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Technical Brief

Hardware-in-the-Loop Simulation Study on the Fuel Control Strategy of a Gas Turbine Engine

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A hardware-in-the-loop simulation of a three-shaft gas turbine engine for ship propulsion was established. This system is composed of computers, actual hardware, measuring instruments, interfaces between actual hardware and computers, and a network for communication, as well as the relevant software, including mathematical models of the gas turbine engine. "Hardware-in-the-loop" and "volume inertia effects" are the two innovative features of this simulation system. In comparison to traditional methods for gas turbine simulation, the new simulation platform can be implemented in real time and also can test the physical hardware's performance through their integration with the mathematical simulation model. A fuel control strategy for a three-shaft gas turbine engine, which can meet the requirement to the acceleration time and not exceeding surge line, was developed using this platform.
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Introduction

"Hardware-in-the-loop simulation" is an effective tool to study the dynamic process of a gas turbine engine. However, many difficulties exist in establishing the simulation system [1]. First, effective communication between the actual hardware and the mathematical model need to be resolved. Second, the mathematical model calculation in the computer must occur in real time. In order to overcome these difficulties, we not only need to construct a hardware-in-the-loop simulation platform to effectively and quickly transfer data; but we also need to develop the mathematical model and corresponding algorithm of the simulation object—the gas turbine engine, and then to synchronize the calculation process with the real processes of the physical parts. A three-shaft gas turbine engine for ship propulsion is taken as an object to establish the hardware-in-the-loop simulation platform, with which the fuel control strategy is investigated.

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Simulation Model of Gas Turbine Engine

Establishing the dynamic characteristics of a gas turbine engine is an important task during its development. The thermal inertia, volume inertia, and rotor inertia are three important factors that affect the engine performance. For some engines (especially the aeroderived engine), the thermal and volume inertia are usually omitted in conventional models [2,3]. Only the rotor inertia is considered, making the equation very simple. In order to capture the coupling of the pressure and flow rate between components, the calculation must be iterative. Because the time for the iteration is not known a priori, the real-time simulation, which demands strict time constraints, must not contain the iterative calculation. Here we modeled the volume inertia [4,5], by adding one volume module between the components. Thus the inlet and outlet pressure of the components, such as the compressor and the turbine, can be determined; the flow rate change in the volume module yields the pressure change. The model reflects the real physical process, and the iteration calculation can be eliminated, which is vital to the hardware-in-the-loop simulation.

A three-shaft gas turbine is taken as the object, its modular simulation model is shown in Fig. 1, where LCP and HCP represent low-pressure and high-pressure compressor, respectively; HTB, LTB, and DTB represent high-pressure, low-pressure, and power turbine, respectively; HRD, LRD, and DRD represent high-pressure rotor, low-pressure rotor, and power rotor and gear box; CC is the combustion chamber; LD is the load to the propeller, and V are volume modules. Because of introducing the volume module, we can implement real-time simulation without iterative calculation. SR indicates the speed-regulator module; its input parameter is the rotor speed of the high-pressure rotor (HRD) and its output variable is the fuel flow rate. Here, we will use an actual speed regulator to study the control strategy of fuel flow rate when the gas turbine engine accelerates the ship.

Configuration of Simulation Platform

The system configuration of the hardware-in-the-loop simulation platform is shown in Fig. 2.

Section I of Fig. 2 implements the mathematical model of the gas turbine. The HP rotor speed, which is calculated from the model, is transferred to the control PC through a network switch. In Section II of Fig. 2, the control PC interfaces the actual hardware (speed regulator) and performs data acquisition. The frequency converter drives the motor and speed regulator according to the HP rotor-speed value received from Section I. When the regulator rotates, the rack bar will move with the change of HP rotor speed. The displacement of the rack bar is read into the Control PC via the position displacement sensor and converted to the appropriate fuel flow rate. The fuel flow rate is transmitted to Section I of the figure as a model input and forming a closed-loop simulation. Section III of Fig. 2 is for the dynamic display of system information; it receives and displays, via a network connection, the running status and results of Sections I and II.

