) &+ \frac{\partial f}{\partial x}\bigg|_{\substack{x=x_0\\u=u_0}}(x-x_0) + \frac{\partial f}{\partial u}\bigg|_{\substack{x=x_0\\u=u_0}}(u-u_0) \\ &+ \frac{\partial^2 f}{\partial x^2}\bigg|_{\substack{x=x_0\\u=u_0}}(x-x_0)^2 + \frac{\partial^2 f}{\partial u^2}\bigg|_{\substack{x=x_0\\u=u_0}}(u-x_0)^2 \\ &+ \textit{other higher order terms} \end{aligned} \tag{3}$$

If $x = x_0$ and $u = u_0$, namely the engine is at a steady state operating point, the system is in equilibrium and hence $\dot{x}_0 = 0$. Thus equation (3) can be rewritten as

$$\begin{aligned} \dot{x} = &\frac{\partial \dot{x}}{\partial x}\bigg|_{\substack{x=x_0\\u=u_0}}(x-x_0) + \frac{\partial \dot{x}}{\partial u}\bigg|_{\substack{x=x_0\\u=u_0}}(u-u_0) \\ &+ \frac{\partial^2 x}{\partial x^2}\bigg|_{\substack{x=x_0\\u=u_0}}(x-x_0)^2 + \frac{\partial^2 u}{\partial u^2}\bigg|_{\substack{x=x_0\\u=u_0}}(u-x_0)^2 \\ &+ \textit{other higher order terms} \end{aligned} \tag{4}$$

In a suitable neighborhood of the steady-state operating point x_0 and u_0, the higher order terms of equation (4) are negligible and equation (4) can be approximated by using only the first partial derivative terms consequently.

By letting $\Delta\dot{x} = \dot{x} - \dot{x}_0, \Delta x = x - x_0$ and $\Delta u = u - u_0$, equation (4) becomes the linear equation

$$\Delta\dot{x} = \frac{\partial \dot{x}}{\partial x}\bigg|_{\substack{x=x_0 \\ u=u_0}} \Delta x + \frac{\partial \dot{x}}{\partial u}\bigg|_{\substack{x=x_0 \\ u=u_0}} \Delta u \qquad (5)$$

Using this way, an actual system with a multitude of states, inputs and outputs, when linearized about an operating point, can be described by the form of equation (1)

We developed the calculation method of A, B, C and D matrix based on commercial S/W with Netherlands research lab NLR*. This S/W is called GSP (Gasturbine Simulation Program[4], Fig. 3) that is operated on Windows based OS and API**.

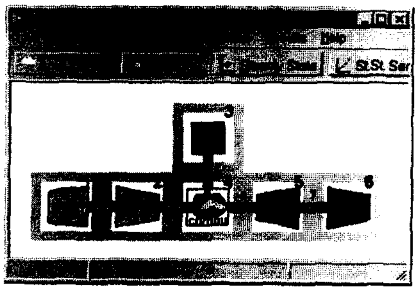

Fig. 3 Engine ABCD Matrix Generation S/W API Module (co-developed with NLR)

We designed core ABCD matrices calculation routine and utilized an expertise foreign institute for implementation. Since equation (1) is only valid when engine rotor RPM is over the minimum of analytical equilibrium point and at an operating point, we need additional model applicable to non-analytical areas. For generating such low RPM model, we decided to use long period experimental database. In addition, to enhance the simulation flexibility of low RPM model, GT3GS provides a variety of variables affecting engine starting, ignition and acceleration (Fig. 4).

Most of functions are created by linear regression method[6] to derive correlation equations of multiple variables. The similarity between simulation and real test results was found to have high correlation value.

