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FEASIBILITY ANALYSIS AND COMPARATIVE ASSESSMENT OF STRUCTURAL POWER TECHNOLOGY IN ALL-ELECTRIC COMPOSITE AIRCRAFT

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Abstract

Increasing environmental awareness and expected growth in air traffic over the next decades drive the need for the development of new technologies in the aviation industry. To meet established emission and noise reductions, all-electric aircraft are a promising technology. Yet, current battery technology is far from attaining the specific energy required to design economically viable commercial transport aircraft. To address this problem, much work is undertaken on improving the efficiency of individual components separately. Ongoing research on structural power technology however, focuses on combining load-bearing and electric energy-storage capabilities in a multifunctional material, promising considerable savings in overall aircraft mass. In this paper, a feasibility analysis and a comparative assessment of this technology in two small all-electric reference aircraft is undertaken. The Airbus E-Fan 1.0 and the Bristol Eco-Flyer are evaluated with respect to their mission performance and mass of material eligible for substitution with multifunctional material. Required specific energy and power of multifunctional material for these two-seater aircraft is calculated considering lower mechanical properties of multifunctional material and compared against state-of-the-art capabilities of multifunctional material. Finally, implications on mission performance, possible weight savings and on aircraft design are investigated. The results show that for a constant amount of carried energy, endurance gains of about $31~\%$ are possible. The required minimal specific energy for multifunctional material in aircraft of the considered category is $51.8~Wh/kg$ and the required specific power is $103.3~W/kg$ for the same mission performance.

Keywords

Structural power technology; multifunctional material; all-electric aircraft; composites

1. INTRODUCTION

Reducing the environmental impact of air traffic has become an integral topic in research, especially since passenger volumes are expected to grow between $3.7~\%$ and $4.4~\%$ per year [1, 2]. Additionally, the targets for noise and emission reductions set by the Advisory Council for Aviation Research and Innovation in Europe to be attained by 2050 have augmented research efforts substantially. To achieve these targets, progress in aerodynamics, propulsion, structure and system technologies is required [3]. Battery powered, all-electric aircraft seem to be a promising technology offering reductions in emissions, noise and complexity as well as increasing efficiency, reliability and passenger comfort [4, 5, 6]. However, even if battery technology has quadrupled the amount of storable energy per unit mass (specific energy) since the first battery powered flight in 1973, present-day batteries still have a 60 times lower specific energy than jet fuel [7]. The respective specific exergy of both propulsion systems is about 25 times lower [8]. This leads to limited cruise speed and endurance of all-electric aircraft and thus their operation in niche markets only [9]. Hence, lightweight constructions are crucial to develop economically viable all-electric aircraft.
Commonly, efforts are made to maximise the efficiency of components such as the propulsion system and the structure independently. Nonetheless, in a novel approach multifunctional material is being developed combining load-bearing and electric energy-storage capabilities and reducing overall mass and volume [10]. This so-called structural power technology (SPT) could mark a major milestone towards all-electric aircraft. The aims of this paper are thus to provide an overview of the state-of-the-art of SPT, to calculate the required performance of SPT in aircraft and to develop an understanding of its implications in aeronautical applications.
First, an overview of the research areas of SPT and of the state-of-the-art performance is given. Development as well as engineering and operational challenges are presented. In the next step, required performance values for SPT in two reference aircraft are calculated by first developing a model to determine their required energy and power during a design mission and then estimating the mass of material eligible for a replacement with SPT components. After comparing the results with present-day performance of SPT, potentials in aircraft applications regarding mission performance, weight reduction and aircraft design are evaluated.

2. STRUCTURAL POWER TECHNOLOGY

In recent years, interest in materials with advanced functionalities has grown considerably across many engineering

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fields [11]. Due to the inherent advantages of mass and volume savings when combining multiple functionalities, plenty of research is performed in this field, mostly focusing on combining structural (e.g. load-bearing) and non-structural functions [11]. Non-structural functions include, among others, electrical and thermal conductivity, morphing, self-healing and energy-storage capabilities, electromagnetic interference shielding as well as recyclability [11]. In the aerospace industry, several ideas are being pursued including: optically transparent, impact-resistant material for military aircraft [12, 13], morphing trailing edges for blended wing body aircraft [14] and shape memory alloys for active jet engine chevron application [15, 16].

The focus of this study lies on the combination of load-bearing and electric energy-storage capabilities (structural power technology). Combining these two capabilities offers great potential, since the highest shares of the operating empty weight of single aisle aircraft can be attributed to the structure, the powerplant and the systems [3]. In general, great benefits of using SPT in aircraft are expected, as systems with mass or size constraints are foreseen to profit most from SPT [17].

Current research in this field is undertaken in the areas of multifunctional structures (MFS) and multifunctional material (MFM). In MFS, thin, conventional batteries are embedded in structural components, whereas in MFM the material itself stores the electric energy. A comparison of both approaches reveals that higher savings are to be expected with MFM [18]. Furthermore, for MFS issues regarding packaging load transfer and delamination at battery-structure interface have been reported [19, 20], making MFM technology even more promising. However, whereas the application of MFS in unmanned aerial vehicles and spacecraft has been widely explored in e.g. [19, 21], research regarding the application of MFM in aircraft is still limited.

2.1. Multifunctional Material Concepts

Most concepts for SPT components rely on fiber-reinforced polymer (FRP) composites to create load-bearing material. This is due to the advantages composites offer: 1) similarity of the layered architecture to the structure of batteries and capacitors, 2) malleability, 3) customizability and 4) integrability of electrical conductors [22].

Research groups are pursuing different concepts for structural power components. Adam et al. distinguish between four scales and five degrees of multifunctionalization [23]. The scales of multifunctionalization describe the geometrical organization level and range from component level over macro-scale and meso-scale to micro-scale. The degree of multifunctionalization characterizes the proportion of the battery integration into the FRP composite. Due to savings in peripheral mass and electrode surface enlargements at smaller scales, it is believed that the specific energy of the components increases with the degree of multifunctionalization [23].

