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Automated Virtual Testing Rig Incorporating Multi-level Models of Gas Turbine Engines

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Abstract

This article describes the multi-level approach to developing the virtual testing rig of gas turbine engines and power plants. The described virtual rig is developed on the basis of computer-aided system of thermogasdynamic calculations and analysis ASTRA, developed at Samara National Research University. Existing testing rig is widely used in educational process to supply the students' research activities with the information on engine operation in a variety of ambient and flight conditions during transients. An approach to upgrading the virtual testing rig is proposed. The described modifications would provide the capabilities to solve more complex research tasks, including investigation of influence of geometry of engine elements on the engine characteristics, multidisciplinary investigations, identification of engine models using the results of experimental investigations and identification of sources of engine deficiencies during the development phase of engine designing.

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1. Introduction

Experimental investigations accompany most of the stages of engine life cycle, and especially the designing stage. Starting with research experiments to determine material properties and performance maps of turbomachinery and including a vast list of testing types, the experiments support the development process of every engine.

Actual tests provide the irreplaceable source of information (especially speaking about the delivery trials of engines after the corrective maintenance), but require a huge amount of resources, including timing, money and complex equipment.

These expenses may be decreased by using virtual testing [1], which mainly differ from the mathematical models of engine designing in that they simulate transient processes.

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2. Description of existing virtual rig

During the past decade, the computer-aided system of thermogasdynamic calculations and analysis was developed at the Department of Aircraft Engine Theory of Samara National Research University [2, 3]. This system covers the following tasks of a conceptual design stage of gas turbine engines and power plants:

- conditional multi-criteria optimization of the working process parameters of gas turbine engine (including efficiency criteria of engine as an element of aircraft system);
- simulation of aircraft flight (mission simulation) to provide more precise values of aircraft efficiency criteria;
- calculation of engine operational characteristics using the performance maps of engine elements;
- optimization of the working process parameters of engine family, developed on the basis of a specified unified engine core (ASTRA uses the Nelder-Mead (simplex) method of optimization and directly calculates the goal function on the basis of efficiency criteria values) [4];
- optimization of the working process parameters of unified engine core;
- estimation of modernization capabilities of a specified engine [5];
- optimization of the air-gas channel and principal parameters of engine turbomachines;
- identification of engine models using the results of experimental investigations;
- simulation study of the engine (virtual testing rig) [6].

Numerical integration operation routine is used for the calculation of parameter values and their variation during engine operation process. This routine enables to control and modify parameters at real time calculation process.

The power balance of turbine and compressor is not satisfied during the transients. And it is the feature of these operational modes. The difference between the turbine and compressor power determines the kinetic energy increment of the rotating mass of the rotor:

$$N_T \cdot \eta_m - N_K = \frac{dE}{dt},$$

where

$E = I \cdot \omega^2/2$ – kinetic energy of the rotating mass of the rotor; I – rotor polar moment of inertia; $\omega = \pi n/30$ – angular velocity.

Values of power produced by the turbine and consumed by the compressor at the specified value of fuel flow-rate during the calculations of transient modes of operation are evaluated on the basis of combination of working process parameters and angular velocity of the rotor at the given moment of time.

These values, in turn, determine the value of angular acceleration. The angular velocity of the rotor is evaluated by numerical integration of rotor motion equation. Other parameters are evaluated using the quasi-stationary concept (using the same equations as for the stationary modes of operation). Thus, the transient thermogas-dynamic model includes the same modules as the steady-state thermogasdynamic model except for the modified module of the engine transmission.

Virtual testing rig of a gas turbine engine developed on the basis of ASTRA system is widely used during the educational process. Virtual tests not only require much less recourses, but also provide better visualization and information completeness. This approach provides capabilities to implement more research elements during the laboratory works. The principal elements of the virtual testing rig are: measurement imitation subsystem, design of experiment subsystem, mathematical model identification subsystem, engine simulation subsystem (ASTRA), information subsystem, documentation subsystem and testing visualization subsystem (Figure 1). The engine mathematical model in the basis of the virtual testing rig was verified by means of NK-56 (JSC "Kuznetsov") and D30-KU (Perm Engine Company OJSC) data in PhD dissertation by A.Yu.Tkachenko. The derivations of the obtained values from the experimental results were within 3%. The interface of the virtual testing rig is shown in Figure 2. Using the virtual testing rig, the students are able to solve the following tasks:

- investigation of impact of testing inaccuracies on the engine design, development and testing process;
- development of a testing rig structure and selection of engine sensors (see Figure 3);
- comparative analysis of various engine control programs and identification of necessity to add control elements;
- analysis of impact of various factors on the engine acceleration capabilities;
- investigation of short-duration peaks of ambient temperature on the engine operation;

• development of testing program including the transients intensity influence.

