A method for checking the possibility of joint work of the auxiliary power unit and the starter

G M Popov, V M Zubanov, Yu D Novikova, V N Matveev and O V Baturin
Samara National Research University, Samara, Russia

1waskes91@gmail.com

Abstract. This paper describes the algorithm developed by the authors for matching the workflow of the auxiliary power unit to the air turbine used when starting the engine. This technique is applied to determine the possibility of starting a gas turbine engine, calculate its time and basic parameters under all operating conditions (including in flight), as well as to select a new auxiliary power unit (APU) 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.

1. Introduction
Starting an aviation gas turbine engine (GTE) is an important step that largely determines the safety, operational efficiency and reliability of the engine and the entire aircraft. The gas turbine engine start-up system (figure 1) includes a whole set of various devices and blocks: a starter (usually an air turbine starter (ATS) mechanically connected to the gas turbine rotor), air and fuel supply line, automatic control systems (ACS), transmissions, power supply systems, ignition systems, etc. For a reliable engine start-up, the operation of all these devices must be coordinated with each other.

Figure 1. Schematic diagram of the start-up system with an air turbine starter.
The following requirements are imposed on the start-up system [1]:

- the operation of the ATS must be matched with the APU operation at all operating modes (under various atmospheric conditions, speeds, and altitudes),
- gas turbine engine start-up time must be minimized,
- the torque on the output shaft must not exceed the maximum value according to the strength conditions of the gearbox and wheel case of the engine.

The authors of the paper solved the problem of choosing the ATS for one of the newly created gas turbine engines. The most important key to the successful operation of the start-up system is to match the work of the APU and ATS. Indeed, if the maximum efficiency of the ATS or the required design power can be achieved at compressed air flow rates or pressure levels inaccessible to the APU, the required characteristics of the entire start-up system will never be achieved.

In available scientific and technical publications [2…6], methods for matching elements of the gas turbine engine start-up system and calculating its start-up time were not found. Therefore, the authors were forced to create their own methodology for determining the possibility of joint operation of a GTE air turbo starter with an APU, determining the engine start-up time and other critical system parameters under given flight conditions.

2. Defining the possibility of joint work of the APU and ATS

The following assumptions are the basis of the proposed methodology for matching the ATS and APU operational processes:

- the characteristics of the APU and ATS are determined separately and are presented as the dependences of the APU and ATS parameters on the pressure ratio of the working fluid \( \pi \);
- matching the characteristics of the APU and ATS is carried out according to the given parameter of the flow \( K_G \).

It is defined as follows:

\[
K_G = \frac{G_{ATSinput} \cdot \sqrt{T_{ATSinput}}}{P_{ATSinput}},
\]

where

- \( G_{ATSinput} \) is the value of air mass flow rate through the ATS;
- \( T_{ATSinput}^* \) is the value of the total temperature at the ATS inlet;
- \( P_{ATSinput}^* \) is the value of the total pressure at the ATS inlet.

The operational process of the APU is usually described by the dependences of the total pressure \( P_{APUoutlet}^* \) and temperature \( T_{APUoutlet}^* \) of the air taken from the APU, on its mass flow rate \( G_{APUoutlet} \):

\[
P_{APUoutlet}^*, T_{APUoutlet}^* = f(G_{APUoutlet}).
\]

The APU characteristics can be obtained for several conditions of its operation, characterized, for example, by flight altitude \( H \), flight Mach number and ambient (atmospheric) air temperature \( t_h \) and by the position of the regulatory elements (for example, stagger angles \( \alpha_{igv} \) of the inlet guide vane (IGV) (Figures 2 and 3).

The condition for the joint work of the APU and ATS can be represented using the following equalities

\[
\pi_{APU} = \frac{P_{APUoutlet}^*}{P_h} = \frac{G_{ATSinput} \cdot \Delta p^*_{hydr}}{P_h} = \pi_{ATS} + \frac{\Delta p^*_{hydr}}{P_h},
\]

\[
T_{APUoutlet}^* - \Delta T^* = T_{ATSinput}^*.
\]

\[
K_G_{APU} = K_G_{ATS}.
\]

2
The developed methodology for matching the operation of ATS and APU that takes into account operational limitations can be presented as the following sequence of actions (Figure 4).

