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Research on the Automatic Control Method of the Multi-Dimensional Gas Turbine Simulation

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ABSTRACT

For the retrofit design of energy systems with mature and unchanged core components but limited test conditions, accurate flow field information for new or modified components is a fast and effective evaluation method. This article employs the gas turbine as the research object, proposing an automatic control method composed of the Newton-Raphson algorithm and the volume method to predict the 0D/3D multi-dimensional simulation performance and complete the ground test verification. The key innovation point of this article is to propose a high-efficiency, accurate, and universal multi-fidelity automatic control method that can realize the fast and low consumption modified performance evaluation of energy machinery. And it is conducive to the design and development of advanced energy machinery in the future when the component characteristics are lacking.

Keywords: multi-dimensional, simulation, gas turbine, retrofit, automatic control

1. INTRODUCTION

With the rapid development of computer technology, numerical simulation is widely used in the design and performance analysis of energy machinery and systems [1-2]. For the retrofit design of energy systems with mature and unchanged core components but limited test conditions, the traditional performance analysis method is a zero-dimensional (0D) simulation based on (non-)linear models, which requires a certain amount of accurate test data [3-5]. However, compared to expensive and complex experiments, the flow field information for new and modified components that lack characteristic maps can be used to achieve fast and low-cost retrofit performance evaluation. Considering the one-dimensional and two-dimensional simulations that rely on a large number of empirical formulas, as well as the full three-dimensional (3D) simulations that require a large number of boundary parameters and computing resources [6-8], taking the gas turbine in the energy mechanical system as a representative research object, this study proposes a general, automatically controlled gas turbine 0D/component 3D multi-dimensional simulation method. And taking the single-shaft split-flow turbofan engine lacking the fan characteristic map as a numerical example, the multi-dimensional simulation model is used to satisfy the flow and power balance of the gas turbine, and the flow field information is used to complete the performance analysis and ground test data verification. The core innovation of this paper lies in that it provides a highly versatile, accurate, and fast multi-dimensional simulation automatic control method, which can realize fast and low-cost retrofit performance analysis of the energy machinery. Moreover, it facilitates the initial design and performance analysis of future advanced energy systems in the absence of component characterization.

The article firstly introduces the 0D/3D simulation model of the gas turbine in detail, then describes the automatic control method for gas turbine multi-dimensional simulation. After these, the ground test data verification is provided, and finally, our conclusions are proposed.

2. THE 0D/3D SIMULATION MODEL OF GAS TURBINE

This section provides the 0D/3D simulation model of the single-shaft split-flow turbofan engine, which is composed of the 0D gas turbine model and the 3D fan component model. In addition, the gas turbine configuration is shown in Fig. 1.

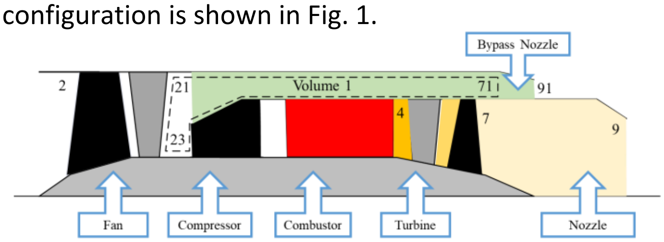

Fig. 1 Gas turbine configuration

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2.1 The 0D gas turbine model

This 0D gas turbine model is established by the Component-Based Method. It is a modeling method widely used by the commercial software GasTurb and authoritative literature [9-10]. In the modeling process, the modeling of the whole engine mainstream adopts the enthalpy entropy aerodynamic thermodynamic relationship based on the working medium, and the main key components are described in the form of characteristic maps. In addition, the gas turbine performance and aerodynamic thermodynamic parameters of each section are obtained by solving the common working equations of all engine components, And the equations include three flow balance equations of adjacent components and one rotor power balance equation, which could be solved through the Newton-Raphson (N-R) algorithm [10-11].

