An Electric Flight Concept

Müller, N.*[1],
Lindberg. B.[1], Mouland, M.[1], Holden, N.[1], Vagani, M. [1], Sharma, K.[1], Iancu, F. [1],
Eyler, A.[1], McPhail, K.[1], Wagenknecht, B.[1], Piechna, J.[2]

[1]Turbomachinery Laboratory, Department of Mechanical Engineering, Michigan State University
2455 Engineering Building, East Lansing, MI 48824-1226, USA
*mueller@egr.msu.edu

[2]Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology
24 Nowowiejska Str., 00-665 Warsaw, POLAND

ABSTRACT

An electric flight concept is presented that is based on a novel design and manufacturing of light-weight high-strength composite impellers with integrated motor and bearing that can be used for propeller or jet propulsion in electrical flight applications. The design also allows for easy implementation of counter-rotating propellers or counter-rotating stages in jet propulsion. The electrical power is generated by distributed micro wave-disc engines and/or solar panels.

1. INTRODUCTION

Electrical Flight can be clean and quiet. These may have been some motivations in the search for solutions. Weight concerns related to power densities of energy sources and drive motors have been issues throughout. Here solar power and onboard generation with micro wave-disc engines is considered as power source and counter-rotating propulsion devices are presented as weight saver. The technical realization of counter-rotation with conventional drive designs often appears to be

