RexMoto – A Range Extender Concept for Light Electric Aircraft

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Abstract- A main limitation of fully electric vehicles is their maximum range, which is principally constrained by the performance (i.e. energy density) of energy storage systems. A range extender, coupled to an electric vehicle, is a system able to store and/or convert energy that is supplied to the vehicle itself with the aim of extending its range. This work deals with the technological development and electrical sizing of a flight range extender concept for light electric aircraft. The presented platform, defined hereinafter as RExMoto, is based on the concept of modularity, obtained by embodying the range extender as a light-weight motorcycle. The benefits and technological challenges are described throughout and a detailed analysis in terms of operations and mission profile is provided. A legacy light aircraft is used as a case-study platform.

I. INTRODUCTION

As the aerospace industry progressively moves towards the concepts of more electric [1, 2] and all-electric aircraft [3, 4], technology enablers to achieve the requirements of these initiatives are becoming more and more important [5-7]. Advancements in electrical machines and drives [8, 9] have in recent years allowed to achieve excellent power and torque densities [10, 11], whilst guaranteeing adequate reliability levels [12]. It is perceived that, in the near future, electrical machines for aerospace applications will have to satisfy even stricter power density requirements in order to meet the ambitious targets of various electrification roadmaps [13, 14]. In all this, advanced materials and manufacturing techniques [15, 16] as well as novel cooling methodologies and modelling tools [17, 18] play a key role. Further, there are recent examples [19, 20], which suggest that important performance improvements can be achieved by a true understanding of the physics behind typical failure mechanisms in machines' critical components [21, 22]. This allows to push materials to their limits, whilst at the same time satisfying strict reliability specifications.

Several air transport platforms are being developed by both leading aerospace manufacturers [23, 24] and smaller enterprises [25]. These aircraft have many excellent features, including reduced direct operating costs, emissions of CO₂, NO_x and noise. However, a main bottleneck in terms of market development is always the energy source for the power plant [26, 27]. Current technology batteries have very low energy density compared to liquid fuels, approximately 2% of the mass specific energy, limiting then the maximum payload and/or the range (distance of flight). A perceived solution to the above can be targeted through the implementation of a

range extender [28], which can be used in an effective way to restore the range and mitigate the payload constraint.

Several technologies and types of range extenders, based on small internal combustion engine (ICE), exist today for various applications [29]. Their main limitations are 1) the extra equipment necessary to integrate with the aircraft, 2) the modifications required on the aircraft itself and 3) the detrimental impact on the existing power systems on the aircraft. From the above, the biggest concern is related to point 1). The extra components have a negative effect especially in terms of the extra weight they add to the aircraft and of course to the zero-emissions claim that goes with a pure-electric platform. However, if one starts to consider aspects that go beyond the realm of simply extending the range of the aircraft, then the benefits of a range extender can outweigh the ensuing concerns. These aspects include 1) a range extender technology that is self-contained and modular, in order to not compromise existing aircraft platforms, and 2) a range extender technology that is easily removable and thus can be carried only when necessary for the desired mission. Considering the latter point, if the extender is easily removable, then it can be packaged in a manner that allows it to be used also as an on-road driving vehicle, in the shape of a scooter or small motorbike. As explained below, the benefits of such a multimodal technology are various and go beyond the scope of the flight cycle itself.

This paper, therefore, proposes a new concept of range extender technology that can be used as an in-flight electrical generator unit. The extender-set is, however, easily detachable from the aircraft and can be used as an on-road motorcycle. A summary of the main components and details on the electrical generator system architecture are provided, together with a case-study in terms of use and mission profile.

II. THE REXMOTO CONCEPT

A. Background and overview

The energy density problem, which results in payload reduction, can be effectively mitigated by utilizing a liquid fuelled ICE as a range extender. However, the extra equipment necessary to integrate with the aircraft implies a compromise with the advantages of the pure-electric aircraft. The hybrid electric power system is clearly more complex and less efficient than a pure ICE or an electrical propulsion system (EPS) alone. Due to the necessity of carrying significant extra weight to enable the range extension, a 2-seat aircraft would

likely be restricted to carrying a single occupant, when the range extender is fitted. A key feature of the proposed concept is that the original aircraft may be operated in its uncompromised form, since the minimal modifications required will not significantly affect the original performance or operational specifications.

