ISSN 1727-7337 (print)
ISSN 2663-2217 (online)

UDC 621.452.322(09)

doi: 10.32620/aktt.2020.5.04

Dedicated to the 90th anniversary of the KhAI, where the main Ukrainian creating turbofan engine ideas were born

V. GERASIMENKO, V. DATSENKO, M. SHEVCHENKO

National Aerospace University "Kharkiv Aviation Institute", Ukraine

CREATION OF AFTERBURNING TURBOFAN ENGINE – HISTORY AND PRESENT

The main problems of the creation of afterburning turbofan engines, among which the irremovable surge of the compressor, is disclosed by historical analysis. According to the published models, such surge is a hydrodynamic instability in the form of rotating stall mutual transitions to surge with the primary cause of instability in the form of stall or vibration combustion in the afterburner. The Pratt & Whitney F100 serial engine, which based on TF30 is one of the first in which the irremovable surge was detected. As a result, several planes F-15 crashed, so far as the compressor could not be restored to a stable state without stopping and restarting the engine. Dissection of the problem with this phenomenon led to the conclusion that this irremovable surge problem was generated by the engine design. To eliminate it, the company had to refine several systems, such as an electronic engine control system, fuel supply of the afterburner along with the nozzle locations, firing belt, combustion stabilization, an extension of flow separation along the contours, etc. According to the analysis of publications, particular difficulties arose with the recoverable unsurge operation of such engines. It is noteworthy that today, the F-135-PW100 engines have been installed on the F-35 aircraft, the predecessors of which are the F-100 engines with the same problems. The results of experimental studies of a fan are presented in the article to deepen in the stall flow mechanism and the occurrence of rotating stall of the fan blades. The perturbations from vibrational combustion in the afterburner combustion chamber to the fan stall boundary in the afterburning turbofan engine system at bench conditions were simulated by independent throttling of the duct over a wide range of the bypass ratio. Numerous monographs and publications according to vibrational combustion, in particular in afterburner combustion chambers TRDF AL-21F and TRDDF AL-31F, of A. M. Lulka, confirm the possibility of the propagation of perturbations against the flow in the bypass duct and the impossibility of their propagation through the turbines. The propagation of surge perturbations in the afterburning turbofan engine to the compressor of the internal duct behind the fan occurs through the interaction of the duct. The more reliable way to prevent emergencies is to provide stability margin area of compressors. Estimation of the pre-stall state of the flow traditionally is carried out by the diffusivity factor of Lieblein FD, which is applicable in 2D calculations. The integral variational principle of nonequilibrium thermodynamics of the "maximum flow of mechanical energy" of V. N. Yershov was applied.

Keywords: *aviation; turbofan engine; compressor; afterburner; rotating stall; surge.*

Introduction

Among the existing set of unstable gas-dynamic phenomena in aircraft gas turbine engines (GTE), such as itching and surge of supersonic air intakes, popping in the inlet duct during high-altitude launching of helicopter power plants, surging, rotating stall, blade flutter and rotating pressure field in compressors, vibration combustion or flame failure in combustion chambers, the most recurring problem of turbofan instability, which was highlighted in this study. This combination of rotating stall and surge of compressor with combustion instability in afterburner are called "irremovable surge". The purposes of this study are analyse and systematize publications according to this issue.

1. History of the problem

When creating afterburning turbofan engine TF30, F100 [1] among the first in the world, Pratt & Whitney and NASA was faced with the problem of "irremovable surge" of the turbofan compressor as a result, several planes crashed. It took about 5 years to solve this problem (1970-1975). A similar problem was solved almost simultaneously (on the F101X F101 DEE) engine by General Electric [2], and later by other well-known companies of the same class of engines M 53, RB 199, AL-31F, RD-33, F 119, EJ 200, M 88, but with a lot of time. The engine RB.199 with m = 1,0 was created by a consortium of three firms MTU, RR, "Fiat" for 12 years (1968-1980). During engine refinement, the occurrence

© V. Gerasimenko, V. Datsenko, M. Shevchenko, 2020

of a single-zone rotational stall at the fan hub was detected in the stall zone. The static pressure increase is 20 % below the average. The surge margin of the high-pressure compressor (HPC) is shifted to the right by 22 %. It is important to note that the AL-31F engine was developed under the direction of Arhip Lyulka, who received a patent for the idea of creating turbofan engine in 1937. The idea was born at Kharkov Aviation Institute. The phenomenon of "irremovable surge" of compressor in the turbofan system consists in the development of hydrodynamic instability in the form of surge cycles alternating with an unstable rotating stall during transient engine operation and disturbances in the form of pressure pulsations through a stall in the afterburner, which occur the most often at high altitudes $H \geq 14$ km and at low speeds $M_{п} \leq 1,0$ of the aircraft. That effects on the stability of the fan along the contours of the turbofan engine, or with disturbances at the engine inlet from the air intake during flight fighters including contact with hot gases from the board arms [3].

Let brief historical instability problem turbojet engine (TJE). Rotating stall was first discovered in 1938, a group of researchers who was led by F. Whittle in England [4] in a centrifugal compressor of a turbojet engine, which developed rapidly during World War II. The results of these studies were published by L. J. Cheshire only in 1945 [5]. As is well known, in this period in Germany, efforts were directed to the creation of TJE with axial compressor, in which were also highlighted areas of stable and unstable modes with the boundary of their separation, called the surge line, a phenomenon that was little studied at that time, which was preceded by a shear flow blades with the rotating stall zones formation.

The intensive development and implementation of gas turbine engines in aviation during the war years caused many problems, among that loss of gas-dynamic stability. It is one of the most complex and significant for all aircraft engine manufacturing companies. Since such instability is the cause of emergency situations. The increased interest in this problem certainly led to increase the number of publications in this research area. As an example of such publications, we cite materials of a symposium of American Society of Mechanical Engineers in 1960 [6], a monograph of V. N. Yershov which is described the results of phenomenal theoretical and experimental studies of rotating stall in axial compressors. The monograph was written at the Kharkov Aviation Institute and reprinted in the USA [7]. Over the same time period as the Yershov monograph, systematic review articles around the rotating stall of axial compressor was published by J. Fabry [8]. Deeper analyses of publications and development by E. Greitser about stall phenomena in axial compressors [9] and loss stability of pumping systems [10] up to 1980 allowed us to deepen our understanding not only about rotating stall as a local instability, but also about surge such as global instability, violation of static and dynamic stability, distinguish distinctive features in the structure of the stall flow during surge and rotating stall according to Taylor [9].

2. The problem essence

"In compressor, flow stall can be observed during part of the time on all blades or during all time on part of the blades." Such an idealized axisymmetric representation of surge isn't always observed in fact [11]. Axial dissymmetry manifested in the formation of backflow at the beginning of surge. The frequency of the surge cycle is determined by the time of filling and emptying of the compressor system capacity. Longitudinal surge fluctuations and flow velocity are directed along the axis of the compressor, which is usually shorter than the circumference rotation of stall zones. At surge, the compressor operating modes change in phase, moving from an unstall flow to a stall flow and vice versa. The presence of the reverse mass flow current is called "deep" surge [11]. With a sluggish surge, the operating point moves around the peak of the maximum on the pressure characteristic of the compressor (in other words, the point of dynamic stability violation [9, 10]. Static instability occurs at the point to the left of the dynamic stability violation, where the slope of the compressor characteristic is greater than the slope of the throttle characteristic. At a low air flow rate, rotating stall can be observed with an oscillation frequency in the range of 50-100 Hz. Surge is much slower than rotating stall with the frequency of 3-10 Hz. The rotation frequency of the stall zones alternation is determined by the rotation frequency of the stall zones and their number. It is equal to their product and depends on the flow structure in the stall zones. According to one of the first publications [12] on a two-dimensional physical model of the rotating stall zones formation in the compressor rotor airfoil cascade of axial compressor based on analysis of boundary layer development on the blades, it is assumed that the moment of flow stall on any one blade or in the inter-blade channel coincides with the beginning of the rotating stall zone formation. It means coincidence of the transition boundary to the rotating stall mode and the initial stall of the flow from the blade. However, this assumption was not confirmed by experimental studies of the stall boundary in airfoil cascade with sparse blades [7], where stall was achieved on all blades of a rare airfoil cascade, without the formation of stall zones. The critical incidence angles corresponding to the formation of stall zones can be much larger than the incidence angles at which the boundary layer comes off from the suction side of the blades [7].

ISSN 1727-7337 (print)
ISSN 2663-2217 (online)

Thus, it can be argued that the formation of rotating stall zones doesn't always coincide with the moment of boundary layer comes off. A similar trend was noted in the work of N. Cumpsty [11], where it is stated that for the formation of the rotating stall zone at the stall limit, the circumferential length of stall channels should occupy about 15%, but not one channel. On the other hand, A. Jackson study of the stall zones number development [13] experimentally confirmed the possibility of forming a new zone by stalling on a "labelled" blade with an increased attack angle (i.e. new zones are formed not by dividing them, but by the formation of an initial flow stall on the blade with a critical attack angle). Here the reference to the term "critical angle" of attack – incidence onto the airfoil of a blade in boundary layer theory requires a retreat. Our understanding of the comes off of the two-dimensional boundary layer is based on the well-known monographs of Hermann Schlichting, J. C. Rotta, Paul K. Chang. The development of Yershov's ideas with the theoretical substantiation of the variational principle "Maximum of energy" [7, 13] allowed to expand the theoretical studies of rotating stall in compressors by 3D modeling, as well as experimental measurements of structure in stall zones, which was a significant contribution to solving rotating stall problem.