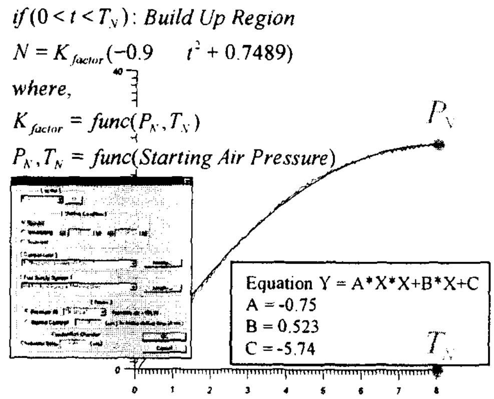

Fig. 4 Engine Starting based on Experimental Results Database – Low RPM Region

For the generation of low RPM model, one important point in making RPM build-up profile is to consider ignition effect. Without ignition, engine RPM keeps a certain velocity energized by just starting system like starting turbine. Therefore, low RPM build-up is a function of time, starting system power, ignition index and so on. Since these variables are determined engine by engine, we applied the above three specific variables to GT3GS.

4. Controller Design

A general control system, as shown in Fig. 5, consists of controller, actuators, plant model and some open/closed loops.

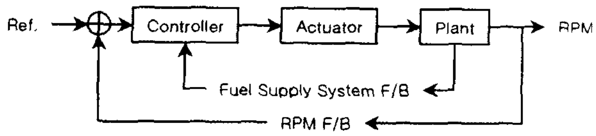

Fig. 5 Block Diagram of Control System

A pilot adjusts a reference input value by moving PLA (Power Lever Angle). Then, this value is converted to have control unit and summed with feedback values. A controller generates actuator command to regulate plant output. Therefore, control behaviors are highly affected by dynamic characteristics of a plant as well as actuators. In our experimental engine, the actuator is a metering valve controlling the amount of engine fuel flow. A control designer has a great many choices in the selection of fuel supply system. Despite the almost infinite possibilities for variation, the selection of the fuel supply system will fall into three popular systems.

- Servo Valve
- Motor and Its Driver
- Pump & Metering Valve

* NLR: Netherlands Aerospace Laboratory

** API: Application Programming Interface

A fuel supply system affects total engine dynamics. GT3GS provides above three kinds of fuel supply system to investigate better matching performance between an actuator and an engine. Fig. 6 shows three different block diagrams of fuel supply systems.

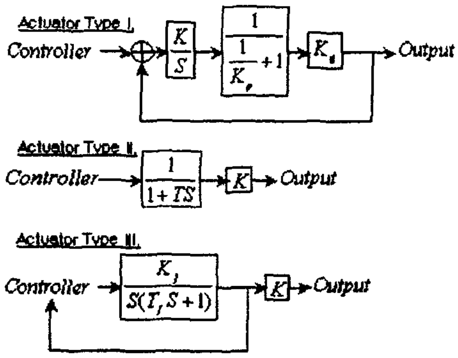

Fig. 6 Basic Block Diagram of Fuel Supply System

Fuel supply system in whole gas turbine engine has to be dynamically simulated for safe engine operation. Therefore, a control designer must have verification method to ensure safe operation. GT3GS was designed for this goal. If there are some candidates for fuel supply system, a control designer can apply GT3GS to identify the best matched system using dynamic simulation functions like Fig. 7. Also, kernel parameters of fuel supply system can be modified to check its stability and reliability.

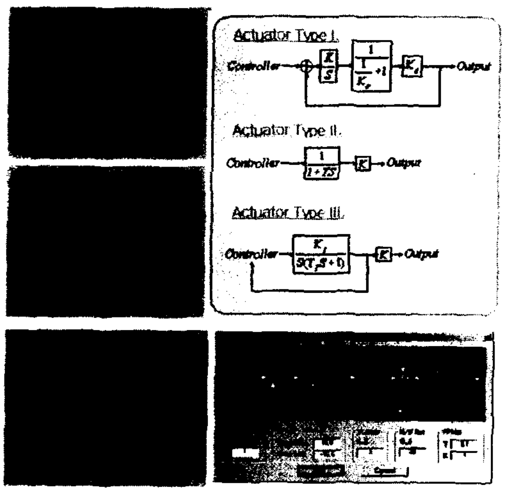

Fig. 7 Different Fuel Supply Systems in GT3GS

After the selection of fuel supply system, control scheme should be selected. The role of control is to keep engine control error within reasonable tolerance. Like a fuel supply system, engine control strategy is also diverse. Traditional control strategy like PID class is still popular but recent technical progress of embedded computer capability makes many challenges into modern control[7]. As a result, GT3GS provides three kinds of controller; PID (Fig. 8), state feedback (Fig. 9) and model predictive method (Fig. 10).

