Mathematical modelling of a gas turbine engine based hybrid propulsion system for regional airplanes

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Abstract. The work is a study of light multi-purpose aircraft hybrid propulsion advantages. A comparison of propulsion system dynamics and the integrated flight performance in the cases of turbo-prop and a hybrid turbo-prop propulsion usage has been carried out. Required battery parameters are calculated for usage of hybrid mode during a flight mission and for emergency landing on the hybrid propulsion electrical component. The calculation results showed that a hybrid propulsion system may have a longer operating life, lower fuel consumption during non-cruising flight modes, and the possibility of landing in case of gas turbine failure.

1. Introduction

Modern gas turbine engines are close to their perfection, with further improvements of thermodynamic cycle parameters and increase of components efficiency bringing less and less benefit at ever greater costs. The next generation of aircraft propulsion systems must have new properties that give them an advantage over existing propulsion systems.

Since the beginning of the 21st century, there has been a lot of research into hybrid propulsion systems. In particular, NASA reports devoted to hybrid propulsion have attracted much attention. The first report [1], published in 2011, highlights the following goals to achieve with advanced propulsion systems: reduced noise and NOx emissions as well as reduced fuel consumption and runway length.

The report contained an extensive economic analysis, analysis of promising propulsion performance, including hybrid propulsion, an assessment of hybrid aircraft flight range and payload ratio, infrastructure requirements, an assessment of engine emissions, a calculation of flight range depending on the battery quality, and other data. According to the report, hybrid propulsion usage can reduce fuel consumption of a passenger aircraft.

The report summarizes results as follows: it is possible to reduce fuel consumption up to 90% by hybrid propulsion usage (a significant part of the flight relies on electricity only); on average, consumption is expected to decrease by up to 63%; a 21% reduction in NOx emissions is expected as well as a 22 dB noise reduction and a 33% shorter takeoff run.

The second report [2], published in 2018, is fully focused on hybrid propulsion and considers the use of such a system in helicopters and convertiplanes. The following advantages are noted: system fault tolerance in case of main engine failure; almost instantaneous response to the control action; possibility to reduce the gas turbine part size to provide only enough energy for cruising flight with lack of energy provision on highly loaded modes by the electrical part and possibility of a distributed propulsion concept usage due to the absence of a mechanical transmission and gearboxes.
In addition, the following potential advantages of hybrid propulsion are considered: reduced noise and lower infrared visibility as well as resilience to external conditions, which allows the engine to deliver full power regardless of altitude and airspeed. The following concepts of hybrid propulsion usage have been proposed: decoupled power and energy management; design of fault-tolerant hybrid propulsion architecture; distributed propulsion via electrical bus; battery-boosted turbine propulsion.

Several difficulties in hybrid propulsion researches are also noted: it is necessary to take into account electric machines thermal management; the complexity of flight mission optimization for an aircraft with several energy sources on board; the need to develop multidisciplinary problems tools.

The report provides data on aircraft flight range and payload as well as altitude-airspeed performance of hybrid propulsion. The following conclusions are made about the advantages of hybrid engines: the possibility of decoupled power and energy management and increased fault tolerance of the hybrid propulsion architecture; the possibility to reduce fuel consumption by more than 10% due to turbine battery-boost for several flight missions.

Another report was prepared by Martin Hepperle [3] from the German Aerospace Center. The report examines a variety of hybrid engine designs and provides data on current and theoretical battery specific parameters. Collected data shows the superiority of the advanced electric motors specific parameters over internal combustion engines and even gas turbine engines. It is concluded that specific energy required for the introduction of hybrid and electric motors into aviation batteries is at the level of 800-1000 Wh/kg.

One of the first research projects on aircraft hybrid propulsion was conducted in 2005 [4] by Frederich G Harmon. His dissertation primarily deals with multiple energy sources propulsion control problems. He proposes using a hybrid propulsion electrical component for a long flight at low airspeed. His conclusions largely coincide with the NASA reports [1, 2], hybrid propulsion is expected to have larger flight range and reduced infrared visibility.

A series of articles on hybrid propulsion was published by R Glassock et al. [5, 6]. The first one centers on experimental and numerical research of hybrid engine performance with a parallel connection of an internal combustion engine and an electric motor to the propeller. Such advantages as more efficient energy management and a greater choice of propellers are noted. For example, it is possible to use a larger diameter propeller with a fixed pitch, which would not be possible without an electrical component. In addition, it is shown that hybrid propulsion can significantly accelerate an aircraft climb. The second work is a continuation of the first and in many ways repeats the same findings. Mathematical equations are added and the possibility of hybrid propulsion usage to reduce visibility is indicated.

