Comparative assessment of different hybrid propulsion system types’ efficiency for commuter aircrafts

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Abstract. This paper contains a comparative efficiency assessment of various concepts of hybrid propulsion systems (traditional, parallel turboelectric based on hybrid turboprop engines and serial hybrid) in accordance with the level of parameters of 2020 and 2030 for commuter aircrafts with capacity up to 19 passengers.

1. Introduction

A hybrid propulsion system (HPS) of commuter aircrafts is considered to be the initial stage of the aircrafts propulsion systems (PS) electrification in the near future. The problem of choosing a layout and conceptual design of a HPS, including a gas turbine engine, electric machines, power converters of electrical energy, control systems for electrical machines and electrochemical power sources, is solved in a complex setting with an aircraft (AC). In this study, preliminary approaches to assessing the effectiveness of the application of various HPS concepts to 19-seat commuter aircrafts are considered at the current level of parameters and in 2030 prospects.

A characteristic feature of these aircrafts is relatively low flight altitudes (less than 3500 m) and the need to be able to take off from a short, sometimes unprepared field. This leads to the fact that the parameters of the turboprop engine (TPE) are determined mainly by the take-off mode, and in cruise mode their power is excessive. To reduce it, the engines are throttled, which leads to a significant increase in the specific fuel consumption. An aircraft similar to L-410 has engines with a maximum continuous power available at cruising altitude of almost double of what is required to ensure cruising flight. As a result, one engine could be turned off, and the other would operate in more favorable conditions in terms of fuel consumption. However, if you simply turn off one turboprop engine during the flight, this will result in a strong turning moment. Its compensation leads to a significant increase in aerodynamic drag.

The concept of the so-called parallel turboelectric propulsion system [1] can solve the problem of increased fuel consumption and at the same time eliminate the problem of directional instability.

In this concept, takeoff power is provided by two so-called hybrid turboprop engines (HTPE). Such an engine contains an integrated reversible electric machine (EM), which can operate in both electric motor and generator modes. The machine can be installed via an overrunning clutch on the free turbine shaft before it enters the gearbox, as shown in figure 1, or in some other way. During takeoff and climb, the EM operates in the "idle" mode. During flight in cruise mode and during descent, the gas-turbine part of one engine is turned off, and the second is switched to the increased power mode, providing the required aircraft power. This is achieved by the electric machine operating in the generator mode taking a given mechanical power. In this case, the second part of the mechanical power is transmitted to the...
propeller. Electric energy is transferred from the generator to the electric machine of the second HTPE operating in the electric motor mode. Breaking the mechanical connection with the free turbine by means of an overrunning clutch, this EM rotates the gearbox and the propeller. As a result, both propellers work, and they are supplied with energy from the gas-turbine part of one HTPE. This allows one to significantly reduce the hourly fuel consumption and increase the life-cycle of the gas-turbine hot part. Moreover, such a layout has no power electrochemical source of electrical energy. This concept can be applied even at the modern technological level.

Taking into account the potential and rates of developing specific weight and operational characteristics of electrical components and electrochemical energy sources in the world and in Russia [2], for the period until 2030 it is possible to consider the use of a hybrid propulsion system as part of an aircraft. Among the variety of system solutions for the use of HPS on commuter aircrafts [3], with the capacity of 9-19 passengers, the concept of a serial HPS with one gas-turbine engine seems to be the most promising. Its schematic layout is shown in figure 2.

Figure 1. Parallel turboelectric propulsion system

Figure 2. Serial hybrid propulsion system with one turboshaft engine

The main idea is to use a battery pack to create additional power in take-off and climb modes. It allows to use a turboshaft gas turbine engine (TSE) rotating an electric generator (EG) optimized for cruise flight. This approach leads, on the one hand, to a significant decrease in fuel consumption, weight and size characteristics of the turboshaft engine linked to the cruise flight mode, and on the other hand, to an increase in the mass of the main control system due to the inclusion of the BP unit and a number
of electrical units. In turn, an increase in the mass of the HPS in comparison with the traditional type of
PS will lead to a decrease in fuel mass, based on the mass balance equation.

The peculiarity of the HPS design is the rejection of the mechanical transmission, which imposes a
limitation on power and torque in the main modes (in order to find the optimum between resource and
weight). In the adopted scheme, the torque is transmitted from the shaft of the free turbine of the TSE
directly to the shaft of the electric generator, excluding the reduction gear (about 20-30% of the dry
mass of the engine).

Thus, this paper is based on the study for the most reasonable appearance and parameters of the HPS
with the aim of improving the efficiency of the commuter aircraft.

2. Problem statement and initial data

To conduct a comparative assessment of the effectiveness of the various concepts of hybrid
propulsion systems (traditional, parallel turboelectric and sequential) application with the parameters’
level of 2030, the L-410, shortened takeoff and landing aircraft, was selected as a commuter aircraft.
The characteristics of the variable-pitch propellers of the L-410 aircraft are formed on the basis of a
number of tabular data and represent the dependences of the specific propeller thrust and thrust
efficiency of the propeller on the altitude and flight speed.

