Method for Determining the Applicability of an Air Turbine for Operation in a Gas Turbine Engine Launch System

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Keywords: Auxiliary Power Unit, Air Turbine, Joint Operation, Gas Turbine Engine, Start-up Time, Torque.

Abstract: The paper describes the methodology developed by the authors for matching the working process of the auxiliary power unit and the air turbine used when starting the engine The need for this technique is caused by an extremely small number of publications on this topic. The developed technique can be used to determine the possibility of starting a gas turbine engine, as well as to calculate its time and main parameters under all operating conditions (including in flight) and to select new auxiliary power units or an air turbine for an existing system. The developed technique considers structural, strength, operational and other limitations. The results were implemented as a computer program.

NOMENCLATURE

GTE - gas turbine engine
APU - auxiliary power unit
NGV - nozzle guide vane
ATS - air turbo starter
IGV - inlet guide vane
K_G - mass flow parameter
K_N - power parameter
P - pressure
T - temperature
G - mass flow rate
α_{IGV} - IGV stagger angle
π - pressure ratio
ΔG - losses (bleeding) of air flow in the aircraft
Δp^* - total pressure losses in the aircraft ducts
ΔT^* - total temperature losses in the aircraft ducts
N - power
p_h - ambient pressure
t_h - ambient temperature
J - moment of inertia
ω - angular velocity
n - rotational speed
M - torque
τ - time

1 INTRODUCTION

The start of an aircraft gas turbine engine is an important mode that largely determines the safety, operational efficiency and reliability of the engine and the aircraft. The gas turbine engine start-up system includes a whole set of different devices and units: a starter, auxiliary power unit, air and fuel systems, automatic control system, transmission, power supply system, ignition system, etc. For reliable engine start-up, the operation of all the devices must be consistent with each other.

The starting system is a "secondary" engine system. A quick analysis of scientific and technical publications on the topic of improving working processes and the design of aviation gas turbine engines showed that there are only a few works relating to this system. However, without a starting system, the operation of any engine will be impossible (it simply will not "turn on").

In the early years of jet aircrafts, the JASU or impingement starter was often used to launch a gas turbine engine. Today, the use of such units has been continued in the universal UNIJASU, which are used in the US Navy (Zoccoli and Cheeseman, 1998).

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However, many decades ago, engineers concluded that the most preferred engine starting system from the efficiency, versatility and reliability of start-up process point is an air turbine mechanically coupled to a gas turbine rotor receiving compressed air from an APU compressor (Figure 1). The advantages of such a system include high specific power, simple design, etc. (Von Flue, 1967). Among the shortcomings of the start systems with ATS, the mandatory need for APU, as a source of compressed air for turbine operation must be mentioned. However, this drawback is not critical, since the APU is used for many other purposes on board of the aircraft, for example, it provides the air conditioning system on the ground and when preparing for the departure.

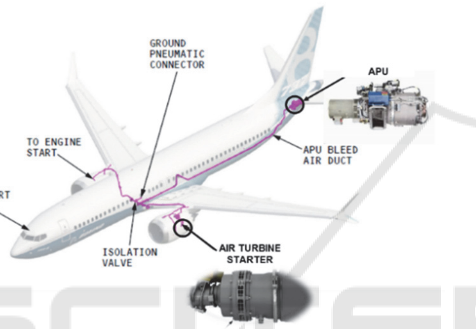

Figure 1: Schematic diagram of the launch system with ATS.

One of the important advantages of the starting system with ATS is the ability to ensure restarting of the engine under any environmental conditions (including in flight). Such an opportunity is important not only for military engines, as it may seem at first glance, but also for civil aviation.

The following requirements were imposed on the launch system:

1) the operation of the ATS must be matched with the work of the APU at all operating modes (under various atmospheric conditions, speeds and altitudes);
2) the GTE startup time must be minimized;
3) the torque at the output shaft must not exceed the maximum value according to the strength conditions of the reduction gearbox and gear box of the engine drives.

The paper's authors work at the Department of Aircraft Engine Theory of Samara National Research University (2020). They have extensive experience in studying and improving the workflow of various components of a gas turbine engine (Matveev et. al., 2018). Currently, the scientific group collaborates with various enterprises that are the part of the United Engine Corporation (Russia) (2020). One of the Customers set the task of assessing the feasibility of using air turbo-starters manufactured at the enterprise to launch a turbojet engine of the same class with a new design.

