Energy Conversion and Management 164 (2018) 429–442

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Fuel consumption of rotorcrafts and potentiality for hybrid electric power systems

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ARTICLE INFO

Keywords:
Hybrid power systems
Fuel economy
Helicopters
Batteries
Turbo shaft engines

ABSTRACT

The paper proposes a simulation approach to evaluate the power required by a rotorcraft in standard flight missions and in emergency landing maneuvers, and the corresponding fuel consumption, in order to compare the feasibility and potential fuel savings for different hybrid power systems. More in detail, three options are analyzed, namely electrification of the tail rotor, fully hybrid electric propulsion and electric emergency landing. Weight penalty and potential fuel saving for the proposed hybridization schemes are evaluated for an Agusta-Westland A109 twin engine helicopter model. Nonetheless the discussed methods of analysis have general validity for single main rotor helicopter configurations.

Two different scenarios are considered in this investigation: current technologies for batteries and motors and improved electrical components, with performance projections as of 2040. According to this analysis, electrification of the tail rotor and parallel hybridization are feasible with available technology, whereas a fully electrical power system for emergency landing could be developed only in the future. Finally, a parallel hybrid electric power system is sized according to the analysis of power request over four different missions. Fuel savings are evaluated for different energy management strategies. According to the results of this investigation, the parallel hybrid electric power system with present-day and future technologies can save fuel up to 5% and 12%, respectively, with an appropriate energy management strategy.

1. Introduction

The trend towards an increasing "electrification" of all classes of aircraft is a well-established one, also because of the need of reducing aircraft environmental impact [1]. Little more than 20 years ago, a fully electrically powered airplane was considered as an almost unrealistic design challenge [2]. Nowadays, electric and hybrid electric powertrains are available for fixed-wing aircraft, where the hybrid electric concept is used to increase safety, reduce noise, improve range and endurance and, therefore, minimize the environmental impact of flight operations [3–7]. This revolution calls for new flight mechanics analysis tools and design techniques, together with the development of experimental test-beds. As an example, the classic Breguet equations for the evaluation of aircraft range and endurance performance have been recently reformulated to take into consideration these innovative propulsion systems [8–11].

Electrical propulsion is already extremely popular for many small-scale rotorcraft, such as light helicopter models and multi-rotor platforms (even if endurance seldom approaches the limit of 30 min [12]). At the same time, a fully electrical propulsion system is unconceivable with current technologies in the case of full-scale rotorcraft, because of the high level of power required and the limits of electric motors and batteries. On the other hand, the wide variation of power required in different flight conditions may provide an interesting scenario for the application of a hybrid powertrain.

Generally speaking, the advantages of hybrid electric power systems for helicopters [13–18] include: separation of the propulsion of main and tail rotor, higher reliability, increased operational lifetime thanks to reduction in the number of devices (such as gear, transmission, etc.), improved maintenance workability and lower operational costs together with lower emissions, consumption, noise and vibration levels. As a further advantage, particularly relevant for single-engine rotorcraft, the battery pack allows for a few minutes of endurance in case of engine failure. Instead of completing an autorotation descent with a critical engine-out landing, the residual energy in the batteries can be used for landing the rotorcraft by means of a more conventional (and inherently safer) powered landing sequence [13–15]. These advantages need to be weighed against the increased weight and complexity of the resulting powertrain.

Possible variants in terms of powertrain configurations are

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https://doi.org/10.1016/j.enconman.2018.03.016
Received 28 November 2017; Received in revised form 6 March 2018; Accepted 7 March 2018

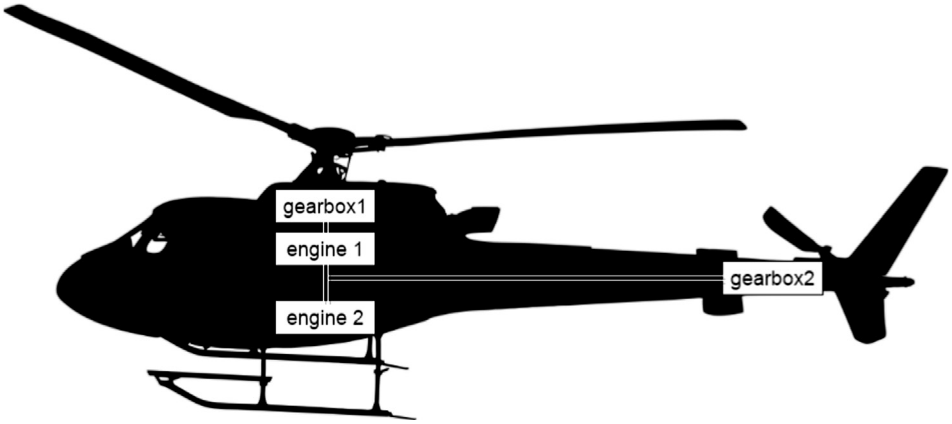

Fig. 1. Conventional twin-engine power systems.

