Comparative Analysis of the Computer-Aided Systems of Gas Turbine Engine Designing

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***Abstract*—The paper reviews the present computer-aided systems (CAE-systems) of conceptual designing and engineering analysis of the gas turbine engines (GTE) and power-plants (GTPP). Each of the examined system is briefly described and the comparative analysis of the following systems: ASTRA, DVIGwT, EngineSim, GasTurb, GSP and Uni_TTF is described. Trends of the development of CAE-systems of gas turbine engines are also indicated.**

***Index Terms*—CAE-system, design, mathematical model, computer model, functionality, gas turbine engine**

I. Introduction

The computer-aided systems that are widely used today for the conceptual design stage of the gas turbine engines and gas turbine power-plants may be divided in two groups. The first one includes the CAE systems developed on the basis of universal software tools, such as Dymola that is developed using the Modelica programming language [1]-[3], Simulink [3]-[7] and TRANSEO [8] that are integrated into the MATLAB environment, PROOSIS that is developed using the EcosimPro [9] and others. The second one includes the specialized software, such as DCOGEN [10], DVIGwT [11], [12], EngineSim [13], GasTurb [6], [7], [14], [15], Graphical Engine Cycle Analysis Tool (GECAT) [16], Gas turbine Simulation Program (GSP) [17], Numerical Propulsion System Simulation (NPSS) [3], [18], TERA [19], Uni_TTF [20], WebEngine [21], ASTRA [22]-[24] and others. The second group includes the software, developed at the engine design departments (e.g. Uni_TTF) which are developed for the scope of this department's problems. The underlying mathematical models of these systems usually consider the features of the engines developed at these design departments and their methodological and experimental experience. It should be mentioned that the development of the all-purpose software tool for the tasks of conceptual design stages of gas turbine engines is a difficult task to solve [25].

II. Comparative Analysis of the CAE Systems of Gas Turbine Engines

This article addresses mostly the specialized software systems based on the mathematical models. The systems were examined and compared in two main aspects:

- The level of implemented mathematical models and the functionality.
- Realization as a computer program (usability etc.).

Table I shows the results of analysis of the most popular computer-aided systems.

A more detailed description of the systems' features is presented below.

A. DVIGwT

Fig. 1 shows the graphical interface of the DVIGwT CAE system. This system was developed at the Ufa State Aviation Technical University (UGATU). The program runs on Microsoft Windows 95/98/2000/Me/XP and Windows NT.

This CAE-system has a simple intuitive interface being based on component technology to build up a model of a gas turbine engine.

The results may be output using various types of representation:

- The results may be transferred to a file or a database in a different formats (full information, standard format, used-defined format).
- Representation of data as a table (user may define the format).
- A graphical representation of the calculation results (Fig. 2) as the interdependencies of the parameters specified by the user, with the capability to plot the results from the other arrays of data. Additional parameters may be calculated using the results of engine simulation to be used as both argument or a function during the plotting.
- Graphical representation of the components' characteristics.

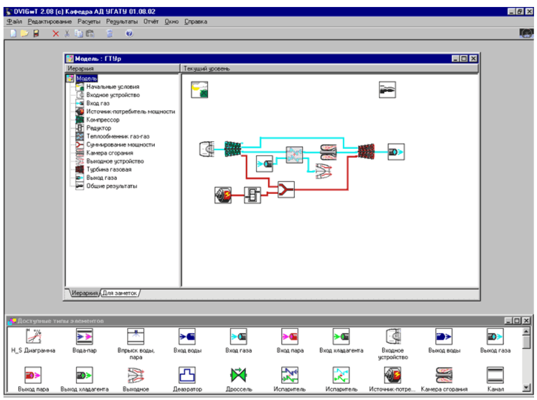

Figure 1. Graphical interface of DVIGwT.

