A method to determine the torque-speed-characteristic of a propulsor-driving motor for an electric aircraft from real mission profiles

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Abstract

This paper proposes a method to derive the torque and speed of an airplane propeller out of a given altitude and velocity profile. The method includes an efficiency optimization for the variable pitch propeller at every single time step and therefore, utilizes the advantage that an electric drive system can dynamically follow the resulting variable speed reference. The determined torque-speed-characteristic forms the basis for designing a suitable electrical motor.

1 Introduction

Conventional aviation is responsible for high greenhouse gas emissions, so that electrically driven airplanes are an interesting option, especially with propeller drives. Challenges are the motor design, selection of power electronics, power supply and energy storage, as well as safety requirements. Ebersberger et al. provide a detailed study on these issues in [1].

For the design of an electric motor, knowledge of the torque-speed-characteristic is crucial. Similar to driving cycles for electric cars, mission profiles can provide the required information for electric airplanes. In this paper, the torque and speed requirements are determined out of of recorded flight data of a real flight, i. e. altitude and velocity. Exemplarily, a flight of an ATR-72-600, which is is a large propeller airplane with one propeller per wing, is studied. The flight data is provided by the OpenSky Network [2].

2 Method description

The mission profile provides the altitude h and velocity v, which is treated as true air speed. That means, the wind velocity is neglected. The procedure illustrated in Fig. 1 is performed for every single time step. First, the required thrust F_T^* is assembled by the normal and tangential components of lift and drag force [3], and the acceleration force. The drag and lift coefficients C_D and C_L are properties of the airplane and are taken from [4]; F_G represents the gravity force and γ the rise angle. To fullfill this required thrust, the advance ratio $J = v/(n\,D)$ is varied until the thrust F_T [5] is as close to F_T^* as possible (n - rotational speed, D - propeller diameter). The thrust coefficient C_T and the, later used, power coefficient C_P are properties of the propeller and are provided by the German Aerospace Center. As data of the original propeller are not available, a similar propeller is assumed. The coefficients C_T and C_P at different pitch angles β are depicted in Fig. 2. Further influences to the thrust are the rotational speed, which is determined by v and J, and the air density ρ, that decreases with increasing altitude. With having J and n, the torque M is calculated [5]. If there is a fixed-pitch propeller, i. e. the pitch angle $\beta = \text{const.}$, the torque and speed are fully determined at this point. If β is variable, an iteration with the steps $x = 0, 1, \ldots$ leads to the pitch angle with optimal efficiency η.

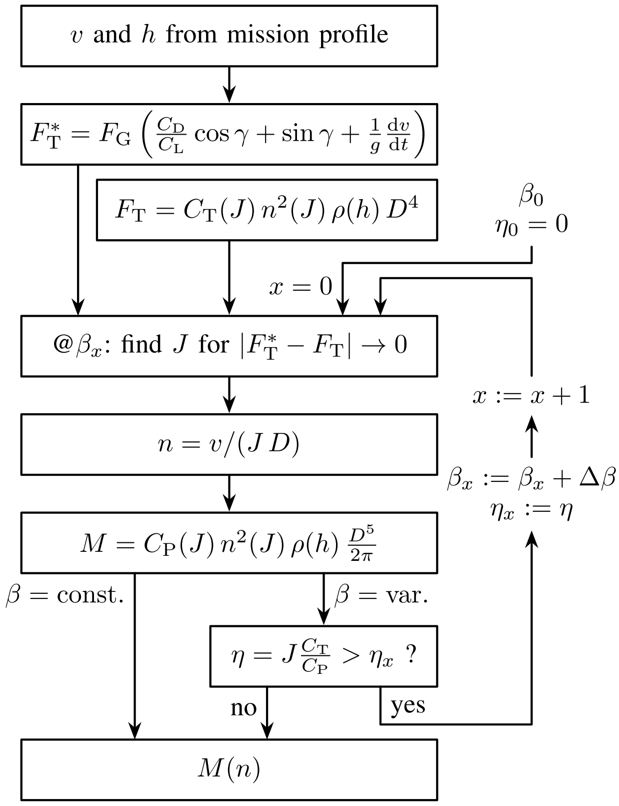


Fig. 1. Schematic of the described method.

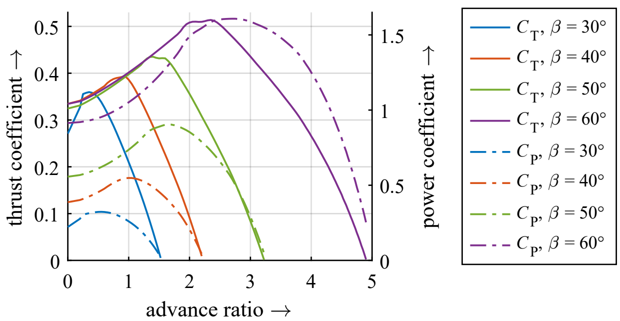


Fig. 2. Properties of the assumed propeller.