Before solving this problem, information was searched on the modern gas turbine engine start-up systems and methods for increasing their effectiveness in scientific and technical literature. The authors were unable to find methods for solving the problem. Moreover, an extremely small number of publications on a topic of interest were found. If work on optimizing the turbine workflow is found (Marchukov et. al., 2018; Salnikov and Danilov, 2019), then not a single work has raised the issue of matching the turbine and APU workflow. The following is a brief overview of some of the found articles.

A detailed simulation of the acceleration of a turboshaft engine during a restart from "standby" to idle mode was considered in (Ferrand et. al., 2018). The authors examined in detail the change in the efficiency of fuel combustion during transients in a starting the engine, and examined the effect of heating the engine structure during the start-up on power losses. In their work, they focused on the processes in the engine, because they used an electric starter in a test unit.

Tan et. al., 2018 in their work paid attention to the development of the control law of starting the gas turbine engines using ATS based on its throttle characteristics. The authors estimated the required starter power when starting the gas turbine engine at various altitudes and flight speeds and under various environmental conditions. At the same time, the authors in their work did not delve into the processes occurring in the ATS.

The account of the processes occurring in the ATS and its design for the engine of a large marine ship/ground gas turbine was studied in the work of (Park et. al., 2015). Due to the specifics of using the ATS in terrestrial conditions, the authors considered only one mode of ATS operation with constant inlet parameters.

No information was found in open sources about the start of an aircraft gas turbine engine using ATS and their matching at all operating modes of the APU while monitoring important operational parameters (maximum torque and start time).

Based on the few information found, the main goal of the work was formulated: the development of a methodology for determining the possibility of joint operation of an air turbo starter of a GTE with an

APU, the determination of the engine start time and other system parameters in given flight conditions.

2 DETERMINATION OF THE POSSIBILITY OF APU AND ATS JOINT WORK

The most important key to the successful operation of the start system is the coordination of the APU and ATS. Indeed, if the maximum efficiency of ATS or the required design power can only be reached at compressed air flow rates or pressure levels inaccessible to the APU, the required characteristics of the whole start system will never be achieved.

For existing APU and ATS, the task of improving start-up characteristics, for example, reducing the start time of an aircraft gas turbine engine, can also be set. In this case, the need to increase the power of the ATS is implied, but at the same time, parameters must be monitored, exceeding which can lead to the destruction of one of the elements of the start system. One of such parameters-indicators of dangerous loads can be the maximum allowable torque on the output shaft of the ATS. Its excessive value can lead, for example, to damage of the parts of the engine accessory-gear box.

Since the methodology for matching the operation of the ATS and APU was not found when studying the literature, the authors had to develop it independently. The methodology is based on the following assumptions:

- characteristics of the APU and ATS are determined separately from each other. Then, they are presented as the dependences of APU and ATS parameters from the expansion/compression ratio of the working fluid π;

- matching the characteristics of the APU and ATS is carried out according to the given mass flow parameter K_G. It is defined as follows:

$$K_G = \frac{G_{ATSinput} \cdot \sqrt{T^*_{ATSinput}}}{p^*_{ATSinput}} \quad (1)$$

where $G_{ATSinput}$ - the value of air mass flow rate through the ATS;

$T^*_{ATSinput}$ - the value of the total temperature at the ATS inlet;

$p^*_{ATSinput}$ - the value of the total pressure at the ATS inlet.

The APU operation is typically described by the following dependencies:

– dependence of the total pressure of the bleed air from the APU $p^*_{APUoutlet}$ from its mass flow rate $G_{APUoutlet}$ ($p^*_{APUoutlet} = f(G_{APUoutlet})$);

– dependence of the total temperature of the bleed air from the APU $T^*_{APUoutlet}$ from its mass flow rate $G_{APUoutlet}$ ($T^*_{APUoutlet} = f(G_{APUoutlet})$).

The characteristics of the APU can be presented for several conditions of its operation, characterized by flight altitude H, flight Mach number and temperature of ambient (atmospheric) air t_h (Figure 2 and 3) (Inozemzev et al., 2008). These characteristics represent the dependence of pressure and temperature in the APU pipeline under various flight conditions (altitudes and speeds) and different positions of the regulatory elements (for example, when changing the stagger angles α_{igv} of the inlet guide vane). The parameters of the APU, the characteristics of which are shown in Figures 2 and 3 are presented in table 1.

