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Review report of the dissertation submitted by MSc, Eng. Magdalena Peciak „Application of Model Based System Engineering (MBSE) methods in designing hybrid and electric propulsion system for aircraft“

Problem

In civil aviation, reducing the energy consumption of aircraft plays a decisive role in their new development. On the one hand, reducing energy consumption directly leads to lower operating costs and, on the other hand, the environmental impact is reduced by lowering pollutant emissions, measured in CO2 equivalents. If sustainable, CO2-neutral fuels, e.g. LH2, are used in the future, the costs of which will be significantly higher than those of today's aviation fuels, both effects will add up. While in recent decades, significantly improved engine technologies have mainly driven the reduction in aircraft energy consumption, other technologies in the areas of structure/weight reduction, aerodynamics, and flight control did not provide the same lever for aircraft energy reduction. Therefore, the research focus remains on propulsion and engine technologies but becomes broader as new energy sources, e.g. LH2, energy converters, e.g. fuel cells, engines, e.g. electric motors, and necessary system components are introduced and are even combined with conventional propulsion systems. Furthermore, integrating these new systems into the aircraft configuration adds complexity, with thermal management in particular becoming a critical subsystem. As a "classic" decoupling of aircraft configuration and engine/propulsion is not feasible anymore for these new energy storage/conversion and propulsion systems, a new integrated approach is necessary starting from conceptual design phase.

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Objective and Scientific relevance

The need for a new integrated approach in conceptual aircraft design described above reveals the gap in research that Ms. Magdalena Peciak aims to fill with her dissertation. Her scientific approach consists of introducing a model based system engineering as backbone of the conceptual aircraft design. In her dissertation, Ms. Magdalena Peciak focuses on general aviation aircraft, which do not contribute significantly to aviation-induced CO2 emissions but represent a scalable testing platform in terms of technical and financial risks. Building on this, larger propulsion systems for commercial aviation can then be developed and operated at a later stage. The first step in this direction is therefore the numerical simulation of general aviation aircraft with alternative propulsion systems using an MBSE approach. Ms. Magdalena Peciak summarizes this in her research hypothesis:

„*The conceptual design as part of the classic design process of aircraft for general aviation initially focuses on the four main forces of lift, weight, drag and thrust and uses historical data to evaluate these forces in order to obtain first design decisions. However, for aircraft with alternative propulsion systems, the historical data are no longer valid or only to a limited extent.* ***As an alternative to historical data, parameterized models can be used, provided that the design parameters of these models are directly related to the four main forces. The thorough identification of these design parameters therefore forms the basis for an appropriate model-based design process for aircraft with alternative propulsion systems.***"

The validation of her governing hypothesis and the sub-hypotheses derived from it are the aim of the dissertation.

With this dissertation, Ms. Magdalena Peciak makes a scientific contribution to engineering science in terms of combining the approaches of classic, on historic data based conceptual aircraft design with the model-based system engineering concept applied for innovative hybrid-electric propulsion concepts. This is valuable step to assess the impact of unconventional and innovative systems without dependency on statistic data already in the early stages of aircraft design allowing to estimate their impact on energy saving, CO2-reduction, performance and overall aircraft efficiency.

Contents of the thesis and methodological approach

The review is based on the written version of the dissertation, written in English, which was submitted to me on July 9th, 2025, by the Faculty of Mechanical Engineering at the Silesian University of Technology at Gliwice and comprises of 117 pages in total. It consists of a cover sheet, the table of contents, a nomenclature (abbreviations and symbols), seven chapters, the bibliography and an appendix. There is no list of figures or tables

In her introduction (Chapter 1), Ms. Magdalena Peciak provides a brief general introduction to the subject area, focusing on the most important framework conditions. From this, she derives relevance for the conceptual design of general aviation aircraft and the fundamental working hypothesis of her dissertation, which was already cited at the beginning. This hypothesis is to be validated by addressing four key questions. The focus is on modeling the four essential forces acting on an aircraft: lift, weight, thrust, and drag. The well-conducted literature review systematically covers the areas of the aircraft as a system, general system modeling and system engineering, alternative propulsion systems, aircraft design, and the associated procedures. The division of alternative propulsion systems into all-electric, hybrid-electric, and fuel cells is not conclusive and is conceptually ambiguous: all-electric is understood exclusively as battery-electric propulsion, and fuel cells describe only one form of conversion from chemical to electrical energy. Here, a more systematic classification into energy storage, energy conversion, and thrust generation using morphological analysis would have enabled a clearer structure and systematization of drive combinations. Finally, the structure and content of the following chapters are explained very clearly. At this point, it would have been helpful to link the chapter content to the answers to the four key questions.