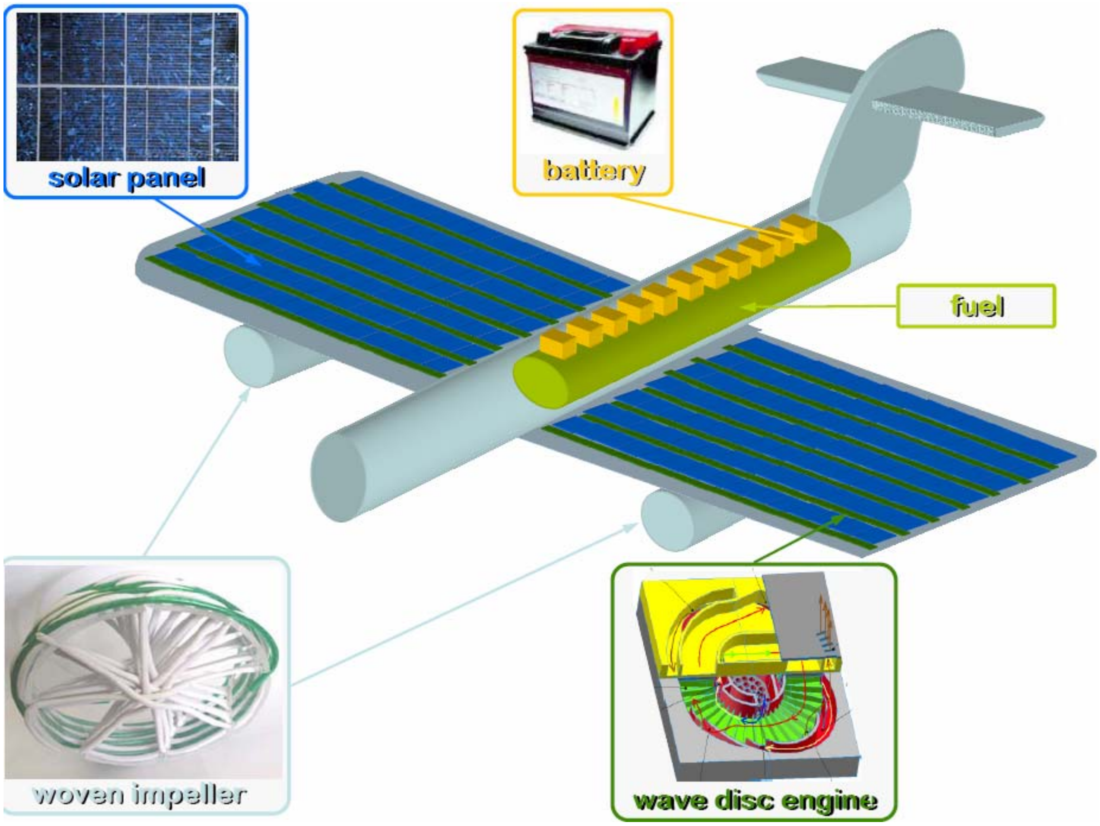

Fig. 1 Schematic of possible components of the electric flight concept

mechanically impractical for more than two stages. The electrical flight opens up new possibilities due to the convenient and versatile transmission of electrical energy instead of mechanical (rotational) energy. Electrical motors can be used right in place where the energy is needed. Integrated in the impeller, no driveshaft is necessary. This eliminates the challenges of mechanically arranging counter-rotating drive shafts. Integrating the motor at the outer diameter of an impeller brings further advantages like reducing the active tangential forces in the impeller, plus introducing them where the least radial stress appears due to centrifugal forces. A novel weaving/winding technology for the impeller allows for integrating such motors in a high-strength composite structure that enables shrouded impellers capable of even transonic tip speeds. This approach not only appears to reduce weight, but also dramatically reduces production costs.

2. THE WOVEN IMPELLER

2.1 Manufacturing

While carbon fiber reinforced polymer (CFRP) structures are well know for there superior strength at low weight, and are already applied in aerospace, it is typically anticipated that they are costly. The costs are generally not generated by the cost of the materials themselves, but much more by the manufacturing effort like labor, required time, and special tools. This is especially true for hand laminating, vacuum procedures and various molding processes, including curing. Much of these are still manual work intensive, even in modern manufacturing.

Several methods are known for manufacturing propellers, impellers and blades from CFRP. Originally motivated by scaling needs in the use of water as refrigerant [1, 2], a new relative low-cost manufacturing method is suggested using commercially available filament winding machines. These machines can be used for rapid-prototyping and mass-production. They can work conveniently integrated in CAD/CAM systems. Their computer controls can import spreadsheet files (e.g. XLS) and drawing files (e.g. DXF). From such, an optimized winding/weaving process is computed according to preferred parameter settings. Fully automatic multi-axis machines are available (Fig 2) for about $50.000-$100.000. 4-axis or 5-axis machines, with one or multiple spools may be preferred. Preferably the fiber is wetted in a bath of self-hardening resin (polymer) before it is wound into shape on a rotating support (Fig 3). Motor and bearing elements may be interwoven by different designs (Fig. 6, 7, 8) – all in one production step. Depending on size and sophistication one wheel may cost anywhere from less than ten dollar to several hundred dollars. Using light-weight composite materials and constructions in which fibers are only in force direction, the resulting wheels can be of ultra-light weight possibly eliminating balancing needs for selected applications, which further can reduce costs.

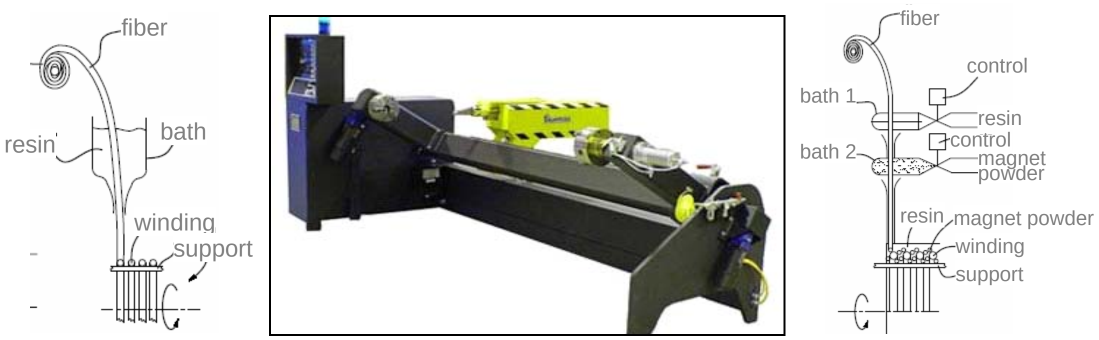

Fig. 2 center: Example of Multiple Axis Winding Machine (www.mccleananderson.com)
left: Fiber Wetting with one Bath, right: Controlled Alternative Fiber Wetting with two baths