$$\boldsymbol{Y} = (y_1, y_2, y_3, y_4)^T \tag{1}$$

$$\boldsymbol{Z} = f(\boldsymbol{Y}) = (z_1, z_2, z_3, z_4)^T = 0 \tag{2}$$

$$\boldsymbol{Y}^{(b+1)} = \boldsymbol{Y}^{(b)} - \left(\boldsymbol{A}^{(b)}\right)^{-1} \boldsymbol{Z}^{(b)} \tag{3}$$

$$\boldsymbol{A} = \begin{bmatrix} \frac{\partial z_1}{\partial y_1} & \frac{\partial z_1}{\partial y_2} & \frac{\partial z_1}{\partial y_3} & \frac{\partial z_1}{\partial y_4} \\ \frac{\partial z_2}{\partial y_1} & \frac{\partial z_2}{\partial y_2} & \frac{\partial z_2}{\partial y_3} & \frac{\partial z_2}{\partial y_4} \\ \frac{\partial z_3}{\partial y_1} & \frac{\partial z_3}{\partial y_2} & \frac{\partial z_3}{\partial y_3} & \frac{\partial z_3}{\partial y_4} \\ \frac{\partial z_4}{\partial y_1} & \frac{\partial z_4}{\partial y_2} & \frac{\partial z_4}{\partial y_3} & \frac{\partial z_4}{\partial y_4} \end{bmatrix} \tag{4}$$

Eqs. (1)-(4) show the specific solving process, where y_i means the guesses in the algorithm, including the auxiliary values of the component characteristic maps and the turbine inlet total temperature, z_i means the residual of the balance equations, vector $\boldsymbol{Z}$ can be regarded as a function of vector $\boldsymbol{Y}$, b is the iteration times, $\boldsymbol{A}$ is a partial derivative matrix. When the residual vector $\boldsymbol{Z}$ meets the convergence precision, it is considered that the N-R algorithm converges and the 0D gas turbine simulation performance could be obtained. Moreover, Table 1 shows the design parameters of the 0D gas turbine model, where the design conditions are zero in height and speed.

Table 1 Design parameters of the 0D gas turbine model

Mass flow rate (kg/s)	Turbine inlet total temperature (K)	Nozzle exit area (m^2)	Bypass nozzle exit area (m^2)
22	1247	0.065	0.028

2.2 The 3D fan component model

The 3D fan component model is simulated from an in-house code, named MAP (Multi-block Aerodynamic Prediction code). The code has been developed since around 2000 and is suitable for multi-block structured meshes. The finite-volume method at the center of the grid element is used for spatial discretization. In addition, references [12-14] provide a detailed description and verification of the code.

Then, the fan is composed of 15 rotor blades and 17 stator blades. Fig. 2 shows the meridional geometry of the fan. Besides, the OH and HO topology is employed to generate the mesh for the fan model, whose 3D mesh is shown in Fig. 3. While the total number of grids for the fan model is 9.33×10^5. And the Spalart-Allmaras (S-A) turbulence model is used to complete the 3D steady-state simulation. Here, Table 2 presents the boundary conditions of the 3D fan model at the design point.

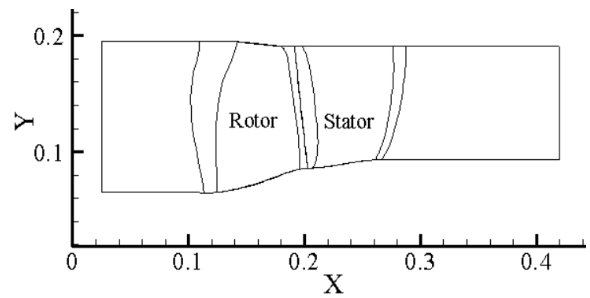

Fig. 2 Meridional geometry of the fan

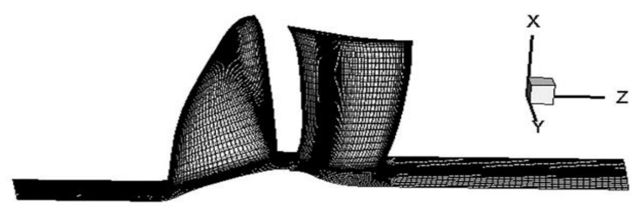

Fig. 3 3D mesh of the fan

Table 2 Boundary conditions of the 3D fan model at the design point

Rotor speed (rpm)	Inlet total temperature (K)	Inlet total pressure (Pa)	Outlet static pressure (Pa)
22000	288	101325	136350

3. AUTOMATIC CONTROL METHOD FOR MULTI-DIMENSIONAL PERFORMANCE SIMULATION OF GAS TURBINE

After the description of the 0D gas turbine model and the 3D fan component model, this section introduces the automatic control method of the gas turbine 0D/3D multi-dimensional simulation, which could automatically complete data transmission, model convergence, and performance simulation. Compared with the traditional multi-dimensional gas turbine simulation that relies on manual adjustment, considering the high computational time consumption of high-precision models, the automatic controller fully reflects the intelligent control concept, which greatly improves the simulation efficiency and reduces the workload of researchers.