In one article [7] hybrid propulsion is also seen as a way to achieve NASA-set noise, emission and fuel consumption levels. Hybrid propulsion with superconductors is considered. It is concluded that there is a need to use fully superconducting electrical machines to obtain specific parameters equal to gas turbine engines.

James L Felder’s report et al. [8] also considers hybrid propulsion and distributed hybrid propulsion in particular as a way to achieve NASA N+3 goals. It is concluded that a high number of low speed fans with superconducting motors is a possible way to achieve required thrust, fuel consumption and noise levels.

Extensive research carried out by Friedrich and Robertson [9] considers a wide power range of hybrid propulsion from 460 W and over 4 MW including various flight missions. Conclusions about the possibility of reducing fuel consumption by usage of hybrid propulsion are elaborated, with the greatest effect, up to 47%, achieved for a small UAVs, and up to 10% for medium size aircraft. For large vehicles further batteries and electric machines specific parameters improvement is required.

Recently, a large amount of research on hybrid propulsion has been conducted in Russia. The Central Institute of Aviation Motors published results of a research project on hybrid propulsion [10] which considers hybrid propulsion architectures, its advantages, specific parameters, and areas of application. Many papers are focused on regional aircrafts with hybrid propulsion on board [11, 12]. One article describes the simulation of hybrid propulsion performance during a flight mission of an ATR 42-300 aircraft. Another contains an assessment of the efficiency of regional aircrafts with hybrid propulsion.
The large amount of research conducted in recent years allows us to summarize several conclusions. Firstly, such engines are expected to achieve the target parameters set by NASA for noise, emissions, and fuel consumption. Other expected benefits are increased reliability, reduced take-off roll and reduced visibility. The application of such engines in civil aviation, primarily for regional aircraft, is considered.

The main obstacles to the development of aircraft with hybrid propulsion are low specific parameters of the battery and electric components. The need to develop simulation tools that allow performing multidisciplinary research including gas turbine engines, electrical components and cooling systems during flight missions is also noted.

This article is focused on the usage of a parallel hybrid propulsion system for a regional aircraft. The aim of the study is to determine the reduction in fuel consumption during the flight mission due to hybrid propulsion and the requirements for the battery to ensure the possibility of landing in case of a gas turbine failure.

2. Mathematical model

At the first stage, a mathematical model of the turboshaft engine was prepared. The mathematical model includes an air intake device, a compressor, a combustion chamber, a turbine, a power turbine, a jet nozzle, an inertial rotor, a bleeding air system and a control system. Reference engine performance data is used to validate the model. The engine control system supports a required gas temperature or turbine power with maximum RPM and temperature constraints. To provide both required parameters support and constraints P.I.D. regulator, additional global parameters and parameter links are used. The mathematical model architecture is shown in Figure 1.

![Fig. 1. Model of a hybrid propulsion gas turbine component](image)

A comparison of the calculation results showed that reference engine parameters coincide with the calculated ones by more than 98%. The results in dimensionless form are presented in Table 1.

| Table 1. Relative difference in model parameters in comparison with reference data |
The hybrid propulsion model included a previously shown turboshaft engine, flight mission and atmosphere conditions, a generator, a battery, a control system, an electric motor, and a propeller. The control system provides required power on a propeller shaft by adding additional power to the electric motor. The general view of the model is shown in Figure 2.

A comparison of the propulsion dynamics and integral parameters was carried out by the results of the flight mission modeling. A simple passengers carriage mission was chosen.

The flight mission began with engine start, pre-flight tests and taxiing for 810 seconds. The next stage was the takeoff run, takeoff and a short climb section at maximum power in 36 seconds. The next stages were acceleration up to 950 seconds and then cruise flight altitude climb up to 1500 seconds. The cruising flight lasted up to 3460 seconds. After the cruising flight, there was a decrease to a quarter of the cruising flight altitude at 4250 seconds. The next section was braking and throttling the engine down to 20% of the cruising power with runway touchdown at 4410 seconds. Rolling on the runway continued until the aircraft and engine stopped at 4800 seconds.

A dimensionless regional aircraft flight mission is shown in Figure 3. The altitude and airspeed on charts are normalized, required power is relative to the engine maximum power.
During the flight mission simulation in case of a non-hybrid turboprop propulsion the control system provided required power on the power turbine shaft.