2.2 Design and weaving pattern

While Fig. 3 through Fig. 5 show different winding patterns that are possible for winding with endless fibers, Fig. 3 also shows a simple support structure and a matching impeller that can be produced on such support. The support can be held by the rotating 3-jaw self-centering chuck of the winding machine. All winding patterns result in a design with outer shroud and fibers in force direction for high-speed rotation. The outer shroud widely diminishes issues of blade tip vortices or tip clearance, and adds additional strength in the tangential direction. It also allows for an integrated motor at the outer diameter. However, the outer shroud may also be cut off if preferred so, but this is not further considered here. After the matrix material (resin) is hardened during or after the winding process, the support structure can either be removed or it can remain in the impeller as a structural element of the impeller, especially if the support is of magnetic material and used as electromagnetic element of an integrated motor and bearings (Fig. 6 center). Winding patterns like those shown in Fig. 4 (as several in Fig. 5) result in a bladeless inner hub area that can be blocked off or house other elements, e.g. an axle, shaft, or hub motor. These patterns also can provide additional flow guidance in the outer hub area that can aid in preventing flow separation from the hub. Winding patterns like that in Fig. 3 (and several in Fig. 5) have radial-line blading. All patterns allow for curved blades. This can be visualized by applying an incremental small rotation to each complete pattern layer (Fig. 4).

Fig. 3 Wound Impeller; left: Simple Support Structure; right: Matching Manually Wound Model with 2 Fibers that are approx. 10 X Enlarged for Demonstration (Fig. 5, in 1st row – 2nd Pattern from left)

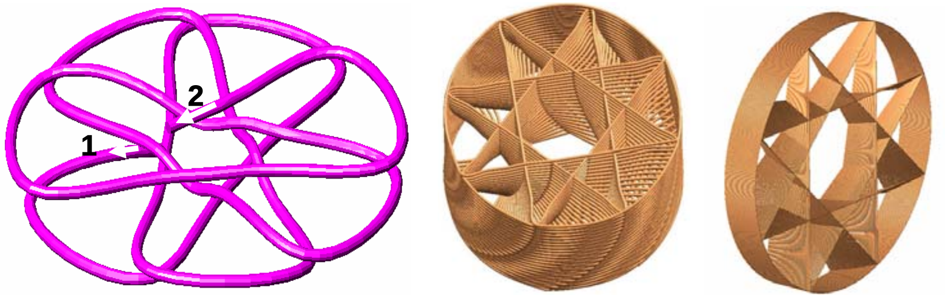

Fig. 4 Alternative Winding Patterns; left: One Complete Layer for Endless Fiber Winding (Fig. 5, in 2nd row - 3rd Pattern from left); center: Computer Model Wound with Single Endless fibers that is approx. 10x enlarged for demonstration (Fig. 5, in 2nd row – 4th Pattern from left), right: shorter Impeller with 0.4 mm Fiber thickness (Same Pattern as middle)