Table 1: The main parameters of the APU.

Mass flor rate of the extracted air, kg/s	1.7
Pressure of the extracted air, atm	4.7
Temperature of the extracted air, °C	230
Electric power, kW	60
Equivalent power, kW	335
Weight, kg	190

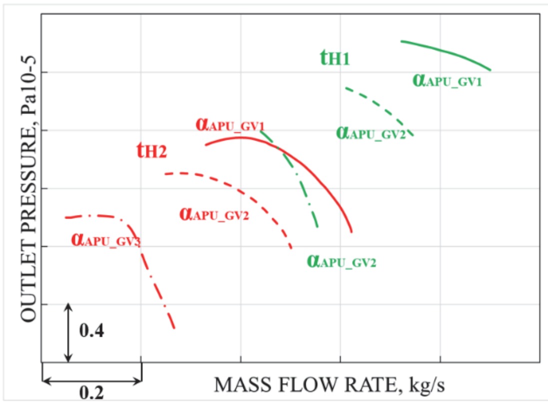

Figure 2: Changing the pressure of the working fluid at the APU outlet depending on the mode of its operation.

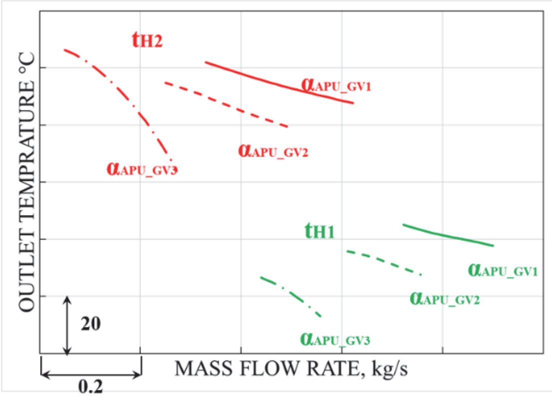

Figure 3: Changing the temperature of the working fluid at the APU outlet depending on the mode of its operation.

As can be seen from Figure 4, air is taken from the APU with the parameters $G_{APUoutlet}$, $p^*_{APUoutlet}$, $T^*_{APUoutlet}$. It goes to the ATS entrance through the main pipelines of the aircraft. At the same time, there are hydraulic losses and leaks in the lines, which are characterized by the values ΔG, Δp^*, ΔT^*. Compressed air passing through the ATS turbine is discharged into the atmosphere.

To match the operation of the ATS and APU, the characteristics of the latter are transformed to the form of $K_{G\,\mathrm{APU}} = f(\pi_{\mathrm{APU}})$. In this case, it is necessary to consider the interaction of the APU and ATS. The interaction scheme between the APU and the ATS parameters is shown in Figure 4.

The condition for the joint work of the APU and ATS, considering Figure 4, can be represented using the following equalities:

$$\pi_{APU} = \frac{p^*_{APUoutlet}}{p_h} = \frac{p^*_{\mathrm{ATSinput}} + \Delta p^*_{hydr.}}{p_h} = \pi_{ATS} + \frac{\Delta p^*_{hydr.}}{p_h} \quad (2)$$

$$T^*_{\mathrm{APUoutlet}} - \Delta T^* = T^*_{\mathrm{ATSinput}} \quad (3)$$

$$K_{G\,APU} = K_{G\,ATS} \quad (4)$$

The developed methodology for matching the operation of ATS and APU considering operational limitations can be presented as the following sequence. The flow chart of the methodology is shown in Figure 5.

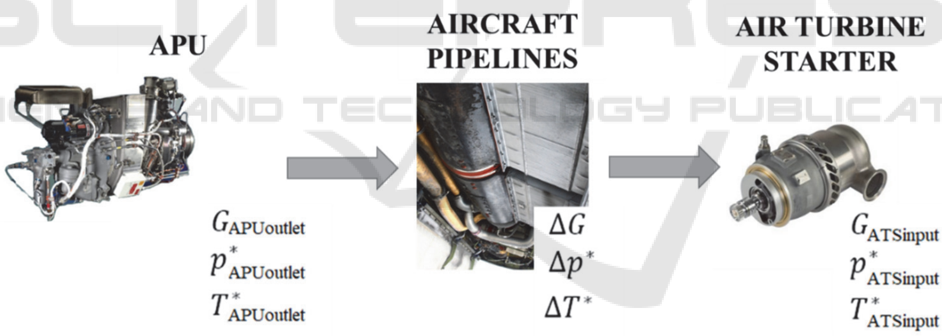

Figure 4: The interaction scheme between the APU and the ATS parameters.