NASA (National Aeronautics and Space Administration) as a criterion for evaluating the pre-stall state of the flow, it is customary to evaluate the diffusivity factor Lieblein F_D [49] both in the compressor blade row and in compressor two - dimensional airfoil cascade

$$F_D = 1 - \frac{W_2}{W_1} + 0,5\frac{t}{b}\frac{\Delta W_u}{W_1}, \qquad (1)$$

where W1 and W2 are average flow velocities in relative motion, respectively, at the inlet and outlet of the blade cascade;

ΔWu – changing the circumferential velocity component in the blade row;

t – airfoil spacing between the blades in the airfoil cascade;

b – airfoil chord.

According to Liblein's experimental studies of NASA 65 –(A10) and C.4 airfoil cascades, a value of the FD factor exceeding 0,6 corresponds to the flow stall mode in the blade row, and $F_D = 0,45$ is recommended for choosing of the design mode. The right-hand side of expression (1) consists of two components, the first one characterizes deceleration of the one-dimensional flow at the suction side of the airflow, and the second is the flow rotation, which characterizes the aerodynamic loading of the airfoil cascade of the two-dimensional flow. Subsequently, the two-dimensional boundary layer to comes off, the name of the Moor - Rott - Sears model where F. K. Moor developed his ideas about the nature of boundary layer unsteady comes off in subsequent publications about the rotating stall theory [15]. Thus, the above analysis of the conditions for the transition to rotating stall indicates the lack of uniqueness of the term "stall limit" [11]. There is also no generally accepted understanding of the relationship between surge and rotating stall, moreover, vibrational combustion in the augmenter [10] of afterburner turbojet engine at the irrecoverable surge mode. With the existing confusion in terminology, stall is understood as a broader concept from a fully developed stall [11] to a dynamic stall [16], taking into account the effects of delay in the manifestation of inertial properties in the flow of the airfoil blade in the stall process with increasing attack angles. If the combustion instability in the combustion chambers is determined by the region of poor flame stall [4, 17] and the three frequency ranges of pulsating combustion are recognized, then the combustion instability in the afterburner are caused by well-known aircraft altitude and speed restrictions.

3. Modelling post stall processes in gas turbine engines

The phenomenological approach proposed in [16, 19] for the rotating stall theory in axial compressor is based on the form application of the generalized pressure characteristic (as follows from the hypothesis nonequilibrium thermodynamics about energy maximum and experimentally confirmed in Fig. 1 for a single-stage compressor [7], the independence of the pressure parameter $\psi_{TS}(1)$ on the left stall branch of characteristics from design parameters and in particular from the curvature of the blades θ), with the following features: data of Fig. 1 indicate when the design parameters are changed, the maximum pressure increases(at the unstall mode) more than two times. While the pressure increases at the unstall mode, at the full rotating stall mode (at the flow coefficient $\varphi = 0,5$, $\psi_{TS}(1) \approx 0,11$) it is changed much less.

In particular, it should be noted the absence of any systematic increase dependence in pressure at the stall mode from unstall characteristics of the compressor. Whereas the complete stall $\psi_{TS}(1) \approx 0,11$ it is confirmed by correlation information [9, 19, 20].

Then, for the characteristic of the N stage compressor at the stall mode in the form of a dimensionless difference between the static pressure at the outlet and the total pressure at the compressor inlet, the pressure is N times higher than the same parameter for one stage

$$\psi_{TS}(N) = N \cdot \psi_{TS}(1). \qquad (2)$$

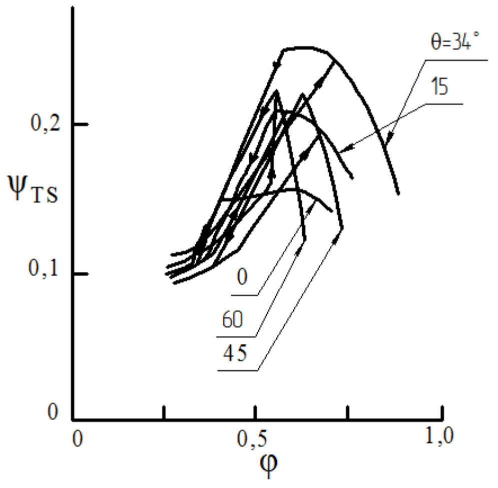

Fig. 1. The influence of the blades profile curvature θ on the pressure characteristic $\psi = f(\varphi)$ with the full single-zone rotating stall at the unstall and stall modes (experimental data [7])

It should be noted that, since an increase in pressure under consideration is the difference between the static pressure at the outlet and the total pressure at the compressor inlet, this assumption indicates a fundamentally different case from the unstall mode. If we assume that the pressure increase occurs at N identical stages, then under the conditions of the unstall regime, a reasonable approximation is the assumption that for N stages, the increase in both total and static pressure is N times higher than for one stage. In other words, if both $\psi_{TT}(1)$ and $\psi_{TT}(N)$ are dimensionless increases in total pressure in cases of one and N stages, their relationship takes the form:

$$N \cdot \psi_{TT}(1) = \psi_{TT}(N), \tag{3}$$

similar for the parameter above (2) ψ_{TS}.

For the single stage with an axial direction of flow at the outlet, the dimensionless value of the difference between the static pressure at the inlet is described for a continuous mode by the relationship

$$\psi_{TS}(1) = \psi_{TT}(1) - \tfrac{1}{2} \cdot \varphi^2. \tag{4}$$

Similarly for N stages in unstall mode, the expression is

$$\psi_{TS}(N) = N\psi_{TT} - \tfrac{1}{2} \cdot \varphi^2, \tag{5}$$

i.e. it isn't means that it in N times larger than $\psi_{TS}(2)$, because

$$N\psi_{TS}(1) = N\psi_{TT}(1) - \tfrac{N}{2} \cdot \varphi^2. \tag{6}$$

It is easy to see that the right sides of equations (5) and (6) are completely different, therefore the assumption that the expression $\psi_{TS}(N) = N \cdot \psi_{TS}(2)$ is valid for compressors at the stall mode cannot be considered as a summation result of the steps pressure ψ, but can characterizes a fundamentally different hydrodynamic model. It is completely different from the model that is usually used in analysis of the unstall flow. In particular, if a partial stall is often formed in a single-stage compressor, then their multistage execution leads to a complete stall [7].

The assumption of the constancy of the dimensionless increase in pressure by one stage in the stall mode raises one more remark. The stall zone and the non-discontinuous region are characterized by the same values $\psi_{TS}(2)$. This Ψ means that during throttling of compressor at the rotational stall mode, the operating points of both of these flow zones remain unchanged. Rather, the ratio of the areas of the cross-sectional sections of the annular channel of the compressor occupied by each of both types of flow changes: with the covering of the throttle, the proportion of the cross-section occupied by the stall flow region increases. These provisions were used to determine the left branches of the pressure characteristic of the axial compressor stages based on the Yershov hypothesis of maximum energy approach.

Exit from the surge is possible by opening the throttle of the engine outlet nozzle at the moment the throttle characteristic intersects with the maximum pressure point without hysteresis and from the rotating stall – with it (Fig. 2).

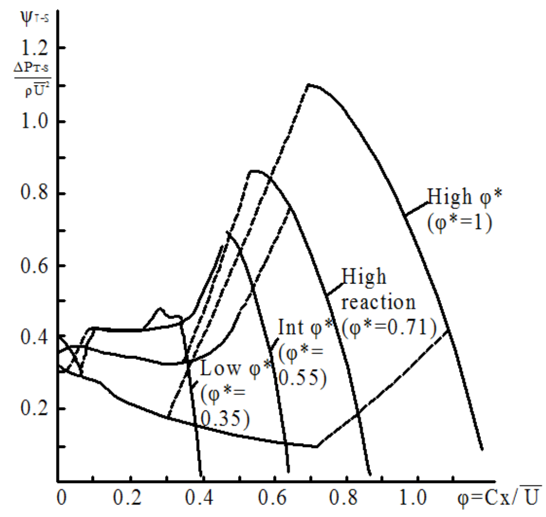

Fig. 2. Total-to-static characteristics of four three-stage constructions of different design

 ISSN 1727-7337 (print)
ISSN 2663-2217 (online)

These features require both consideration at the development of surge and at the modelling of post-stall processes [1, 15]. Also including to clarify the effect of a circumferential flow irregularities at the inlet to the compressor. The increase in circumferential flow irregularities at the compressor inlet during surge or rotating stall shifts the surge line to lower airflow [18]. And the way out of instability occurs at the points on the characteristic of violation of dynamic or static stability, respectively. It is known [11] that compressor can satisfactorily operate when the presence of large areas of flow come off. The appearance of stall is called a breakaway in the separate blade row, which does not portend loss of compressor gas-dynamic stability without taking into account the fact that under conditions of multi-stage axial compressor, the stages are mismatched, which is different manifested in the stall process in stages. Vast areas of flow come off can be without the formation of rotating stall. The listed features can naturally be taken into account in the mathematical modelling of the compressor in the engine system, especially afterburning turbofan engines, where the adjacent nodes have a significant effect on the compressor stability. The low-pressure compressor (afterburning turbofan engine fan) usually has 2-4 stages with compressor pressure ratio π_F^* increase up to 4,3 at the design mode. In this case, all stages lose stability approximately at the same time, and their characteristics break off near the maximum pressure (Fig. 2) [19]. The first stage with the flow coefficient ($\varphi^* = 0,35$) (Fig. 2) at the same time works to the left of the maximum pressure point with the subsequent formation of a partial stall and a small gap without the hysteresis loop on characteristic that turns out to be the same for matched and mismatched compressor [9, 11, 19]. The compressors with high values design flow coefficient $\varphi^* \geq 0,55$ are characterized by the formation of the complete stall with a significant hysteresis loop, which precedes a hard surge.