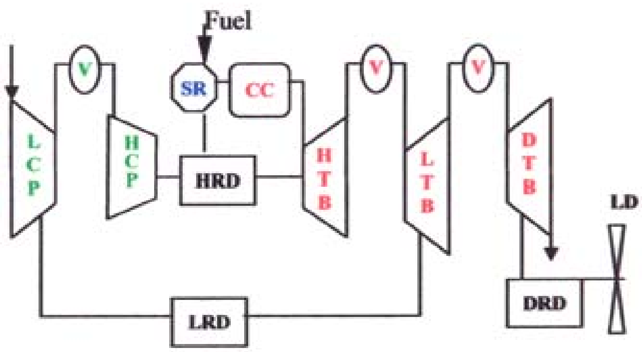

Fig. 1 Modular simulation model of three-shaft gas turbine

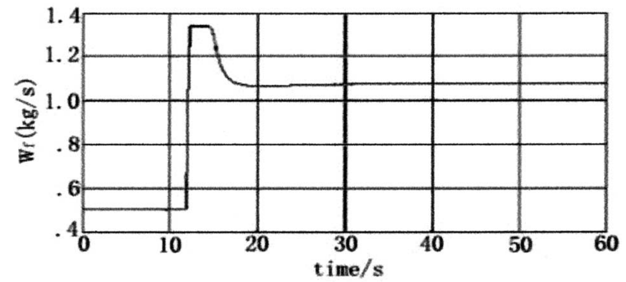

Fig. 3 Fuel flow rate based on the real displacement of rack bar

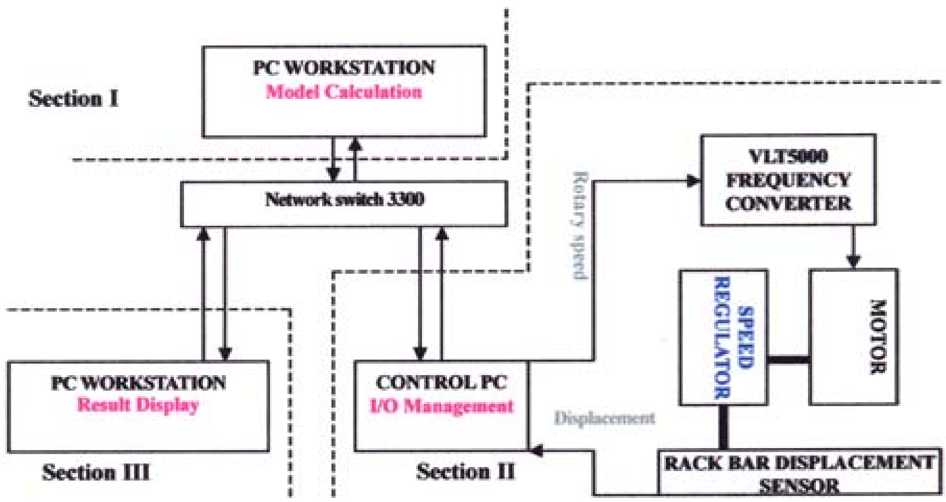

Fig. 2 System configuration of hardware-in-the-loop simulation platform

Simulation Results and Analysis

The speed regulator is considered as the controller for the gas turbine engine. The function of speed regulator handle is analogous to an engine throttle command. When the speed of the speed regulator is disturbed, the displacement of the rack bar will be changed. Because the position of the rack bar corresponds to the fuel flow rate into the combustor, a change in rack bar position will affect the fuel going into the combustion chamber. The fuel flow control must be designed to achieve the desired performance without exceeding operating limits, such as compressor surge lines or maximum rotor speed limits.

Compressor surge, particularly at high speed and pressure ratio, must be avoided under all circumstances. Surge is a condition of repeated flow breakdown so catastrophic that it propagates back through the compressor exit. In addition to causing very high cyclic stresses in the long low-pressure compressor blading, surge will almost certainly extinguish combustion.