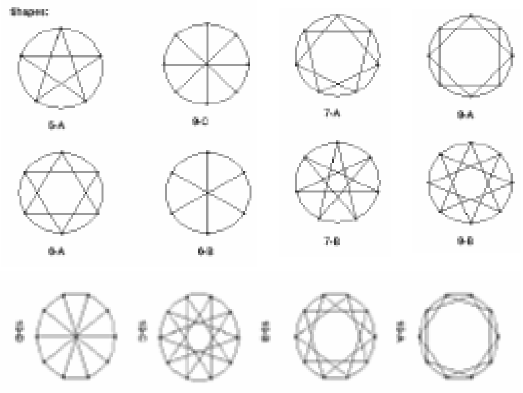

Fig. 5 Various Winding Patterns for Endless Fiber Winding

2.3 Integrated Electric Motor

The woven design allows for integrating an electrical motor in various ways. While it could be hub integrated in a more conventional design, integration in the outer shroud is presented here. Main advantages of motor integration at the outer shroud are (1) that for the same torque, the tangential forces on the rotor structure driving it are much smaller due to the larger radius and (2) that they act at the outer radius where the radial stresses due to centrifugal forces are smallest. Typically a variable speed motor shall be implemented. It can be of induction or permanent magnet type. For reduced losses the latter one may be preferred. For both types there are generally 3 ways to incorporate the motor elements in the outer shroud of the impeller (Fig. 6) (1) a thin shell or sleeve motor may be press fitted over the composite impeller; (2) the motor elements may be attached at the inner radius of the outer shroud, which would preferably also serve as support during winding (Fig. 3), and probably most elegantly (3) the motor elements may be incorporated within the outer shroud. This can be conductive fibers (wires) for induction type; or magnetizeable material in form of fiber or matrix material for permanent magnet type. A most preferred method may be introducing magnetic powder into the resin matrix while winding and magnetizing it according to design thereafter. Also for the stator an interweaving method can be applied. There motor coils can be interwoven into a composite duct (housing) for the impeller (Fig. 8).

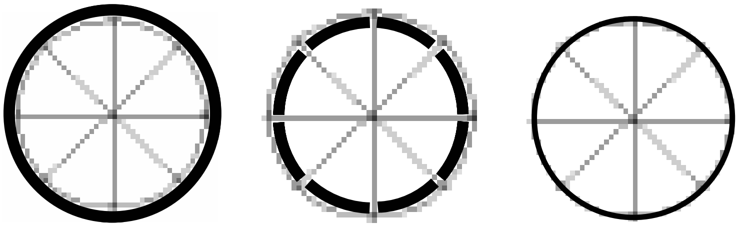

Fig. 6 Three Ways of Integrating a Motor at the Outer Shroud (left: Thin Shell or Sleeve Motor Press Fitted over the Outer Shroud; middle: Individual Elements Attached to Inner Diameter of Outer Shroud; right: Integrated into the Composite Material