Degree (0) represents the conventional approach of separated load-bearing structure and energy-storing battery. Degrees (I) to (IV) are shown in Figure 1 with their respective scales.

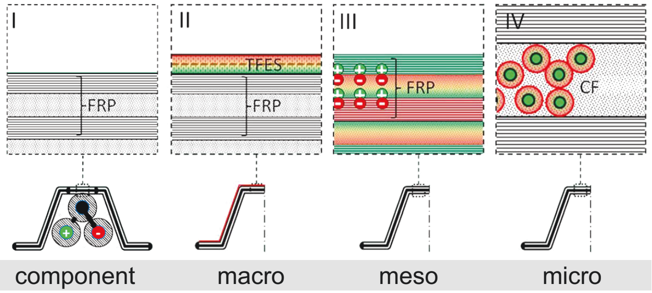


FIGURE 1. Degrees and scales of structural power components demonstrated for an omega stringer (adapted from [23, Fig. 2])

Adam et al. classify the integration of non-load-carrying conventional batteries as degree (I) on component level and thin-film energy storages (TFES) on top of the FRP as degree (II) on the macro-scale. Degree (III) on meso-scale categorizes MFM where the energy-storage capability is achieved by using FRP-laminae as electrodes and separators and the respective matrices as electrolytes. The last approach is classified as degree (IV) on micro-scale and represents individual, coaxial fibres (CF) being the anodes and the matrix being the cathode. [23]

Following the introduced nomenclature of MFS and MFM, MFS can be classified as degree (I) and (II), whereas degrees (III) and (IV) represent MFM.

2.2. Mechanical and Electrical Performance

Structural power components can be divided into structural batteries, capacitors and supercapacitors. In the following, some concepts of degrees (III) and (IV) (MFM) are described and their mechanical and electrical performances are stated, if provided. The state-of-the-art of further concepts can be found in [24]. In general, it has to be noted that the performance of MFM - when compared to a conventional structure or battery - is lower due to the fact that MFM performs two functions. However, the overall system performance may still be higher, depending on the level of performance of the MFM [25].

2.2.1. Structural Batteries

Structural batteries have the same basic architecture as conventional batteries: they consist of a cathode (positive/oxidizing electrode), an anode (negative/reducing electrode) as well as a separator and an electrolyte situated between them. An ‘electrolyte is a medium containing mobile ions’ [26, p.50], having a good ionic conductivity, but being electrically insulating. To prevent short circuits, an electrically insulating and ionically conducting separator is introduced between the two electrodes.

The first working structural battery was developed by Wetzel et al. at the U.S. Army Research Laboratory [27]. It is comprised of a carbon fabric anode, a glass fabric separator and a stainless steel foil coated with a mixture of $\mathrm{LiFePO_4}$, acetylene black and polyethylene oxide serving as the cathode. The polymer matrix is a vinyl ester random copolymer and forms the electrolyte. It therefore classifies as a degree (III) structural battery. The stainless steel foil and the carbon fabric serve as current collectors. The structural battery was tested mechanically and was found to have an elastic modulus of $8\ GPa$ and a specific stiffness of $3.6\ GPa/(g/cm^3)$. However, no electrochemical testing was carried out, because of an electric short circuit within the structural battery. [27]

The research group headed by Prof. Asp developed a degree (IV) structural battery. In this structural battery, each fibre is coated with a solid polymer electrolyte and embedded in a matrix serving as the cathode. The matrix is connected to an aluminium foil collector and the IMS65 carbon fibre anodes are connected to a copper collector. It was shown that this structural battery exhibits a specific capacity of up to $107\ mAh/g$ at high currents (1C) [28] and a specific energy of about $10\ Wh/kg$ [24]. According to [24], improvements of the cathode dispersion could ultimately lead to a specific energy of $175\ Wh/kg$ and a shear modulus of $1\ GPa$ for this approach.

2.2.2. Structural Capacitors

A capacitor is made of two electrodes (conductors) and a dielectric (an electric insulator). Capacitors can be (dis-)charged quickly, since only electrons must move [28]. They have high specific powers and low specific energies when compared to batteries [26]. This makes them more suitable for applications where short bursts of power are required [26]. Different attempts have been made to build structural capacitors. A team headed by E. D. Wetzel at the U.S. Army Research Laboratory tested a structural capacitor of degree (III) with different dielectrics. Using a dielectric made of fire-resistant epoxy and woven glass fibre, a capacitance of $2.68\ nF$ was reached. The specific energy of the capacitor was measured to be $52.78\ mWh/kg$ and it had a specific modulus of about $6.1\ GPa/(g/cm^3)$. [22]

2.2.3. Structural Supercapacitors

Supercapacitors follow the same working principle as capacitors, but the dielectric is replaced by a separator immersed in an electrolyte [28]. The separator is electrically insulating, but ion-permeable and the electrolyte connects the two electrodes ionically [28].

The STORAGE consortium at Imperial College London designed a structural supercapacitor of degree (III) using two woven carbon fibre laminae as the electrodes and a glass fibre separator which were soaked in a matrix serving as the electrolyte [24]. A specific energy of $1.39\ mWh/kg$, a specific power of $4.32\ mW/kg$ and a specific capacitance of $10.04\ mF/g$ were measured in tests [10]. The shear modulus and the compression modulus of this material were stated to be $0.45\ GPa$ and $61.2\ GPa$, respectively [10].

2.3. Development Challenges

In the development of structural components various scientific challenges remain. This section provides a short overview of these challenges. Further information can be found in references [24, 29].