presented in Gurevich et al. [13]. The electric drive can be used for the tail rotor only or for both rotors, with both parallel and series schemes. Other hybridization schemes have been proposed in literature to improve safety and fuel economy in rotary wing aircraft [14–18]. However, these studies do not take into account the time histories of power request during a typical mission and do not quantify the variability of efficiency and performance of the main components of the power systems (engines, electric machines and batteries) in off-design conditions. In fact, the main potentiality of hybrid powertrains is the possibility for the thermal engine to work (almost) always at its best efficiency. This is obtained by downsizing the engine and by accurately controlling the energy management in order to save the excess power in a battery pack during flight phases that require low power, and use the stored battery energy during some (usually short) phases, when more power is required.

Hybrid Electric Propulsion Systems (HEPS) are characterized by the use of two energy storage systems: a fuel tank and an electric storage system (usually a battery). HEPS can be classified into parallel and series powertrains [19]. In the case of series configurations, the propeller (in fixed-wing aircraft configurations) or the rotor (for application of HEPS to helicopters) is moved by an electric motor while the internal combustion engine is used to drive a generator. The current to the motor is the algebraic sum of the battery current and of that produced by the engine through the generator. In the parallel case, both the thermal engine and the electric motor are mechanically connected to the drive and their mechanical power is summed algebraically. The series configuration is suitable for low-speed, high-torque propulsion applications or distributed propulsion systems, but it is less efficient and it requires larger batteries and electric machines than the parallel one.

The paper aims at analyzing the viability of hybridization of a conventional single main rotor helicopter by means of numerical simulations of power required along different mission profiles, including an emergency landing. A hybrid electric power system for safe emergency landing was studied in a previous work of the authors [20]. The objective of the present paper is to extend that study to investigate a wider set of conditions over a variety of full mission scenarios. Fuel consumption is evaluated for each mission, thus determining the potential advantages of a hybrid electric powertrain in different operating conditions. A well documented and widely used twin-engine helicopter, the Agusta Westland A109, is used as a test case for the analysis.

Four mission profiles are considered in this study: a simple transport mission, an air-sea rescue and two search-and-rescue (SAR) mission profiles in a mountain environment. These missions are also used for generating starting points for engine failure scenarios, simulating two different types of landing maneuvers: (i) a fully electrically powered descent with final approach and emergency landing and (ii) an autorotation descent, where electrical power is used only for the final deceleration, approach to the landing spot and landing. As a contribution with respect to [20], the present paper provides a detailed analysis of the power demand along the whole mission profiles and the estimation of the energy and power that batteries and motors should generate with different hybridization schemes. The analysis is performed by means of a mathematical model of the powertrain developed in-house, which is thus demonstrated as a useful design tool. The results are used to compare different hybridization schemes for helicopters, using literature data for batteries and electric generators and motors. However, technological trends for high-performance batteries and motors are also investigated to assess the viability of most promising hybridization schemes that can allow a significant reduction of fuel consumption.

2. Helicopter baseline model

The analysis performed in the present investigation is based on the Agusta-Westland A109 helicopter, a lightweight, twin-engine rotorcraft used in various roles, such as light transport, search-and-rescue, and military tasks. In the case of engine failure, the twin-engine configuration allows a power reserve to perform an emergency landing. The original power system of the rotorcraft is shown in Fig. 1. Each of the two Arriel 1 K1 engines has a nominal power of 538 kW and a nominal Specific Fuel Consumption (SFC) of 0.32 kg/kWh.

The investigation considers two sets of operating conditions:

1. Missions without failure;
2. Missions with engine failure.

The first set is used to estimate the potentiality of saving fuel with different hybridization schemes. The second set is employed to size an electric power system for emergency landing that could allow the replacement of the twin-engine configuration with a larger and more efficient single engine.

2.1. Missions without failure

Power demand along a flight mission is evaluated with a time-step of one second by means of a set of simple numerical tools implemented in a computer program. The characteristics of the mission profile are defined first in terms of distance covered, cruise altitude h, velocity profile V and climb or descent angle γ during the terminal phases. The altitude and speed profiles that define the missions without failure are shown in Figs. 2 and 3, respectively. Two mountain SAR missions are supposed to be performed at an altitude of 2500 m. In the first case, referred to as “Mountain 1”, the helicopter takes off from an altitude of 280 m at 64 km from the operation site (Fig. 2a), whereas in the second one, “Mountain 2”, from an altitude 1200 m with a transfer of only 11 km (Fig. 2b). The helicopter hovers for 10 min for performing SAR operations, and then goes back to the base. In the last two missions,