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Master Thesis – Excerpt for the Swiss Association of Aeronautical Sciences

Mission Definition, Analysis and Operation Potential of a Hybrid-Electric Aircraft based on the Do228 Design

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Abstract

In today's world, living space gets scarcer and population density increases. Worldwide air traffic is forecasted to double in the next 15 years. Thus, the number of people affected by aircraft noise grows. Besides, also other environmental concerns such as global warming attracts increasing social attention and claims major priorities in political agendas. The European Commission's vision for aviation "Flightpath 2050" therefore states ambitious goals: A reduction of 90% in NO_x, 75% in CO_2 and 65% in perceived noise emissions relative to performance of new aircraft in 2000. Regarding these social, political and environmental trends and the fact that the world's transportation system still heavily relies on fossil fuels although running out of crude oil in this century, alternative, sustainable propulsion systems need to be developed. Pure electric vehicles offer an attractive solution but are quite limited in range due to the relatively low specific energy density of current batteries. Hence pure-electric propulsion is mainly reserved to terrestrial applications and not yet feasible for commercial air transport. Hybrid-electric propulsion systems (HEPS) therefore combine a battery based electric power train with a fuel-based drive train and thus provides an interesting alternative to overcome the limited capacity of batteries. With the stored electrical energy for maximum power requirements, the internal engine can be sized for average power consumption and be run at its optimal operating point. A serial HEPS configuration increases overall efficiency while reducing noise emissions.

This work investigates the operational potential of a retrofitted Do 228 aircraft with a hybrid-electric propulsion system. The thesis is divided into two parts: A technical investigation and an economic analysis. The first part includes a sound model which provides a first evaluation of the noise reduction potential for the modified aircraft. Moreover, the operational fields are analyzed and suitable missions defined. Based on these missions, the operational potential is finally verified with according flight performance modellings comparing the computational results of the retrofitted version with the baseline aircraft. The second part focuses on a market analysis to assess the market potential for such a hybrid-electric aircraft. The opportunities and threats, strengths and weaknesses of the project are identified and evaluated with an external and internal analysis as well as additional information from a market research provided by RUAG Aviation. Finally, based on these findings, a market strategy is developed.

To sum up, it is found that a hybrid-electric modification of the Do 228 aircraft leads to several promising potentials to be exploited. On one hand, the noise modelling confirmed a sound reduction by minimum 4 dB(A) during take-off with the same propeller and power setting as for the baseline aircraft. The silent flight capability therefore offers operational potential and competitive advantage to conduct flights with reduced acoustic emissions. An optimized propeller design could further increase the noise reduction potential of the aircraft. On the other hand also the mission performance stated favorable results in terms of range. Assuming current technology level and a 300 kg battery installed, the overall efficiency advantage of the HEPS drive train allows to outperform the baseline aircraft by 54 NM at a design payload of 1020 kg. It is also shown, that the hybrid-electric propulsion enables an increase of 38% in specific range. Moreover, special market potential for such a silent aircraft is identified for transport missions operated in densely populated areas, night operations but also to increase the general community acceptance for air traffic in airport surroundings. Further, the reduced acoustic detectability of the aircraft in electric flight mode is also regarded as a tactical advantage for special mission operations.