3. Multi-level models of gas turbine engines

The virtual testing rig has a principal shortcoming of using one-level mathematical models (1st level models). These models have high processing speed, but provide limited information (on the basis of actual test results - performance maps of engine elements) only. Thus, the task of improving the research capabilities of the above-mentioned testing rig is of high importance.

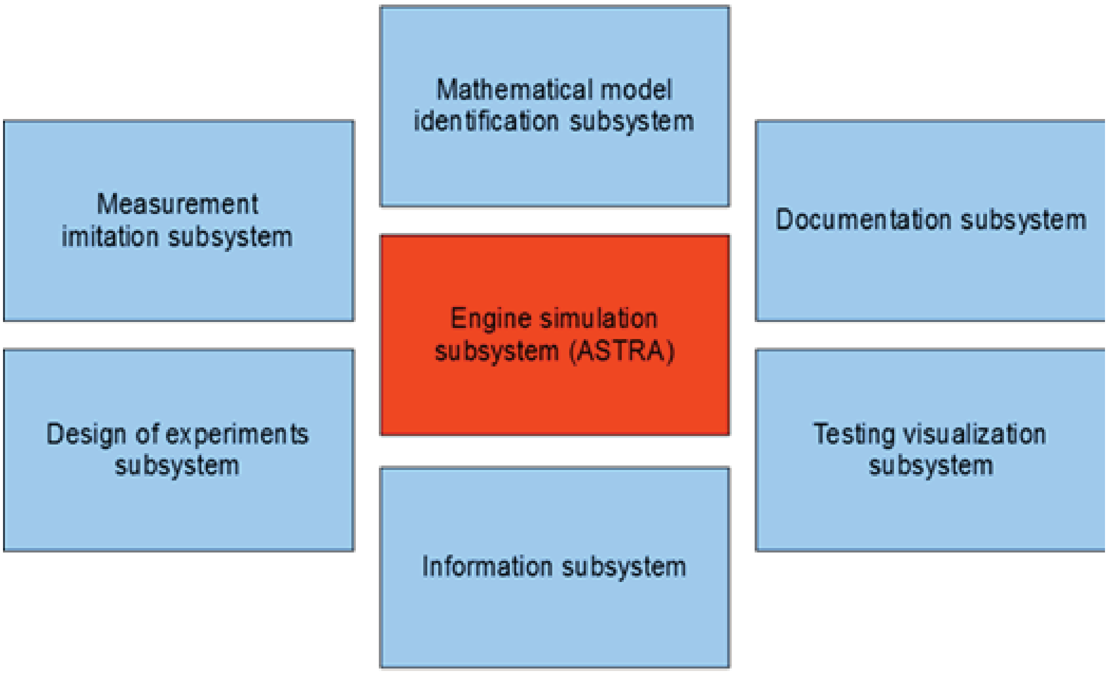

Figure 1: Virtual testing rig structure.

The 2nd level models provide these functions, but require much more computational resources.

These models are difficult to use in modelling the real-time processes. And as for the 3D problem statement for modelling the whole engine, they require such a huge amount of computational power that could not be used at all (especially for the complex engine architectures).