Such a wide variety of reasons of stall processes development indicates the sufficient complexity of the task of restoring the unstall operation of afterburning turbofan engines. Extensive physical studies of post-stall processes in F100 [1] made it possible to create a model with their reflection, which allows to deep an understanding of their development. The deep understanding of compressor system processes instability is necessary in order to further prevent gas-dynamic instability of GTE. The model is based on use of some regularities of the generalized compressor pressure characteristics during rotating stall [15, 19, 20, 21] and development of surge oscillations [10]. It was established that the irremovable surge is preceded by an irrecoverable stall, and this stall depends on duration of destabilizing disturbance [18]. In this case, there may be a situation of self-eliminating stall (Fig. 3) when opening the throttle - nozzle with a duration of less than 0,2 s for highly mechanized engines.

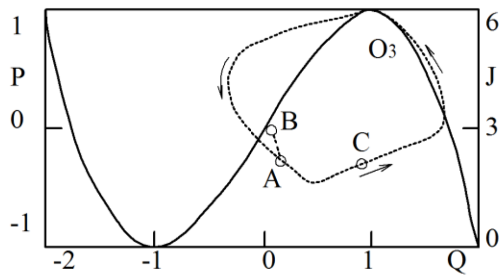

Fig. 3. Recovery from rotating stall

4. Recovery from rotating stall

In case of rotating stall at the maximum pressure point of compressor characteristic, the trajectory on the phase plane and the system operating mode point goes to the surge loop intersection point A (Fig. 3) with the characteristic of the throttle. When the throttle is covering, the system moves to the point B according to the throttle lines intersection. When the throttle is opening, the movement occurs to the opposite point C of touching the characteristics of the throttle and compressor. In [18], an attempt was made to create a general model that combining into one previously developed two separate models of surge and rotating stall [10, 15, 19], which takes into account the interaction and mutual transitions of one type of unstable mode operation to another. In this case, it is important to keep in mind frequency and time properties of the analysis processes of irrecoverable stall [22] and the identification of characteristics [23]. The process of leaving the stall mode proceeds according to the throttle characteristic that close the hysteresis loop (Fig. 2). At the same time, with repeated self-eliminating stall with surge, as a result, their recoverable stall (surge) can occur. Therefore, it is very important to prevent it by eliminating the initial disturbance, for example, flame failure, delaying its ignition [1] or oscillations in afterburner [10]. Due to the danger of the GTE compressor stalling modes has developed various mathematical models of post-stall processes [1, 2, 21, 23, 24] that are used to restore normal operation mode. For calculation of the irrecoverable stall, e.g., in the turbofan F 101X [2], the calculating transient processes program in the engine is improved, namely: the range of fan characteristics at the ends of the blades is expanded with the identification of stall conditions, including counter flow; the ignition limits are established for the fuel-air mixture. For surge and rotating stall, the calculations have satisfactory agreement with the experiment. Thus, the resulting model can be described surge, rotating stall and irrecoverable stall, similarly to [1]. In [25], for such a turbofan engine, flight conditions (H = 6–16 km, $M_п$ = 0,6–1,2) were simulated by experimental verification of protection possibility against the irremovable surge. It has been established that the engine stability is not restored when the stall duration is from 0,125 to 2,5 s. In addition, it was confirmed that unsteady heat transfer [26] adversely affects the gas-dynamic stability margin of the compressor during transient engine operating modes. In particular, with counter-throttle response, the stability margin decreases due to the high-pressure compressor, and with a sharp discharge of gas, due to the low-pressure compressor. In mathematical modelling when the engine control systems turned on [27], in contrast to [1, 2], where the surge often required an unacceptable engine shutdown with restarting. The use of variable guide vanes and air discharge from high-pressure compressor [27], regulation of fuel supply and ignition are especially effective in combination. Furthermore, it was found that compressor output from stall depends heavily on the shape of its characteristics at the equilibrium point of rotating stall and the location of the gas network characteristics [19]. Thus, a simple two-dimensional mathematical model in the form of axial compressor stages active disk at the rotating stall mode is reduced to solving the Poisson equations for ideal gas pressure (Cousins& O'Brien, 1985). It confirms that the development of stall phenomena in compressor depends on its characteristic form, hydraulic network characteristics and its volume [19, 20, 29]. So with a small volume, the loss of stability occurs in the form of rotating stall, and with a large one - surge. The known methods of actively suppressing compressor instability by periodically flow perturbing and impacting the surge or stall line which is one of the reserves for eliminating it [30]: slotted casing treatment [31, 32];control of the output (recovery) of unstall compressor operation mode, taking into account the differences in surge and rotational stall for favourable conditions [33, 34]; the manifestation of acoustic impedance [35] and parallel work of the compressors [36] of the main and bypass afterburning turbofan ducts, between them there is a dynamic interaction with a natural leakage flow of air and changes in the bypass ratio [37]. Naturally, the volume of compressor and the adjacent engine network has complex acoustic and elastic-damper effect at their removable surge due to the unsteady flow processes along the contours, unsteady transitional engine operating modes in the service conditions of a highly manoeuvrable aircraft in an disturbed atmosphere, which creates uneven and pulsating entry and disturbance conditions in any of the mechanisms of vibrational combustion and flame failure [17] in the afterburner or main combustion chamber [37]. Despite the fact that such a large list of agreed factors is unfortunately still impossible to take into account in calculations to prevent the instability of GTE. The existing ideas about the development of surge and rotating stall in axial compressors make it possible to recover the unstall operation mode of GTE, based on the patterns of characteristics changes.

Namely: the beginning of surge from the limit stall point manifests itself in the form of an intensive cyclic decrease in the airflow through the compressor to zero and negative values (Fig. 4) [33]. Further, rotating stall periodically appears in the form of separate stall zones. The possible restoration regime of unstall operation during the reverse movement along the surge loop in the direction of increasing airflow at the point of the pressure characteristic with a normal flow (Fig. 4) is being approached by control and regulation means.

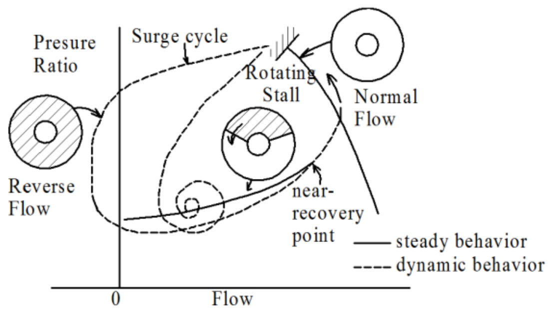

Fig. 4. Generic compressor map showing differences between surge and rotating stall

In general, surge is a more recoverable condition that rotating stall because the compressor is transiently operating on the unstalled portion of its performance characteristic for part of the surge cycle (Fig 4). As a result, surging will cease if the surge-producing mechanism is relieved i.e. throttle is opened sufficiently to prevent the stall limit from being reached). Rotating stall, however, is characterized by quasi-steady performance at a reduced flow rate and pressure rise.

5. Supervisor type engine electronic control system

A lot of attention (when creating F100 engine) was given to control system [38] to prevent the irremovable surge for both the twin-engine F-15 aircraft and the single-engine F-15 aircraft, wherein instead of hydro mechanical elements mainly the engine electronic supervisory control system (EEC) was used. Considering the positive experience of the EEC system on F100 engine, the works were done to create a fully electronic digital automatic control system ACS. It were done together with specialists from engine and aircraft manufacturers with the participation of the US Air Force. As a result, the digital ACS DEEC (Digital Electronic En-

ISSN 1727-7337 (print)
ISSN 2663-2217 (online)

gine Control) was created in a variant suitable for conducting demonstration tests on the F-100 engine taking into account the identification of its qualities.

ACS DEEC is made in the form of a fully electronic and digital, but with simplified duplication of hydromechanical regulator, allowing continuing flight of aircraft with engines at dry thrust operation mode when the main electronic system completely failed. Improving the electronics reliability is achieved by duplicating its most critical circuits.

Comprehensive design and research work around the DEEC ACS, over a five-year period (1974-1979) made it possible to establish importance of consider the flow disturbances at the engine inlet, as well as the feedback of the position of the main geometric parameters for regulating the compressor flow path, the main and afterburner fuel dispensers according to the afterburners chambers and nozzle flaps Fn.

Checking the influence of the level of perturbations at the engine inlet during compression in the air intake during complex manoeuvres of the aircraft was found that a high level of perturbations arising, for example, when control over the compression planes of the air intake fails, leads to a decrease π_c^* compared with a small level of perturbations. Such behaviour of π_c^* with the increase in the level of perturbations reduces the probability surge of the engine. Individual units bench tests led to decision to form a system from them as a whole. Further bench tests with modelling the engine as a single system were the basis for conducting ground tests on F 100 engine in F-15 aircraft system by modelling of installation of the DEEC ACS, which became the basis for preparing for flight tests [38]. A similar way to improve ACS using the DEEC system was chosen by General Electric in F101X engine, as well as for many similar afterburning turbofan engines. Detailed tests of the DEEC ACS [38], in a wide range of experimental flights, confirmed the possibility of ensuring the reliability and safety of flights by introducing regulation of the DEEC ATS via π_c^* with refusal of manual adjustments of engine performance. However, this requires a continuous check of engine systems state and the improvement of the diagnostic system in addition to the DEEC ACS that already installed on F-100 engine. At the same time, it must be recognized that the problem of afterburning turbofan instability is so complex in flight conditions that it cannot be considered finally solved to install it on F-16 single-engine aircraft, since it is characteristic of the engine design itself. A clear understanding of all interrelated (different in nature) processes, that are described above can be a success in solving such a difficult task as the elimination of surge. It is evidenced by the wide variety of afterburning turbofan subclasses of various engine manufacturers F101, F404, TF30, F119, EJ200, M.88, RB.199, RD-33, AL -31F. Distinctive features of this subclass of afterburning turbofan engines are the presence after mixing flows of main and bypass duct with parallel working compressors of the afterburner chamber. As a result the emergence of vibrational combustion leads to flame failure and it is the main root cause of the development of hydrodynamic unstable stall and surge. The possible flow leakage of air between the ducts behind the fan is accompanied by a change in the bypass ratio and certainly affects the development of stall processes. The study of this issue is also given due attention in this article, because in the above analysis of publications it was not given such attention. As is known [1, 9, 36], the natural change in the bypass ratio of a turbofan engine due to overflow affects the gas-dynamic stability of GTE.