Zusammenfassung

In der heutigen Welt wird der Lebensraum immer knapper und dichter besiedelt. Gleichzeitig wird vorausgesagt, dass sich der weltweite Luftverkehr in den nächsten 15 Jahren verdoppelt. Als Folge steigt die Zahl der Menschen, die von Fluglärm betroffen ist. Aber auch Umweltbedenken wie die globale Erwärmung erregt immer mehr gesellschaftliche Aufmerksamkeit und belegt hohe Prioritäten in politischen Agenden. Die Vision der Luftfahrt "Flightpath 2050" der Europäischen Kommission setzt dabei ambitionierte Ziele: Eine Reduktion von 90% NO_x, 75% CO_2 und 65% Lärmemissionen im Vergleich zur Leistung von neuen Flugzeugen aus dem Jahr 2000. In Anbetracht dieser politischen, sozialen und ökologischen Trends und des Faktes, dass sich das weltweite Transportsystem immer noch stark auf fossile Treibstoffe verlässt obwohl die Erdölreserven dieses Jahrhundert aufgebraucht werden, scheint es offensichtlich, dass alternative und nachhaltige Antriebssystem entwickelt werden müssen. Rein elektrische Fahrzeuge bieten dabei eine attraktive Lösung, sind aber aufgrund der beschränkten spezifischen Energiedichte von gegenwärtigen Batterien in ihrer Reichweite ziemlich eingeschränkt. Darum bleiben batterie-betriebene Fahrzeuge terrestrischen Anwendungen vorbehalten und rein elektrische Antriebe für kommerzielle Flugzeuge noch nicht umsetzbar. Hybrid-elektrische Antriebe dagegen ermöglichen durch die Kombination von einem Batterie betriebenen und einem auf Treibstoff basierenden Antriebsstrang die eingeschränkte Kapazität von Batterien zu überbrücken. Durch die gespeicherte elektrische Energie als Puffer für Maximalleistung, kann der interne Motor auf den durchschnittlichen Leistungsbedarf ausgelegt und beim optimalen Betriebspunkt operiert werden. Dies führt zu einer Steigerung der Gesamteffizienz und zur Reduktion von Lärmemissionen.

Diese Arbeit untersucht das operative Potential eines umgebauten Do 228 Flugzeuges mit einem hybrid-elektrischen Antriebssystem. Sie ist in zwei Teile aufgeteilt: Eine technische Untersuchung und eine ökonomische Analyse. Der erste Teil beinhaltet eine einfache Lärmmodellierung, welche eine erste Abschätzung des Lärmminderungspotentials für das modifiziertes Flugzeug bietet. Des Weiteren werden die verschiedenen Anwendungsfelder analysiert und passende Missionen definiert. Das operative Potential wird basierend auf diesen Missionen anschliessend mit entsprechenden Flugleistungsmodellierungen verifiziert indem die berechneten Resultate des umgebauten Flugzeuges mit dem Originalflugzeug verglichen werden. Der zweite Teil untersucht im Rahmen einer Marktanalyse das Marktpotential für ein solches hybrid-elektrisches Flugzeug. Die Chancen und Gefahren, Stärke und Schwächen des Projektes werden mit einer externen und internen Analyse sowie zusätzlichen Informationen einer Marktforschung der RUAG Aviation identifiziert und evaluiert. Basierend auf diesen Erkenntnisse aus dieser Untersuchung wird schliesslich eine Marktstrategie formuliert.

Zusammenfassend wird festgestellt, dass eine hybrid-elektrische Modifikation einer Do 228 verschiedene vielversprechende Leistungspotentiale ausschöpfbar macht. Einerseits besagt die Lärmmodellierung, dass ein solcher Umbau eine Lärmreduktion um mindestens 4 dB(A) während des Starts bewirkt bei gleicher Propeller- und Leistungssetzung. Die einmalige "Leiseflug-Eigenschaft" ermöglicht Flugsegmente mit reduzierten akustischen Emissionen durchzuführen. Ein lärmoptimierter Propeller könnte darüber hinaus weiteres Potential zur Lärmreduktion bieten. Andererseits haben auch die Missionsberechnungen interessante Resultate ergeben: Bei aktuellem Technologiestand, einer Batterie von 300 kg und einer festgelegten Zuladung von 1020 kg, erreicht das hybrid-elektrisch angetriebene Flugzeug im Vergleich zum Originalflugzeug eine um 54 NM höhere Reichweite. Es wird gezeigt, dass ein hybrid-elektrischer Antrieb eine um 38% höhere spezifische Reichweite erzielen kann. Darüber hinaus wird ein spezielles Marktpotential für ein solches lärmarmes Flugzeug für Transportmissionen in dicht besiedelten Gebieten, Operationen bei Nacht und zur generellen Steigerung der Akzeptanz der Bevölkerung rund um Flughäfen identifiziert. Andererseits wird die reduzierte akustische Detektierbarkeit im rein elektrischen Flugmodus auch als ein taktischer Vorteil für Spezialmissionen erachtet.

1 Outlook

This chapter discusses limitations of the modelling carried out in this thesis and states basic considerations which could be taken into account for future work on this topic. Further implementation ideas concerning the realization of the modification and a possible upgrades of the aircraft are presented.