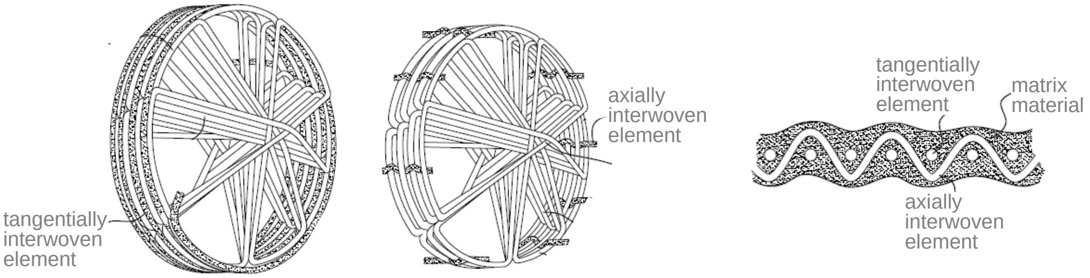

Fig. 7 Interweaving of Inductive and/or Magnetic Motor and Bearing Elements

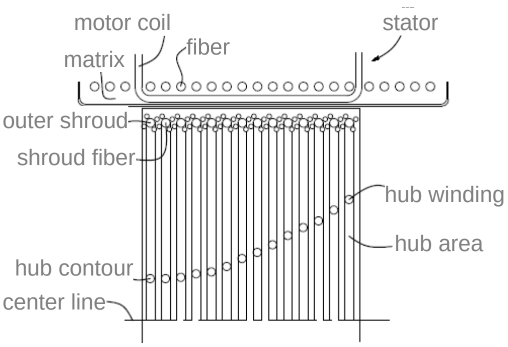

Fig. 8 Schematic Impeller Motor Assembly

2.4 Bearings

The woven impeller design allows for a wide variety of bearings to be used on the outer shroud or at an inner shaft or axle. Since only integrated motor solutions are considered here for versatile and compact designs, no shaft is necessary. However, a stationary axle may be used to support the impeller axially and radially. Because such axle does not need to transmit torque it can be of small diameter if it is still of sufficient stiffness. Such small diameter results in low tangential bearing speed and hence less frictional losses. Roller and journal bearings may be choices. Dynamic fluid (air) bearings with special carbon coating may be preferred. The same way as the electric motor can be integrated in the outer shroud also electromagnetic bearings can be integrated. Such bearings can actively control remaining or acquired imbalances of the impeller, possibly enhancing the robustness of the design.

2.5 Counter Rotation

The design of impeller integrated motors allows for easy implementation of counter-rotating propellers or counter-rotating multi-stage jet devices for high thrust. The main advantage of counter-rotation is the possible elimination of stationary guide vanes that are necessary to redirect the flow in uni-directional rotating stages that are usual in conventional jet engines. Stationary guide vanes do not transmit power, but they add weight and frictional surfaces to the system. Further, if they are not adjustable, they may narrow the operating range. Eliminating them can dramatically enhance power density, while improving performance and operational flexibility. Figure 9 demonstrates schematically how counter-rotation can enhance volumetric power density 3 times. The conventional system (a) with inlet guide vanes (IGV) and diffuser guide vanes has only one power transmitting impeller. The counter rotating version with two power transmitting impellers gives double power at 2/3 volume and the counter-rotating version (c) with three power transmitting impellers gives 3 times the power in the same volume as the conventional system. Mass can be expected to be somewhat proportional to volume. Impeller integrated motors allow to save weight not only by elimination of power transmitting shafts and supporting structures, but also can reduce mass of the jet turbomachinery through utilization of counter-rotation.

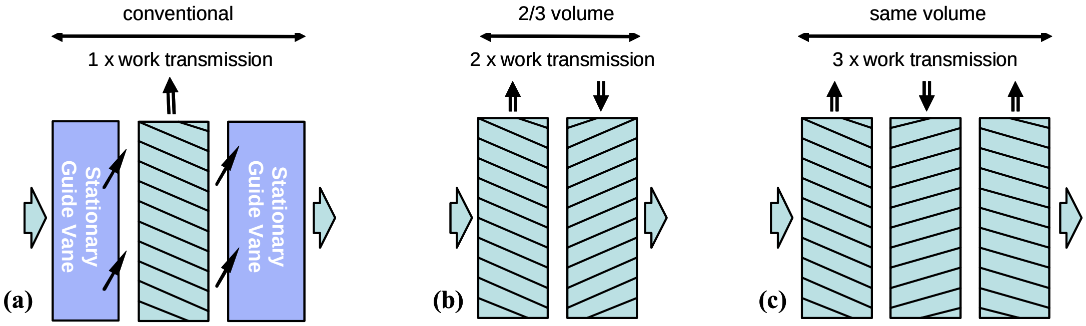

Fig. 9 Power density comparison between conventional unidirectional impeller that requires stationary guide vanes and counter-rotating impellers that can eliminate stationary guide vanes and increase power density 3 times

3. ELECTRICAL FLIGHT

An electrical propulsion system allows for fully electrical flight if the power source is available and sufficient. Figure 1 shows three different power sources: solar power, batteries and onboard generation from fuel by distributed micro wave-disc engines. Only the first one can surely enable non-polluting and environmentally sustainable power. For this reason it may appear most preferable.