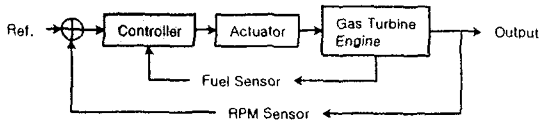

Fig. 8 PID Control

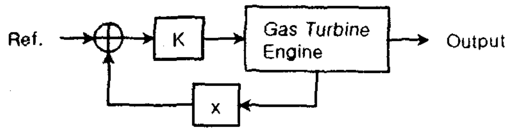

Fig. 9 State Feedback Control

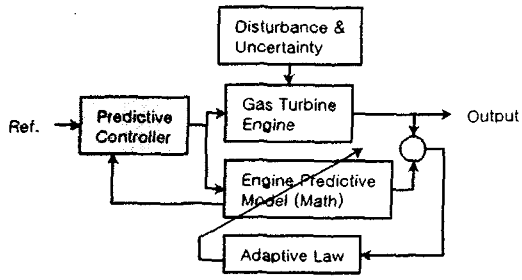

Fig. 10 Model Predictive Control

5. Various Outputs

Except calculations, the purpose of simulation is to provide easy way to understand and be applicable to real engine control system development. GT3GS has many graphical features that show 2/3D engine operational behaviors, 2D graphs, rotor vibrations, heat distribution on main components and numerical data table. Fig. 11 shows these special functions of GT3GS.

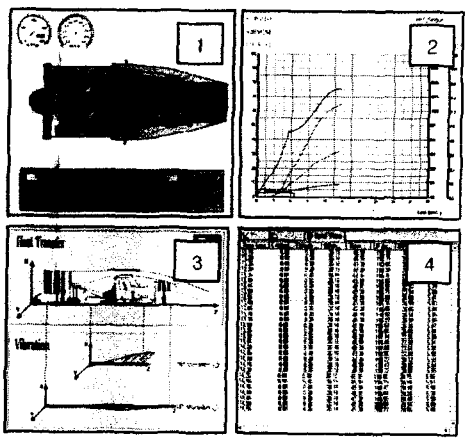

Fig. 11 Various Outputs of GT3GS

Visualization feature (upper left side at Fig. 11) shows the function of full or cross sectional an engine 3D drawing that is useful method to grasp engine inside pressure, temperature and airflow at each gas flow stages. Also, 3D engine configuration display, navigation into the inside engine and highlight function of a certain component are provided and they are a new concept simulation output presentation.

2D Graph Plot (upper right side at Fig. 11) is fundamental element of simulation S/W. GT3GS also supports graphs with amounts of over 50 parameters, different time axis to analyze inconformity between two variables and replay function after simulation done.

Analysis View (lower left side at Fig. 11) provides intuitive picture to show the temperature distribution on main components, rotor vibrations, and some warning and alarm functions.

Data Table (lower right side at Fig. 11) is numerical results of simulation providing essential functions like general OTS simulation S/W.

Special features mentioned here improve the reality of simulation with aid of engine sound effect.

6. Implementation and Simulation Results

Fig. 12 shows the S/W mainframe of GT3GS.