Three-level classification is used in this article: 0-level models are non-dimensional (these models are essentially tables or approximations), 1st level models are zero-dimensional (these models are sets of algebraic equations; they simulate a process of some element of the engine, not simulating the processes with regard to any points/control volumes etc.), 2nd level models may be 1-3 dimensional (these models

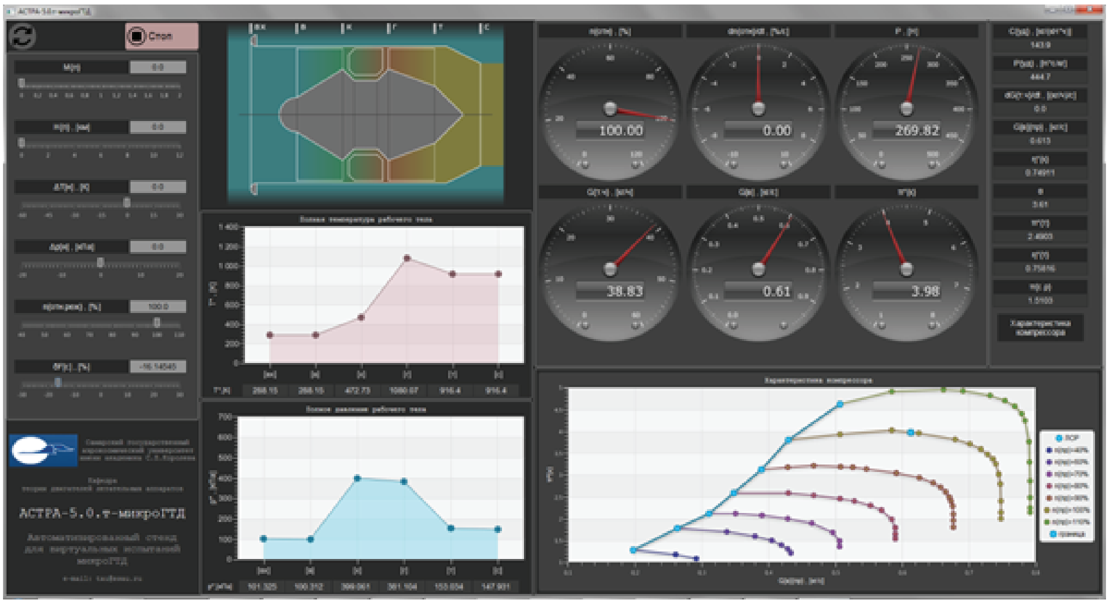

Figure 2: Interface of the virtual testing rig.

are sets of partial derivative equations; they simulate the process of the engine element as an integral characteristic of a finite volume processes).

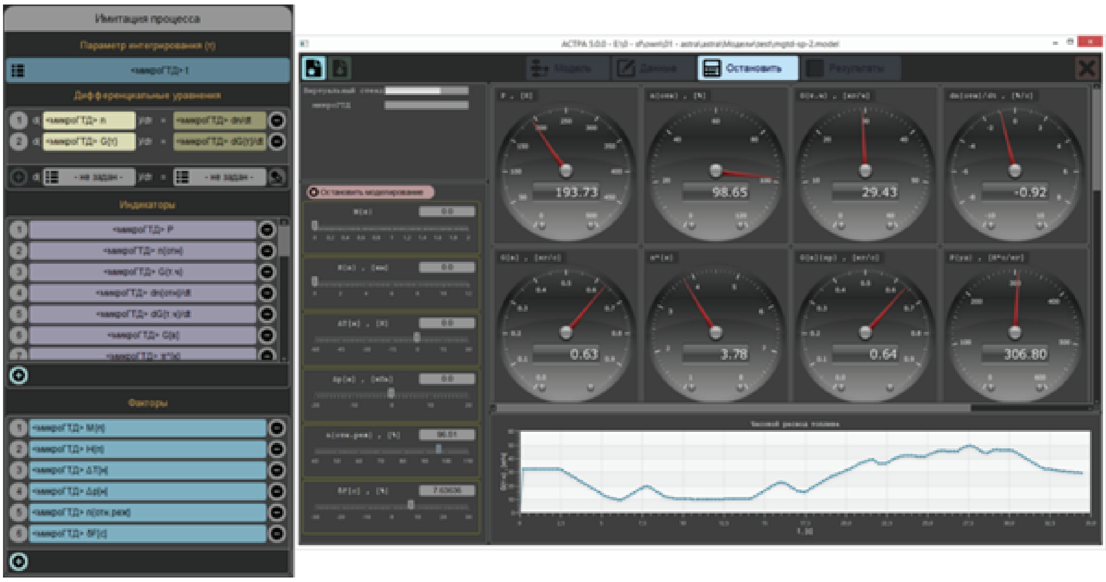

Figure 3: Selection of testing rig structure and engine sensors.