<u>Chapter 2</u> covers key aspects of the design process for aircraft with innovative propulsion systems over a total of 19 pages. Section 2.1 begins by examining the key force relationships in aircraft and the dependencies of range and flight duration on the forces acting on the aircraft, which are essentially derived from Breguet's well-known range formula. From this, the relationship between the forces and the components referred to as "main systems" in Ms. Magdalena Peciak's dissertation—wings, fuselage, tail, propulsion, etc.—is then derived. The well-known "classical" design process for conventional aircraft is well explained in Section 2.2 and supported by references. Section 2.3 provides a good and comprehensive overview of the design methods for aircraft with alternative propulsion concepts, with the definition of the different degrees of hybridization and specific ranges in the analytical methods being particularly well done. The numerical design methods briefly explain the commonly used program systems. The literature review could also have included the PrADO program system and the commercial software tool APD/Desmo from PACE. The mention of retrofitting existing aircraft from conventional to alternative propulsion concepts is an important point, but deserves its own section due to other requirements and constraints in the design process. The adaptation of the design process to novel propulsion systems concludes the chapter in section 2.4. Although Fig. 2.5 illustrates the main differences, there remains some ambiguity in the term "model-based system," with reference being made to both ´parametric simulation models´ and 'systems' without the term ´system´ being defined in this chapter. The classification of modeling approaches into accuracy classes (´fidelity levels´), which is otherwise common in aircraft design, would also have helped to clarify some points in this otherwise well-written section.

The parametrically constructed models of the individual subsystems are dealt with extensively in <u>Chapter</u> 3 on 21 pages, whereby they are first divided into the three groups "providing energy," "converting energy," and "generating thrust." Since the simulation in the dissertation is carried out using the Matlab/Simulink tool, the basic models provided in the tool are used. The first group includes batteries, tanks for conventional and alternative fuels, and storage for gaseous and liquid hydrogen. The essential relationships between the model parameters, which later represent the parameters in the overall simulation, are presented. It would have been desirable to briefly identify the relevant parameters for each group member that will later be varied or fixed. In the case of hydrogen storage systems, the dependence of the tank mass on tank volume, pressure, and temperature is not explained in further detail. The second group of energy converters covers electric motors, combustion engines, and fuel cells. In the case of combustion engines in particular, the system boundaries could have been explained in more detail by comparing air- and water-cooled engines with and without transmissions in terms of performance and mass. In contrast to fuel cells, the cooling requirements for electric and combustion engines are not considered further. In the case of fuel cells, it could have been clarified whether only the mass of the individual cell or the installed mass including the support structures for the individual cells, the treatment of the air (compression, if necessary), and the conditioning of the hydrogen (pressure, temperature) are considered. The "Generating Thrust" group contains a highly simplified propeller model that determines the quality of energy conversion via a constant efficiency factor. Finally, another group presents the parametric models of the "auxiliary systems" power electronics, electrical power distribution, thermal management system, avionics/cabin systems, and transmission. The design and mass of the cabling are not covered. Overall, Chapter 3 provides a thoroughly successful overview, but it still leaves many questions unanswered regarding the specific use and interconnection in the overall system model.