6. Results and discussion

Analysis of bypass ratio influence on an aerodynamic characteristics of an afterburning turbofan fan is one of the main purpose of this study. It is known that bypass air from the main duct to the bypass one in turbofan engine contributes to the expansion of the range of its stable work, while increasing the bypass ratio m. However, in flight operation of afterburning turbofan engine, presence of an afterburner as a source of perturbation (when changing its operating mode) leads to a different change in the stability range and aerodynamic characteristics of the fan, which is accompanied by the mutual influence of the fan ducts, and, consequently, the engine as a whole. Blade of axial fan, as well as stages of axial compressor are initiates of the zones appearance of rotating stall as a result of separation phenomena in blade channels [39]. A particularly difficult change of the flow pattern in a fan is the transition to unstable stall processes with a significant redistribution of flow along the ducts behind the fan RB.199 [40] due to the throttling effect of the afterburner with the flap mixing device of the bypass duct air flows with the main duct gas behind the turbine and the subsequent jet nozzle.

When compressor gas-dynamic stability is violated adjacent nodes and even the separator ducts behind the fan, as is known, significantly affect the flows separation aerodynamics and the shape of rotating stall. In mathematical modelling of the violation stability process of turbofan engine, it is necessary to have information about the aerodynamic characteristics of fan that can be used to identify fan model. Such information was obtained by the authors in KhAI on a specially created experimental setup (Fig. 5) and according to the appropriate test procedure. The bypass ratio was changed by throttling with a common bench throttle after mixing of the flows behind the separator ducts and throttle rings on each duct (they were fixed to the output of the separator). As a result, the fan characteristics are obtained separately for the main (I) and bypass (II) ducts in a wide stall and unstall flow range (Fig. 6) [52].

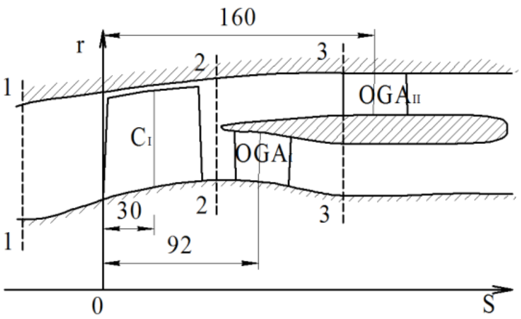

Fig. 5. Scheme of the air gas channel of the bypass fan stage

The characteristics are presented for reduced circumferential speed of the blade $U = 100\,м/с$. When the bypass ratio $m = 0,5$ (Fig. 6, a) stability violation occurred as a result of the occurrence of a six-zone partial rotating stall with a relative rotation speed $\bar{\omega}_3 = 0,59$ that subsequently transfers to a complete single-zone stall with a speed $\bar{\omega}_3 = 0,36$ with a sharp deterioration in characteristics with a break of the main contour. The partial rotating stall leads to a sharp deterioration of the characteristics of the bypass duct, while the characteristic of the main duct undergoes only a kink.

At the bypass ratio $m = 2$ (Fig. 6, c) the appearance of a complete single-zone rotating stall with $\bar{\omega}_3 = 0,5$ was appeared after irregular pressure pulsations, especially in the bypass duct with a sharp deterioration of the characteristics. The break of the characteristic of the main duct occurs without decreasing pressure and efficiency. In this case, there was a sharp decrease by 30 % of the bypass ratio. In all cases, when there is the complete stall, outflow (at the entrance of the blade) is observed.

The presented results have good correlation with preliminary studies of the stall regimes of two two-link of high-pressure fan stages with wide-chord working blades of small elongation that are close in geometrical characteristics with the presented one. In particular, detailed studies of one of the blades of the flow separation process from the suction side of the blade by visualizing the surface of the blade by oil paint are showed that the critical separation conditions are primarily achieved, similarly to the fan of afterburner turbofan engine RB.199 [40], acquiring a three-dimensional character near the hub in the dihedral angle (Fig. 7).

It is already universally recognized that the boundary layers on the surfaces of the airfoil channels of turbomachines are three-dimensional rather than two-dimensional [41, 42, 43]; therefore the flow separation is also three-dimensional. In contrast to the two-dimensional model of the appearance of rotating stall based on the separation of the two-dimensional boundary layer according to the Moore - Rott - Sears's model item (2), a three-dimensional rotating stall is modelled on a model of three-dimensional separation of the boundary layer. This separation is characterized by the presence on the surface of the blades of runoff lines (separation), which separates the continuous and separation regions with flows of various origin. This line is directed along the height of the blade and bends at the ends of the blades and is close to the limiting streamlines. At the hub, the root vortex reunites in the dihedral angle with the separations and continuous regions,

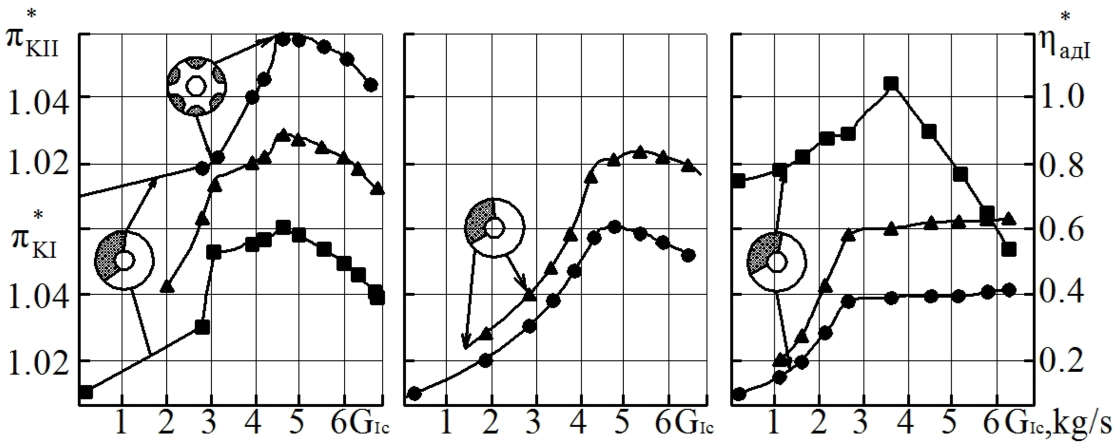

Fig. 6. Characteristics of the fan ducts in the stall and unstall flow range:

a) $m \approx 0,5$; b) $m \approx 1$; c) $m \approx 2$

■ - $\pi^*_{k\,II}$ ● $-\pi^*_{k\,I}$ ▲ $-\eta^*_I$

ISSN 1727-7337 (print)
ISSN 2663-2217 (online)

which at the tip clearance are reunited with the overflow vortex (Fig. 7).

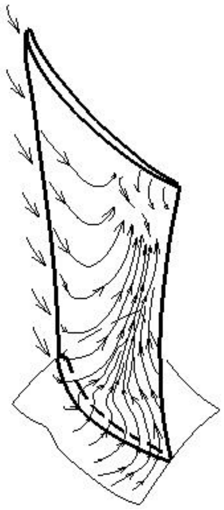

Fig. 7. Illustration of the limiting lines flow

As the main flow throttles through the blade, the limiting streamlines directed along the height of the blade, on the surface of its suction side, coincide with the lines of surface friction, and the separation line is the envelope of the limiting streamlines. Often, our habit thinking in two-dimensional categories of separation makes it difficult to understand the process of a three-dimensional separation even on relatively simple bodies, not to mention complex blade rows. That makes it difficult to explain both the three-dimensional separation and the reasons of separation. A more important reason for our inability to accurately predict the three-dimensional separation is the complexity of the analytical problem due to the addition of another third spatial coordinate. Based on the calculated attempts to develop the three-dimensional boundary layer on an elongated spheroid (an ellipsoid) of rotation, taking into account a number of results of visualizing of the flow of existing publications at that time, K. Wang [44] made a sensational statement about a “new” the three-dimensional type of separation. Although the model of the three-dimensional separation of the boundary layer was first suggested in 1956 by F. K. Moor simultaneously with [12], and then by H. Werle on axisymmetric bodies. He distributed its success in the methods of flow visualizing to studying the structure of the flow in the rotating stall zones in compressor cascade [45]. Later [46], significant successes were achieved in recognizing the flow structure with cavitation and stalling processes in axial compressors during the formation of rotating stall zones by the flow visualization methods.

