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Simulation of gas turbine engines considering the rotating stall in a compressor

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Abstract

A set of models and software tools for the simulation of gas turbine engines considering the rotating stall in a compressor is presented. A new one-dimensional method (implemented in COMPRESSOR_S software) for the prediction of the performance of axial-flow compressors was developed. A model is capable of predicting the axial compressor performance in the following conditions: stable off-design; part-span and full-span rotating stall; reverse flow. The developed tool COMPRESSOR_S is verified via comparison against a set of individual compressor stage and multistage compressor experimental maps. A new model for the simulation of gas turbine engines considering the rotating stall in a compressor is presented. A multi-sheet map is generated for a wide operational range of the compressor (one sheet for the stable off-design and another one for the rotating stall and reverse flow). Results for a turbojet engine acceleration-stall onset-deceleration-unstall are presented. Developed tools are useful for preliminary design of gas turbine engines for a wide operational range and control problems solving.
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Keywords: gas turbine engine; compressor; rotating stall; control; simulation

1. Introduction

The development of gas turbine engines played a significant role in the advancement of current-technology flying vehicles. The growing demand for increased performance of gas turbine engines has been resulted in the engine design that operate close to the aerodynamic, thermal and structural limits of the gas turbine engine components. One of the challenges in the state-of-the-art gas turbine engines design is to ensure the aerodynamic stability of main components and especially the compressor aerodynamic stability. During operation the gas turbine engines is

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exposed to transient events such as a fuel rate change. A transient event (if it is not carefully made) can potentially force the engine into unstable operation which is dynamic in nature. Unstable engine operation is resulted in loss of thrust, loss of control and possible engine damage due to high heat loads and dynamic loading (cyclic stresses) [1]. The mostly subsonic flow throughout the engine and open flow paths result in aerodynamic coupling of the engine components. This coupling permits the engine to operate as a propulsion device, however the aerodynamical problem in one component engine can lead to significant problems in another components. For example the transient increase in a fuel rate can lead to a compressor stall or an engine surge [2]. It is important for an engineer to be able to predict the situation where an engine will encounter dynamic event such as stall or surge and to understand how the engine will react once such a dynamic event occurs.

Several 1-D codes are now available that simulate the steady and transient flow through a multistage compressor. These coeds typically solve the steady and unsteady Euler equations with the effect of the blades being modeled by appropriate source terms in the momentum and energy equations [1, 3]. The classical compression system model for surge control design problem was proposed by Greitzer et al. in 1976. The model has two states, normalized mass flow and normalized pressure and the compressor is treated as an actuator disc with a third order polynomial flow-pressure rise characteristic. The Moore-Greitzer model compression system model [4, 5] is widely used in industry for compression systems stall and surge investigations. The model has following assumptions: large hub/tip ratio, irrotational inviscid flow in the inlet duct, incompressible compressor mass flow, short throttle duct, small pressure rise, constant rotational speed. Later an advanced model with variable rotor rotational speed was developed [6]. A similar approach is used in DYNTECC software [3], widely used in industry for compressor stall/surge control. An alternative model of rotating stall was presented by Paduano et al. [7, 8], where rotating stall was described as a traveling wave and spatial Fourier analysis was used. The aforementioned models have two main problems, they can only be used for compression systems (inlet-compressor-plenum-throttle) and need specific axisymmetric polynomial compressor map representation.

Dynamic modeling and simulation of gas turbine engines received considerable attention during the 1970's from NASA. A wide range of models is developed for gas turbine engines transient analysis and automated control system design. Most models are restricted by compressor surge line, without post-stall analysis (GasTurb, GSP, Proosis etc.) A significant amount of research is conducted in Pratt&Whitney [9], General Electric [10], Arnold Engineering Development Complex [1], NASA [11]. The development of an integrated gas turbine engine model and simulation that can efficiently handle both transient and dynamic events and their interactions has not occurred to date and, as such, the development of such a model and simulation would be an advance in the state-of-the-art.

2. Compressor-off design prediction method

An original method for axial flow compressor off-design performance prediction based on the compressor stage generalized functions was developed in the P.I. Baranov Central Institute for Aviation Motors (Russia) under scientific supervision of L. E. Ol'shtein. This is a simple meanline method, there is no need for 2-D analysis and spanwise integration of airflow parameters [12-14]. Generalized functions are obtained from a statistical analysis of significant amount of individual compressor stage performance maps.