2.3.1. Achieving Good Performance

Clearly, the main development challenges remain in achieving a good performance of MFM. According to [18], these can be broken down into three main areas of research:

1. *Fibres*: In the past, composites fibres have been optimised for mechanical performance only. However, this hampers achieving electrically performing electrodes without reducing the mechanical performance of the fibres. [18]
2. *Matrix*: The higher the conductivity of solid polymer electrolytes (used as matrix), the lower the stiffness and vice versa [29, Fig.1], making it difficult to achieve high electrical and mechanical performance simultaneously.
3. *Fibre-Matrix-Interface*: The matrix has to conduct ions and transfer loads between the fibres to ensure high mechanical performance. However, ionic conductivity is reduced by a strong bond between the matrix and the fibres and vice versa. [18, 29]

2.3.2. Mechanical Deformation and Electrical Cycling

It is essential that the performance of MFM is good, even if the mechanical loads are high and/or the electrical loads are high. Studies have been undertaken to evaluate the impact of electrical cycling on mechanical performance. Jacques et al. report that fibre tensile properties are not affected by electrical cycling [30]. However, the ultimate tensile strength was reduced by $20\ \%$ during lithiation, but partially recuperated during delithiation [30].

The impact of mechanical deformation on electrical performance has been investigated by Jacques et al., too. It was found that the electric capacity is unaffected by electrical cycling [31]. Even though the research shows promising results, more studies have to be undertaken in this field.

2.4. Engineering and Operational Challenges

Especially in aircraft applications of MFM, several engineering and operational challenges need to be considered. These include the design methods, manufacturing and costs, aircraft operation and maintenance.

2.4.1. Design Methodology

For the design of an aircraft the engineers need design methods to predict the performance of the components and the aircraft itself. However, as SPT is an emerging technology, its inherent characteristics are still subject to research and not fully understood by the engineers. Thus, design data and tools for mechanical and electrical efficiency and durability prediction are still lacking.

However, the prediction of overall system mass m_{MFM} for the multifunctional system has been characterized by Wetzel [32] as follows:

$$m_{MFM} = m_{struct} + m_{batt}\frac{1-\sigma_S^{batt}}{\sigma_E^{batt}} \tag{1}$$

The variables m_{struct} and m_{batt} represent the masses of the conventional structure and battery for a similar mechanical and electrical performance, respectively, and σ_S and σ_E are the structural and energy mass efficiencies, respectively. They are defined according to [32] as $\sigma_S^{batt} = 0$, $\sigma_E^{batt} = 1$ and $\sigma_S^{struct} = 1$, $\sigma_E^{struct} = 0$ for a conventional system (battery is not load-carrying and the structure is not energy-storing). Examples and an illustration of the relationship can be found in [23, 32].

2.4.2. Manufacturing and Costs

As an emerging technology, MFM are only produced at small-scale in laboratories. The challenges of scaling these processes to a large-scale production, especially regarding production volume and automation, need to be explored and solutions have to be developed. Additionally, current manufacturing processes for composites are at ambient temperature, whereas MFM needs to be processed in a moisture-free environment [24]. Furthermore, as a single current-connection between the electrodes can lead to short-circuiting of the MFM, it has to be assured that finishing processes such as cutting, polishing and drilling do not cause this malfunction [18].

Hence, when scaling-up, existing manufacturing processes need to be modified, increasing the production cost and thus the acquisition cost for the aircraft manufacturer. Nevertheless, costs are highly important for the turnover of a product and therefore its economic efficiency. The STORAGE consortium proposed a cost calculation method for multifunctional material. It is based on the cost of a conventional system with equivalent load-bearing and energy-storage performance [10]:

$$C_{MFM} = (C_{struct} + C_{batt})\frac{2-\sigma_S^{batt}}{\sigma_E^{batt}} \tag{2}$$

where C_{MFM} is the cost per kg of the multifunctional material, C_{struct} the cost per kg of the conventional structure, C_{batt} the cost per kg of the conventional battery, σ_S^{batt} the structural mass efficiency and σ_E^{batt} the energy mass efficiency of the battery, as defined in Section 2.4.1. However, in [10] no information about an application or a validation of this method was provided. Furthermore, as this method does not include the required changes in the current manufacturing process mentioned above, the costs are likely to be higher.

2.4.3. Aircraft Operation

During an aircraft's operational life cycle, its constituents are subject to high demands. Firstly, they need to withstand the variation of operational conditions, especially temperature, humidity and ultraviolet radiation changes. Hence, the impact of these variations on MFM mechanical and electrical performance needs to be explored. Secondly, the long-term performance of MFM, its durability and reliability throughout the life cycle of an aircraft has to be assessed. Lastly, issues such as impact and damage tolerance need to be investigated further. Especially fire resistance and thermal runaway in case of a crash with high voltage discharge or in case of overcharge should be explored [18, 33]. All-solid-state structural batteries are promising candidates to resolve these issues, as they are flame retardant when based on ceramics or ionic liquids [23]. Furthermore, the anticipated lower specific energy of MFM than of conventional batteries is expected to diminish the hazard of thermal runaway [33].

Additionally to the above mentioned demands, the inherent disadvantage of the impossibility of replacing batteries has to be addressed. The depleted batteries of an MFM aircraft cannot be replaced by charged batteries, meaning that the aircraft itself has to stay on the ground to be charged. Depending on the specific power of the MFM, this increases the turn around time drastically. Alternative use-cases for MFM, such as in military UAV expected to be lost during the mission, might be considered.

2.4.4. Maintenance, Repair and Overhaul

Existing aircraft maintenance, repair and overhaul regulations include certified inspection and repair methods for metal and composite aircraft. However, as the energy storage of MFM-aircraft will be within the aircraft structure, new methods need to be developed, validated and certified. These should include testing methods monitoring the mechanical as well as the electrical performance of the MFM and repair methods restoring structural and energy-storage capabilities.

Furthermore, as the life cycle of MFM is not yet determined, some MFM-components might need to be replaced before the aircraft's life cycle ends. However, replacement might be expensive and difficult [17] and corresponding resources and replacement parts would have to be hold available. In case a replacement of individual components is not possible, the life cycle of MFM determines the life cycle of the aircraft. Hence, a high cycle life of MFM is required. For this, the use of structural supercapacitors could be a promising solution, as supercapacitors have a higher cycle life than batteries and therefore do not need to be replaced as frequently [17].