1.1 Future Work

The conceptual modelling of the HEPS but also the NG aircraft and the implementation in the simulation environment has been investigated in previous works [13] [14] and was provided by ALR Aerospace. The simulation model of the HEPS aircraft is based on the NG model. The fuel consumption was therefore programmed to account for two fuel consuming engines. This led to the little error in the simulation program to double the fuel consumption as well for the HEPS aircraft which in fact only has one fuel consuming engine, the range extender. This caused of course much less promising flight performance results in the beginning of this project. After identifying the error, it was corrected and the computations revised. The new results were interpreted to be too optimistic and therefore the consumption model needed to be adapted. Therefore, the previously Wankel rotary engine based REX was changed to a gas turbine REX. Gas turbines are on one hand proven and dependable engines for auxiliary power units and on the other hand compete with higher overall efficiency and less noise while power and volume densities are comparable. A brief research on specific fuel consumption of aerospace turbines led to an assumed value of 350 g/kWh for the standard version. The power loss with altitude was estimated with a very basic equation (2).

For a future work therefore a more sophisticated gas turbine modelling for such a range extender would be desirable in order to support the significance of the herein presented results.

Moreover, a succeeding work could investigate on a more detailed, comprehensive noise model for the aircraft. The model could probably be implemented in the APP and based on the power setting of the aircraft directly calculate the noise level perceived in a specific distance to the ground during all flight phases.

Another project could further also examine the potential of a parallel HEPS in terms of probable increase of overall system efficiency disregarding the silent flight capability.

1.2 Modification Keynotes

For the modification of the baseline aircraft into a HEPS version, several adaptations and adjustments need to be carried out. Some few basic ideas about the modification are stated in this short section .

Electric Motors: Due to the fact, that the electric motors have a higher volumetric power density compared to turboprop engines the nacelles can be downsized and aerodynamically redesigned.

Batteries: Compared to NiCd or lead acid batteries, state of the art Li-Ion batteries have a wide temperature range (i.e. -10°C to 50°C) in which operation is safe. In minus temperatures though, their cell capacity is reduced due to the impedance effect leading to higher resistance for charging and discharging. Aris and Shabani [143] therefore found that state of charge at such low temperatures have been reduced by 7-23 % of its maximum capacity (i.e. 100%). Therefore, an integration of the battery in the cabin or an extension of the cabin climate to the battery compartment with controllable climatic conditions is required. Moreover, effective battery installation within the aircraft structure further decreases the specific energy density. Weight and balance considerations are further crucial installation constraints which need to be taken into account. Therefore, battery mass placement near the center of gravity is desirable but also to minimize the cable run between the battery and the electric motors.

Range Extender: Noise reduction is a prior concern of this thesis and in order to maximize its potential, an integration of the REX within the internal aircraft structure is required, preferably also in vicinity of the center of gravity. The REX needs to be acoustically insulated to further reduce noise emissions. The installation of BAT and REX within the cabin or internal aircraft structure though leads to space penalties within the cabin. Therefore, a REX installation in the aft fuselage and an effective integration of the battery in the cabin underfloor or in the undercarriage housing with climate control could finally be another solution to be considered.

In conclusion, it is obvious that a clean sheet design benefits in the possibility to combine several new aircraft technologies at once and for that reason incorporates greater overall efficiency potential than a modification of an existing aircraft. On the other hand, a proven aircraft design like the Do 228 with its outstanding performance and versatile cabin provides a suitable testbed in order to verify the potential of hybrid-electric propulsion for commercial aircraft.

1.3 Do 228 Upgrade Keynotes

As discussed in Chapter 8.7 first strategy proposal, a launch of a potential Do 228HEPS aircraft should also incorporate further upgrades concerning MTOW, avionics, cabin versatility and mission equipment system installations.