The method requires a nominal (reference) on a speed line being analyzed. The nominal point for the preferred speed line in Ol'shteyn's method is considered as maximal isentropic efficiency point and is determined by an empirical model. Assume that the angles $\alpha_1 = \alpha_{10}$ (rotor row inlet absolute flow angle) and $\beta_2 = \beta_{20}$ (rotor row outlet relative flow angle) are constant both for the nominal design point and the off-design points (in a wide range of incidence angles up to surge line) [14, 15]. In accordance with the elementary stage velocity diagram the stage loading coefficient for the nominal point and for off-design conditions can be written as

$$\bar{H}_{th0} = 1 - \bar{c}_{a0}\left(ctg\alpha_1 + ctg\beta_2\right),\ \bar{H}_{th} = 1 - \bar{c}_a\left(ctg\alpha_1 + ctg\beta_2\right). \quad (1)$$

where $\bar{c}_a$ - is a flow coefficient. The nominal point is indexed 0, off-design point is without an index. The relationship between stage loading, isentropic stage loading, and isentropic efficiency for the design and off-design points can be described by the following equation:

$$\frac{\bar{H}_{th}}{\bar{H}_{th0}} \cong \frac{\bar{H}\eta_0}{\bar{H}_0\eta}. \tag{2}$$

Using equations (1) – (2) two dimensionless groups are obtained:

$$K_1 = \frac{\bar{H}}{\eta} - \frac{\bar{c}_a}{\bar{c}_{a0}}\frac{\bar{H}_0}{\eta_0},\ \ K_2 = \bar{H} - \bar{H}_0\frac{\bar{c}_a}{\bar{c}_{a0}}. \tag{3}$$

The complex relationships $K_1 = f\left(\bar{c}_a/\bar{c}_{a0}, M_u\right)$ и $K_2 = f\left(\bar{c}_a/\bar{c}_{a0}, M_u\right)$ are generalized performance characteristics of an individual compressor stage. Variation of dimensionless groups K_1 and K_2 with $\bar{c}_a/\bar{c}_{a0}$ и M_u criterions (which determine compressor stage operating conditions), are shown in figure 1 [15]. Stage pressure ratio and isentropic efficiency for off-design condition are determined as the following:

$$\pi = \left(1 + \frac{\left(K_2 + \bar{H}_0\dfrac{\bar{c}_a}{\bar{c}_{a0}}\right)\cdot u^2}{\dfrac{k}{k-1}R\cdot T^*}\right)^{\frac{k}{k-1}},\ \ \eta = \frac{K_2 + \bar{H}_0\dfrac{\bar{c}_a}{\bar{c}_{a0}}}{K_1 + \dfrac{\bar{H}_0}{\eta^*_{\kappa 0}}\dfrac{\bar{c}_a}{\bar{c}_{a0}}}. \tag{4}$$