3. MISSION PERFORMANCE

In order to calculate the required specific energy (RSE) and power (RSP) of MFM to be employed in the two reference aircraft, the total energy and maximum power of the respective aircraft for a design mission have to be known. To be able to calculate these performance metrics for different aircraft take-off weights, a performance model has been developed. Both reference aircraft, their design missions and the developed performance model are described in the following. The performance model is validated for the respective baseline aircraft configuration.

3.1. Reference Aircraft and Design Mission

This research is based on two small reference all-electric aircraft to provide real-world examples: the technology demonstrator aircraft Airbus E-Fan 1.0 (referred to as E-Fan) and the experimental aircraft Bristol Eco-Flyer (referred to as Eco-Flyer) which is currently under development by the Airbus Group. Both are two-seater aircraft in fixed-wing configuration as can be seen in Figure 2 (a) and (b).

(a)

(b)

FIGURE 2. (a) Technology demonstrator aircraft E-Fan 1.0 [34, p.7,8]. (b) Experimental aircraft Bristol Eco-Flyer [35, p.4].

It can be observed that the E-Fan is powered by two ducted fans mounted over the wings. The Eco-Flyer however, is driven by a propeller in the aircraft's nose. The E-Fan is built with composites to be as lightweight as possible, making it the ideal reference aircraft for this study. The Eco-Flyer on the other hand is intended to 'have 3D-printed major components and ... a 3D-printed fuselage' [35, p.4]. For the scope of this study, it is assumed that equivalent composite structures would have the same weight and mechanical properties such that a replacement would not lead to changes in required structural mass. Tables 1 and 2 summarize key design and performance data of both reference aircraft.

TABLE 1. Data of the Eco-Flyer [35]

Parameter	**Value**
Wingspan	$18.6\ m$
Wing reference area	$18.0\ m^2$
Maximum take-off mass	$750\ kg$
Lift-to-drag ratio [a]	25
Total available energy	$20\ kWh$
Cruise speed	$139\ km/h$
Cruise altitude	$3000\ ft$
Maximum endurance	$60\ min$

[a] Assumed to denote max. lift-to-drag ratio.

In order to calculate the mission energy and power profile, a design mission is defined as follows: taxiing to the runway, take-off, climb to cruise altitude, cruise at constant altitude and speed, descent, go-around, landing at airport of destination and taxiing to parking position.

TABLE 2. Data of the E-Fan [34, 36, 37, 38]

Parameter	**Value**
Wingspan	$9.5\ m$
Wing reference area [a]	$10.45\ m^2$
Maximum take-off mass	$600\ kg$
Total battery mass	$167\ kg$
Total available energy	$29\ kWh$
Maximum shaft power [b]	$64\ kW$
Cruise speed	$160\ km/h$
Cruise altitude	$3500\ ft$
Maximum lift-to-drag ratio	16
Maximum endurance	$60\ min$

[a] Estimated.
[b] Assumed to denote max. continuous power.

3.2. Modelling Approach and Assumptions

The performance model is subdivided into the individual mission segments. The taxiing performance is estimated by an electric motor model. Specifications of motors with similar rated power are used and it is assumed that the motor acts like a hub motor in both aircraft (although the Eco-Flyer uses the propeller). Taxiing is assumed to be at constant, fast walking pace. The taxiing time is assumed to be $2\ min$ equating to about $300\ m$ travelled, which is longer than the expected take-off/landing ground roll and thus deemed adequate.

To calculate the required energy for take-off, the take-off time of each aircraft is calculated according to [39] and then multiplied by the maximum power available. Assumptions include a levelled and dry concrete runway at sea level, no wind, preserved aircraft attitude and instantaneous power provision. Included in the calculations is a ground effect approximation based on the Biot-Savart law and vortex theory.

It is assumed that the climb is undertaken with maximum continuous power. The calculations are based on a constant climb angle and velocity, the latter being estimated from similar aircraft or provided by the Airbus Group. As density varies linearly between sea level and cruise altitude, its average is taken. The efficiencies of the ducted fan (E-Fan) and the propeller (Eco-Flyer) are assumed to be $2\ \%$ lower than during cruise, as their design point is expected to be at cruise conditions.

The cruise phase of the mission is calculated presuming constant speed and altitude. The cruise endurance of the Eco-Flyer had been provided by the Airbus Group, whereas the cruise endurance of the E-Fan was adjusted such that the block mission endurance is $60\ min$ long (compare Table 2). The efficiency of the electric motor of the E-Fan is taken to be $90\ \%$ [40], whereas for the Eco-Flyer it is assumed to be $92\ \%$, to account for improvements in technology over the past years. The Eco-Flyer's propeller efficiency during cruise has been provided; the efficiency of the ducted fan however not. It depends on many unknown design variables. Typical values lie in the range of $80 - 90\ \%$ [41, Fig. 3]. In a first approximation $80\ \%$ are adopted, bearing in mind that the model is very sensitive to this efficiency.

It is expected that both aircraft will use the continuous descent approach reducing required energy. Hence, a constant descent rate, angle and power are assumed. A throttle setting of $5\ \%$ providing reasonable descent angles is adopted. However, when analysing the results it has to be considered that the pilot might opt to glide during descent.

The go-around consists of another climb, cruise (at go-around altitude) and descent phase. The models used for these phases are the ones presented above. The final approach and landing have not been modelled. It is assumed that the energy consumption is comparably small and can be neglected.

Additionally to the energy required for the flight mission, avionics and systems consume energy. Reportedly, the E-Fan is equipped with a Garmin 1000 avionics system with one screen [42] and the e-Fadec energy management system [34]. The Garmin 1000 with two screens consumes $250\ W$ [43]. A typical computer monitor uses about $20\ W$ [44]. Hence, a power consumption of $230\ W$ is employed. No further specifications on the e-Fadec were available. Thus, it is assumed that it consumes the power of a typical desktop computer without screen $(100\ W)$ [45]. As the Eco-Flyer is still under development, no further specifications on the avionics and other systems are provided. Nevertheless, both aircraft are of the same category and hence, the above assumptions are adopted for the Eco-Flyer, too.