Fig. 4 shows the Graphics User Interface of the automatic controller where the INPUT button means to input the design parameters to the 0D gas turbine model in the form of Excel. Then the DESIGN button means the calculation of 0D gas turbine model design point performance and key geometric parameters. Next, the STEADY button means the gas turbine steady-state multi-dimensional performance simulation. Finally, the following table indicates the output results of the steady-state multi-dimensional simulation after multi-dimensional model convergence.

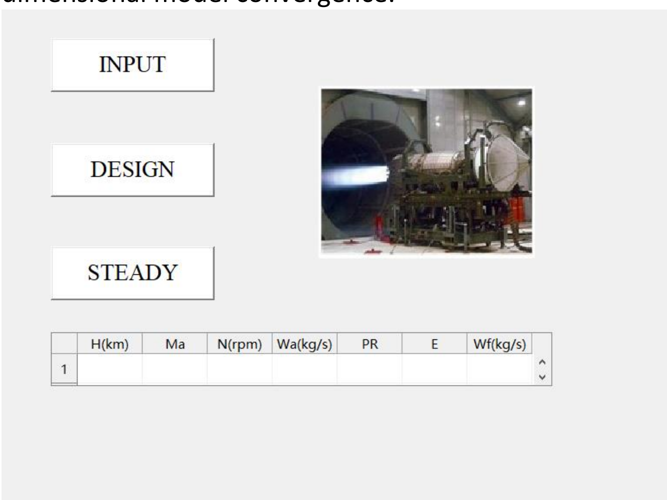

Fig. 4 Graphics User Interface of the automatic controller

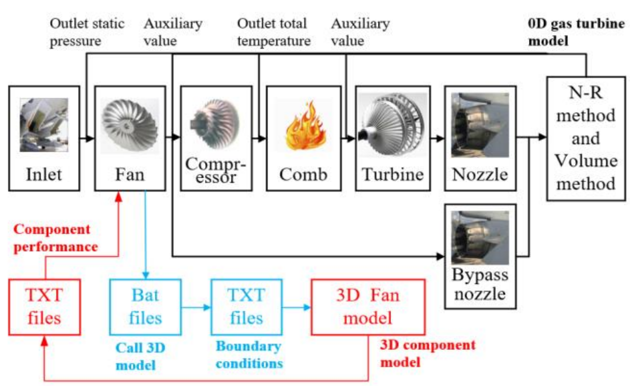

Fig. 5 Automatic control method flowchart of the gas turbine multi-dimensional simulation

The core technology of the automatic controller includes two key difficulties: the automatic control method of the variable-dimensional simulation process and the convergence of the operating point. From the automatic control method flowchart of the gas turbine multi-dimensional simulation in Fig. 5, it can be seen that the 3D fan model directly replaces the corresponding components in the 0D gas turbine model. Then, the automatic controller can freely call the 0D gas turbine model through the code and call the 3D component model using bat files. Apart from these, parameters including boundary conditions and component performance are transferred between 0D/3D models through TXT files where the internationally accepted method of mass flow weighted average and homogenization are performed [16]. In addition, the N-R algorithm and the volume method [15] are performed to realize the convergence of the 0D and 3D models. Here, the flow balance of the compressor, turbine, and nozzle, and the power balance of the rotor are satisfied by the N-R algorithm, as shown in Eqs. (1)-(4). While the flow balance of the fan, compressor, and bypass nozzle is realized by the volume method.

In the volume module behind the fan in Fig. 1, the mass accumulation effect is fully utilized. When there is no flow in the volume module and the static pressure at the fan outlet does not change, the flow balance is considered to be achieved. And the specific convergence process is realized by the volumetric dynamic equations (5)-(7). According to the continuity equation in the cavity, Eq. (5) could be derived.

$$(\sum_i W_{in,i} - \sum_j W_{out,j})dt = Vd\rho \;\Rightarrow\; \frac{d\rho}{dt} = \frac{(\sum_i W_{in,i} - \sum_j W_{out,j})}{V} \tag{5}$$