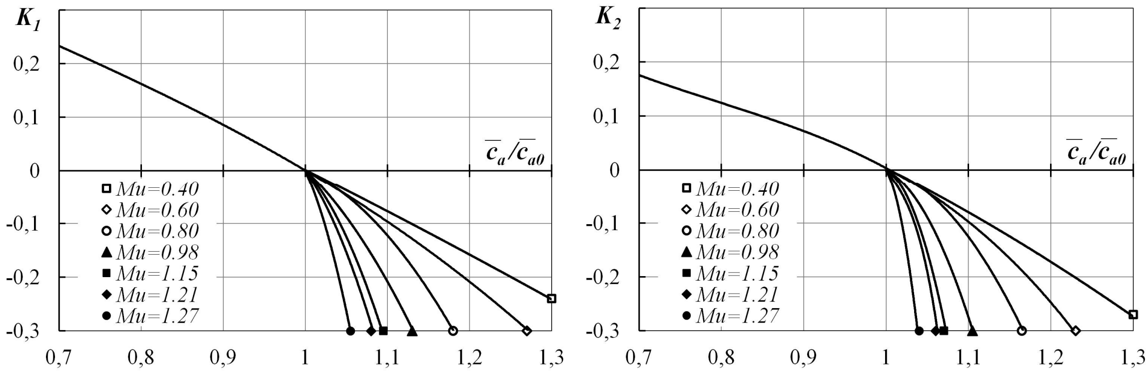


Fig. 1. Compressor individual stage generalized functions

The next problem in the prediction of the compressor off-design performance is the determination of a surge line. Compressor off-design performance prediction is based on a simplification that the flow outlet angles do not change appreciably in a wide range of operating conditions characterized by incidence angles. This simplification suggests the critical incidence angle as a criterion for a compressor surge line prediction. The critical incidence angle for each blade row is being calculated with use Howell's method [16]. The nominal deflection in the compressor cascade must be set in predicting a compressor surge line. The nominal deflection is related to maximal deflection in the compressor cascade as the follows $\Delta\beta_0 = 0,8\cdot\Delta\beta_{\max}$ This nominal deflection has a corresponding nominal incidence angle i_{nom}.

Compressor cascade stall limit is determined by a maximum point on the performance curve $\dfrac{\Delta\beta}{\Delta\beta_0} = f\left(\dfrac{(i-i_0)}{\Delta\beta_0}, \dfrac{b}{t}\right)$. related to flow the separation on the suction surface. Flow separation causes the significant decrease in the cascade deflection and increases in pressure losses Thus, the analysis of Howell's compressor cascade performance curves gives the justifiable criterion for the meanline compressor surge line prediction. Two empirical models have been used – the critical incidence angle (for the surge line prediction) and the stall onset incidence angle:

$$\frac{\left(i_{crit} - i_0\right)}{\Delta\beta_0} \approx 0.4, \quad \frac{\left(i_{stallonset} - i_0\right)}{\Delta\beta_0} \approx 0.2. \tag{5}$$

3. Compressor stalled and reverse flow performance prediction

The developed method for the stalled compressor performance prediction is based on the statistical analysis of a large set of experimental compressor stage individual maps. Axial compressor part-span stall performance experimental data was obtained from NASA, General Electric, Pratt&Whitney, University of Cambridge, Massachusetts Institute of Technology, Cornell University. Statistical analysis is used for the determination of correction relationships for a calculation of the load coefficient and isentropic efficiency, fig. 2. The model for part-span stall compressor performance prediction:

1. Firstly parameters on the surge line for preferred rotational speed are determined: the flow coefficient $\overline{v} = \overline{c}_{a0} / \overline{c}_{astall}$, isentropic efficiency η_{stall} and load coefficient $\overline{H}_{thstall}$.
2. Compressor parameters $\overline{H}_{thstable}$, $\overline{H}_{stable}$ and η_{stable} for an off-design condition are calculated with use of equations (1-4) for the preferred flow coefficient.
3. Correction relationships are used for the load coefficient (fig. 2) and isentropic efficiency considering part-span stall in the compressor (determined by means of statistical analysis):

$$\eta = -0.2482 \cdot \left(\overline{v}\right)^2 - 0.3362 \cdot \left(\overline{v}\right) + 0.5847. \tag{6}$$

4. Real performance data is determined by the use of correction relationships:

$$\overline{H} = \overline{H}_{stable} - \delta\overline{H} \cdot \overline{H}_{thstall} \cdot \eta_{stall}, \quad \eta = \left(1 - \delta\eta\right) \cdot \eta_{stall}. \tag{7}$$

5. Stage pressure ratio and isentropic efficiency are determined using equation (4).

Results of the compressor full span stall experimental research conducted in NASA, General Electric, Pratt&Whitney, Snecma are being used for the development of compressor off-design performance prediction method. The classical criterion is used for the transition from part-span to full-span stall. rotating stall with blockage less than 30 percent will be assumed to be part-span and stall having blockages greater to be full-span. Another criterion for the transition from one model to another one is hub-to-tip ratio which is greater than 0.65.