3.3. Model Validation

The calculated required electrical energy for each phase of the mission is shown in Figure 3 for both reference aircraft. However, as stated above, final approach and landing energy have been neglected in the calculations.

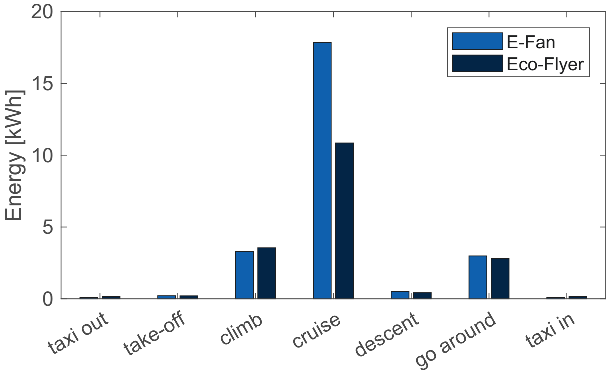


FIGURE 3. Energy required per mission segment

The distribution of energy throughout the mission meets the expectations, e.g. in comparison to [7, Fig. 2.2]. However, it can be seen that the E-Fan requires about $41\ \%$ more energy during cruise than the Eco-Flyer. This is mostly due to the higher induced drag of the E-Fan (lower aspect ratio).

Adding the required energy of the avionics, the total required energy for the design mission of the E-Fan and the Eco-Flyer equate to $25.4\ kWh$ and $18.6\ kWh$, respectively. To validate the performance model with the few data provided by the manufacturer, these values are compared to the total energy both aircraft carry. For this comparison it is assumed that the battery capacity of both aircraft has been designed such that the state of charge (SoC) is $20\ \%$ at the end of the block mission (excluding go-around) and $10\ \%$ at the end of the design mission to prevent battery damage due to deep discharge [46].

The E-Fan's batteries capacity at $10\ \%$ SoC is $26.1\ kWh$ and at $20\ \%$ SoC is $23.2\ kWh$. The batteries of the Eco-Flyer have capacities of $18\ kWh$ and $16\ kWh$, respectively. The respective deviations at the end of the design mission equate to $-2.5\ \%$ and $+3.5\ \%$ and at the end of the block mission to $-3.5\ \%$ and $-2.2\ \%$. Even if final approach and landing would be considered (energies in the range of the take-off energy are expected [7, Fig. 2.2]), the deviations lie within an acceptable range and can be attributed to model uncertainties. Nevertheless, the high sensitivity of the model to the efficiencies of the powertrain components has to be considered. In a first approximation the chosen values provide reasonable results, but for a deeper analysis further details on component performance are required.

The calculations in the performance model are undertaken assuming that the aircraft operate at maximum power (e.g. take-off). For both aircraft the maximum shaft power of the engine(s) is provided by the manufacturer and thus used in the calculations without further validation. To calculate the electrical power at the battery, the shaft power is divided by the efficiency of the electric motor. For the E-Fan this equates to a maximum required electrical power of $71.1\ kW$.

4. ELIGIBLE MATERIAL MASS

To determine the required performance of MFM in aircraft, the eligible mass for replacement with MFM has to be known. In this work, it is assumed that this mass equals the mass of all structural components of the aircraft. However, additional research is required to determine if that is feasible or if other constraints are relevant (e.g. use of isolating material). For the Eco-Flyer a detailed mass breakdown is provided; for the E-Fan it has to be estimated. Two approaches have been undertaken: in approach one, the mass of all non-structural components is estimated with regression functions by [47] as well as specifications of similar components and then subtracted from the aircraft's empty weight. Details of this approach can be found in [48]. It is used to validate approach two. The overall structural mass of the E-Fan was found to be $192.6\ kg$ [48].

As stated in Section 2., the mechanical properties of MFM are likely to be lower than those of conventional composites. Thus, a model to include this degradation and its implications on eligible structural mass is required. Therefore, for the second approach, a finite element (FE) model of the composite wing of the E-Fan is built (see Figure 4). From [37, Fig. 2] it is known that the wing structure consists of a C-beam front and rear spar and a box-beam main spar. The ribs are modeled without weight-saving holes and adhevsives (and their respective weight) are not considered. The carbon/epoxy composite AS4/3501-6 with a fibre volume fraction of $60\ \%$ is chosen as material, because it is often used in commercial aircraft structures [49, 50]. Its properties as stated in [51] are employed. The lay-ups of the composite are defined according to stacking sequence guidelines proposed by the Airbus Group [52]. The applied aerodynamic loads (lift and torque) are calculated with the vortex lattice method Tornado [53]. The structure is then sized to withstand a maximum load factor of 4.2.

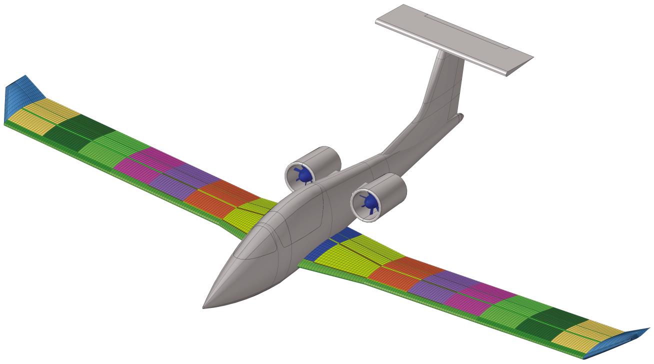


FIGURE 4. Finite element model of the E-Fan wing

The sizing was based on the failure criterion after Tsai-Wu. In addition, the critical buckling load was determined by a linear eigenvalue analysis. In order to calculate the minimum mass of the wing, the ply thickness is varied until the failure criteria are just about satisfied. The wing weight was found to be $92.9\ kg$ at a ply thickness of $0.078\ mm$ constrained by the buckling criterion. This is a theoretical result as this thickness is not obtainable and has to be interpreted as a percentage arrangement of the plies. An optimization of the stacking sequence could change the overall wing mass. In addition, the uncertainties regarding exact positions of the spars, airfoil and wing twist have to be considered when evaluating this result.