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TABLE I. COMPARATIVE ANALYSIS OF THE COMPUTER-AIDED SYSTEMS

Feature	CAE system					
	DVIGwT, Ufa State Aviation Technical University	EngineSim v.1.8a, NASA Glenn Research Center	GasTurb v.12, J.Kurzke, MTU	GSP v.11, NLR	Uni_TTF v.5.22, Experimental Design Bureau named after A. Lyulka	ASTRA, Samara National Research University
1	2	3	4	5	6	7
The principle of building up the engine model	Composing from the elements	Predefined set of models	Predefined set of models	Composing from the elements	Universal model	Composing from the elements + predefined set of models
Scope of use	Aircraft GTEs, GTPPs, hybrid GTEs, combined cycle GTPPs, heat pump systems	Aircraft GTEs	Aircraft GTEs, GTPPs	Aircraft GTEs, GTPPs	Aircraft GTEs	Aircraft GTEs, GTPPs
Types of fuel	Any fuel that may be described using the $C_aH_bO_c$ formula	Kerosene, hydrogen, arbitrary composition	Kerosene, diesel fuel, natural gas, hydrogen, arbitrary composition	Any fuel that may be described using the $C_aH_bO_cN_dAr_e$ formula	Any fuel that may be described using the $C_aH_bO_c$ formula	Any fuel that may be described using the $C_aH_bO_cS_dN_eNe_fAr_g$ formula
1	2	3	4	5	6	7
Representation of elements' characteristics	Approximation of the characteristics tables with scaling capability	–	Standard and arbitrary characteristics with scaling capability	Standard and arbitrary characteristics with scaling capability	Approximation of the characteristics tables with scaling capability	Standard and arbitrary characteristics with scaling capability
Engine performance calculation	Throttle, speed, altitude, climatic characteristics with any type of engine control program	Throttle, speed, altitude, climatic characteristics	Throttle, speed, altitude, climatic, load characteristics	Throttle, speed, altitude, climatic characteristics	Throttle, speed, altitude, climatic, load characteristics with any type of engine control program	Throttle, speed, altitude, climatic, load characteristics
Air-gas channel designing and visualization, mass and overall dimensions estimation	no (only in some versions)	yes	yes	no	no	yes (ASTRA-TEOS subsystem)
Strength analysis of the main elements	no (for compressor only)	no	yes	no	no	yes (ASTRA-TEOS subsystem)
Emission evaluation	no (only in some versions)	no	yes	yes	no	no
Transient analysis	yes	no	yes	yes	yes	yes
Heat leakage and simulation of clearances deviation	no (for compressor only)	no	yes	heat leakage only	heat leakage only	yes
Takes the rotor inertia into the account	yes	no	yes	yes	yes	yes
Takes the air capacity into the account	yes	no	no	yes	yes	yes
Water and steam injection	yes	no	yes	yes, but in combustion chamber only	no	yes
Thermal dissociation	yes (only in some versions)	–	yes	yes	–	no
Different characteristics for the primary and secondary flow of the fan	yes	–	yes	yes	yes	yes
Takes the Reynolds number into the account	yes	–	yes	yes	yes	yes
Multistage turbines with cooling	yes	no	no	yes	no	yes
Air bleeding from the intermediate stages of compressor	yes	no	yes	yes	yes	yes
Calculation of engine performance as a subsystem of an aircraft (matching the	no	no	yes	yes	no	yes

characteristics of engine with characteristics of aircraft)						
Optimization of the working process parameters	yes	no	yes	–	no (coupled with other system only)	yes
Flight simulation	no	no	yes	yes	no	yes
Multi-objective optimization of the engine control program	no	no	no	–	–	yes
Real-time simulation modeling (virtual testing)	no	no	yes	no	yes	yes

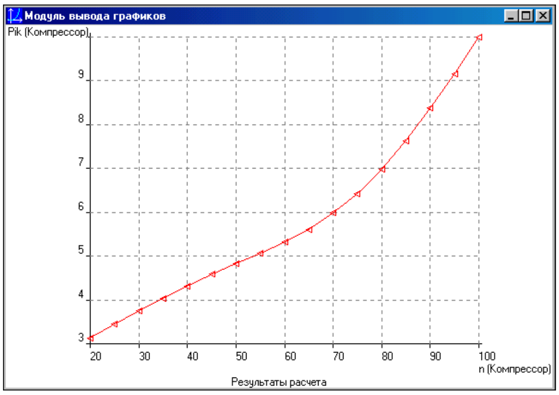

Figure 2. Graphical representation of the results.