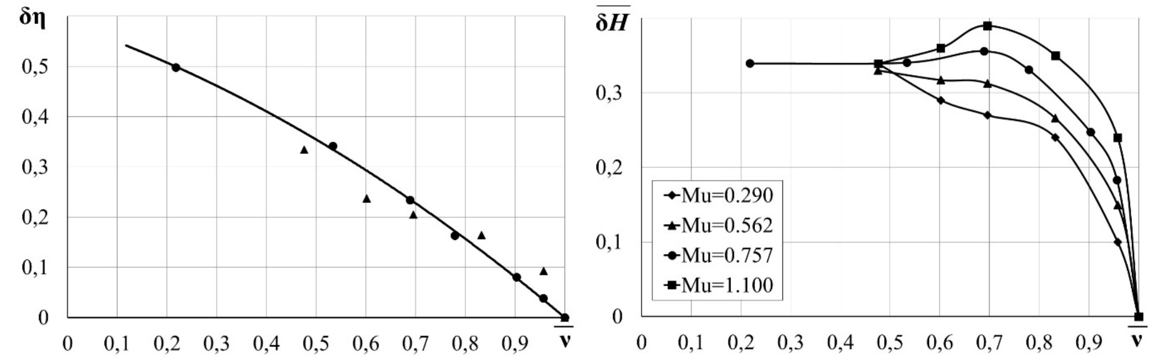


Fig. 2. Correction relationships for calculation of compressor stage load coefficient and isentropic efficiency in part-span stall

One of the features of full-span stall in a compressor is that the performance curve can exhibit a large discontinuity where the pressure rise and mass flow jump to significantly reduced values. The abrupt performance characteristics are modelled by a set of correction relationships identified via analysis of experimental data.

$$\overline{H} = \overline{H}_0 \cdot \left(\frac{\overline{c}_a}{\overline{c}_{a0}}\right) + K_2 = \overline{H}_0 \cdot \left(\frac{\overline{c}_a}{\overline{c}_{a0}}\right) - 0.2367 \cdot \left(\frac{\overline{c}_a}{\overline{c}_{a0}}\right)^3 - 0.0545 \cdot \left(\frac{\overline{c}_a}{\overline{c}_{a0}}\right) + 0.2908. \tag{8}$$

$$\left(i < i_{crit}\right) : \overline{H} = \overline{H}_0 \cdot \left(\frac{\overline{c}_a}{\overline{c}_{a0}}\right) + K_2 - K_3 ; K_3 = \overline{H}_{stall\,onset} \cdot \left(-0.391 \cdot \left(\frac{\overline{c}_a}{\overline{c}_{a0}}\right) + 0.394\right). \tag{9}$$

$$\left(i > i_{crit}\right) : \overline{H} = \overline{H}_0 \cdot \left(\frac{\overline{c}_a}{\overline{c}_{a0}}\right) + K_2 - K_3 - K_4 ; K_4 = \overline{H}_{stall} \cdot \left(1.975 \cdot M_u^3 - 2.704 \cdot M_u^2 + 0.329 \cdot M_u + 0.5\right). \tag{10}$$

The developed method for the reverse-flow performance prediction is based on the data obtained in NASA, Massachusetts Institute of Technology, University of Cambridge, Cranfield University. The reference point for the reverse-flow performance prediction is located on a surge line for the preferred rotational speed. A virtual value of load coefficient for a zero flow coefficient is also required. This virtual point is being determined during the stalled performance prediction. Reverse-flow performance prediction is based on the following empirical model:

$$\overline{H} = \overline{H}_{G=0} \cdot \left(12.6110 \cdot \left(\overline{v}\right)^2 - 8.1577 \cdot \left(\overline{v}\right) + 1.1592\right), \ \eta = \eta_{stall} \cdot \left(-0.2482 \cdot \left(\overline{v}\right)^2 - 0.3362 \cdot \left|\overline{v}\right| + 0.5847\right). \tag{11}$$

An empirical model is represented for a stall/unstall hysteresis loop determination:

$$\frac{\left(i_{crit} - i_{unstall}\right)}{i_{crit}} = 0.623 - 0.42 \cdot 10^{-4} \cdot \left(\frac{b}{t}\right) - 4.3 \cdot 10^{-7} \cdot \mathrm{Re} + 0.12 \cdot 10^{-5} \cdot \mathrm{Re} \cdot \left(\frac{b}{t}\right). \tag{12}$$

where b/t is a cascade solidity, Re is a blade chord Reynolds number.

Each empirical model from the developed set was verified via a comparison against individual compressor stages performance experimental data. Developed empirical models were implemented in the COMPRESSOR_S software tool for the compressor preliminary design.