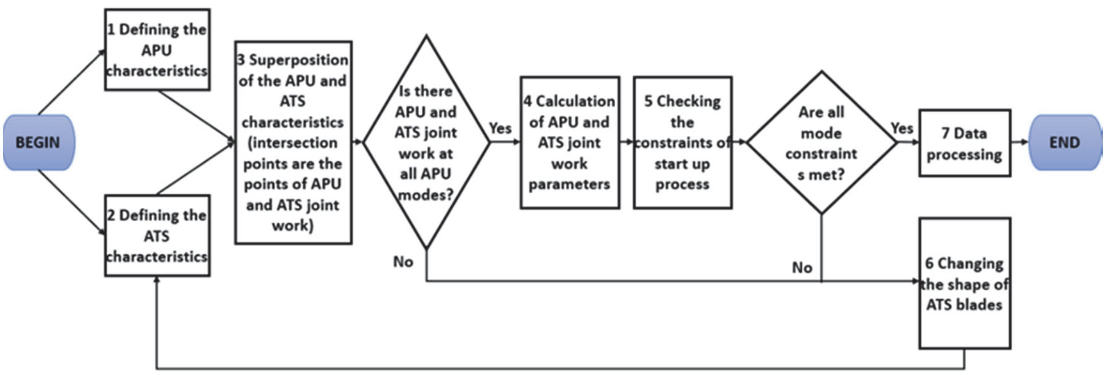

Figure 5: Brief flowchart of the developed methodology for an ATS refinement considering operating constraints.

Stage 1. Considering the losses on the transmission of compressed air, the characteristics of the APU of the initial form $p^*_{\text{APUoutlet}} = f(G_{\text{APUoutlet}})$ and $T^*_{\text{APUoutlet}} = f(G_{\text{APUoutlet}})$ are transformed to the form $K_{G\,\text{APU}} = f(\pi_{\text{APU}})$ calculated by the parameters at the ATS inlet using the following formulas:

$$K_{G\,\text{APU}} = = \frac{(G_{\text{APUoutlet}} - \Delta\text{G}) \cdot \sqrt{(T^*_{\text{APUoutlet}} - \Delta T^*)}}{p^*_{\text{APUoutlet}} - \Delta p^*_{hydr.}} \quad (5)$$

$$\pi_{\text{APU}} = \frac{p^*_{\text{APUoutlet}} - \Delta p^*_{hydr.}}{p_h} \quad (6)$$

where $K_{G\,\text{APU}}$ – APU air mass flow parameter at the inlet of the ATS considering losses in the pipelines;

π_{APU} – pressure ratio in the ATS determined by the parameters of the air at the inlet to the ATS considering losses in the pipelines;

G_{ATSinput} – the value of the mass flow rate of air taken from the APU considering losses in the pipelines, $\left[\frac{kg}{s}\right]$:

$$G_{\text{ATSinput}} = G_{\text{APUoutlet}} - \Delta\text{G} \quad (7)$$

T^*_{ATSinput} – the value of the temperature of air taken from the APU considering losses in the pipelines, (K):

$$T^*_{\text{ATSinput}} = T^*_{\text{APUoutlet}} - \Delta T^* \quad (8)$$

p^*_{ATSinput} – the value of the total pressure of air taken from the APU considering losses in the pipelines, $(\frac{kgf}{cm^2})$:

$$p^*_{\text{ATSinput}} = p^*_{\text{APUoutlet}} - \Delta p^*_{\text{hydr.}} \quad (9)$$

p_h – atmospheric pressure for altitude in standard atmospheric conditions, $\left[\frac{kgf}{cm^2}\right]$.

Stage 2. The turbine characteristics are transformed to the relations $K_{N\,\text{ATS}} = f(\pi_{\text{ATS}})$ and $K_{G\,\text{ATS}} = f(\pi_{\text{ATS}})$ using the following formulas:

$$K_{G\,\text{ATS}} = \frac{G_{\text{ATSinput}} \cdot \sqrt{T^*_{\text{ATSinput}}}}{p^*_{\text{ATSinput}}} \quad (10)$$

$$K_{N\,\text{ATS}} = \frac{N_{\text{ATS}} \cdot}{p^*_{\text{ATSinput}} \cdot \sqrt{T^*_{\text{ATSinput}}}} \quad (11)$$

where N_{ATS} – the value of ATS power, W.