Development of theoretical ideas of nonequilibrium thermodynamics by V. Yershov [7] about the occurrence of rotating stall and the determination of the left branches of the pressure characteristics $\Psi(\Phi)$ with the transition from the two-dimensional flow in the compressor airfoil cascade to the three-dimensional flow in axial turbomachines led to the condition of the blade airfoil cascades interaction along the radius r [47].

$$\frac{\partial(\Psi_{TS}\cdot\Phi)}{\partial(\Phi)}-\lambda-\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial(\Psi_{TS}\cdot\Phi)}{\partial(\Phi)'}\right]=0, \qquad (7)$$

where: λ – Lagrange multiplier,

$(\Phi)'=\dfrac{\partial(\Phi)}{\partial(r)}$ – coefficient with a fixed value at a given Φ.

The generalized pressure characteristics obtained in the work [47] that are presented in figure 8 and are used to solve equation (7).

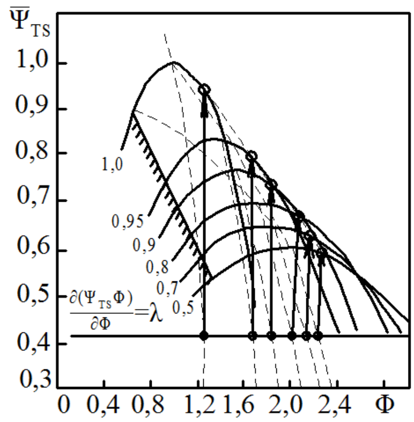

Fig. 8. Definition of joint operation modes of sections:
– Ψ_{TS};
– $\partial\Psi_{TS}\Phi/\partial\Phi$;
– $\partial^2\Psi_{TS}\Phi/\partial\Phi^2=0$;
– sections lines of joint operation modes

This kind of characteristics make it possible to determine the shape of the flow in compressor stage in the continuous region, at the boundary layer separation modes and at the rotating stall modes.

A particularly significant interaction of the airfoil cascade along the radius occurs (during the three-dimensional separation of the flow boundary layer) on the surface of the blades with a small relative diameter of the hub, which was confirmed not only by visualization (Fig. 7) but also by a generalization of the static characteristics of elementary sections along the blades height. In particular, the critical separation condition is primarily achieved at the hub, where the flow stabilizes as a result of the outflow of the boundary layer, while equation (7) takes the form (8)

$$\frac{\partial(\Psi_{TS}\cdot\Phi)}{\partial(\Phi)}=\lambda=\Psi. \qquad (8)$$

Measurement of the three-dimensional structure of the flow in the rotating stall zones in the blade, on which the aforementioned (Fig. 7) visualization of the separation in the dihedral angle was carried out by using a specially developed technique with low-inertia equipment and spherical nozzles, which was confirmed by G. Werle visual studies (Fig. 8). In addition to the significant interaction between the cross sections along the height of the blades due to the radial overflow along the surface of the boundary layer, also equally important information about previous conditions of the stall boundary in the form of periodic flow disturbances at front of the blade at the tip region with the frequency of the subsequent rotating stall was found. This interpretation is very valuable for preventing compressor instability. Both the indicated disturbances and the counterflow in the stall zone can be eliminated by the help of an annular grooves casing treatment (in the case which provides annular bypass). An equally important task is the search for criteria of the occurrence of rotating stall. In the methods of design calculation compressors, the Leiblain diffusivity factor is known as such a criterion, which is used as a criterion for assessing the aerodynamic load both when choosing the design mode with minimal losses and to determine its limiting values in a prestall mode of the two-dimensional flow.

A criterion for axial compressor for estimating the size and strength for the three-dimensional hub-corner stall is presented in [48]. The articles shows that for cases without incoming endwall boundary layer skew there is a rough correlation between the two parameters. However, the diffusion parameter, D, does not correlate with F_D when cases with incoming boundary layer skew are included. Also, for skewed incoming boundary layers there are compressor geometries a diffusion factor of $F_D = 0,7$ greater than the "critical value" of 0,6 [49] in which the passages are free of hub-corner stall.

Conclusions

The irremovable surge some unstable hydrodynamic phenomenon, that all aircraft engine manufacturers collide when create the afterburning turbofan engine. As a result of the publications analysis relevant to overcoming the various causes of emergencies on highly manoeuvrable aircraft was established that the problem of the irremovable surge is characterized by the constructive scheme of the afterburning turbofan engine with mixing flows along the contours in afterburner front. The main reason of this phenomenon is the simultaneous combination of three forms of instability: the surge and rotating stall in compressor with vibration combustion in afterburner. The brief historical digression into the beginning of the creation of the first such engines by the well-known firms TF30, F100, F101, RB199, M53, AL-31F [50], AI-322F [51] in parallel with the publication of information about the phenomenon of rotating stall, surge and vibration combustion, including participation of the authors, allowed us to come to conclusions:

- the irremovable surge is an interesting complex poorly described phenomenon;
- information about the post stall processes and recovery hydrodynamic stability in the compressors is theoretically described, however, it is practically difficult to implement, since they do not guarantee the required accident-free operation of the aircraft when entering the surge;
- requires a deeper study and modelling of the three-dimensional structure of the flow of stall phenomena in afterburning turbofan engine compressors, which would help prevent aircraft accidents due to fatal surge.

Solution of these problems as we see facilitates the holding of special association's symposia such as an ASME. We have given only the limited information about: the dynamic stall, the acoustic impedance and the three-dimensional study of the rotating stall development and individual surge models in axial compressors.

A well-adjoining direction to that discussed above topic with axial compressors is the study of systems with centrifugal compressors, and in particular turbojet engines, which significantly deepened our understanding of the development of unstable phenomena.

References (GOST 7.1 2006)

1. French, J. V. Modeling Poststall Operation of Aircraft Gas Turbine Engines [Text] / J. V. French // AIAA Paper. – 1985. – Vol. 1431. – 9 p.

2. Hosny, W. N. Turbofan Engine No Recoverable Stall Computer Simulation Development and Variation [Text] / W. N. Hosny, S. J. Bitter, W. G. Steenker // AIAA Paper. – 1985. – Vol. 1432. – 12 p.

3. Small, C. I. High Speed Compressor Rig as a Stall Recovery Research Tool [Text] / C. I. Small, J. I. Levis // AIAA Paper. – 1985. – Vol. 1428. – 10 p.

4. Gas Turbine Theory.4th edition [Text] / H. I. H. Saravanomuttoo, G. F. C. Rogers, H Cohen. – Harlow GB. : Longman, 2001. – 442 p.

5. Cheshire, L. J. The Design and Development of Centrifugal Compressors for Aircraft Gas Turbines [Text] / L. J. Cheshire // Proceedings of the Institution of Mechanical Engineers. – 1945. – Vol. 426. – P. 426 – 440.

6. Symposium on Compressor Stall, Surge and System Response [Text] // ASME. – New York. – 1960. – 56 p.

7. Yershov, V. N. Unstable Conditions of Turbodynamics, Rotating Stall [Text] / V. N. Yershov // U.S. Air Force Foreign Technology Division Translation FTD-MT-24-04-71. – 1971. – 180 p.

8. Fabri, J. Rotating stall in Axial Flow Compressor. Internal Aerodynamics, Institution of Mechanical

Engineers [Text] / J. Fabri // Conference Cambridge., Session 5: Unsteady flow effects. – London, 1967. – P. 96 – 110.

9. Greitzer, E. M. Review – Axial Compressor Stall Phenomena [Text] / E. M. Greitzer // Transactions of the ASME. Journal of Fluid Engineering. – 1980. – Vol. 1022. – P. 134 – 151.

10. Greitzer, E. M. The Stability of Pumping System – "The 1980 Freeman Scholar lecture" [Text] / E. M. Greitzer // Transactions of the ASME. Journal of Fluid Engineering. –1981. – Vol. 1032. – P. 193 – 212.

11. Compressor Aerodynamics [Text] / N. A. Cumpsty // Wiley, New York, 1989. – 552 p.

12. Emmons, H. W. Compressor Surge and Stall Propagation [Text] / H. W. Emmons, C. E. Pearson, H. P. Grant // Trans ASME. – 1955. – Vol.77. – P. 455 – 469.

13. Герасименко, В. П. В. М. Ершов зразковий приклад для наслідування, особистість, яка заслуговує виняткової поваги, - Людина з великої літери [Текст] / В. П. Герасименко // Авиационно космическая техника и технология – 2017. – № 8 (143). – С. 5-9.

14. Jackson, A. D. Stall Cell Development in an Axial Compressor [Text] / A. D. Jackson // Transactions of the ASME. Journal of Turbomachinery. – 1987. – Vol. 4. – P. 24 – 33.

15. Moore, F. K. A Theory of Rotating Stall of Multistage Axial Compressors. Part I, II, III [Text] / F. K. Moore // ASME Journal of Engineering for Power. – 1984. – Vol. 1062. – P. 313 – 336.

16. Ericsson, L. E. Dynamic Stall Analysis in Light of Recent Numerical and Experimental Results [Text] / L. E Ericsson, J. P. Reding // J. Aircraft. – 1976. – Vol. 134. – P. 248 – 255.

17. Gatsulenko, V. V. On the Problem of Control of Relaxation Oscillation of a "Singing" Flame special Modes of the Riyke Phenomenon [Text] / V. V. Gatsulenko // Journal of Engineering Physics and Thermophysics. – 2007. – Vol. 803. – P. 563 – 569.

18. Moore, F. K. Stall Transients of Axial Compression System with Inlet Distortion [Text] / F. K Moore // AIAA Paper. – 1985. – Vol. 1348. – 12 p.

19. Day, I. J. Predictions of Compressor Performance in Rotating Stall [Text] / E. M. Greitzer, N. A. Cumpsty // Trans ASME Journal of Engineering and Power. – 1978. – Vol. 1001. – P. 1 – 14.