3.1 Solar Flight

Sun reaches the outer layers of the earth's atmosphere with a about 1.4 kW/m^2 [3]. When the sun irradiation reaches the ground its radiation has been reduced by absorption and reflection so that e.g. in North America about 3…9 kWh are received per day (24 hours). Assuming half the time day light gives 250…750 W/m^2. Tending to the lower end, 400 W/m^2 during 6 hours peak time are assumed here as available sun irradiation. The question shall be addressed if self-sustained electrical flight of a small unmanned aerial vehicle (UAV) is possible under this condition. For such an aircraft a lift to drag ratio of 10 may be assumed [4]. Assuming 2 m^2 solar panels on the wing of high 37% efficiency [5] gives 296 W for flight. Flying with two propellers of 5 cm diameter with integrated motor at the outer shroud with 0.8 motor efficiency and 0.8 turbomachinery efficiency the aerial vehicle can fly up to almost 100 km/h with 7.37 kg total mass. Using a simple calculation for designing a permanent magnet motor adapted to the woven impeller design [6], the mass for both motors with iron core, copper wire and ferrite magnet material could be together 0.370 kg, for 100 m/s propeller tip speed. The body of the aircraft would be CFRP of conservatively assumed low grade density 1750 kg/m^3. The wing structure would be of two layers 0.4 mm thick, with 0.3 mm thick solar panels on top assumed with density of silicon 2330 kg/m^3. This gives 1.4 kg silicon, plus 2.8 kg CFRP for the wings. The CFRP mass is doubled to account for fuselage and auxiliaries, resulting in 7kg for the body. With 7.2 N thrust, the overall motor power density can be given with close to 20 N/kg or 800 W/kg. The motor design was not much optimized. Further, aluminum could be used instead of copper. At lower speed a small payload could be carried. The energy density of the solar power source can be calculated with 212 W/kg and for the 6 hours mission 1.27 kWh/kg. These are favorable results compared to about 0.2-0.5 kWh/kg high energy density Li-ion batteries [7].

3.2 Wave Disc Engine Generation

For higher flight velocities much more thrust and power is required that cannot yet be sustained with solar power. Also energy carried on board provides independence in operation time. The idea of using micro engines has been inspired by the cube square law which promises higher power densities at small scale [8]. Recently the idea of using wave devices to enhance the efficiency of these micro engines [9, 10, 11, 12, 13] has emerged or even using them as stand alone devices like in wave disc engines [9, 14, 15] directly for propulsion or electrical generation. The wave disc engine uses shock waves to transmit energy directly from a high pressure fluid to a low pressure fluid. It works typically with lower speed than comparable gas turbines and has a very flat geometry that allows implementation even in a very thin wing (Fig. 10). There with its intake at the upper wing side, it can actively ingest boundary layer material, reducing the boundary layer thickness at the critical upper side of the airfoil. The wave disc engine's exhaust jet may be directed under the wing aiding propulsion and lift. However, such effects are not included in below consideration, where the wave disc is only considered as power generating device, having a generator integrated on the back of the rotating disc. The wave disc itself may be micro fabricated out of silicon.