It has been seen in the competitor analysis that some rival aircraft have successfully improved flight performance characteristics and even surpassed the Do 228 in some respects. As aerodynamics performance gain of the supercritical wing are almost exploited, structural improvements need to be taken into account. Therefore, the structural design need to be partially revisited and punctually reinforcement in order to increase MTOW and therefore offer customer more payload (or compensate the battery mass penalty). Moreover, in today’s interconnected world with accelerated technology improvements it is also crucial for aircraft manufacturer to keep updated with current avionic systems. On the other hand, avionics should of course also be selected with respect to customer desires and costs. The Do 228 is besides its competitive flight performance and low operational costs appreciated for its cabin versatility. Therefore, an effective installation of the REX and BAT is of major importance in order to maintain cabin versatility. As the cabin needs to be adjusted anyway for the retrofit version, new cabin conversion kits could be developed. Further, based on the current mission computer and sensor equipment choice, systems could be updated, extended and offered in flexible and integral special mission installations. Such customized solutions would further increase overall product value for special mission operators.

2 Conclusion

This master thesis has investigated several missions and the operational potential of hybrid-electric propulsion system for a retrofitted Do 228NG aircraft. The first part included a noise modelling, the design and definition of suitable missions and the according mission performance computations for a simulation model of the modified HEPS as well as the baseline NG aircraft. The operational potential has been verified by comparing the computational results of both models. The second part covered a market analysis and a strategy formulation for the retrofitted aircraft. Based on strategic management tools, a market analysis approach was developed. An external analysis was carried out to identify opportunities and threats for the project whereas an internal assessment provided information about strengths and weaknesses for the aircraft in the market. With conclusion of the internal and external analysis and additional information about the current fleet and forecasted demand of aircraft in this class, a market approach strategy was finally formulated.

Although the herein presented noise model is restricted to the take-off, it has clearly confirmed the noise reduction potential of such a modified aircraft. It was found that a pure-electric take-off benefits in a noise reduction of minimum 4 dB(A) which is more than half the noise energy emitted by the baseline aircraft during departure. Further the noise model also enabled an estimation for the altitude on which the activation of the range extender is not noise relevant anymore. This altitude was found on 2000ft AGL.

The assessment of the operational fields with focus on exploiting its “silent flight capability” resulted in four representative missions: Transport, Patrol, ISTAR and Paradrop Mission. The assessment further identified two key benefits of the silent flight capability: On one hand the electric flight offers a promising noise mitigation possibility to protect the environment and to bargain on an extension of the operational hours. On the other, silent flight also reduces acoustical detectability of aerial vehicles and is therefore an interesting feature for tactical operations. The tactical interests more applies to non-civil operations whereas the environmental protection is beneficial for all fields of operation. However, initial point performance calculations were carried out to assess mission speeds and to define battery and REX engine size. It was found that a REX size of 635 kW and a standard battery of 500 kg is sufficient to accomplish a basic transport mission and to perform electric climb, landing and missed approach or take-off after landing with respecting current technology parameters. Moreover, a lower battery size limit of 300 kg was set and is sufficient for electric for take-off and landing. An upper battery size limit of 975 kg was set for electric loiter flight of about 21 minutes for low level surveillance segments. Based on these sizing limits and further operational requirements, the missions were defined. Extensive flight performance computations followed with the NG and HEPS model to verify its potential. The results for the HEPS model were calculated for different battery masses within the sizing limits. The results confirmed the efficiency advantage of the HEPS to operate the engine - sized for power required at cruise - at its best efficiency point by an increase of specific range of approximately 38 % in cruise configuration. As a demonstrative example, it was shown that the HEPS aircraft with respect to current technology parameters for its components and a 300 kg battery installed outperforms the baseline aircraft by 54 NM at a design payload of 1020 kg. An additional parameter study verified the dramatic effect of increasing specific energy density by technology improvements in future on flight performance. An improvement from 150 Wh/kg to 250 Wh/kg for instance reduces the battery mass penalty dramatically by 200 kg at a constant battery energy of 270 MJ and therefore allows more fuel to be carried and finally offers better range performance. Also for the more complex patrol, ISTAR and paradrop missions promising results were found: The HEPS aircraft with a 300 kg battery installed and respective mission payload, performed with better range in the patrol and paradrop mission compared to the NG model. For the ISTAR mission a 500 kg battery version outperformed the baseline aircraft.

In conclusion this work verified the potential of a hybrid-electric Do 228 not only in terms of the noise reduction but also with respect to flight performance benefits. The pure-electric flight mode enables silent departure, approach and low level flights. By sizing the internal engine for cruise requirements and thus operating it at its best efficiency during the most of the flight offers very economic fuel consumption.