Stage 1. Considering the losses on the transmission of compressed air \((\Delta G, \Delta p^\ast_{\text{hydr}}, \Delta T^\ast)\), the characteristics of the APU of the initial form \(p^\ast_{\text{APU outlet}} = f(G_{\text{APU outlet}})\) and \(T^\ast_{\text{APU outlet}} = f(G_{\text{APU outlet}})\) 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:

\[
K_{G_{\text{APU}}} = \frac{(G_{\text{APU outlet}} - \Delta G)}{p^\ast_{\text{APU outlet}} - \Delta p^\ast_{\text{hydr}}} \sqrt{(T^\ast_{\text{APU outlet}} - \Delta T^\ast)}.
\]  
(5)

\[
\pi_{\text{APU}} = \frac{p^\ast_{\text{APU outlet}} - \Delta p^\ast_{\text{hydr}}}{P_h}.
\]  
(6)

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:

---

**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.

**Figure 4.** Brief flowchart of the developed methodology for an ATS refinement considering operating restrictions.
Stage 3. It is necessary to combine characteristics \( K_{G\, APU} = f(\pi_{APU}) \) and \( K_{G\, ATS} = f(\pi_{ATS}) \) for the APU and ATS in one diagram respectively and to determine the intersection points that will be the points that meet the joint operation condition.

Stage 4. If for some operational modes no joint points are 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 operational process are determined during its joint work with the APU at each APU mode in the following sequence.

- at the intersection points of characteristics \( K_{G\, ATS} = f(\pi_{ATS}) \) and \( K_{G\, APU} = f(\pi_{APU}) \), parameters \( p^*_{APU\, outlet}, T^*_{APU\, outlet}, G_{APU\, outlet} \) are determined at the output of the APU;
- 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.

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

Stage 6. Based on calculated parameters of the ATS operational 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, linear dependencies \( M_{torque\, out\, sh.} = f(n_{out\, sh}) \) [7] are determined for each operating mode:

\[
M_{torque\, out} = A \cdot n_{out\, sh} + B. \tag{9}
\]

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

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

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.

The developed method allows to use both experimental and calculated (design) characteristics of the APU and ATS.

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 5). 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 necessary to change the APU, ATS or to select new components. In addition,
the torque on the ATS shaft is greater than the maximum allowed torque [8], which can lead to damage to the gearbox and engine drive box.

![Figure 5. Combined flow characteristic of APU and ATS.](image)

### 3. Calculation of the GTE start-up time

The spin-up of the GTE rotor at the 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.

At the first stage (from the start of the launch to the start of the active operation of the main turbine with rotor speed \(n_1\)), the engine is spun-up only by the starter. 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. At the third stage (after the rotational speed \(n_2\) is achieved), the air starter is switched off, and the engine rotor is spun-up to the rotor speed at idle mode \(n_{idle}\) only by the main turbine. Summarizing the above-mentioned stages of starting the engine, a generalized equation of the engine rotor motion at startup can be written down as:

\[
J \cdot \left( \frac{\pi}{30} \right) \cdot \left( \frac{\Delta n}{\Delta \tau} \right) = \frac{i \cdot M_{ATS} - M_{\text{resistance}} + M_{\text{turbine}} + \Delta M_{\text{autorotation}}}{J} \tag{10}
\]

where
- \(i\) is gear ratio to the ATS in the box of units;
- \(\Delta \tau\) is time calculation step, s;
- \(\Delta n\) is change in the rotational speed of the high pressure rotor per calculation step, rpm;
- \(\Delta M_{\text{autorotation}}\) is torque, considering the energy input of the oncoming air flow at the autorotation frequency.

\(J\) is moment of inertia of the high-pressure rotor of the engine;

\(M_{ATS}\) is torque on the output shaft developed by the ATS,

\(M_{\text{turbine}}\) – positive torque developed by the engine turbine,

\(M_{\text{resistance}}\) is torque required to rotate the compressor, drive units and overcome friction.