DVIGwT system may be used both for solving the complex engineering problems and during the learning process of students (currently used at Ufa State Aviation Technical University).

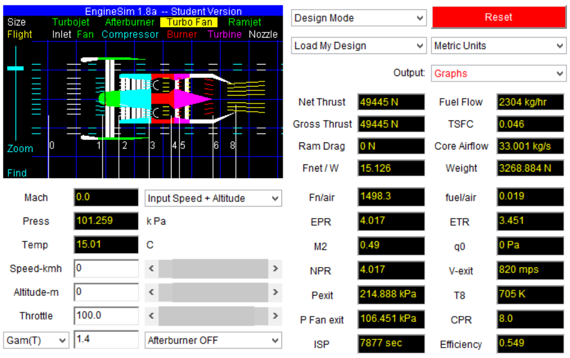

Figure 3. Graphical interface of EngineSim v.1.8a.

B. *EngineSim v.1.8a*

This CAE system (Fig. 3) is developed at the NASA Glenn Research Center. Interactive program is executed as an applet that makes it cross-platform, but requires a browser and JavaVirtualMachine runtime environment.

This program may be considered as the most simple one between the other examined in this article, as it has the most simple and intuitive interface and the functional capabilities of EngineSim are also scanty.

There are only two modes of operation:

- DesignMode (flight conditions, engine dimensions and the parameters of engine components may be changed).
- TunnelTestMode (only the flight conditions and engine throttling may be changed, but the engine layout remains the same).

Resulting information may be represented in the following ways:

- Graphical output, providing the diagrams of temperature and pressure corresponding to the characteristic sections of the engine, the temperature-entropy and pressure-volume diagrams.
- Output of the engine parameters and its elements' parameters.

An interesting feature of this program is a warning message reporting that the temperature in the air-gas channel of the engine has exceeded the temperature that the material can withstand. This limit is also displayed on the chart (Fig. 4).

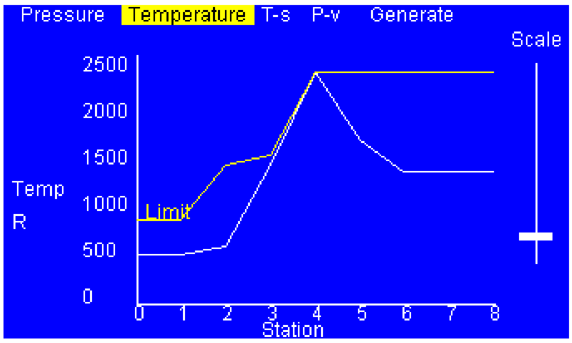

Figure 4. Plot of stagnation temperature at the characteristic sections of engine.

The program implements a limited set of engines: single-shaft turbojet, turbojet with afterburner, turbofan and ramjet. The predefined set of models includes such engines as J85, F100, CF6 and others.

Thus, EngineSim may be used by beginners, such as students, to examine the impact of various factors upon the engine performance.

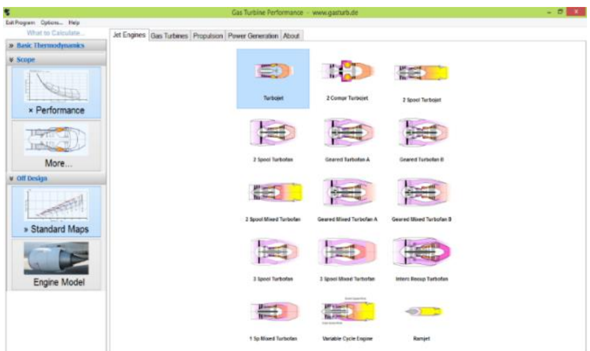

Figure 5. Graphical interface of GasTurb v.12.