4. Validation of COMPRESSOR_S software tool

Robert Gamache's PhD thesis in 1985 is still the only detailed investigation of the compressor reverse flow operation, in which a complete set of overall performance characteristics has been presented. In his work, experiments were carried out on two builds of three-stage, constant annulus compressors preceded by an IGV, but for each compressors with the different blade reaction. The compressor was operated at the stable off-design modes, stall and steady reverse flow with use an auxiliary fan to draw the air backwards while a conical nozzle was each time adjusted to give the desirable mass flow rate. Abovementioned work is a unique data set for the validation of the developed method. The comparison of experimental and numerical results for 3-stage compressor and one of individual stages is shown on fig. 3.

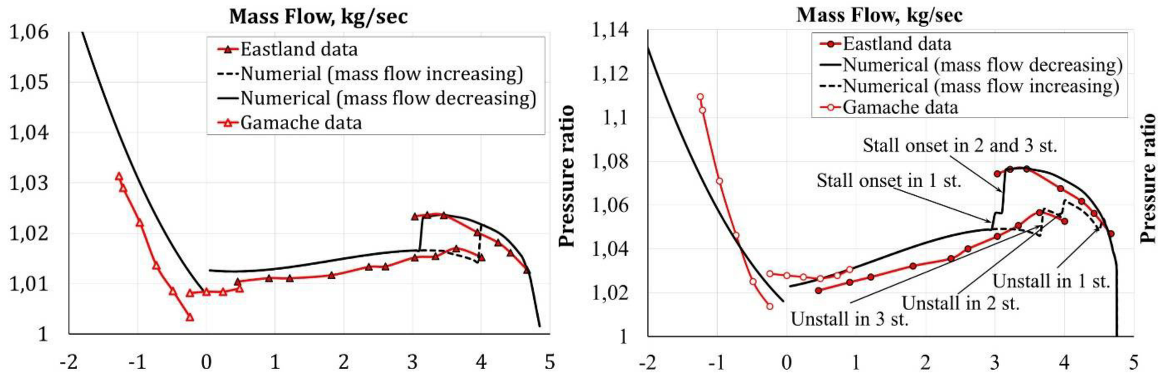


Fig. 3. Developed model validation

Fig. 3 shows the developed set of models characterized by high accuracy in a wide range of operation conditions. Numerical results also show a stage-by stage unstall of 3-stage axial compressor.

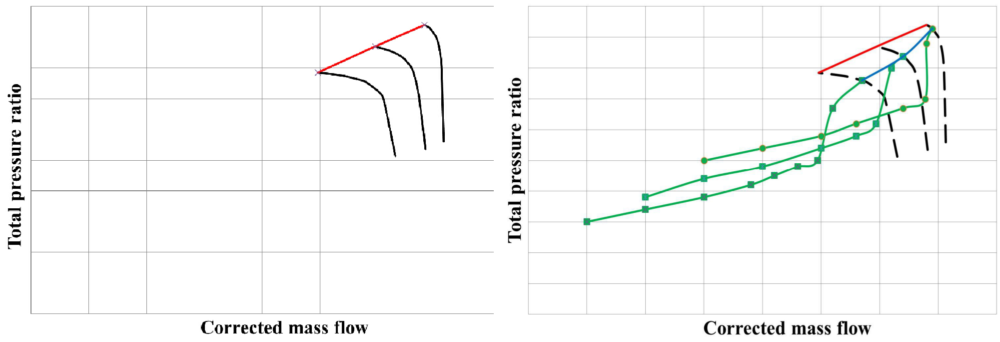
One of the features of the developed method is the integrated approach – the method is capable of the off-design performance prediction in a wide range of operating conditions (stable off-design, part-span and full-span stall, reverse flow) based on a limited data set (meanline design parameters). For the stable operational conditions the off design performance and the surge line prediction calculation error of model is less than 5%. Maximal error for stalled and reverse-flow conditions performance prediction is about 7%. Obtained results show the high accuracy level of designed software tool for the comperssor preliminary design in despite of the simplicity of empirical models is being used. COMPRESSOR_S software tool is useful for the generation of compressor static performance characteristics for dynamic analysis of compression systems stall and surge. In this paper the generated compressor static performance data is used for gas turbine engines rotating stall analysis.

5. Gas turbine engine simulation software

The DVIGwp software [17] developed at the Ufa state aviation technical university is a component-based modelling environment used for gas turbine engines performance analysis. The program has flexible object-oriented architecture and allows steady-state and transient simulation of any gas turbine engine configuration using a user-friendly drag & drop interface. Gas turbine configurations are simulated by establishing a specific arrangement of engine component models in a model window.