20. Moore, F. K. A Theory of Post Stall Transients in Axial Compression Systems: Part I – Development of Equations [Text] / F. K. Moore, E. M. Greitzer // ASME Journal of Engineering for Gas Turbines and Power. – 1986. – Vol. 1081. – P. 68 – 76.

21. Greitzer, E. M A Theory of Post – stall Transients in Axial Compression Systems: Part II – Application [Text] / E. M. Greitzer, F. K. Moore // ASME Journal of Engineering for Gas Turbines and Power. – 1986. – Vol. 1082. – P. 231 – 240.

22. Rock, S. M. Application of Frequency Domain and Time Domain Analysis Tools to the Analysis of Non recoverable Stall [Text] / S. M. Rock // AIAA Paper. – 1985. – Vol. 1350. – 6 p.

23. Anex, R. P. Identificarion of Quasi – Steady in Stall Compressor Maps From Transient Data [Text] / R. P Anex, S. M. Rock // AIAA Paper. – 1985. – Vol. 1351. – 10 p.

24. Chung, K. A turbine Engine Aerodynamic Model for in – stall Transient Simulation [Text] / K. Chung, K. R. Leamy, T. P. Collins // AIAA Paper. – 1985. – Vol. 1429. – 10p.

25. Burwell, A. E. Dynamic Engine Behavior During Post Surge Operation of a Turbofan Engine [Text] / A. E. Burwell, G. T. Potterson // AIAA Paper. – 1985. – Vol. 430. – 10 p.

26. Crawford, R. A. Quantitative Evaluation of Transient Heat Transfer on Axial Flow Compressor stability [Text] / R. A. Crawford, A. E. Burwell // AIAA Paper – 1985. – Vol. 1352. – 9 p.

27. Hopf, W. R. Stall Recovery Control. Strategy Methodology and Results [Text] / W. R. Hopf, W. G. Steenken // AIAA Paper – 1985. – Vol. 1433. – 14 p.

28. Hosny, W. M. Aerodynamic Instability Performance of on Advanced High – Pressure – Ratio Compression Component [Text] / W. M. Hosny, W. G. Steenken // AIAA Paper – 1986 – Vol. 1619. – 14 p.

29. Cousins, W. T. Axial Flow Compressor Stage Post stall Analysis [Text] / W. T. Cousins, W. F. O'Brien // AIAA Paper. – 1985. – Vol. 1349. – 8 p.

30. Epstein, A. N. Active Suppression of Compressor Instabilities [Text] / A. N. Epstein, J. E. F. Williams, E. M. Greitzer // AIAA Paper. – 1986. – Vol. 1994. – 12 p.

31. Davis, M. W. A Stage – by – stage post – stall compression System modeling technique [Text] / M. W. Davis, W. F. O'Brien // AIAA Paper. – 1987. – Vol. 2088. – 14p.

32. Редин, И. И. Диагностика предпомпажного состояния осевого компрессора с надроторным устройством [Текст] / И. И. Редин, М. А. Шевченко // Авиационно-космическая техника и технология. – 2018. – № 8 (152). – С. 97-107. DOI: 10.32620/aktt.2018.8.15.

33. Boyer, K. M. Model Predictions for Improved Recoverability of a multistage Axial Flow Compressor [Text] / K. M. Boyer, W. F. O'Brien // AIAA Paper. – 1989. – Vol. 2687. – 12p.

34. Редин, И. И. Улучшение топливной эффективности газотурбинного двигателя установкой в компрессоре надроторного устройства [Текст] / И. И. Редин, М. А Шевченко // Открытые информационные и компьютерные интегрированные технологии. – 2018. – № 81. – С. 72-85. DOI: 10.32620/oikit.2018.81.08.

35. Sparks, C. R. On the Transient Interaction of Centrifugal Compressors and their Piping Systems. [Text] / C. R. Sparks // Journal of Engineering for Power. – 1983. – Vol. 1054. – P. 891 – 901.

36. Mazzawy, P. S. Multiple Segment Parallel Compressor Model for Circumferential Flow Distortion. [Text] / P. S. Mazzawy // Trans. ASME J. Engineering for Power. – 1977. – Vol. 993. – P. 203 – 213.

37. Przybylko, S. I. Application of System Identification Techniques to Post Stall Combustor Dynamics [Text] / S. I. Przybylko // AIAA Paper. – 1985. – Vol. 1353. – 8 p.

38. Barrett, W. J. Flight Test of a Full Authority Digital Electronic Engine Control System in an F15 Aircraft [Text] / W. J. Barrett, J. P. Rembold // AIAA Paper. – 1981. – Vol. 1501. – 9 p.

39. Zoppellari, S. Analytical Modeling of Rotating Stall and Surge [Text] : Ph. Doctorate Thesis. Cranfteld University, 2014. – 23 p.

40. Schaffler, A. Experimental Evaluation of Heavy Fan-High-Pressure Compressor Interaction in a Three-Shaft Engine: Part II – Analysis of Distortion and Fan Loading [Text] / A Schaffler, D. C. Miatt // Journal of Engineering for Gas Turbines and Power – 1986. – Vol. 1081. – P. 171 – 174.

41. Xianjun, Yu. A Prediction Model for Corner Separation Stall in Axial Compressors [Text] / Yu. Xianjun, Liu Baojie // Proceedings of ASME Turbo Expo 2010: Power for Land, Sea and Air, GT2010-22453. DOI: 10.1115/GT2010-22453.

42. Teng, Fei. Investigation of the Dihedral Angle Effect on the Boundary Layer Development Using Special-Shaped Expansion Pipes [Text] / Fei. Teng, Ji. Lucheng, Yi. Weilin // Proceedings of ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition, GT2018-76383. DOI: 10.1115/GT2018-76383.

43. Jiabin, Li. An Improved Prediction Model for the Corner Stall in Axial Compressors with the Dihedral Effect I: Principle and Validation [Text] / Li. Jiabin, Ji. Lucheng // Proceedings of ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition, GT2019-90712. DOI: 10.1016/j.cja.2019.12.031.

44. Wang, K. C. Separating Patterns of Boundary Layer over an Inclined Body of Revolution [Text] / K. C. Wang // AIAA Journal. – 1972. – Vol. 10. – P. 1044 – 1050.

45. Werle, H. Ecoulement ans une maquette hydraulique De Turbomachine axiale [Text] / H. Werle, M. Garlon // La Recherche Aerospatiale. – 1977. – Vol. 5. – P. 267 – 288.

46. Visualizations of Flow Structures in the Rotor Passage of an Axial Compressor at the Onset of Stall [Text] / H. Chen, D. Tan, Y Li, I. Katz // Proceedings of ASME Turbo Expo 2016: Turbomachinery Technical Conference, GT 2016-57054. DOI: 10.1115/1.4035076.

47. Герасименко, В. П. Анализ процессов и разработка методов повышения эффективности компрессоров на нерасчетных режимах работы [Текст] : автореф. дис. … д-ра техн. наук : 05.04.12 / Герасименко Владимир Петрович. – Харьков, ХПИ, 1993. – 38 с.

48. Lei, V. M. A Criterion for Axial Compressor Hub-Corner Stall [Text] / V. M. Lei, Z. S. Spakovszky, E. M. Greitzer // Proceedings of ASME Turbo Expo 2006: Power for Land, Sea and Air, GT 2006-91332. DOI: 10.1115/GT2006-91332.

49. Lieblein, S. Aerodynamic Design of Axial-flow Compressors. VI - Experimental Flow in Two-Dimensional Cascades [Text] / S. Lieblein // Research memorandum, NACA RM E55KOla, National Advisory Committee for Aeronautics.

50. Герасименко В. П. До річниці академіка А. М. Люльки [Текст] / В. П. Герасименко // Інтегровані комп'ютерні технології в машинобудуванні ІКТМ 2018 : тез. доп. Всеукр. наук. – техн. конф., 31 октября – 3 ноября 2018 р. – Харьков, 2018. – Т. 2. – С. 60 – 61.

51. Кравченко, И. Ф. Определение области запуска форсажной камеры сгорания в эксплуатационном высотно-скоростном диапазоне применения самолета при испытаниях ТРДДФ разработки ГП “Ивченко-Прогресс” на стенде в термобарокамере [Текст] / И. Ф. Кравченко, Д. В. Козел // Авиационно космическая техника и технология. – 2016. – № 8 (135). – С. 46-50.

52. Влияние степени двухконтурности на аэродинамические характеристики вентилятора [Текст] / В. П. Герасименко, В. Н. Ершов, В. А. Коваль и др. // Известия высших учебных заведений. Авиационная техника. – 1978. – Т. 1. – С. 108-111.

References (BSI)

1. French, J. V. Modeling Poststall Operation of Aircraft Gas Turbine Engines. *AIAA Paper*, 1985, vol. 1431. 9 p.

2. Hosny, W. N., Bitter, S. J., Steenker, W. G. Turbofan Engine No Recoverable Stall Computer Simulation Development and Variation. *AIAA Paper*, 1985, vol. 1432. 12 p.

3. Small, C. I., Levis, J. I. High Speed Compressor Rig as a Stall Recovery Research. *AIAA Paper*, 1985, vol. 1428. 10 p.

4. Saravanomuttoo, H. I. H., Rogers, G. F. C., Cohen, H. Gas Turbine Theory. 4th edition. Harlow GB. Longman, 2001. 442 p.

5. Cheshire, L. J. The Design and Development of Centrifugal Compressors for Aircraft Gas Turbines. *Proceedings of the Institution of Mechanical Engineers*, 1945, vol. 426, pp. 426 – 440.