To keep this analysis simple, no similar analysis for the other structural components has been undertaken. Instead, the dimensions of the structure of each component have been estimated and the mass calculated: horizontal tail $13.2\ kg$, vertical tail $11.4\ kg$, fuselage $57.5\ kg$ and duct $12.4\ kg$. A comparison with the respective masses of the Eco-Flyer showed good agreement. The total structural mass of the E-Fan without property degradation as calculated in approach two thus equates to $187.4\ kg$. Validating this against the result of approach one, reveals a difference of $-2.7\ \%$. This difference may arise due to inaccuracies in both approaches, e.g. due to estimated dimensions, modelling of the ribs without holes and neglected filler, adhesive and paint weight in the wing FE model. However, both results are of the same order of magnitude, showing that the results can be deemed acceptable in a first approximation.

Having developed the FE model, it is possible to apply a degradation factor to the mechanical properties of the used material, vary the ply thickness such that the failure criteria are met and calculate the respective wing mass. Even though it is likely that MFM will have degraded material properties, not all properties will be affected equally. Different scenarios are possible as MFM is still under development. Due to a lower fibre adhesion and a higher compliance of the resin of MFM, it is likely that the matrix-dominated properties will be decreased [18, 24, 48]. The most important properties of composites, however, are in fibre direction, as can be seen in the results. In this work, the following (matrix-dominated) properties of the material are decreased in order to simulate a MFM: longitudinal compressive strength, transverse tensile and compressive strength, shear modulus and strength, transverse modulus and interlaminar shear stress. An equal degradation of all properties is assumed. Future analyses have to show if that assumption needs to be modified.

The results show that with decreasing degradation factor f_d, the wing mass increases (see Figure 5). The analysis showed that, as expected, the sizing was dominated by elasto-stability failure of the thin wing shell. However, at $f_d < 0.14$ the strength became predominant, leading to a step change in the increase in mass. These results emphasize the statement that the fibre-dominated properties are more important with respect to the structural stiffness, which is only reducing slightly. Hence, the degradation potential of the matrix-dominated properties is very high.

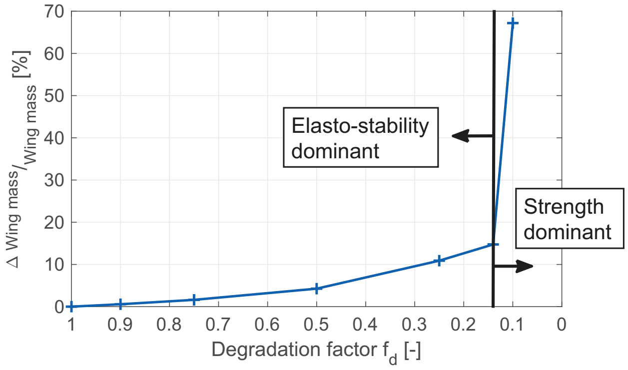


FIGURE 5. Wing mass increase versus degradation factor f_d

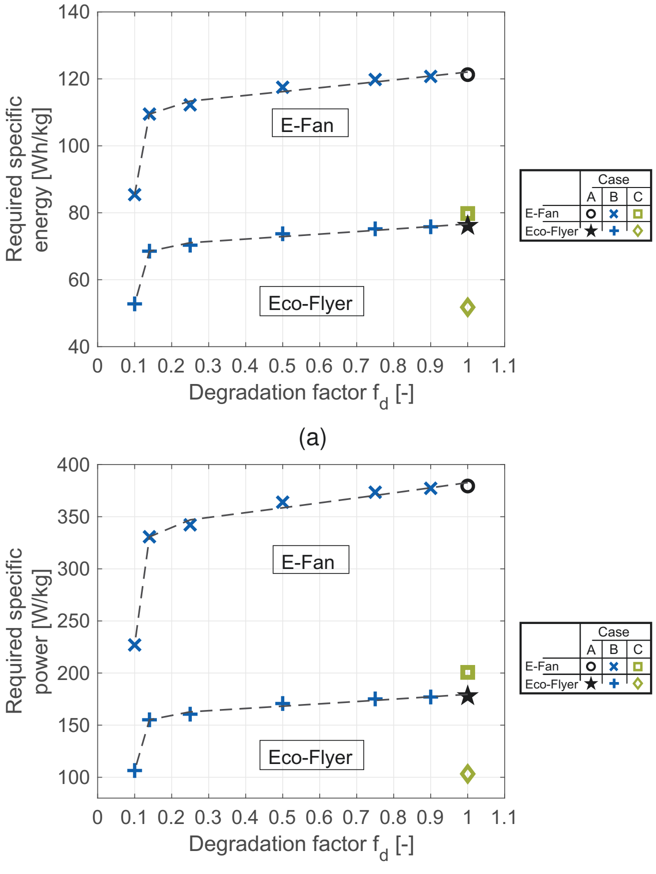
The figure shows: the higher the degradation (the lower the degradation factor), the higher the increase in mass. In a first approximation, these percentage increases in wing mass are used to reflect the mass increase of the other structural components, too. However, they might vary as the composition and load-case of the components are different. Implementing this assumption, the total eligible mass of the E-Fan increases to $313.3\ kg$ for $f_d = 0.10$. The percentage increases are also used to analyse the Eco-Flyer, because no model could be developed due to a lack of specifications about the wing structure.

5. REQUIRED PERFORMANCE OF MFM

Having estimated the amount of material eligible for replacement with MFM, the required performance of MFM for use in small all-electric aircraft can be computed. To do so, the required energy and power of the design mission (considering a $10\ \%$ SoC at the end) are calculated for different MFM masses (and hence different take-off masses) and then divided by the mass of MFM. Three cases are accounted for:

A) No property degradation. The new take-off mass equals the original take-off mass minus the mass of the conventional batteries.
B) Property degradation for different f_d. The new take-off mass is computed by adding the mass of the additional material to the original take-off mass without conventional batteries.
C) No property degradation and a replacement of the conventional batteries by a MFM block. The original take-off mass is maintained.