The proposed RExMoto in flight range extender mode is depicted in Fig. 1, whilst an artist impression of the concept in flight configuration is shown in Fig. 2. The range extender machinery is incorporated as the necessary drive components of a road scooter or motorcycle, but the aircraft and scooter technologies are largely independent of each other. The motorcycle functionality is addressed by incorporating road wheels, steering, a seat and suspension to the range extender, along with a wheel drive. The road drive is achieved using a small on-board battery for pure-electric operation, or the engine driven generator to supply the road wheel power. A major synergistic benefit, which allays the negative consequence of the increased weight of the road equipment, is that it allows ease of fitting the unit to the aircraft. The wheels allow rolling of the range extender to the mounting point under the aircraft, and the suspension allows powered jacking and then retraction with zero human physical effort as well as a low aerodynamic drag configuration. It is also possible to utilize the road wheels for aircraft taxiing operations while on the ground.

Fig. 1. RExMoto in flight range extender mode.

Fig. 2. RExMoto in flight: Artist impression.

B. Energy requirements and electrical power system

Each stage of the flight requires a different power level to be delivered by the propeller. The power must be supplied by the aircraft battery and the range extender. The developed range extender power unit uses a rotary engine of 25 kW nominal power output. Factory-supplied data indicate fuel efficiency of 25% when operating at 20 kW. Therefore, by knowing the energy density of petroleum fuel, the fuel mass demanded for each kWh generated (i.e. converted) by the ICE to the electrical power system is straightforwardly calculated.

The range extender components comprise an ICE, an electrical generator and a power electronics system. A block diagram of the full electric power system is illustrated in Fig. 3, along with the adopted power flow sign convention. Considering Fig. 3, the fuel tank and generator set (i.e. gen-set) are embedded in the motorcycle (i.e. range extender), while the aircraft integrates the electrical energy storage system (i.e. electro-chemical batteries), the power electronics converters and the propulsor.

The propulsion system consists of a permanent magnet synchronous machine (PMSM), coupled to a fixed pitch propeller without any gearbox (i.e. direct drive). A PMSM is preferred to other machine solutions thanks to its excellent power to weight ratio [30, 31], which is a critical requirement in mobile applications [32].

The PMSM has a continuous power rating of 25 kW and it can provide 60 kW peak power for up to 10 minutes. The bidirectional inverter, directly connected to the propulsion PMSM, is sized for the peak power, plus a 30% safety margin (i.e. ≈ 80 kW). The range extender ICE acts as a prime mover for a 20 kW PMSM operating in generator mode. A converter, whose DC link is shared with the propulsor's bidirectional inverter, rectifies the generator's output voltage. The electrochemical energy storage system is a bank of lithium ion cells with a pack level energy density of 180 Wh/kg. The overall batteries capacity is 35 kWh. The batteries are interfaced to the electrical system through a bidirectional dc/dc converter, which adapts the voltage levels and optimizes the charging / discharging of the batteries.

Fig. 3. RExMoto in flight range extender mode.

Fig. 4. Considered mission profile

III. ENERGY FLOW DURING A MISSION PROFILE

The typical mission profile reported in Fig. 4 is exploited for describing the power system's energy flow during each flight stage.

In accordance with the nomenclature and power flow sign convention shown in Fig. 3 the equality (1) must be satisfied in every operating condition.

$$P_{prop} = P_{gen} + P_{batt} \quad (1)$$

In addition, the energy storage system must comply with the limitation given by (2) regarding the state of charge (SoC), where SoC_{min} is the minimum SoC, which guarantees the safe operation of lithium cells and SoC_{max} is set to 95% of the total battery capacity.

$$SoC_{min} < SoC < SoC_{max} \quad (2)$$

Before starting the flight mission, it is assumed that both SoC and fuel quantity are maximum. During take-off and climbing phases, the maximum power must be delivered (i.e. 60 kW) for 10 minutes. Due to the presence of the range extender, such power can be transferred to the propeller in two different ways: 1) drawing all the required power from the batteries (i.e. $P_{gen}=0$ and $P_{prop}=P_{batt}$), which is the approach employed in a pure-electric aircraft, or 2) sharing the demanded power between energy storage system and gen-set relying to the range extender capability which is the approach used for many hybrid propulsion systems [33]. For the second option, the power sharing can be performed by drawing 2/3rd of the power from the battery and the remaining 1/3rd from the gen-set. The power flow during take-off and climbing is depicted in Fig. 5.