The change in the rotational speed of the rotor per calculation step, according to the generalized equation (11), can be represented in the following form:

\[
\Delta n = \frac{\Delta \tau}{J \cdot \left( \frac{\pi}{30} \right)} \cdot \left( k_{M_{ATS}} \cdot i \cdot M_{ATS} \cdot M_{\text{resistance}} \cdot \left( 1 - k_{M_{\text{turbine}}} \right) + \Delta M_{\text{autorotation}} \right), \tag{11}
\]
where \( k_{M_{ATS}} \) – coefficient considering the change in the starter torque during the opening of the shutter or shutdown of the ATS;

\[
k_{M_{turb}} = \frac{M_{turb}}{M_{resist,ce}}
\]

– 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_{turb}} = 0 \ldots k_{M_{turb,\text{max}}}. \quad \text{Until there is no combustion in the main combustion chamber, } k_{M_{turb}} = 0. \quad \text{After the fuel supply, the coefficient } k_{M_{turb}} \quad \text{increases and at a certain rotational speed of the HP rotor } n_{\text{HPshaft,equilibrium}}, \quad \text{the torque of the main turbine is comparable to the compressor resistance moment } M_{turb} = M_{resist,ce}. \quad \text{After that, the turbine torque increases to the maximum excess at the start-up } k_{M_{turb,\text{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 \( n_{t+\Delta t} = n_{\text{idle}} \).

The values of the rotation speed \( n_1, n_2 \) and \( n_{\text{idle}} \), \( k_{M_{turb,\text{max}}} \) 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 [9].

Conclusion

The presented paper describes methods to match the working process of the APU and the air turbine developed by the authors and used when starting a gas turbine engine as well as to calculate the time of turning the engine on. The developed methods can be used to verify the possibility of joint operation of the turbine and the APU in 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 on the possibility of starting the engine under specific conditions can be made.

The obtained technique can be used:

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

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

References

[1] Inozemcev A A, Nihamkin M A and Sandrackii V L 2008 Osnovy konstruirovaniya aviaciannyh dvigatelej i jenergeticheskix ustanovok (Fundamentals of designing aircraft engines and power plants) (Moscow: Mashinostroenie) p 207

[2] Zoccoli M J, Cheeseman W H 1998 Development of the Next Generation Gas Turbine Based Jet Air Start Unit for the US Navy Proceedings of the ASME 1998 International Gas Turbine and Aeroengine Congress and Exhibition 98-GT-084 DOI 10.1115/98-GT-084

[3] Von Flue R J 1967 Pneumatic starting systems Proceedings of the ASME 1967 Gas Turbine Conference and Products Show 67-GT-15 DOI 10.1115/67-GT-15

[4] Ferrand A, Bellenoue M, Bertin Y, Cirilgeanu R, Marconi P and Mercier-Calvairac F 2018 High Fidelity Modeling of the Acceleration of a Turboshaft Engine During a Restart Proceedings
of the ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition GT2018-76654 DOI 10.1115/GT2018-76654

[5] Tian T, Yu-chun C, Xin-yue C and MaChao Z 2018 Turbo Engine Starting Control Law Design and Process Simulation Proceedings of the 2018 9th International Conference on Mechanical and Aerospace Engineering (ICMAE) pp 546-551 DOI 10.1109/ICMAE.2018.8467712

[6] Park J H, Park S and Baek JeH 2015 Design of an Air-Starter Turbine and Starting Performance Prediction Through the Numerical Analysis Proceedings of the ASME Turbo Expo 2015: Turbine Technical Conference and Exposition GT2015-43062 DOI 10.1115/GT2015-43062

[7] Alabin M A, Kac B M and Litvinov Ju.A 1968 Zapusk aviacionnyh gazoturbinnyh dvigatelej (Start-up of aircraft gas turbine engines) (Moscow: Mashinostroenie) p 227

[8] Aviacionnye pravila. Chast' 29. Normy letnoy godnosti vintokrylyh apparatov transportnoj kategorii (Aviation Rules Part 29 Airworthiness standards of rotorcraft in the transport category) OAO «Aviaizdat» 2003

[9] Zubanov V M, Popov G M, Gorjachkin E S, Novikova Ju D, Volkov A A and Kolmakova D A 2019 Program for determining the start time of a turbomachine Turbomachine Start Time Calculation". Certificate of state registration of a computer program No2019663216