A fourth case with a new take-off mass exceeding the original maximum take-off mass is disregarded. Furthermore, not part of this work was to explore the required performance of MFM in combination with conventional batteries, even though this might be of interest as a transition technology. The RSE and RSP of all cases are shown in Figure 6.



(a)

(b)

FIGURE 6. Required specific energy (a) and power (b) for case A, B and C

It can be noticed that the lower the degradation factor the lower the RSE/RSP, despite the fact that the required energy increases as the take-off mass increases from case A to C (the required power is fixed in the model). This phenomenon can be explained by the fact that the increase in eligible mass is higher than the increase in required energy. The higher the eligible mass, the higher the energy that can be carried. Thus, the RSE for $f_d = 0.90$ is by a factor of about 1.4 higher than for $f_d = 0.10$ and the RSP by a factor of about 1.7.

Furthermore, it can be observed that the required performance of the Eco-Flyer is lower than for the E-Fan. This was expected as the design of the Eco-Flyer is more efficient leading to lower energy and power requirements (see Tables 1 and 2). A mean difference of $-36.3\,\%$ in RSE and $-50.8\,\%$ in RSP with regard to the E-Fan can be determined.

The highest values appear at case A, whereas case C produces the lowest values ($79.8\ Wh/kg$ and $200.7\ W/kg$ (E-Fan), and $51.8\ Wh/kg$ and $103.3\ W/kg$ (Eco-Flyer)). It has to be noticed that these values represent the installed specific energy/power, because no additional weight due to e.g. monitoring, control and cooling is considered. A comparison to the currently installed specific energies of the conventional batteries of the E-Fan and Eco-Flyer shows possible reductions of $30.2 - 54.1\ \%$ and $36.0 - 56.5\ \%$, respectively, depending on the case. This confirms the statement that the performance of MFM when compared to the respective conventional components is lower without compromising on overall system performance (see Section 2.2.).

Comparing these values to the state-of-the-art performance of MFM reveals the necessary amount of research to be undertaken to make this technology feasible for aircraft applications. The reported specific energy of $10\ Wh/kg$ of MFM needs to be at least increased fivefold to meet the required performance. Nevertheless, the structural battery developed by Asp et al. shows great potential as a specific energy of $175\ Wh/kg$ is within reach [24]. However, as with conventional energy storage technology, difficulties in achieving simultaneously high specific energy and power are expected [48].

Furthermore, it should be noted that developing a MFM with the calculated required performance only allows to replace state-of-the-art energy-storing and load-bearing technology of already flying small all-electric aircraft*) . The goal however, is to enable the development of larger all-electric transport aircraft which have different requirements on range and cruise speed as well as on-board entertainment and emergency oxygen systems consuming energy during flight [48].

6. POTENTIALS IN AIRCRAFT APPLICATIONS

Whereas the focus of the preceding sections was to establish required performance values for MFM in small all-electric composite aircraft applications, this section emphasizes the potential benefits the use of MFM in aircraft could have.

6.1. Endurance Benefits

Due to the inherent overall system weight reductions of MFM aircraft, increases in the cruise endurance can be expected. Adam et al. [23] proposed a modified range equation to evaluate potentials in range increase. Adapting the equation for

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*) No information about the state of development of the Bristol Eco-Flyer is provided, but it is expected to have its maiden flight in the coming years.

endurance assuming a constant cruise velocity, it reads:

$$\frac{\Delta t_{cruise}}{t_{cruise}} = \frac{1}{1-\lambda\Theta} - 1 \tag{3}$$

where the parameter λ represents the ratio of the mass of the conventional battery to the total baseline aircraft mass (without MFM) and Θ the ratio of energy in MFM to the energy in the respective conventional battery. The overall carried energy is assumed to be constant and the difference is supposed to be provided by a conventional battery of reduced size and weight. The higher both parameters, the higher the possible benefit. Assuming that the specific energy of the used MFM is adjusted such that $\Theta = 1$ (no additional conventional battery carried as assumed throughout this work), the theoretic endurance increases of several aircraft are shown in Figure 7.

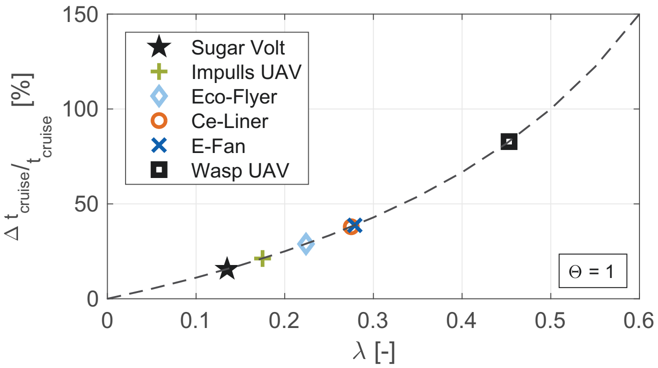

FIGURE 7. Cruise endurance variation with respect to λ shown for exemplary aircraft (data from [19, 34, 54, 55, 56] and the Airbus Group)

The higher λ, the higher the possible increase in endurance, provided that the respective required specific energy can be reached. According to the previous calculations, for the E-Fan that would require a specific energy of the MFM of about $122.0\ Wh/kg$ and for the Eco-Flyer $76.7\ Wh/kg$ (case A).

A comparison of the results for $\Theta = 1$ with respect to the results of the developed performance model shows a good agreement. Fixing the total energy and reducing the take-off mass by the respective battery mass, it is $\frac{\Delta t_{cruise}}{t_{cruise}} = 31.0\ \%$ and $25.4\ \%$ for the E-Fan and the Eco-Flyer respectively. These results are lower than in [23], because the performance model considers all phases of the mission and not only the cruise. Fixing the total available energy in the model does not fix the cruise energy, as a different aircraft mass leads to differences in the required energy for the other mission phases.