C. GasTurb v.12

This computer-aided system was developed by Joachim Kurzke (MTU) and runs under the Microsoft Windows XP with SP2, Vista и Windows 7.

This system has rather intuitive but a bit complex interface (Fig. 5), so it is more suitable for more experienced users. The system includes predefined set of 15 models of gas turbine engines and 12 models of gas turbine power-plants. The use of predefined models makes the system less universal, but their number and diversity would be enough for most of the users.

As may be seen from the Table I, the main advantages of this system are the visual representation of engine air-gas channel designing (Fig. 6), emission indices estimation, integrated elements of strength analysis, engine weight and dimensions estimation, flight simulation and real-time simulation modeling (virtual testing). GasTurb also provides the capability to optimize the working process parameters of the GTE using the efficiency criteria of aircraft as the higher level system. These features turn GasTurb into the universal tool for solving the multilevel and multidisciplinary tasks of the conceptual design stage of gas turbine engines and power-plants.

According to the developers, the main advantages of GasTurb over the similar software are the user-friendly interface and the quality of graphical output (Fig. 7) [26].

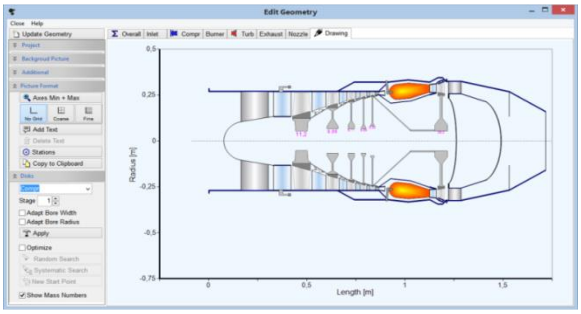

Figure 6. Engine geometry editor.

In addition to the standard elements' characteristics provides the capability to import the user-defined characteristics, edit them and scale using a user interface (Fig. 8). The results and initial data may be transferred to MS Excel for further processing.

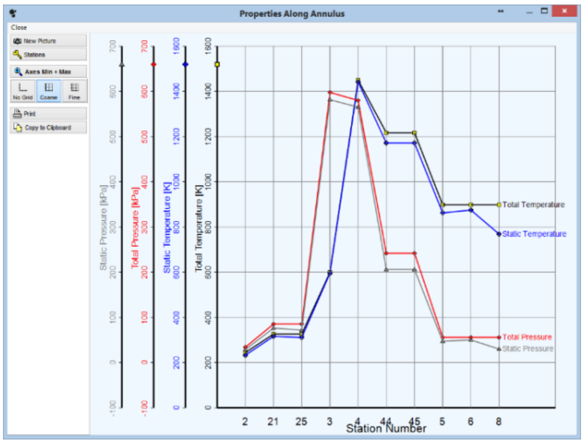

Figure 7. Output in a graphical form.

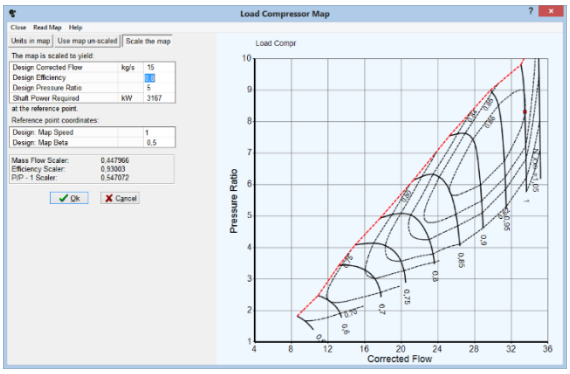

Figure 8. Compressor characteristic scaling.

GasTurb may be used for both learning process and for solving the complex engineering problems.