The principal idea for upgrading the virtual testing rig described above is to implement the multi-level models that operate in agreement (actually, adding the 2-level models to an existing testing rig):

1. initially, 2-level models are used to create 0-level models using a quasi-stationary approach;

2. then, these models are supplemented by the 1-level transient models to solve the transient tasks in a real-time;

The 0/1-level models can be supplemented by the 2-level models using one of the following approaches:

1. a single 1-level model of engine element is substituted by the 2-level model, and the remaining models are essentially providing the boundary conditions for this 2-level model [7, 8];

2. all the elements are modeled with 2-level models and only some attributes of an engine are modeled using the 1-level models, decreasing for example, the required computational power for modeling the transients (see Figure 4) [9].

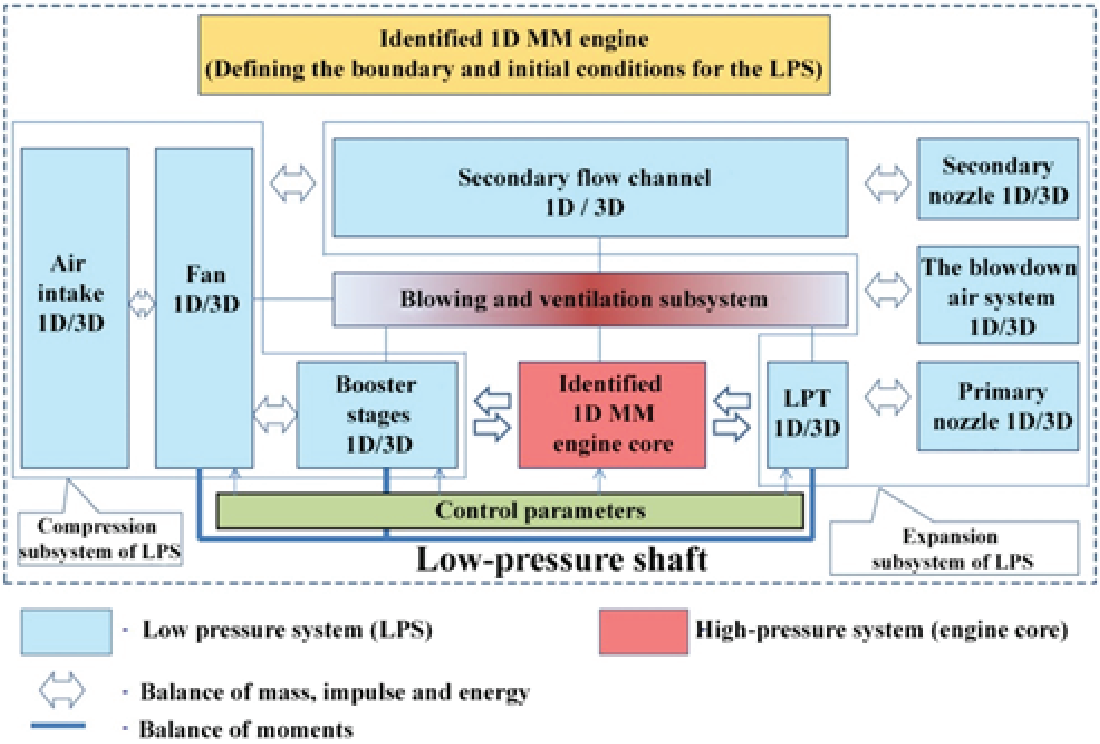

Figure 4: Example of multi-level model of engine (CIAM).

Combination of the models of various levels provide higher amounts of information only for the required elements, while not increasing excessively the computational resources to provide more accurate results.

4. Conclusions

The upgraded multi-level virtual testing rig, developed on the basis of ASTRA system provide the capabilities to solve more complex research tasks, including the following:

- investigation of the influence of geometry of engine elements on the engine characteristics;
- multidisciplinary investigations (strength-gas dynamics-heat transfer-etc.);
- identification of engine models using the results of experimental investigations;
- identification of sources of engine deficiencies during the development phase of engine designing.

The virtual testing rig can also be used to simulate the flight/ambient conditions, which are diifficult to provide during the actual testing. This increases the capabilities of modeling the complex unsteady processes.

Acknowledgments

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