The DVIG_DISTORTION software is based on the classical DVIGwp program and is used for steady-state and transient gas turbine engines analysis. To accurately model the gas turbine engine dynamics the following factors are being accounted for: rotor inertia; thermal mass; workflow compressibility; sensor and actuator lags; tip clearance effect etc. The main feature of DVIG_DISTORTION software tool is capability of in-stall transient simulation.

The COMPRESSOR_S software tool is used to generate compressor maps. Each generated map is divided into two linked objects – classical map for stable operating range $\left(d\pi / dM_{corr} < 0\right)$ and additional map for stalled-flow conditions $\left(d\pi / dM_{corr} > 0\right)$. An example of generated multi-sheet compressor map is presented in fig. 4. A criterion for transition from stable compressor map sheet to stalled-flow sheet is $\Delta K_y = 0$. The criterion function for reverse transition is compressor unstall line function $\pi = f\left(M_{corr}\right)$.



a *b*

Fig. 4. Compressor multi-sheet map

6. DVIG_DISTORTION software tool approval

The simple one-spool turbojet model is used to demonstrate the capabilities of developed software tool. The COMPRESSOR_S software tool is used to generate the multi-sheet compressor map. A six-stage axial compressor with interstage air bleed valve is used for analysis, the figure 5 shows experimental and calculated data. In this figure we can see that the general tendency of calculated compressor performance is close to experimental data. Compressor map is divided into two maps in low rotational speed region because of the air bleed valve influence. The verified compressor model is used to generate compressor performance data for stalled-flow conditions. The model of turbojet engine with compressor air bleed valve is presented in fig. 6. To accurately simulate gas turbine engine off-design performance a set of experimental components maps (inlet, compressor, air bleed valve, combustor, turbine, and nozzle) is used. An engine dynamic characteristic $M_{Fcorr} = f\left(n_{corr}, \dot{n}\right)$ is used for verification of the engine model. The dynamic characteristic is relationship between corrected fuel flow, corrected rotational speed and corrected acceleration rate. The results presented on fig. 5 and 6 demonstrate the level of adequacy of developed models. This verified turbojet engine model was used to simulate engine in-stall transient performance.

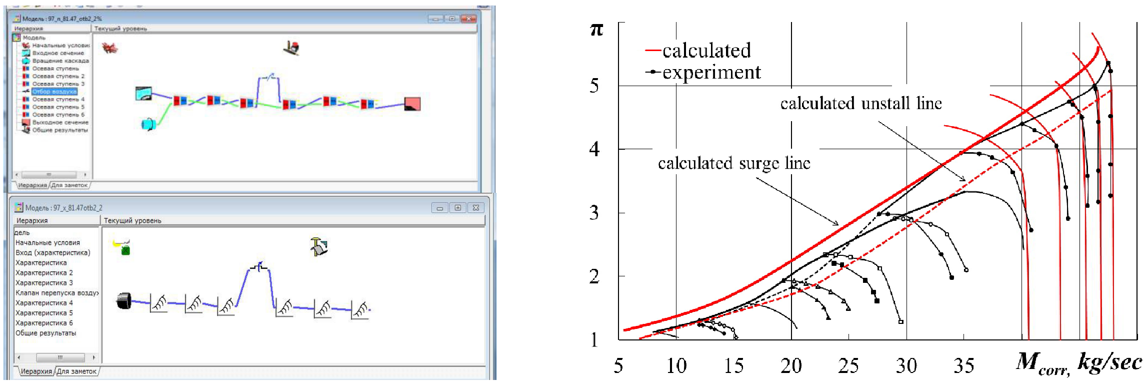


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Fig. 5. Compressor multi-sheet map