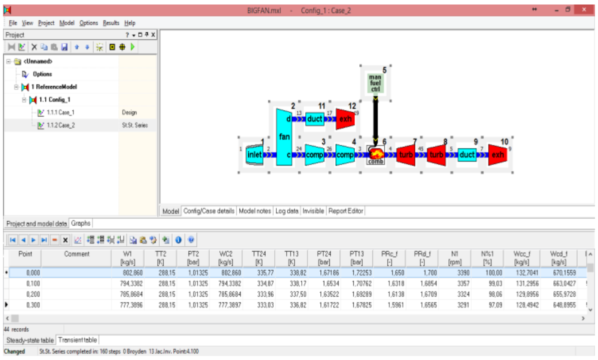

Figure 9. Graphical interface of GSP.

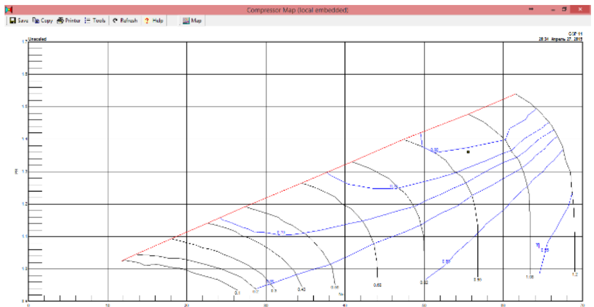

Figure 10. Graphical representation of compressor characteristic.

D. GSP v.11

This computer-aided system was developed at the National Aerospace Laboratory (NLR). It runs under MS Windows Vista, Windows 7 and Windows 8.

The system has a simple intuitive interface (Fig. 9). All modules are divided into categories, so one can quickly select the one that fits the task to be solved. Each module contains all the necessary parameters and settings, and this feature greatly simplifies the work with the system. According to the developers, the interface of GSP allows new users to easily perform a "quick start" of analysis tasks without having to know all of the advanced features.

GSP provides capability to plot the graphical representation of elements' characteristics (Fig. 10) and to import the characteristics from a text file.

Capabilities of the graphical user interface of GSP are somewhat similar to GasTurb: up to four curves may be put on a single plot (Fig. 11).

Emission indices estimation (using the ICAO tabular data interpolation, direct prediction simulator or the multi-reaction simulation) is one of the most important capabilities of GSP.

The multi-level structure of the computer model provides capability to include various types of models, each containing a variety of tasks as the elements (subsystems) of a top-level model.

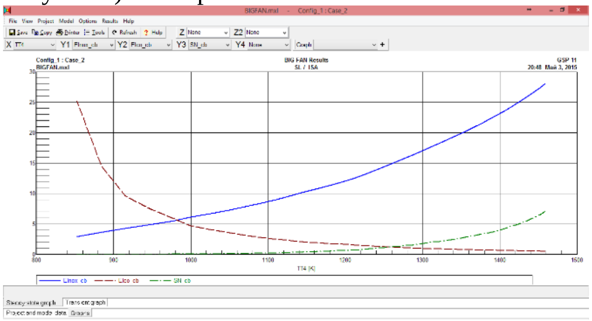

Figure 11. Diagram of $EINO_x$, EICO and soot number versus the turbine inlet temperature.

GSP system can be used for both beginners (for learning needs) and experienced users (for complex engineering calculations).

E. Uni_TTF v.5.22

This CAE system was developed on the basis of experimental and methodological experience of Experimental Design Bureau named after A. Lyulka. The program runs under various versions of MS operating system.

This CAE-system has a simple user-friendly interface. The simplicity of the interface, like the one of EngineSim, is partially due to the limited set of predefined models of engines (actually, there is only one universal model of turbofan) and the limited functional features. The turbofan is suggested to be the most common type of gas turbine engine that may be additionally adjusted for various types of tasks.

Uni_TTF provides the capability to input the user-defined characteristics of the engine elements using a text file just like the GasTurb and GSP and the capability to plot the graphic representation of these characteristics (Fig. 12).

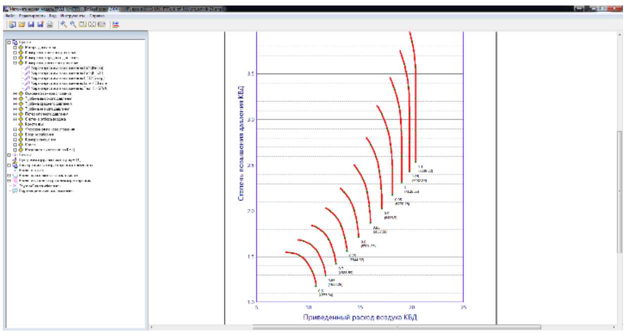

Figure 12. Graphical representation of compressor characteristic plotted by Uni_TTF.