A diagram of a typical flight profile of a commuter aircraft L-410 is shown in figure 3.

The following are used as the criteria for assessing the effectiveness of promising propulsion systems
for the L-410 aircraft:

- flight range with a maximum take-off weight of the aircraft of 6600 kg and the number of
  passengers – 19 people (payload weight 1800 kg);
- fuel efficiency (the amount of fuel consumed per one kilometer of travel per person).

We consider 3 types of propulsion systems for the L-410 aircraft:

- a traditional PS with two turboprop engines with a takeoff power of 800 hp each and the level
  of parameters for 2020 and 2030;
- parallel turboelectric propulsion system of 2020 (figure 1);
- serial hybrid propulsion system with performance level of 2030 (figure 2)

Fully equipped HPS or turboelectric propulsion system includes:

- gas turbine engines (dry weight);
- turboshaft engine systems (electric starter, electronic regulator, fuel filter, pumps, heat
  exchanger, oil unit, sensors, oil tank, actuators, fire extinguishing system, etc.);
- structural elements of turboshaft engine fastening;
- electric generators (EG);
- rectifier units (RU);
- electric motors (EM);
- electric motor control system (EM CS);
- storage battery;
- power control and distribution system (PCDS);
• cables, sensors, connectors, accessories, structural elements for fastening electrical components of the HPS.

A complex mathematical model of the propulsion system as part of the aircraft is used for various propulsion system types effectiveness evaluation. The model allows performing the estimates for both serial and parallel HPS. In order to determine the characteristics of the gas turbine engine and the turboshaft gas turbine engine, a conceptual design of a promising engine core was developed for the period of 2020 and 2030.

3. Results of calculations

The results of a comparative assessment of the effectiveness of a parallel turboelectric propulsion system (propulsion system with hybrid turbine engines), assuming the turn off of one gas-turbine part in the cruise flight mode, and the existence of a traditional turboprop with the parameters level of 2020 as part of a commuter aircraft, are presented in table 1.

| Parameter                                           | PS with hybrid TPE | Turboprop |
|-----------------------------------------------------|--------------------|-----------|
| Aircraft takeoff weight, kg                         | 6600               | 6600      |
| Takeoff power, hp                                   | 800 x 2            | 800 x 2   |
| TPE power in cruising flight, hp                    | 561.8              | 265.4 x 2 |
| Weight of the TPE and its systems, kg               | 172 x 2            | 172 x 2   |
| EM weight as a part of one HTPE, kg                 | 20                 | -         |
| Weight of the ED CS as part of the one HTPE, kg     | 12                 | -         |
| Weight of other electrical components, kg           | 15                 | -         |
| (control unit, power cables, sensors, accessories)  |                    |           |
| PS weight                                           | 423                | 344       |
| Fuel weight consumed in flight, kg                  | 285                | 364       |
| Flight range along a given profile, km              | 549                | 602       |
| Fuel efficiency for a given profile, g/(pass. km)   | 27.3               | 31.9      |
| Kilometer fuel consumption, average in cruising flight, kg/km | 0.476             | 0.571     |

The results of a comparative assessment of the effectiveness of a serial HPS with TSE based on a promising core of different power (950-1200 hp) and a traditional propulsion system with two turboprop engines TPE-800 (800 hp each) are presented in table 2.

| PS option               | Aircraft efficiency characteristics |
|-------------------------|-----------------------------------|
| PS with TPE-800         | 886                               |
| HPS with TSE-950        | 574                               |
| HPS with TSE -1000      | 624                               |
| HPS with TSE -1050      | 658                               |
| HPS with TSE -1100      | 726                               |
| HPS with TSE -1150      | 713                               |
| HPS with TSE -1200      | 684                               |
|                         | 28.7                              |
|                         | 24.6                              |
|                         | 24.8                              |
|                         | 24.9                              |
|                         | 25.0                              |
|                         | 25.2                              |
|                         | 25.4                              |

4. Conclusion

A comparative efficiency assessment showed that using a serial hybrid propulsion system at a technological level of 2030 in comparison to a traditional turboprop engine propulsion system based on the TSE with a promising core provides the best outcome (TSE-1100) with a fuel efficiency advantage of about 13% (25 g/(pass.km) versus 28.7 g/(pass.km) for the base version), and the flight range decrease by 18% (726 km versus 886 km) at the same aircraft take-off weight of 6600 kg.
The most suitable design for today (2020) is using a parallel turboelectric propulsion system based on the hybrid turboprop engines, in which the gas-turbine part of one of them is turned off during cruise. Comparison of flight characteristics of an aircraft with the same take-off weight of 6600 kg shows that the PS based on hybrid TPE in comparison to the traditional turboprop PS, loses in flight range by 8.8%, but provides 14.4% increase in the fuel efficiency. If the same flight distance is preferable the take-off weight of an aircraft should be around 6640 kg, and the fuel efficiency will remain at the same high level of 27.2 g/(pass.km). In addition, such a layout prolongs the life-cycle of the gas-turbine part of engines.

5. References

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