Where V means the cavity volume, t means the time, ρ means the density, subscript i and j are the serial numbers of the cavity inlet and outlet flow channels respectively, $\sum_i W_{in,i}$ means the sum of the cavity inlet gas flow, $\sum_j W_{out,j}$ means the sum of the cavity outlet gas flow. Because the component efficiency has considered the loss, the equation of the state of the gas in the cavity could be shown in Eq. (6).

$$\frac{dP_s}{P_s dt} = \frac{kd\rho}{\rho dt} \Rightarrow \frac{dP_s}{dt} = \frac{P_s k d\rho}{\rho dt} = kRT_s \frac{d\rho}{dt} \tag{6}$$

Where P_s means the static pressure, k is the gas adiabatic index, and R is the gas constant. Then, in volume module 1, Eq. (7) could be derived by substituting Eq. (5) into Eq. (6).

$$\frac{\Delta P_s}{\Delta t} = kRT_s \frac{(\sum_i W_{in,i} - \sum_j W_{out,j})}{V}$$
$$\Rightarrow P_{s23}^{(a+1)} = P_{s23}^{(a)} + \Delta t k R T_{s23}^{(a)} \frac{(Wa_2^{(a)} - Wa_{71}^{(a)} - Wa_{23}^{(a)})}{V_1} \tag{7}$$

Where a means the iteration number, P_{s23} and T_{s23} are the fan outlet static pressure and static temperature, Wa_2, Wa_{71}, and Wa_{23} are the airflow of the fan, bypass nozzle, and compressor, V_1 is the volume of the cavity module 1. And the airflow, static temperature, and static pressure in the a^{th} iteration are used to calculate P_{s23} in the $(a+1)^{th}$ iteration. When the relative error of the inlet and outlet flow of the volume module is less than 0.05%, we believe that there is no flow in the volume module, the static pressure at the fan outlet does not change, and the flow balance is satisfied. So far, the automatic convergence of the gas turbine 0D/3D multi-dimensional simulation model is realized.

Taking the 100% rotor speed operating point as an example, Fig. 6 presents the automatic convergence process of the gas turbine multi-dimensional simulation model. After the relative error satisfies the convergence conditions, Fig. 7 shows the relative Mach number distribution of the fan at a 50% span.

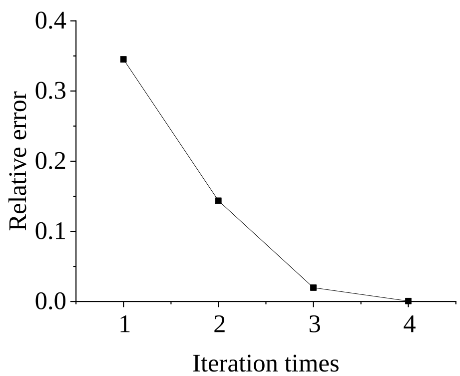

Fig. 6 Convergence process of the multi-dimensional simulation model

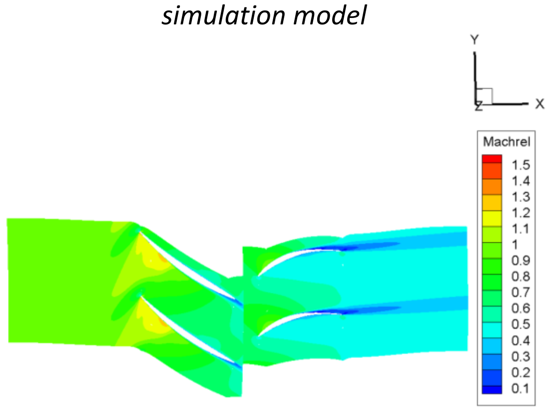

Fig. 7 Relative Mach number distribution of the fan at 50% span at 100% rotor speed operating point

4. PERFORMANCE ANALYSIS AND GROUND TEST VERIFICATION

After the description of the gas turbine multi-dimensional simulation that can realize automatic control, taking three operating points (rotor speed=80%-100%) as numerical examples, this section provides the performance prediction and the ground test verification of the gas-turbine multi-dimensional simulation as shown in Fig. 8-11. Where N means the rotor speed, Wa_2 means the fan inlet air flow, π_{fan} means the fan pressure ratio, W_f means the fuel flow rate, and EGT means the exhaust gas temperature. In addition, Fig. 8 shows that without the fan characteristic map, the initial prediction of the 0D gas turbine model is far from the test data, which justifies the necessity of variable-dimensional simulation. Apart from this, from these figures, it can be seen that the relative error of most performance parameters of the gas turbine multi-fidelity simulation model is less than 1.5%. Thus, the gas turbine multi-fidelity simulation performance agrees well with the ground test results, which proves the accuracy of the automatic control algorithm for multi-dimensional simulation. Finally, the multi-dimensional automatic control method could effectively and accurately predict the gas turbine performance without new or modified component characteristics, and realize the automatic invocation of models and data transfer.