Displaying the scheme of air bleeding and supply ports is one of useful features of Uni_TTF (Fig. 13).

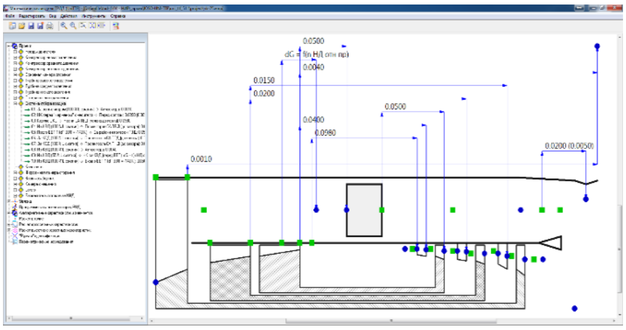

Figure 13. Graphical representation of bleeding air flow-paths.

Linkage of the engine model may be complicated for the beginners, so the adequate theoretical basis of the user is highly recommended, although the system may be used for the learning purposes as well as for the engineering analysis of the aviation turbofans.

F. ASTRA

Developed at Samara State Aerospace University, this system is cross-platform, but require a Java Virtual Machine installed to run. The interface of ASTRA is peculiar, but rather user-friendly (Fig. 14).

Beginners may use the set of 15 predefined engines models, but an arbitrary model may be composed of the elements models as well. The models of engines and elements are grouped in categories (in the similar to GSP way), providing an easier navigation. New models may be developed using the models of standard mathematical operations. Each model or element may be given a user-defined name.

User may develop complex multi-level models that may comprise both elements and submodels on each level with interconnections both at the same level and between the levels.

Using this feature, such problems like an optimization of the parameters of a line of gas turbine engines developed on the basis of a unified engine core (with a simultaneous optimization of parameters of this engine core) with a flight simulation for the aircraft efficiency criteria estimation [30] may be set up and solved.

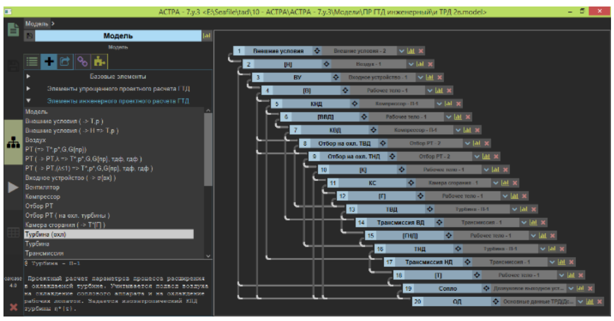

Figure 14. Graphical interface of ASTRA.

At present, the high efficiency of the modern gas turbine engines, provided by the high level of working process parameters, may be further increased by means of optimization of the engine control program [27, 28]. ASTRA provides the capability to solve this kind of engineering tasks including the optimization of control program using the aircraft efficiency criteria, calculated upon the results of flight simulation [29].

Another feature of ASTRA is a real-time simulation modeling of the gas turbine engines (Fig. 15) that is becoming more and more popular nowadays [31].

This method of simulation is a real-time experimental investigation of a virtual prototype of an engine that is implemented using a simulator instead of an engine itself (Fig. 16).