The equation developed by Schlichting et al. allows to compare the endurance of two systems 1 and 2 with different overall weight W (without additional conventional battery) and different total carried energy E [17, Eq. 3]:

$$\frac{\Delta t_{cruise}}{t_{cruise}} = \frac{E_1 W_2^{3/2}}{E_2 W_1^{3/2}} - 1 \tag{4}$$

This equation assumes that the aerodynamics during cruise and the powertrain efficiencies remain constant for both systems. Assuming the theoretical possible specific energy of MFM of $175\ Wh/kg$, replacing the structure with MFM and reducing the take-off mass by the conventional battery mass, shows possible increases in cruise endurance of about $161.6\ \%$ (E-Fan) and $273.5\ \%$ (Eco-Flyer). Nevertheless, to reach these high increases in endurance, assumptions such as that a replacement of the entire structure is possible and, that the specific energy as well as power of MFM will improve, have to be fulfilled. For comparison, applying Equation 4 with present-day MFM technology ($10\ Wh/kg$) and assuming a replacement of the whole structure with MFM (case A), leads to a decrease in cruise endurance of about $85.1\ \%$ (E-Fan) or $78.7\ \%$ (Eco-Flyer).

6.2. Weight Reduction Possibilities

Reducing aircraft weight leads to reductions in fuel burn (about $0.03\ kg$ kerosene per $1000\ km$ per kilogram saved weight [57]), or, more generally spoken, energy consumption. It is therefore desirable to reduce the aircraft's weight. Besides the inherent weight reduction possibilities of MFM, reductions in the amount of required wiring and in the cooling system might be expected.

In modern aircraft, the wiring often accounts for a substantial amount of weight. Reducing the required wiring not only reduces the operating empty weight, but also reduces the hazard of defective cables and connectors [48]. In contrast to conventional aircraft, in MFM aircraft all consumers can be connected to the battery/structure locally. Especially for remotely located consumers such as navigation lights and control surface actuators this offers saving possibilities. Additional benefits might arise as no battery packs need to be interconnected, except if some structural parts are manufactured separately. Nevertheless, an in-depth study considering the distribution of collectors, insulation, impact resistance and fire protection as well as number, location, energy and power requirements of local consumers should be undertaken [48]. Designing and developing a prototype MFM aircraft (e.g. UAV), could also help to assess possible benefits and implications.

Incorporating MFM in the whole aircraft structure, including in its skin, improves the heat transfer through convection. Thus, heat is removed from the system more efficiently [23]. Depending on the architecture of the thermal management system this leads to possible reductions in energy consumption and weight for cooling of the propulsion system. However, studies on the optimal operating temperature range of MFM should be undertaken. If similar to Lithium-Ion batteries (about $20-40\ ^{\circ}C$ [58]), heating of the respective components should be considered, too. Developing a thermal management system using the waste heat of the propulsion components for the heating would then be of great value.

6.3. Aircraft Design Opportunities

Using the technology of MFM offers several opportunities in the design of aircraft. Weight savings increase the range and endurance of the aircraft in its baseline configuration, but also offer to enhance the baseline design at the cost of increased weight (e.g. increasing the aspect ratio and thus wing weight reducing induced drag). Nevertheless, a trade-off study has to be undertaken evaluating the benefits of such an enhancement with respect to the performance requirements. Volume savings might offer the possibility to reduce the aircraft's wetted area and therefore form and skin friction drag, depending on the volume of battery packs in the conventional aircraft.

As described in Section 6.2., savings in wiring are expected and will be the greater, the greater the distance of a consumer to the battery in the conventional system. This fact shows the potential of MFM in distributed electric propulsion (DEP) aircraft, adding to the efficiency gains due to a wing inertial relief and a higher power-to-weight ratio of the motors of DEP aircraft.

A degradation of the fibre-dominated properties of MFM would significantly reduce the strength and stiffness and therefore the usability of MFM in aircraft. Although this is not a likely scenario (see Section 4.), reviewing the strut-braced or box-wing configuration in this case might be of great value, as the wing stiffness in such configurations is improved. Furthermore, in box-wing configurations the structural mass (and therefore eligible mass for replacement with MFM) is higher than in a conventional configuration, increasing the amount of carried energy.

Furthermore, these configurations (DEP, strut-braced and box-wing) are expected to lead to reductions in energy consumption which might be of great value if the performance of MFM is not as high as required. In that case, a combination of MFM with conventional batteries and hybrid-electric powertrain architectures might be considered, too.

7. CONCLUSION AND FURTHER WORK

In this work an overview of SPT and its state-of-the-art regarding MFM has been provided. Scientific challenges of the development of MFM have been summarized based on a literature review and engineering as well as operational challenges regarding the use of MFM in aircraft applications have been compiled and clustered. A methodology to assess the required performance of MFM in all-electric composite aircraft has been successfully applied to two reference aircraft. It consists of a mission performance model and a FE wing model considering a potential degradation of mechanical properties of MFM with respect to conventional composites. In addition, benefits of the employment of MFM in the aviation context have been evaluated.

The results show the great potential of MFM in aircraft. However, present-day specific energy of MFM has to be increased fivefold to meet the minimum required specific energy of $51.8\ Wh/kg$ for two-seater aircraft. The specific power has to attain a value of $103.3\ W/kg$, simultaneously. Besides endurance gains of $31.0\ \%$ (in case of a MFM with $122.0\ Wh/kg$), reductions in wiring and cooling system weight are expected. Combining the technology with DEP, strut-braced or box-wing configurations could reduce the required performance of MFM, accelerating the technology readiness. Nevertheless, further challenges regarding design methodology, manufacturing methods, cost estimation tools and aircraft operation as well as maintenance have to be responded to.

Making MFM a viable technology for use in small commercial aircraft, still requires much work. Despite addressing the development, engineering and operational challenges, future work should consist in exploring its potential in combination with conventional batteries and hybrid-electric system architectures to address a shortcoming of this work. Next steps also include the application of the presented methodology to larger all-electric transport aircraft and to DEP aircraft. Future research should then focus on the design and development of an experimental, small-scale aircraft to further understand the use of MFM in the relevant environment.

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