Stage 3. It is necessary to combine characteristics ($K_{G\,\text{APU}} = f(\pi_{\text{APU}})$ and $K_{G\,\text{ATS}} = f(\pi_{\text{ATS}})$) for the APU and ATS at one diagram, respectively and to determine the intersection points that will be the points that satisfy the joint operation condition.

Stage 4. If for some operational modes no joint points were found (no intersections of ATS and APU characteristics), then it is necessary to adjust the shape of ATS blades and repeat stages 1-3 determining the modified turbine characteristics using CFD.

Step 5. The parameters of the ATS working process are determined during its joint work with the APU at each APU mode in the following sequence.

- at the intersection points of the characteristics $K_{G\,\text{ATS}} = f(\pi_{\text{ATS}})$ and $K_{G\,\text{APU}} = f(\pi_{\text{APU}})$, the parameters $p^*_{\text{APUoutlet}}$, $T^*_{\text{APUoutlet}}$, $G_{\text{APUoutlet}}$ at the output of the APU are determined;
- for the points of joint work of the APU and ATS, the air parameters at the ATS inlet are determined by the found values of the air parameters at the APU exit (equations 7-9).

Thus, based on the intersection points of the above characteristics, the physical characteristics of the ATS are found when operating together with the APU at all its modes.

Stage 6. Based on calculated parameters of the ATS working process during its joint work with the APU, the parameters of the start-up system (torque on the turbine shaft and start-up time) are calculated at each operation mode of the APU.

On the basis of the data on the torque of the output shaft, the linear dependencies $M_{torque.out.sh.}=f(n_{out.sh})$ (Tihonov et. al., 2001) are determined for each operating mode:

$$M_{torque.out} = A \cdot n_{out.sh} + B \quad (12)$$

Based on the found dependence, the start time of the aircraft gas turbine engine is determined in the future. The calculation is carried out using the program that will be described in section 4. The coefficient B is the maximum torque at startup, which must be controlled.

Stage 7. If at least one of the found parameters of the start system does not meet the technical specifications or operational constraints, it is necessary to adjust shape of ATS blades and repeat stages 1-6 until the requirements are met (Figure 6).

Stage 8. If at all operating modes the limiting quantities (first of all, the torque on the turbine shaft) satisfy the constraints and the conditions of joint work are fulfilled, a conclusion is made about the possibility of coordinated operation of the APU and ATS for the considered modes of operation of the APU.

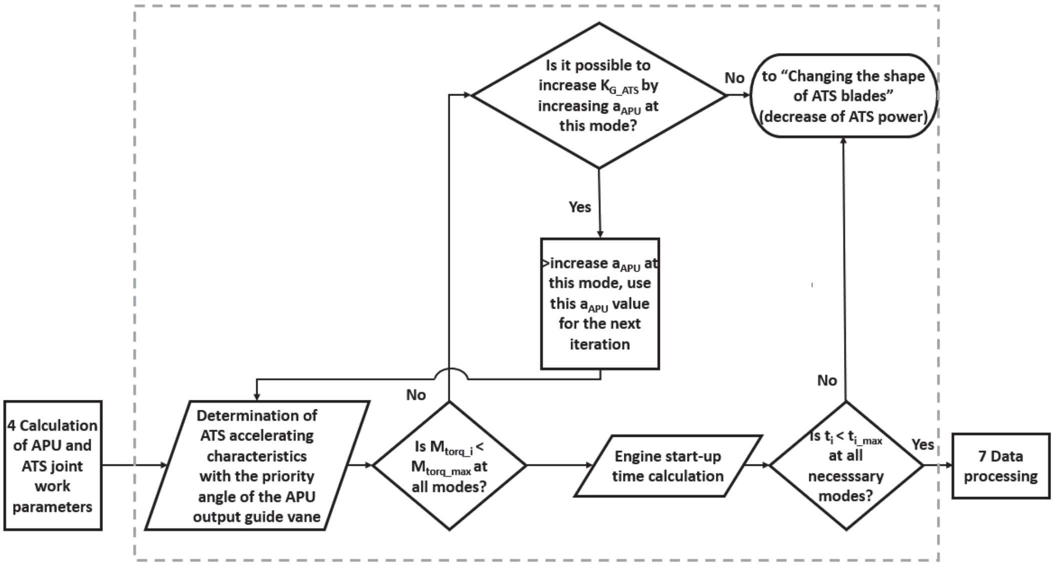

Figure 6: Flowchart of the «Checking the restrictions of startup process».