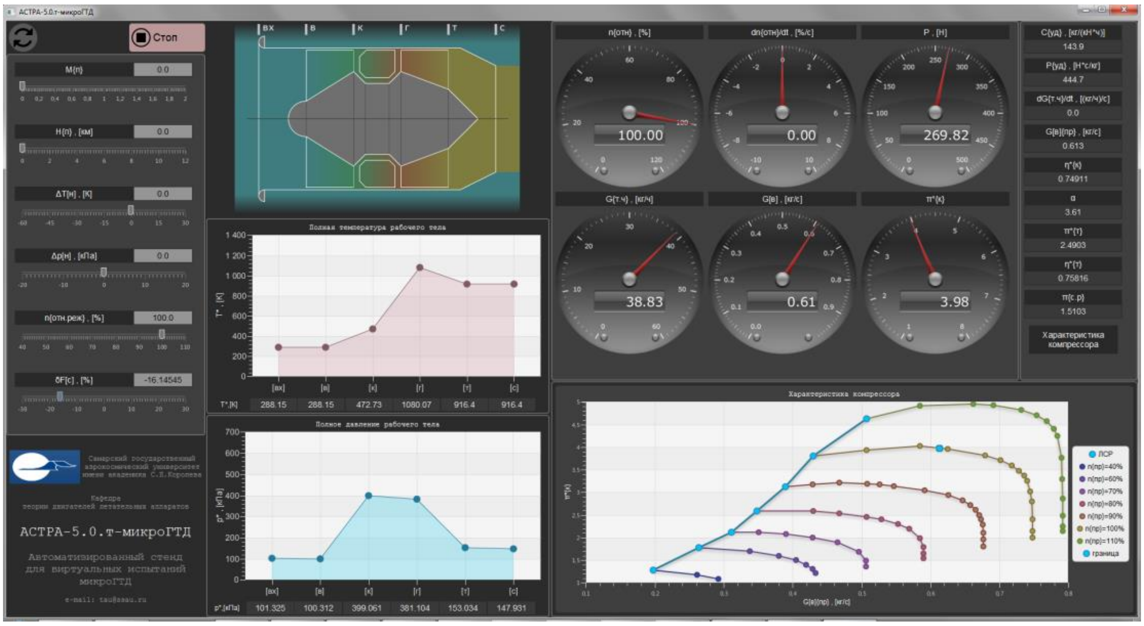

Figure 15. Virtual testing lab of the ASTRA system.

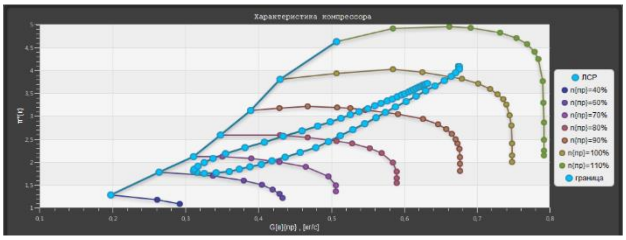

Figure 16. Graphical representation of compressor characteristic with calculated operating points during the transients.

Parallel computing function of the ASTRA may be useful for solving complex computationally intense tasks, e.g. functional optimization of the control program with a nested flight simulation tasks.

III. Conclusion

All of the examined CAE systems have roughly the same core functionality, but various unique features for solving the specialized engineering tasks. Most systems may be easily used for both engineering analysis and during the learning process.

DVIGwT is the most suitable for simulating the gas turbine engines and power-plants with complex thermodynamic cycles with heat recovery and water/steam injection.

The most simple (although having less functionality) program is EngineSim that is most suitable for students.

GasTurb fits best for solving multi-objective and multi-disciplinary tasks including weight-dimensions estimation and emissions evaluation.

GSP implements the most sophisticated models of emissions evaluation.

Real-time simulation modeling may be performed using the GasTurb, Uni_TTF and ASTRA.

ASTRA is the only system among the examined that provide the flight simulation and optimization of the engine control program.

All the systems examined during this study are poorly equipped with noise emissions simulators that may be used during the conceptual design stage of a gas turbine engine, although influence of noise and emissions restrictions upon the development of modern aviation engines has substantially increased lately.

One of the important ways of development of the CAE systems is a development of interconnected 1- 2- and 3-dimentional models that are used consequently during the development of engine in compliance with the amount of available data.

Another way is the creation of hybrid expert systems of design and analysis, which will include not only the mathematical models, but the logical-linguistic models, representing the accumulated knowledge.

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