6. Symposium on Compressor Stall, Surge and System Response. *ASME*, New York, 1960. 56 p.

7. Yershov, V. N. Unstable Conditions of Turbodynamics, Rotating Stall. U.S. *Air Force Foreign Technology Division Translation FTD-MT-24-04-71*, 1971. 180 p.

8. Fabri, J. Rotating stall in Axial Flow Compressor. Internal Aerodynamics, Institution of Mechanical Engineers. *Conference Cambridge, Session 5: Unsteady flow effects*, London, 1967, pp. 96–110.

9. Greitzer, E. M. Review – Axial Compressor Stall Phenomena. *Transactions of the ASME: Journal of Fluid Engineering*, 1980, vol. 1022, pp. 134–151.

10. Greitzer, E. M. The Stability of Pumping System – “The 1980 Freeman Scholar lecture”. *Transactions of the ASME: Journal of Fluid Engineering*, 1981, vol. 1032, pp. 193–212.

11. Cumpsty, N. A. *Compressor Aerodynamics*. New York, Wiley Publ., 1989. 552 p.

12. Emmons, H. W., Pearson, C. E., Grant, H. P. Compressor Surge and Stall Propagation. *Transactions of the ASME*, 1955, vol. 77, pp. 455–469.

13. Gerasimenko, V. P. *V. N. Yershov zrazkovy`j pry`klad dlya nasliduvannya, osoby`stist`, yaka zaslugovuye vy`nyatkovoyi povagy`, - Lyudy`na z vely`koyi litery`* [V. N. Yershov is an exemplary example to follow, a person who deserves exceptional respect –

ISSN 1727-7337 (print)
ISSN 2663-2217 (online)

A man with the capital letter]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2017, no. 8 (143), pp. 5-9.

14. Jackson, A. D. Stall Cell Development in an Axial Compressor. *Transactions of the ASME. Journal of Turbomachinery*, 1987, vol. 4, pp. 24–33.

15. Moore, F. K. A Theory of Rotating Stall of Multistage Axial Compressors. Part I, II, III. *ASME Journal of Engineering for Power*, 1984, vol. 1062, pp. 313–336.

16. Ericsson, L. E., Reding, J. P. Dynamic Stall Analysis in Light of Recent Numerical and Experimental Results. *J. Aircraft,* 1976, vol. 134, pp. 248–255.

17. Gatsulenko, V. V. On the Problem of Control of Relaxation Oscillation of a "Singing" Flame special Modes of the Riyke Phenomenon. *Journal of Engineering Physics and Thermophysics*, 2007, vol. 803, pp. 563–569.

18. Moore, F. K. Stall Transients of Axial Compression System with Inlet Distortion. *AIAA Paper*, 1985, vol. 1348. 12 p.

19. Day, I. J., Greitzer, E. M., Cumpsty, N. A. Predictions of Compressor Performance in Rotating Stall. *Transactions of the ASME Journal of Engineering and Power*,1978, vol. 1001, pp. 1–14.

20. Moore, F. K., Greitzer, E. M. A Theory of Post Stall Transients in Axial Compression Systems: Part I – Development of Equations. *ASME Journal of Engineering for Gas Turbines and Power*, 1986, vol. 1081, pp. 68–76.

21 Greitzer, E. M., Moor, F. K. A Theory of Post – stall Transients in Axial Compression Systems: Part II – Application. *ASME Journal of Engineering for Gas Turbines and Power*, 1986, vol. 1082, pp. 231–240.

22. Rock, S. M. Application of Frequency Domain and Time Domain Analysis Tools to the Analysis of Non recoverable Stall. *AIAA Paper*, 1985, vol. 1350. 6 p.

23. Anex, R. P., Rock, S. M. Identificarion of Quasi – Steady in Stall Compressor Maps From Transient Data. *AIAA Paper*, 1985, vol. 1351. 10 p.

24. Chung, K., Leamy, K. R., Collins, T. P. A turbine Engine Aerodynamic Model for in – stall Transient Simulation. *AIAA Paper*, 1985, vol. 1429. 10 p.

25. Burwell, A. E., Potterson, G. T. Dynamic Engine Behavior During Post Surge Operation of a Turbofan Engine. *AIAA Paper*, 1985, vol. 430. 10 p.

26. Crawford, R. A., Burwell, A. E. Quantitative Evaluation of Transient Heat Transfer on Axial Flow Compressor stability. *AIAA Paper*, 1985, vol. 1352. 9 p.

27. Hopf, W. R., Steenken, W. G. Stall Recovery Control. Strategy Methodology and Results. *AIAA Paper*, 1985, vol. 1433. 14 p.

28. Hosny, W. M., Steenken, W. G. Aerodynamic Instability Performance of on Advanced High – Pressure – Ratio Compression. *AIAA Paper*, 1986, vol. 1619. 14 p.

29. Cousins, W. T., O'Brien, W. F. Axial Flow Compressor Stage Post stall Analysis. *AIAA Paper*, 1985, vol. 1349. 8 p.

30. Epstein, A. N., Williams, J. E. F., Greitzer, E. M. Active Suppression of Compressor Instabilities. *AIAA Paper*, 1986, vol. 1994. 12 p.

31. Davis, M. W., O'Brien, W. F. A Stage – by – stage post – stall compression System modeling technique. *AIAA Paper*, 1987, vol. 2088. 14p.

32. Redin, I. I., Shevchenko, M. A. *Diagnostika predpompazhnogo sostoyaniya osevogo kompressora s nadrotornym ustroistvom* [Diagnostics of Pre-Surge Condition of the Axial Compressor with the Annular Grooves Casing Treatment]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2018, no. 8 (152), pp. 97–107. DOI: 10.32620/aktt.2018.8.15.

33. Boyer, K. M., O'Brien, W. F. Model Predictions for Improved Recoverability of a multistage Axial Flow Compressor. *AIAA Paper*, 1989, vol. 2687. 12 p.

34. Redin, I. I., Shevchenko, M. A. Uluchshenie toplivnoi effektivnosti gazoturbinnogo dvigatelya ustanovkoi v kompressore nadrotornogo ustroistva [Improving the Fuel Efficiency of a Gas Turbine Engine by Installing in the Compressor a Casing Treatment]. *Otkrytye informatsionnye i komp'yuternye integrirovannye tekhnologii – Open information and computer integrated technologies*, 2018, no. 81, pp. 72–85. DOI: 10.32620/oikit.2018.81.08.

35. Sparks, C. R. On the Transient Interaction of Centrifugal Compressors and their Piping Systems. *Journal of Engineering for Power*, 1983, vol. 1054, pp. 891–901.

36. Mazzawy, P. S. Multiple Segment Parallel Compressor Model for Circumferential Flow Distortion. *Transactions of the ASME J. Engineering for Power*, 1977, vol. 993, pp. 203–213.

37. Przybylko, S. I. Application of System Identification Techniques to Post Stall Combustor Dynamics. *AIAA Paper*, 1985, vol. 1353. 8 p.

38. Barrett, W. J., Rembold, J. P. Flight Test of a Full Authority Digital Electronic Engine Control System in an F15 Aircraft. *AIAA Paper*, 1981, vol. 1501. 9 p.

39. Zoppellari, S. *Analytical Modeling of Rotating Stall and Surge*. Ph. Doctorate Thesis. Cranfteld University, 2014. 23 p.

40. Schaffler, A., Miatt, D. C. Experimental Evaluation of Heavy Fan-High-Pressure Compressor Interaction in a Three-Shaft Engine: Part II – Analysis of Distortion and Fan Loading. *Journal of Engineering for Gas Turbines and Power*, 1986, vol. 1081, pp. 171–174.

41. Xianjun, Yu, Baojie, Liu Prediction Model for Corner Separation Stall in Axial Compressors. *Proceedings of ASME Turbo Expo 2010: Power for Land, Sea and Air*, GT2010-22453. DOI: 10.1115/GT2010-22453.

42. Teng, Fei., Lucheng, Ji., Weilin, Yi. Investigation of the Dihedral Angle Effect on the Boundary Layer Development Using Special-Shaped Expansion Pipes. *Proceedings of ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition*, GT2018-76383. DOI: 10.1115/GT2018-76383.

43. Jiabin, Li., Lucheng, Ji. An Improved Prediction Model for the Corner Stall in Axial Compressors with the Dihedral Effect I: Principle and Validation. *Proceedings of ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition*, GT2019-90712. DOI: 10.1016/j.cja.2019.12.031.

44. Wang, K. C. Separating Patterns of Boundary Layer over an Inclined Body of Revolution. *AIAA Journal*, 1972, vol. 10, pp. 1044–1050.

45. Werle, H., Garlon, M. Ecoulement ans une maquette hydraulique De Turbomachine axiale. *La Recherche Aerospatiale*,1977, vol. 5, pp. 267–288.

46. Chen, H., Tan, D., Li, Y., Katz, I. Visualizations of Flow Structures in the Rotor Passage of an Axial Compressor at the Onset of Stall. *Proceedings of ASME Turbo Expo 2016: Turbomachinery Technical Conference*, GT 2016-57054. DOI: 10.1115/1.4035076.

47. Gerasimenko, V. P. *Analiz protsessov i razrabotka metodov povysheniya effektivnosti kompressorov na neraschetnykh rezhimakh raboty.* Avtoref. dis. dokt. teh. nauk [Process Analysis and Creating of Compressors Efficiency Improvement Methods at Off – Design Modes. Dr. eng. sci. thesis]. Kharkov, National Technical University “Kharkiv Polytechnic Institute”, 1993. 38 p.