Both experimental and calculated (design) characteristics of the APU and ATS can be used in the developed method.

The methodology was tested in assessing the possibility of joint operation of a two-stage air turbine and APU as part of a turbofan engine for a civil aviation aircraft (Figure 7). In this figure, the shaded part of the characteristic corresponds to the operating rotational speeds of the ATS. The intersection points of the characteristics are the points where the conditions for the joint operation of the APU and the ATS (equations 5 and 6) are satisfied. An analysis of the figure shows that when using the investigated ATS, the coordinated work of the ATS and the APU was not provided for all the modes of APU operation and it is needed to change the APU, ATS or to select new components. In addition, the torque on the ATS shaft is greater than the maximum allowable, which can lead to damage to the gearbox and engine drive box.

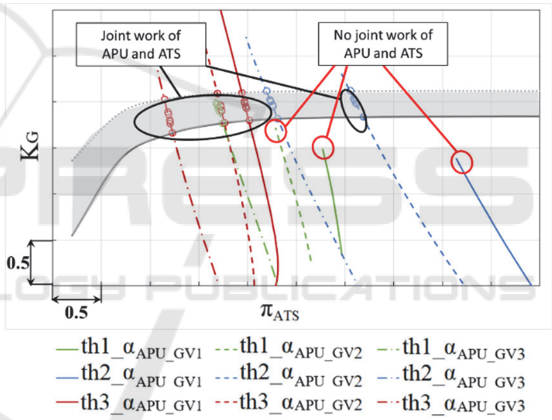

Figure 7: Combined mass flow characteristics of the APU and ATS No. 1.

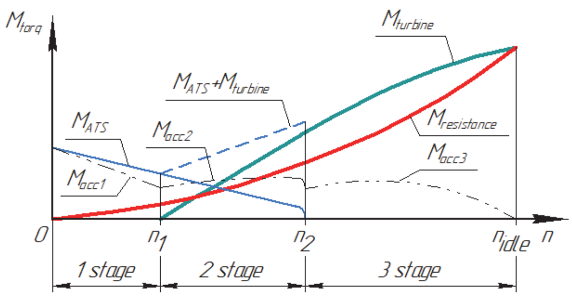

Figure 8: GTE start stages with an ATS (Alabin et. al., 1968).

3 CALCULATION OF THE GTE START TIME

The spin-up of the GTE rotor at start is carried out by the air turbine of the starter and the main turbine of the engine, which are involved in the spin-up during not the entire start-up period, but only at certain stages. The process of starting the engine can be divided into three main stages (Figure 8).

At the first stage (from the start of the launch to the start of the active operation of the main turbine with the rotor speed n_1), the engine is spun-up only by the starter. The acceleration moment of the high-pressure rotor of the engine at this stage is:

$$M_{\text{acc1}} = M_{\text{ATS}} - M_{\text{resistance}} = = J\frac{d\omega}{d\tau} = J \cdot \left(\frac{\pi}{30}\right) \cdot \left(\frac{dn}{d\tau}\right) \quad (13)$$

where M_{ATS} – torque on the output shaft developed by ATS;

J — moment of inertia of the high-pressure rotor of the engine;

ω - angular speed of rotation of the engine rotor, s^{-1};

n – engine rotor speed, rpm;

$M_{\text{resistance}}$ – torque required to rotate the compressor, drive units and overcome friction.

At the second stage of the start-up (from n_1 to the starter shutdown at the speed n_2), the rotor is jointly rotated by the turbo starter and the main turbine. In this case, the acceleration moment of the high-pressure rotor of the engine is calculated with the formula:

$$M_{\text{acc2}} = M_{\text{ATS}} + M_{\text{turbine}} - M_{\text{resistance}} \quad (14)$$

where M_{turbine} – positive torque developed by the engine turbine.