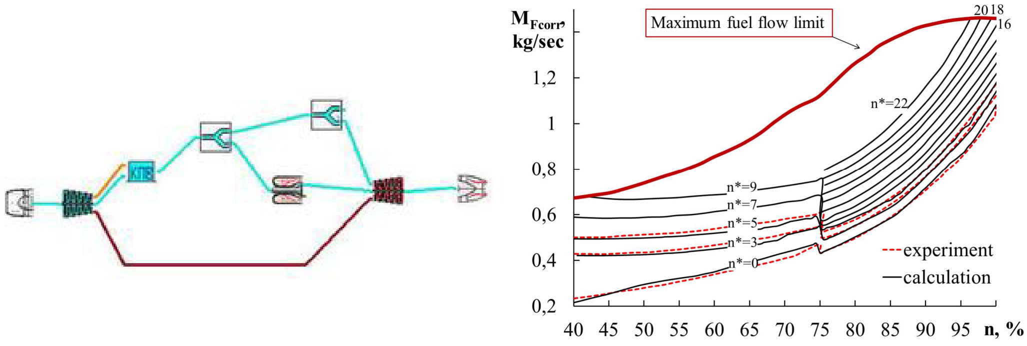

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Fig. 6. One-spool turbojet model and generated engine dynamic characteristic

The engine acceleration process was simulated by predetermined specific control to demonstrate the capabilities of the developed software. Figure 7 shows the engine acceleration control law, the fuel flow rate is plotted against engine rotational speed. The feature of the used control law is the high acceleration rate leading to different compressor instabilities, in particular stall or surge.

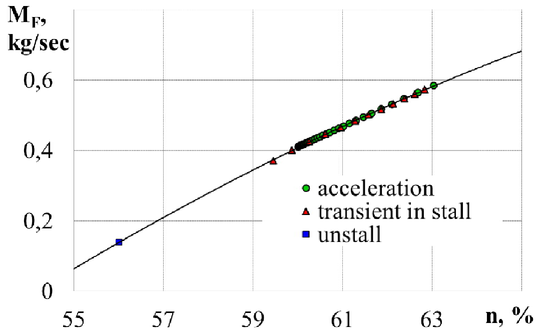

Fig. 7. Engine control law

The figure 8 shows a transient operating line on the compressor map. Initially operating point is located on the steady-state operating line. During the initial portion of the transient the compressor pressure ratio is increasing rapidly, reaching the compressor surge line. At this moment there is a transition between two sheets of multi-sheet compressor map, the operating point enters stalled-flow compressor map.

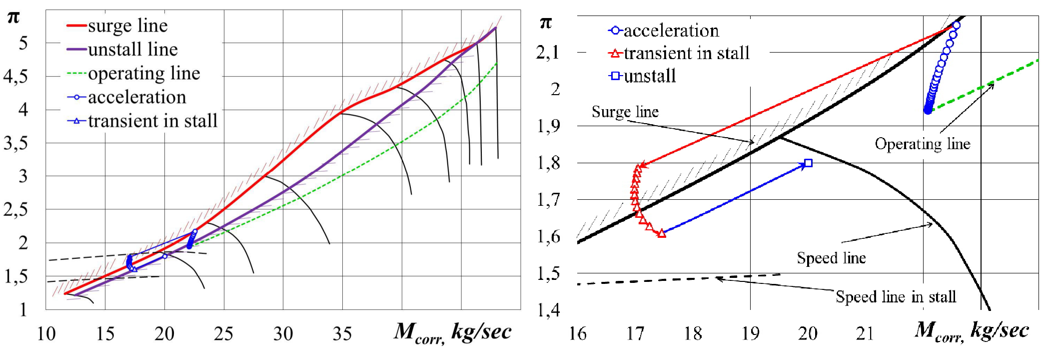

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Fig. 8. Transient operating line on compressor map

In stalled-flow conditions compressor the operating point jumps to significantly reduced values of pressure ratio and air mass flow. Reduced values of pressure ratio and air mass flow cause the engine rotation speed to decrease. As mentioned above the control law is a relationship between fuel flow rate and rotation speed, so reduction of rotational speed cause reduction of fuel flow rate. The predetermined control law force the operating point close to compressor unstall line.