In this paper, we will study a fuel flow control strategy to avoid compressor surge. After the engine has been running for 12 s, the handle is pushed from a lower-power to a higher-power setting. If the fuel flow is suddenly increased to the maximum, a compressor surge will occur. Figure 3 shows fuel flow versus time as determined by the displacement of the rack bar. When we adopt this fuel flow, the system will experience a compressor surge, as can be seen from the performance map of low-pressure compressor (Fig. 4, PR_LCP is the pressure ratio). The dashed line indicates

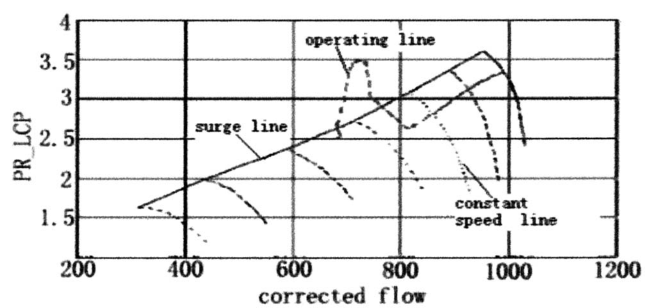

Fig. 4 Performance map of low-pressure compressor

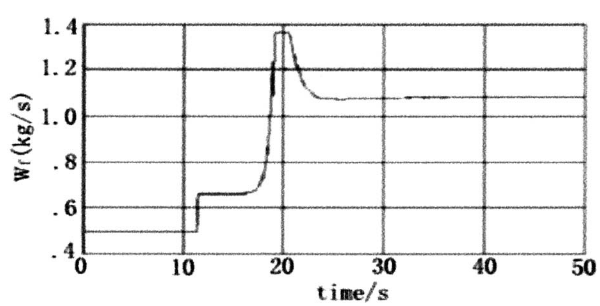

Fig. 5 Fuel flow rate based on the fuel control strategy

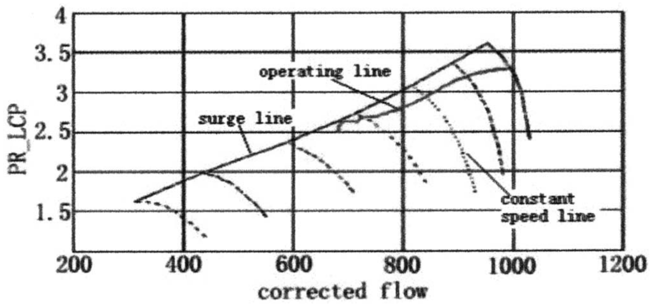

Fig. 6 Performance map of low-pressure compressor

the compressor operating line based on the fuel flow shown in Fig. 3. This line exceeds the surge line, which is not allowed. Thus, a control strategy must be developed that keeps the operating line below the surge line.

When the speed regulator handle is pushed, the rack bar will move suddenly. The sudden increase of fuel will change the system performance. Because of the inertia of the low-pressure compressor, the system tends to run immediately toward the surge line. In order to prevent the compressor working line from crossing the compressor surge line, the fuel flowing into the combustion chamber should be limited at the beginning of the acceleration. After many experimental tests on the gas turbine engine using this hardware-in-the-loop simulation platform, we obtained a successful fuel control strategy for the engine, which is shown in Fig. 5. The corresponding working line on the performance map is indicated in Fig. 6.

Because the fuel is limited at the beginning of the acceleration, the fuel input can be efficiently consumed and compressor surge is avoided. From the result of three rotor speeds associated with this control strategy, we can know that the acceleration process is accomplished in less than 10 s. This also meets the maneuverability requirement for marine shaft-power ships. Additionally, these rotor transients are similar to the optimum acceleration process, according to Refs. [4], [6], [7].

Besides controlling the fuel input, a control system requires, on many engines, other means of affecting the engine characteristics, such as turbine inlet temperature, smoke formation, etc. These additional requirements can also be studied using this hardware in the loop simulation technology.

Concluding Remarks

This paper reports a fuel control simulation implementation of hardware-in-the-loop system for gas turbine. The main conclusions of this work are

i. Based on the volume inertia and modular modeling ideas, the modular simulation models of a three-shaft gas turbine engine have been established. This method is more convenient than conventional modeling concepts because it eliminates the iterative calculation in the coupling of pressure and flow rate.
ii. The hardware-in-the-loop simulation platform is established using a modular framework with independent functions; it is flexible to add or delete a module. This platform implements the hardware-in-the-loop simulation, it is a useful tool for the simulation study of gas turbine engine dynamics.
iii. A fuel control strategy is determined for a three-shaft gas turbine engine system that experiences sudden acceleration. This demonstrates that we can study the transient characteristics of a gas turbine engine using this platform.

Acknowledgments

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