For the hybrid propulsion, the control system provided required power on the propeller shaft with a constraint to ensure a full charge of the battery after the cruising flight to allow an emergency landing in case of a gas turbine failure. Additionally, a series of calculations were performed for control system optimization. Optimality criteria were fuel consumption, maximum engine RPM and maximum gas temperature. Additional criteria were the constant gas temperature and RPM.

3. Results
Figure 4 shows that during takeoff, the power of the gas turbine as a part of the hybrid propulsion was lower than the turboprop propulsion, part of the power was provided by the hybrid propulsion electrical component, and battery charge was consumed.

On the contrary, during the second half of the cruising flight, the power of the hybrid propulsion was higher and the battery was being charged. This compensated the consumption of energy during takeoff.

Figures 5 and 6 show that hybrid propulsion allows to reduce maximum gas temperature and engine RPM during takeoff, acceleration and climb flight stages.
In addition, a hybrid propulsion gas turbine can operate at maximum efficiency during most of the flight mission. As a result, if a flight mission requires non-cruising operation fuel consumption is reduced. The considered flight mission mostly is a cruise flight and is optimized for the chosen engine, therefore the decrease in fuel consumption is insignificant. In the considered flight mission, the maximum RPM decreased by 3.3%, and the maximum gas temperature by 6.2%. The results are shown in Table 2.

**Table 2. Simulation results**

| Parameter                        | Turboprop | Hybrid propulsion | Relative decrease, % |
|----------------------------------|-----------|-------------------|----------------------|
| Fuel consumption, kg             | 169.3     | 169.2             | 0.1                  |
| Relative maximum RPM             | 0.975     | 0.943             | 3.3                  |
| Relative maximum gas temperature | 0.982     | 0.921             | 6.2                  |
One of the major obstacles to the introduction of aircraft hybrid propulsion is batteries’ mass. Two options for rechargeable batteries are considered. The first option allows hybrid flight, it provides an opportunity to have constant RPM and gas temperature and to reduce maximum RPM and gas temperature. Reduced fuel consumption is not achieved during the current flight mission. In this case, the difference in power from Figure 4 is consumed from the battery or used to recharge it. The battery charge dynamic is shown in Figure 7. During takeoff, the battery charge is quickly consumed: more than 45% of the charge in 200 seconds. The next step is a gradual discharge during the first half of the cruise flight and charging during the second half until it is fully charged by the time of descent for the landing approach.

The second option allows an emergency landing on batteries. Emergency landing requires a battery to have large capacity with relatively low power. The energy consumption for a flight in the hybrid mode is negligible compared to the energy consumption for an emergency landing. The battery charge dynamic is shown in Figure 8. The battery charge dynamic is similar to those shown in figure 7 until the start of descent at 3460 seconds. At the initial moment of descent, the gas turbine failure event starts and its power becomes 0. After that moment the entire flight continues on batteries and the electrical motor only.

Table 3 shows a comparison of the minimum required parameters of batteries for a hybrid flight and for an emergency landing with the current level batteries specific parameters with a specific energy of 90 Wh / kg, current advanced level of specific energy 200 Wh / kg and future advanced level of specific energy 800 Wh / kg.
Table 3. Battery required parameters

| Parameter                                      | Hybrid flight | Emergency landing |
|------------------------------------------------|--------------|-------------------|
| Discharge time, s                              | 1500         | 1500              |
| Mass with specific energy 90 Wh/kg (2020) kg   | 35           | 710               |
| Mass with specific energy 200 Wh/kg (2020 advanced), kg | 16           | 320               |
| Mass with specific energy 800 Wh/kg (2035) kg | 4            | 80                |
| Average power, kW                              | 7.5          | 315               |
| Maximum power, kW                              | 120          | 360               |

4. Conclusion

The obtained results allow us to make several conclusions. Modern technology ensures that the mass of hybrid propulsion with a battery is kept at an acceptable level. In the considered example, the operation of a gas turbine engine as a part of hybrid propulsion allowed to reduce maximum gas temperature and RPM in particular during takeoff and climb, but did not allow to reduce fuel consumption due to the flight mission type. For the majority of the flight mission, the engine runs at a constant temperature and RPM. Such exploitation can significantly increase the service life of a gas turbine engine.

It is possible to increase the power and energy of the hybrid propulsion electrical component and provide the possibility of an emergency landing in case of a gas turbine failure. Such propulsion architecture allows to operate aircraft with only one engine without losing reliability.

This work was performed for a state assignment of the Ministry of Science and Higher Education of the Russian Federation, reference number FSFF-2020-0014.

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