Ms. Magdalena Peciak discusses the modeling and analysis of alternative propulsion systems in Chapter 4 of her dissertation. The first section, 4.1, clearly presents the four configurations under consideration: a) battery-electric propulsion only, b) serial and c) parallel hybrid-electric propulsion, and d) battery-supported propulsion with fuel cells. There is no introductory note stating that the thermal management subsystem only considers the battery and fuel cell subsystems. This is a subsystem that should not be neglected, especially in hybrid electric propulsion with combustion engines, and its omission would need to be explained. The illustrations for a) (Fig. 4.1), b) (Fig. 4.2), and d) (Fig. 4.4) do not show a possible gearbox between the electric motor and the propeller, which, like the cooling of the combustion engines, could have a noticeable effect on the mass estimation. Section 4.2 successfully combines the approach of system modeling of the propulsion system via an energy analysis with the overall design approach based on the forces explained in Chapter 2. The simulation models of the alternative propulsion systems a) to d) are presented in a compact and clear manner in Section 4.3. It would have been desirable to link Figures 4.7 to 4.10 more closely with Figures 4.1 to 4.4 and the individual subsystem models in Chapter 3. These subsystem models incorporate a large number of parameters and interdependencies that must be mapped very carefully and centrally in order to be able to interpret the later results correctly.

An overview and qualitative description of general aviation aircraft with alternative propulsion configurations that have been realized to date is provided in Section 5.1 of Chapter 5. Section 5.2 below presents a table showing the effects of integrating the propulsion subsystems on key configuration parameters (geometry, mass, aerodynamics, etc.) of the aircraft as a whole. The effects of the integration aspects on the subsystem (performance, efficiency, cooling requirements, etc.) are not considered. Finally, Section 5.3 briefly introduces the modeling and analysis of aircraft in the OpenVSP software without an in -depth explanation of the methods used in the tool. Chapter 5, which could be improved overall, only partially fulfills the objectives formulated by Ms. Magdalena Peciak in section 1.3. Especially, an in-depth consideration or implementation of the relation between the alternative propulsion systems (chapter 4) and the design process proposed in chapter would be helpful.

In Chapter 6, Ms. Magdalena Peciak applies the concept phase expanded in Chapter 2 to include model-based propulsion system design to the design of a general aviation aircraft. Accordingly, the essential requirements for the aircraft are first defined in Section 6.1. An overview of the certification requirements to be considered in the concept phase in accordance with CS-23 and in particular for electric propulsion systems is not provided. The actual realization of the concept design is carried out in Section 6.2, where all essential steps are briefly explained and the most important results are presented. Essential aircraft design parameters such as wing loading and thrust/weight ratio are not considered. A lift coefficient of 0.0507 in Table 6.2 and a landing speed that is higher than the take-off speed in Table 6.3 do not appear plausible and are not discussed further. The aerodynamic parameters required for the mission calculation with flaps extended during take-off and landing are missing. A comparison of the available and required thrust for the usual cases of take-off, engine failure during climb and climb after landing abort is not provided. Figure 6.3 contains no information on the altitude and speed of the aircraft. Information on take-off and landing distance are missing. Overall, the proof of the suitability of the integration of the model-based system design of the propulsion system into the concept design of aircraft is thus fundamentally successful, but requires a substantial expansion in the presentation of the results in the dissertation and the addition of the proofs absolutely necessary for certification according to CS-23 in the concept phase.

The relatively brief two-page summary in Chapter 7 summarizes the key content and results. A brief outlook is also provided. A critical discussion of her own work and the results achieved, as well as a reflection on the extent to which the work can answer the working hypothesis and the derived scientific questions in the chapter, would have rounded off the work.

Summary

Ms. In her dissertation, she has worked on and answered the research hypothesis she posed herself and the scientific questions derived from it in a fundamentally comprehensible and structured manner. With her approach of expanding the classical aircraft conceptual design to include the model-based design of essential systems not known from historical data, particularly in the area of propulsion, she demonstrates her ability to conduct independent scientific work. The formal elaboration of the dissertation can be considered successful overall, but requires significant reworking in chapters 4, 5 and 6 in order to make the procedures more comprehensible and the results achieved more transparent and reproducible. I therefore recommend that the doctoral dissertation of Ms. Magdalena Peciak, M.Sc. Eng., be admitted for defense in the discipline of mechanical engineering.

Prof. P. Bardenhagen

/podpis odręczny/

*wyłączenie jawności w zakresie danych osobowych oraz ochrony prywatności osoby fizycznej na podstawie art. 5 ust. 2 ustawy z dnia 6 września 2001 r. o dostępie do informacji publicznej (tj. Dz.U. z 2016 r., poz. 1764)