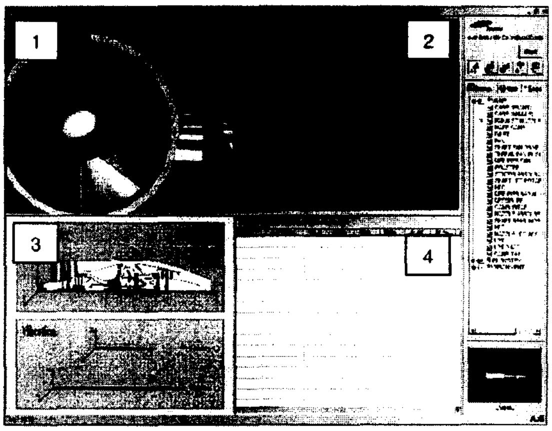

Fig. 12 GT3GS Mainframe

It is composed of many software modules as well as hardware resources to enable HILS (Hardware In the Loop Simulation). Most of modules are implemented by using COTS (Commercial Off The Shelf) product to guarantee development cost problem and maintenance issues[8]. Table 1 has summarized the type of modules implemented in GT3GS.

Module	Type
State Equation Matrix Generation	GSP Core
Engine Math Modeling	API Functions
Fuel Supply Systems Dynamics	DLL
Control Algorithms	DLL
Engine 2/3D Drawings	Multi Threaded
Vibration Analysis	Matlab DLLs
Heat Transfer Calculation	DLL
Structural Analysis	DLL
Engine Operation Routine	ASM/C/C++
Engine Protection Logic	C/C++
Compressor/Turbine Database	Specific Map
H/W Interface	NI Cards & LabView API

Table. 1 GT3GS Module Configuration

The purpose of this simulation can be divided into two groups. The first one is to predict whole process from engine performance analysis into control logic design/verification for control engineer. However, every simulation results cannot correspond with real quantitative values with 100% accuracy because of unpredictable and undefined effects in real environments. In addition, this fact is caused from nonlinearity of gas turbine engine itself and thermodynamic characteristics limit in the view of their operation. In spite of these weakness aspects, gas turbine engine simulation has been important issue for long time as good methods for operational pattern and control performance verification. Since GT3GS was designed for a specific engine configuration, it is useful tool to design control system and verify its validity.

The second group has the role of evaluation method after engine manufacturing. Gas turbine engine requires frequent performance improvement effort and optimization process for the best operation. For this end, cumulative test data are transferred into GT3GS and used for the accurate post development work, that is, optimization. In this section, the implementation issues and simulation results are focused on the above purposes.

Fig. 13 is a good example of how closely the simulation follows the real operation pattern.

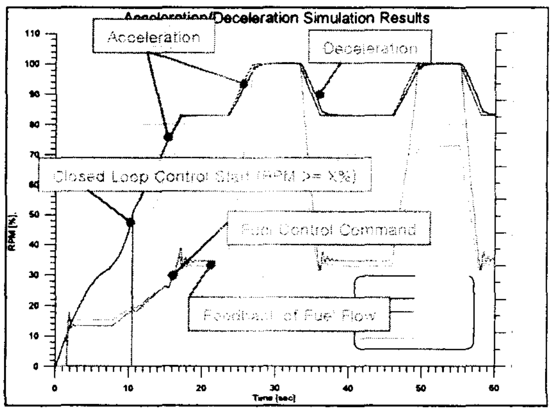

Fig. 13 Control Simulation (Start – Idle/Max RPM)

As a result, the following key evaluation items were checked and summarized in Table 2.

Evaluation Items	Results	Remarks
Operation Pattern Verification	OK	Fig. 13
Engine Protection Verification	OK	Fig. 14
Accel/Decel Pattern Verification	OK	But Improvement Required (Fig. 13)
Plant/Actuator Dynamics Effects	OK	Showed Different Control Responses (Fig. 15)
Different Transient/Steady State Control	OK	Fig. 16

Table. 2 Summary of Simulation Results

Fig. 14 shows one example of engine protection logic performance. Engine surge limit was predefined by cycle deck as well as test data and then applied to control logic. If engine operational line moves into surge point, control logic will reduce fuel flow to avoid engine stall and surge. Except this simple simulation, other complicated protection functions are included in the GT3GS to observe proper operation.
Fig. 15 shows the different responses produced by different fuel supply system. If the dynamic parameters of fuel supply system change, engine transient and steady state outputs vary according to their stability and dynamic characteristics.
Like fuel supply systems, control response changes depending on position of pole/zero, sampling rate and disturbance. Fig. 16 shows different responses of two different control logics.
Using this simulation functions, a control designer can verify and optimize his logic code before real engine test. This is very important process in the view of engine, facility and human protection.