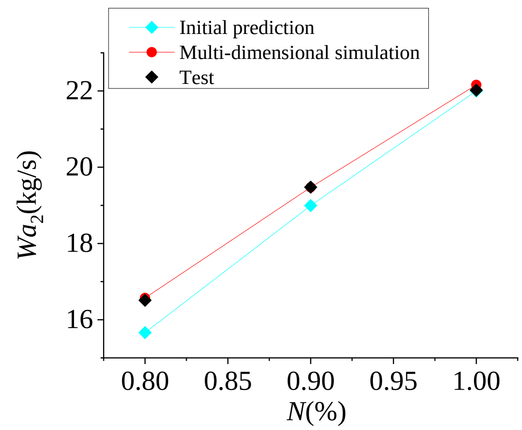

Fig. 8 Wa_2 versus N

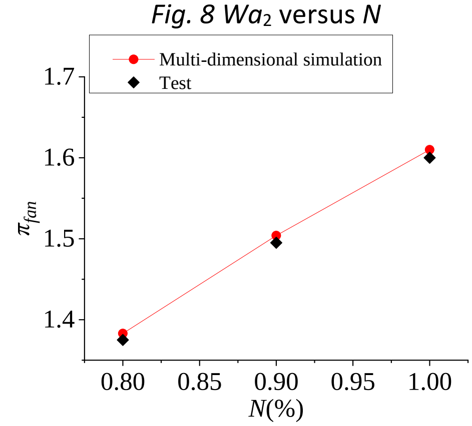

Fig. 9 π_{fan} versus N

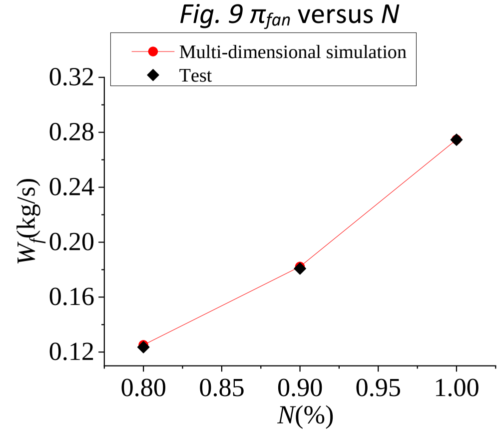

Fig. 10 W_f versus N

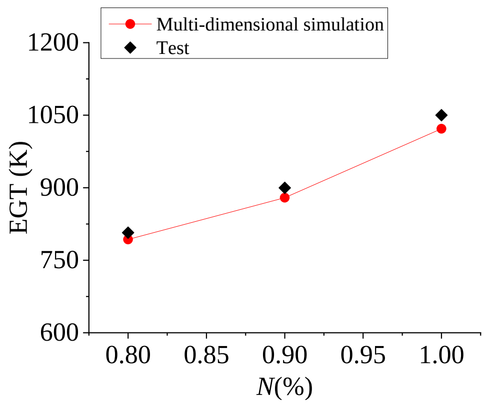

Fig. 11 EGT versus *N*

5. CONCLUSIONS

A multi-dimensional simulation automatic control method is developed to evaluate the retrofit performance of energy systems. For the examples of the gas turbine, the Newton-Rapson algorithm and the volume method are performed to realize the automatic convergence of the multi-dimensional simulation model, and ground test data is used to verify the accuracy of the newly proposed automatic control method. Therefore, the main conclusion could be drawn. The multi-dimensional simulation automatic control method is composed of the 0D/3D simulation model and the automatic control method. Across the numerical examples of the gas turbine, the relative error of most performance parameters is less than 1.5% and they agree well with the ground test data. The core contribution of this paper is that it provides a fast, accurate, and general multi-fidelity automatic control method that can complete the low-cost and efficient modified performance analysis of energy machinery. Moreover, it is conducive to the initial design of the future advanced energy machinery in the absence of component characteristics.

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