At the completion of the climb segment, the aircraft switches to cruise mode, where an overall power of 20 kW must be made available. Under this condition, the inequality (3) must be satisfied, in order to drain power only from the batteries, where k represents a safety factor (>1).

$$SoC > k \cdot SoC_{min} \quad (3)$$

In practice, the battery SoC will be maintained at a high level, $SoC \gg k \cdot SoC_{min}$ or as desired for mission and subsequent ground operation of the range extender system. Once the $SoC = k \cdot SoC_{desired}$, then the battery is isolated from the power network by the dc/dc converter (i.e. $P_{batt}=0$) and the whole power is supplied by the gen-set (i.e. $P_{prop}=P_{gen}$). This latter condition is shown in Fig.6.

Fig. 5. Power flow during take-off and climbing.

Fig. 6. Power flow in cruise mode while the energy storage system is isolated.

After 120 minutes of cruising operation ensured by the range extender, the aircraft begins the descent/landing phases, which overall last 20 minutes involving a power from 10 kW to 5 kW. At this stage, the propulsor needs lower power than the gen-set

power rating, hence the batteries can be partially recharged (i.e. $P_{batt} < 0$), if desired as illustrated in Fig. 7.

Fig. 7. Power flow during the descent phase.

The presence of the Bidirectional Inverter can potentially allow energy regeneration from the propeller acting as a wind turbine. This process is relatively inefficient, but could yield between 5% and 20% of the available potential energy returned to battery storage.

After landing, the batteries can be fully recharged from the grid if available by using an integrated charger. Alternatively, refuelling the range extender and using the gen-set in charger mode, as shown in Fig. 8 is feasible but at the expense of higher energy usage due to the limited engine efficiency. The range extender system can be then used as a road vehicle (i.e. scooter).

Fig. 8. On-ground battery recharging through ICE.

IV. LABORATORY DEMONSTRATOR

A full-scale laboratory demonstrator of the RexMoto electric power system has been developed and assembled in a compact structure as shown in Fig. 9. This demonstrator is necessary for evaluating how the complete power system behaves in various operating conditions before integrating it in an actual two-seater aircraft.

An Advanced Innovative Engineering 225CS Wankel rotary engine is mechanically coupled (direct drive) to an axial flux Emrax 208 PMSM with a nominal output power of 20 kW. An automatic speed regulator is used for maintaining a constant engine speed independently from the applied electrical load (within the maximum 20 kW limit).

Preliminary tests were carried out by electrically connecting the output terminals of the PMSM to a 15 kW resistive load bank, as shown in Fig. 10. The load can be varied by steps of 5 kW each (i.e. 5, 10 and 15 kW).

Fig. 9. Full-scale laboratory demonstrator of the RexMoto power system

The scooter battery pack, with a 2 kWh capacity, is used only for starting the ICE, and then automatically disconnected. After the start-up stage, the ICE is maintained in idle condition for few minutes. Such stage is needed for warming-up the engine and avoiding damages. Thermocouples are installed and connected to a control board for signalling when the ICE has reached the optimal operating temperature. Once the engine has warmed-up, the load resistors are connected. During this stage, the DC link voltage is monitored as well as the PMSM rotational speed.

In all the load settings the full system operates in a stable condition with a 10% drop in DC link voltage when moving from no load to full-load (15 kW), as reported in Table I. No speed variations are noticed (with respect to the no-load condition) when the loads are connected, indicating that the ICE is able to deliver the required torque.

TABLE I
EXPERIMENTALLY MEASURED DC LINK VOLTAGE

Load level	DC link voltage [V]
No load	111
5 kW	108
10 kW	103
15 kW	99

Fig. 10. Preliminary testing of the RexMoto power system

V. CONCLUSION

One of the main factors preventing the widespread adoption of fully electric aircraft is the limited energy storage capability of electrochemical batteries, compared to traditional fuel. Nonetheless, in recent years, the aerospace industry is pushing towards partially electrified (i.e. hybrid) solutions, aiming in reducing CO₂, Noise and Oxides of Nitrogen emissions.

This paper presented an overview and introduction of an innovative range extender concept for pure-electric, light aircraft. The proposed REXMoto concept shows all the benefits of conventional range extenders plus, 1) the capability to be operated as a road vehicle (i.e. scooter) and 2) the modularity and easy integration into existing electric aircraft.

The REXMoto electrical power system has been introduced, alongside the power flow according to each stage of the flight mission. It was shown that the implementation of the system can effectively satisfy the energy requirement for achieving longer duration missions and providing the safety of redundant energy sources.

Future work will focus on a comprehensive on ground testing of the complete REXMoto system and its integration into a commercially available two seater e-aircraft.

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