48. Lei, V. M., Spakovszky, Z. S., Greitzer, E. M. A Criterion for Axial Compressor Hub-Corner Stall. *Proceedings of ASME Turbo Expo 2006: Power for Land, Sea and Air,* GT 2006-91332. DOI: 10.1115/GT2006-91332.

49. Lieblein, S. Aerodynamic Design of Axial-flow Compressors. VI - Experimental Flow in Two-Dimensional Cascades. *Research memorandum, NACA RM E55KOla, National Advisory Committee for Aeronautics.*

50. Gerasimenko, V. P. *Do richny`ci akademika A. M. Lyul`ky`* [To anniversary of academician A. M. Lyulka] *Integrovani komp'yuterni tekhnologiï v mashinobuduvanni IKTM 2018. tez. dop. Vseukr. nauk. – tekhn. konf., 31 oktyabrya – 3 noyabrya 2018 y*. [Integrated Computer Technologies in Mechanical Engineering ICTME 2018: Thesis. add Allukr. sciences - Tech. Conf., October 31 - November 3, 2017]. Kharkiv, 2018, vol. 2, pp. 60–61.

51. Kravchenko, I. F., Kozel D. V. Opredelenie oblasti zapuska forsazhnoi kamery sgoraniya v ekspluatatsionnom vysotno-skorostnom diapazone primeneniya samoleta pri ispytaniyakh TRDDF razrabotki GP “Ivchenko-Progress” na stende v termobarokamere [Afterburner Starting Range Testing for Aircraft Altitude-Velocity Operational Conditions During the Test of SE “Ivchenko-Progress” Developed Engine in the Climatic Test Bench]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2016, no. 8 (135), pp. 46-50.

52. Gerasimenko, V. P., Yershov, V. N., Koval, V. A., Pavlenko, G. V. Vliyanie stepeni dvukhkonturnosti na aerodinamicheskie kharakteristiki ventilyatora [The influence of the bypass ratio on the aerodynamic characteristics of the fan]. *Izvestiya vysshikh uchebnykh zavedenii. Aviatsionnaya tekhnika – Proceedings of higher educational institutions. Aviation technology*, 1978, vol. 1, pp. 108–111.

Поступила в редакцию 12.03.2020, рассмотрена на редколлегии 15.08.2020

СТВОРЕННЯ ТРДДФ – ІСТОРІЯ І СУЧАСНІСТЬ

В. П. Герасименко, В. А. Даценко, М. А. Шевченко

Шляхом історичного аналізу розкриті основні проблеми створення ТРДДФ, серед яких – неусувний помпаж компресора. Згідно опублікованим моделям такий помпаж представляє собою гідродинамічну нестійкість в формі взаємопереходів обертового зриву в помпаж при первинній нестійкості в виді зриву потоку в форсажній камері згорання, або вібраційному горінні. Серійний двигун F100, створений на базі TF30, фірми «Pratt & Whitney» - один з перших, в якому був виявлений неусувний помпаж, в результаті чого зазнали аварії кілька літаків F-15, через неможливість відновлення стійкого режиму роботи компресора без зупинки і повторного запуску двигуна. Дослідження проблеми з цим явищем привели до висновку про те, що ця проблема неусувного помпажу породжена самою конструкцією двигуна. Для її усунення фірмі довелося допрацьовувати кілька систем, як наприклад, електронну систему управління двигуном, подачу палива форсажній камері по поясах розташування форсунок, вогневої доріжки, стабілізації горіння, подовжувача розділення потоків по контурах та ін. Особливі труднощі виникали, судячи з аналізу публікацій, з відновленням безпомпажної роботи таких двигунів. Примітно, що в нинішніх умовах на літаку F-35 встановлені двигуни F-135-PW100, попередниками яких є F-100 з такими ж проблемами. Для поглиблення в процес зривного обтікання вентиляторних лопаток, виникнення обертового зриву і помпажу ТРДДФ наведені в статті результати експериментальних досліджень двоконтурного вентилятора. Імітація збурень від вібраційного горіння в форсажній камері згоряння на границя зриву вентилятора в системі ТРДДФ в стендових умовах здійснювалася незалежним дроселюванням контурів в широкому діапазоні зміни ступеня двоконтурності. Численні монографії і публікації з вібраційного горіння, зокрема в форсажних камерах згоряння ТРДФ AL-21F і ТРДДФ AL-31F А.М. Люльки підтверджують можливість розповсюдження збурень проти потоку в зовнішньому контурі і неможливість їх поширення через турбіни. Поширення помпажних коливань в ТРДДФ на компресор внутрішнього контуру за вентилятором відбувається шляхом взаємодії контурів. Забезпечення запасів стійкої роботи компресорів в двигуні - більш надійний спосіб запобігання аварійним ситуаціям ніж вихід з помпажу. Оцінку запасу беззривної роботи традиційно здійсненої за значеннями фактора дифузорності Лібляйна, який можна застосувати в 2D розрахунках. Для реалізації тривимірних течій застосований інтегральний варіаційний принцип нерівноважної термодинаміки «Максимуму потоку механічної енергії» В. М. Єршова.

Ключові слова: авіація; двоконтурний турбореактивний двигун; компресор; форсажна камера згоряння; обертовий зрив; помпаж.

СОЗДАНИЕ ТРДДФ - ИСТОРИЯ И СОВРЕМЕННОСТЬ

В. П. Герасименко, В. А. Даценко, М. А. Шевченко

Путем исторического анализа раскрыты основные проблемы создания ТРДДФ, среди которых – неустранимый помпаж компрессора. Согласно опубликованным моделям такой помпаж представляет собой гидродинамическую неустойчивость в форме взаимопереходов вращающегося срыва в помпаж при первопричине неустойчивости в виде срыва потока в форсажной камере сгорания или вибрационного горения. Серийный двигатель F100, созданный на базе опытного TF30, фирмы «Pratt & Whitney» - один из первых, в котором был обнаружен неустранимый помпаж, в результате чего потерпело аварию несколько самолетов F-15, так как не мог быть восстановлен устойчивый режим работы компрессора без останова и повторного запуска двигателя. Вскрытие проблемы с данным явлением привели к выводу о том, что проблема неустранимого помпажа порождена самой конструкцией двигателя. Для ее устранения фирме пришлось дорабатывать несколько систем, как например, электронную систему управления двигателем, топливопитания форсажной камеры по поясам расположения форсунок, огневой дорожки, стабилизации горения, удлинителя разделения потоков по контурам и др. Особые трудности возникали, судя по анализу публикаций, с восстановлением (recoverable) безпомпажной работы таких двигателей. Примечательно, что в нынешних условиях на самолете F-35 установлены двигатели F-135-PW100, предшественниками которых является F-100 с такими же проблемами. Для углубления в процесс срывного обтекания вентиляторных лопаток, возникновения вращающегося срыва и помпажа ТРДДФ приведены в статье результаты экспериментальных исследований двухконтурного вентилятора. Имитация возмущений от вибрационного горения в форсажной камере сгорания на границу срыва вентилятора в системе ТРДДФ в стендовых условиях осуществлялась независимым дросселированием контуров в широком диапазоне изменения степени двухконтурности. Многочисленные монографии и публикации по вибрационному горению, в частности в форсажных камерах сгорания ТРДФ AL-21F и ТРДДФ AL-31F А. М. Люльки подтверждают возможность распространения возмущений против потока в наружном контуре и невозможность их распространения через турбины. Распространение помпажных колебаний в ТРДДФ на компрессор внутреннего контура за вентилятором происходит путем взаимодействия контуров. Обеспечение запасов устойчивой работы компрессоров в двигателе – более надежный способ предотвращения аварийных ситуаций чем вывод (recovery) из помпажа. Оценку запаса безсрывной работы традиционно осуществленной по значениям фактора диффузорности Либляйна, который применим в 2D расчетах. Для реализации трехмерных течений применен интегральный вариационный принцип неравновесной термодинамики «максимума потока механической энергии» В. М. Ершова.

Ключевые слова: авиация; двухконтурный турбореактивный двигатель; компрессор; форсажная камера сгорания; вращающийся срыв; помпаж.

Герасименко Владимир Петрович – д-р техн. наук, проф., проф. каф. теории авиационных двигателей, Национальный аэрокосмический университет им. Н. Е. Жуковского «Харьковский авиационный институт», Харьков, Украина.

Даценко Вадим Анатольевич – асп. каф. теории авиационных двигателей, Национальный аэрокосмический университет им. Н. Е. Жуковского «Харьковский авиационный институт», Харьков, Украина.

Шевченко Михаил Анатольевич – асп. каф. теории авиационных двигателей, Национальный аэрокосмический университет им. Н. Е. Жуковского «Харьковский авиационный институт», Харьков, Украина.

Volodymyr Gerasimenko – Doctor of Science, Professor at the department of Aviation Engines Theory, National Aerospace University “Kharkiv Aviation Institute”, Kharkiv, Ukraine,
e-mail: vpgerasimenko40@gmail.com, ORCID Author ID: 0000-0003-2755-6239.

Vadym Datsenko – PhD student at the department of Aviation Engines Theory, National Aerospace University “Kharkiv Aviation Institute”, Kharkiv, Ukraine,
e-mail: datsenkovadym@gmail.com , ORCID Author ID: 0000-0002-0650-562X.

Mikhail Shevchenko – PhD student at the department of Aviation Engines Theory, National Aerospace University “Kharkiv Aviation Institute”, Kharkiv, Ukraine,
e-mail: mikleshevchenko@gmail.com, ORCID Author ID: 0000-0002-0806-6632, ResearcherID: I-1215-2018.