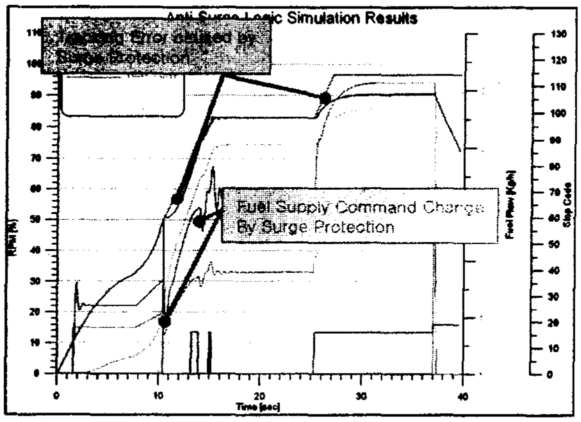

Fig. 14 Operation of Engine Protection

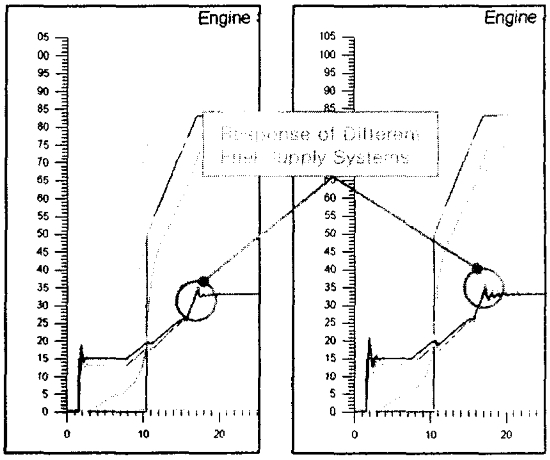

Fig. 15 Control Response of Different Fuel Supply Systems

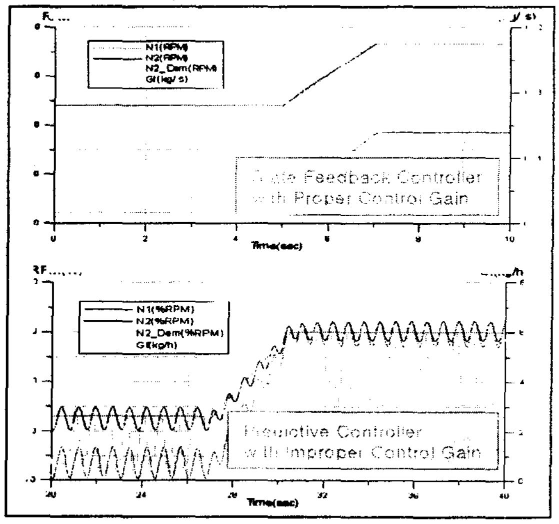

Fig. 16 Transient/Steady State Response with Different Control System

Conclusions

A new methodology for advanced gas turbine engine simulation was proposed and demonstrated on this paper. Since the previous engine simulation was performed within a limited component or part such as fan, compressor, combustor, turbine, etc., the exact engine performance analysis and control simulation cannot be done due to the lack of component interaction effects and whole engine control protection scheme. Therefore, we developed the new simulation S/W GT3GS to solve these problems. GT3GS includes state space engine modeling tools, fuel supply system math models, three kinds of popular control algorithms, vibration calculation for engine protection, heat distribution calculation on main components, structural analysis, whole engine control code with engine protection, and powerful 2/3D visualization for better user interface. All functions have high flexibility to deal with various engine operation environments. GT3GS is expected to contribute to economical efficiency of design and implementation of engine and control system because it enables high quality evaluation before engine manufacturing and test.

For better simulation, high level modern control application, various protection algorithm with sensor failure DIA (Detection, Isolation and Accommodation) scheme and S/W generality will be studied and upgraded continuously.

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