At the third stage (after the rotational speed n_2), the air starter is switched off, and the engine rotor is spun-up to the rotor speed at idle n_{idle} only with the main turbine:

$$M_{\text{acc1}} = M_{\text{turbine}} - M_{\text{resistance}} \quad (15)$$

Summarizing the above stages of starting the engine, a generalized equation of motion of the engine rotor at startup can be written as:

$$J \cdot \left(\frac{\pi}{30}\right) \cdot \left(\frac{\Delta n}{\Delta \tau}\right) = i \cdot M_{\text{ATS}} - M_{\text{resistance}} + +M_{\text{turbine}} + \Delta M_{autorotation} \quad (16)$$

where i – gear ratio to ATS in the box of units;

$\Delta\tau$ – calculation time step, s;

Δn – change in the rotational speed of the high pressure rotor per calculation step, rpm;

$\Delta M_{autorotation}$ – torque, considering the energy input of the oncoming air flow at the autorotation frequency.

The change in the rotational speed of the rotor per calculation step, according to the generalized equation (16), can be represented in the following form:

$$\Delta n = \frac{\Delta\tau}{J \cdot \left(\frac{\pi}{30}\right)} \left(k_{M_{\text{ATS}}} \cdot i \cdot M_{\text{ATS}} - M_{\text{resistance}}\left(1 - k_{M_{\text{turbine}}}\right) + \Delta M_{autorotation}\right) \quad (17)$$

where $k_{M_{\text{ATS}}}$ – coefficient considering the change in the starter torque during the opening of the shutter or shutdown of the ATS;

$k_{M_{\text{turbine}}} = \frac{M_{\text{turbine}}}{M_{\text{resistance}}}$ – coupling coefficient between the moments of the compressor and the turbine of the HP rotor.

The coupling coefficient between the compressor and turbine moments changes in the range of $k_{M_{\text{turbine}}} = 0 \dots k_{M_{\text{turbine\_max}}}$. Until there is no combustion in the main combustion chamber, $k_{M_{\text{turbine}}} = 0$. After the fuel supply, the coefficient $k_{M_{\text{turbine}}}$ increases and at a certain rotational speed of the HP rotor $n_{\text{HPshaft\_equilibrium}}$, the torque of the main turbine is compared with the compressor resistance moment $M_{\text{turbine}} = M_{\text{resistance}}$. After that, the turbine torque increases to the maximum excess at the start-up $k_{M_{\text{turbine\_max}}} > 1$.

The value of the current speed is defined as $n_{t+\Delta t} = n_t + \Delta n$. The calculation continues until the speed of the idle mode is reached ($n_{t+\Delta t} = n_{idle}$).

The values of the rotation speed n_1, n_2 and n_{idle}, $k_{M_{\text{turbine\_max}}}$ depend on the characteristics of the compressor, turbine and starter, the operation of the combustion chamber, design and other operational factors.

The algorithm described above was implemented as a program for which a certificate of state registration for a computer program No. 2019663216 was obtained (Zubanov et. al., 2019). It considers the change in the coefficients $k_{M_{\text{ATS}}}$ and $k_{M_{\text{turbine\_max}}}$, and $M_{\text{resistance}}$ based on the theoretical and experimental data available to the authors. The program supports both launch in batch mode and in graphical mode.

The possibility of using the program in batch mode was provided by the developer for using the program in the automatic ATS optimization cycle.

4 CONCLUSION

This article describes the methodology for coordinating the APU and air turbine workflow used when starting a gas turbine engine and for calculating the start-up time. The need for this technique is because the authors could not find a similar one in the available scientific and technical literature. It was also found that there is an exceedingly small number of publications devoted to the problem of launching a gas turbine engine. No articles were found describing the determination of the start time of a gas turbine engine at all operating modes.

The methodology cab be used to verify the possibility of joint functioning of the turbine and the APU at all operating conditions, the output parameters of the turbine, the expected time of the spin-up of the gas turbine rotor, and the comparison of critical system parameters with limit values. Based on this information, a conclusion can be made about the possibility of starting the engine in specific conditions.

The obtained technique can be used:

– to assess the possibility of starting the engine and calculating its main parameters for the specific elements of the starting system;
– for the selection of APU and ATS, satisfying the conditions of joint work and fulfilling the specified requirements of the launch system, including structural, operational and strength limitations;
– for modernization of elements included in the launch system in order to fulfill specified technical requirements.

The developed techniques were implemented in the computer programs and are ready for practical use.

This technique is the first step in a large integrated work carried out jointly with an industrial partner. The obtained scientific results will be used to optimize existing turbo starter for use on the new gas turbine engine.

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