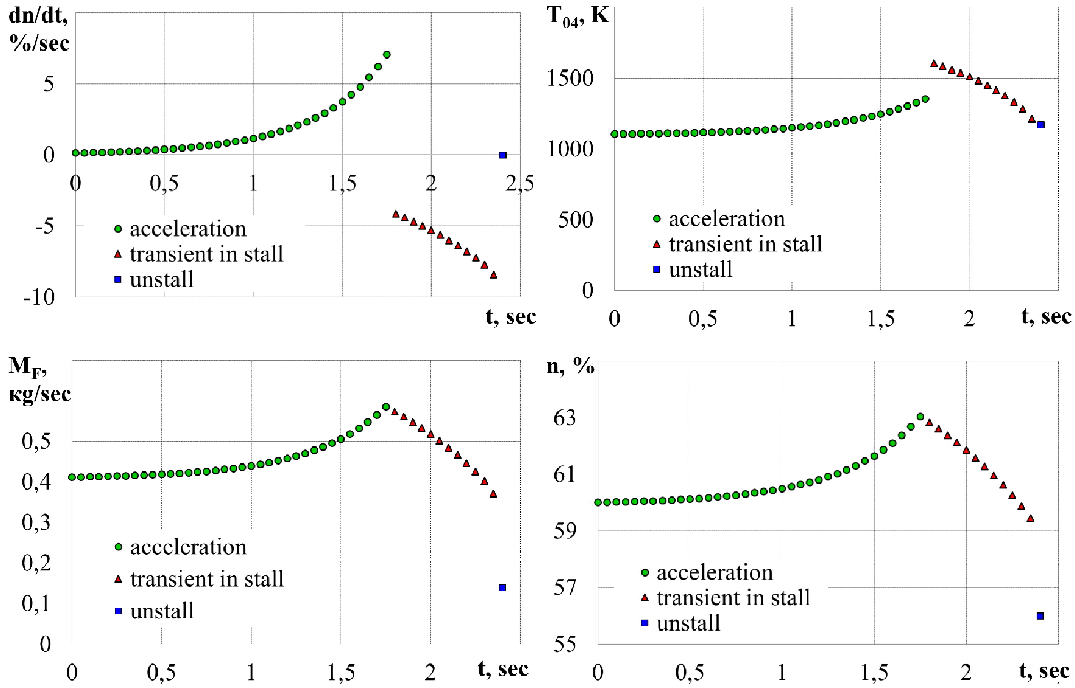

Fig. 9. Turbojet engine acceleration-stall-unstall transient

In accordance with the control law, operating line moves to the compressor unstall line, fuel flow rate (M_F), turbine inlet temperature (T_{04}), pressure ratio and rotational speed are decreasing. When the engine is in rotating stall the operating point on the compressor map can be located under the classical surge line, however the operating point is located in another compressor map sheet. When operating point reaches the compressor unstall line on the second sheet of compressor map, operating point jumps to the first sheet of the map. This jump is associated with the rapid increase in acceleration rate to a value of zero in accordance with control law.

7. Discussion

The authors have developed a set of mathematical models for the prediction of the performance of axial-flow compressors. A set of models is capable of predicting the axial compressor performance in the following conditions: stable off-design; part-span and full-span rotating stall; reverse flow. A feature of the set of mathematical models is their integration into a single software package. COMPRESSOR_S software allows to calculate a compressor map in a wide range of operation conditions – from design point to stalled-flow and reverse flow based on a set of empirical models. A multi-sheet compressor map concept for representation of simulation results is used. Proprietary software CharEdit is used to create a compressor map for gas turbine engine simulation. Therefore, there is no need for polynomial axisymmetric compressor map representation such as in Moore-Greitzer model.

The developed gas turbine engines dynamic model is based on the object-oriented approach, it means that the gas turbine engine with an arbitrary structure can be simulated. Generated multi-sheet compressor map allows to analyze compressor-post-stall transients. Model can be used to analyze the effect of gas turbine engine components aerodynamic coupling, engine component maps on compressor-post stall transients. Simulation results (fig. 8 and 9) indicate the presence of the compressor stall hysteresis, it is useful for gas turbine engine automated control system design.

8. Conclusion

The objective of this research is to develop a mathematical model and computer software that could simulate post-stall transients and surge in gas turbine engines. The main feature is to simulate the gas turbine engine based on the object-oriented approach, to develop universal software for different gas turbine engines but not simple classical compression systems (inlet-compressor-plenum-nozzle). First problem is a mathematical model to predict off-design performance of the axial compressor in stable and stall-flow conditions. A new empirical model and COMPRESSOR_S software was developed, to predict performance characteristics of axial-flow compressors in the following conditions: stable off-design; part-span and full-span rotating stall; reverse flow. The DVIG_DISTORTION software has been developed, being capable of in-stall transient simulation. The multi-sheet map concept is used to consider the compressor stalled performance. Results for a turbojet engine acceleration-stall onset-deceleration-unstall have been presented. The developed tools are useful for preliminary design of gas turbine engines for a wide operational range and control problems solving.

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