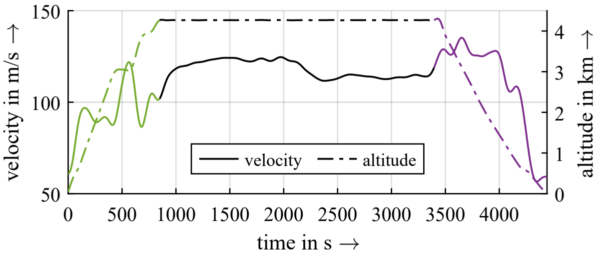
3 Case study and evaluation

The method is applied to the mission profile in Fig. 3a, which was recorded on a flight of an ATR-72-600 from Southampton to Dublin on 2025/01/30. The raw data

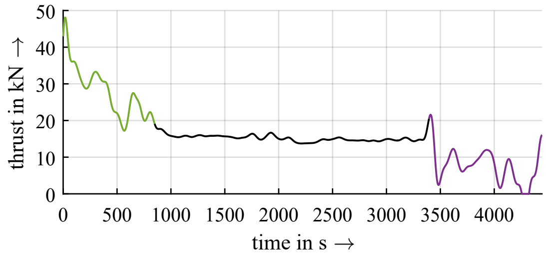
contains some points of uncontinuousness and therefore, is filtered at first. The profile can be divided in three phases: climb (marked in green), horizontal cruise (black) and descent (purple). As Fig. 3b shows, the required thrust is highest during climb because the airplane not only rises, but also accelerates. During horizontal cruise, only the drag has to be overcome and the required thrust decreases to less than half of the initial thrust. During descent, the negative angle γ and the decreasing velocity further reduce the thrust requirement, in some cases even to a negative value. In a first step, negative values are neglected by setting $F_{\mathrm{T}}^{*} = 0$.
Simultaneously to the thrust, the torque and speed for an operation at optimal efficiency are highest at climb, lower at cruise and lowest at descent, see Fig. 3c. At first, it needs to be verified that the maximum tangential speed, i. e. at the propeller tips, does not exceed 85 % of the sonic speed [5], i. e. 292 m/s. With $n_{\max} = 1319\,\mathrm{rpm}$ and $D = 4\,\mathrm{m}$, the maximum tangential speed is 276 m/s and thus, the strategy is permissible. During climb and descent there are remarkable fluctuations in the optimal speed and torque, which indicates that the efficiency can be increased through speed variations, compared to a conventional strategy with constant speed. In the cruise phase, the speed is almost constant and therefore, no significant differences to constant speed operation are expected.
Plotting the torque versus the corresponding speed leads to Fig. 3d. During climb, both speed and torque exceed their cruise counterparts by about 30 %. Of course, this depends on the climb rate, altitude and velocity, which can differ with every single flight. Consequently, the motor torque-speed-characteristic must base on the analysis of different mission profiles or a standardized mission profile similar to automotive driving cycles, to account for all intended use cases. However, even the analysis of one single mission profile allows two main findings:

- A high overload capability of the motor is advantageous, as the points of highest load occur during the transient climb process and thus, for a limited time.
- Highest torque and highest speed arise simultaneously, so that the motor does not have to be designed for field weakening.

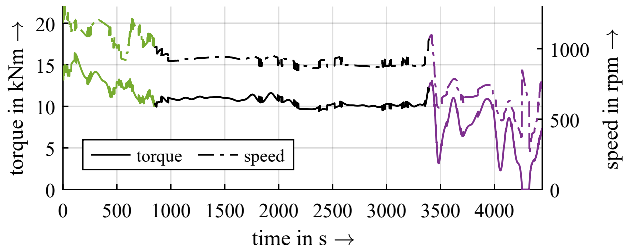
With reference to the motor design process, the rated operation point could be the one marked with a red star in Fig. 3d. The exact choice of this point of course depends on the motor type and cooling conditions.



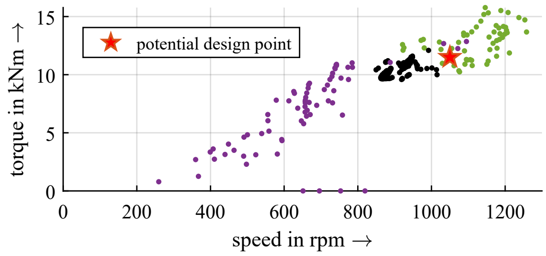
(a) Mission profile.



(b) Required thrust for the whole airplane.



(c) Torque and speed of one propeller.



(d) Torque-speed-characteristic of one propeller.

Fig. 3. Mission profile, required thrust and determined torque and speed for optimal efficiency with variable-pitch propeller.

4 Summary and outlook

The paper proposes a method to determine the torque-speed-characteristic of an electric motor for a propeller-driven airplane. The results imply that field weakening is irrelevant and the motor could be designed to be overloaded to a certain degree during climb.
Further work that will be presented in the final paper bases on the following idea: While conventional drives with combustion engines should be operated with constant speed, electric drives allow for a variable speed as an additional degree of freedom. This can be used to enhance the total efficiency of the mission and to form the torque-speed-characteristic to match a common motor design.
Finally, on the basis of the proposed method, also new drive topologies that are not feasible with combustion engines, but enabled by electric motors, can be developed. Such topologies, e. g. distributed topologies with more propellers, help to use the advantages of electrification to improve the whole drive system.

References

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