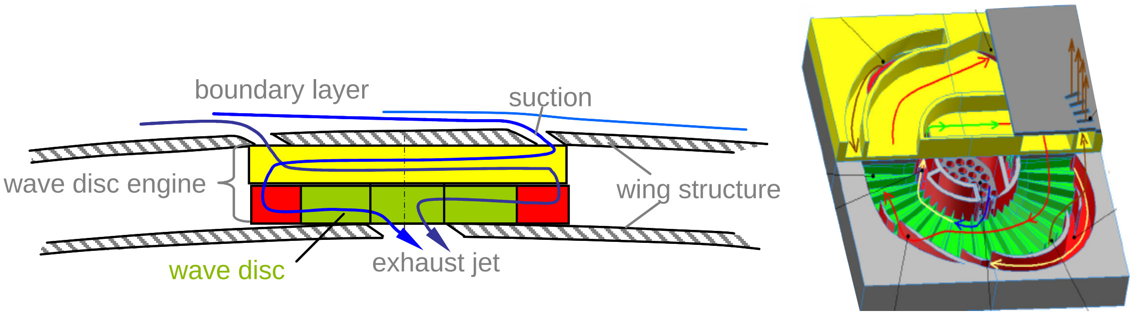

Fig. 10 Wave-Disc Engine and its Integration in a Wing

Non-optimized preliminary Computational Fluid Dynamics (CFD) calculations for wave disc engines have predicted up to 18% efficiency [15] for 1000W heat input in a 30mm wave disc engine. For a 5 mm high structure of 50% solidity this results in 180 W per 5.25g giving a high power density of 35 kW/kg. By considering various fuels and their lower heating values to power the wave disc engine, a energy density diagram (Fig. 11) can be generated that shows the energy density of the electrical source (fuel plus wave disc generator) depending on the mission duration. While expectedly hydrogen yields the highest energy density, the considered solar power system appears comparable with ethanol or methanol powered wave-disc engines only the solar powered mission is limited in time by the day light period. High power density batteries rank below. The wave disc engine has not been optimized, but also no generator efficiency has been accounted for. While the generator electric efficiency may be assumed with 50%, cutting the wave disc values in half, it may be assumed that further optimization enhances the wave disc engine efficiency at least partially compensating for this.

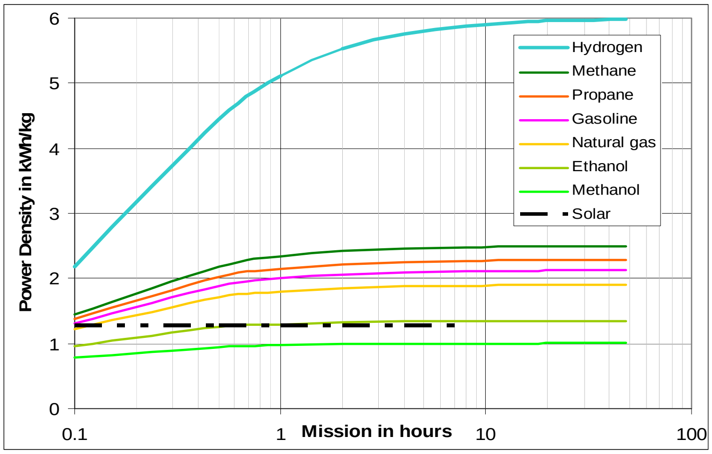

Fig. 11 Electrical Source Net Energy Densities

4. CONCLUSIONS

A novel impeller design is introduced. The design is based on a filament winding technology that already is successfully commercialized. The winding yields low-cost, high-strength, light-weight impellers, in which motor and bearing elements can be interwoven during winding in one single manufacturing step. This yields very compact and scalable designs that can easily be prototyped or mass produced by the one and the same CAD/CAM enabled technology. The technology does not require the use of expensive dies, molds, or tooling.

The impellers typically have an outer shroud that diminishes tip vortex and tip clearance issues in propeller or jet propulsion devices while adding strength in the tangential direction. This allows for an integrating of an induction or permanent magnet motor at the outer shroud. By integrating the motor in the impeller, counter-rotating impeller configurations become feasible. This in turn enhances the power density mainly by eliminating stationary guide vanes. An example calculation shows that solely solar powered flight appears to be possible at up to 100 km/h with a 7.3 kg composite unmanned aircraft. Resulting in 20 N/kg thrust density for the motor impellers or 800 W/kg power density. Utilizing 37% efficient solar cells, the power density of the solar power source was calculated with about 200 W/kg, or for a 6 hours mission the power density was 1.25 kWh/kg. For higher speeds and mass, more propulsive power is needed that may be obtained through electrical onboard generation with wing-integrated wave disc engines that may yield 35kW/kg power density and 1…5 kWh/kg overall energy density, depending on the fuel used. Using conductive carbon fibers to construct the integrated motor, a fully nonmetallic propulsion device may be obtained.

References

1. **Kharazi, A. A., Lindberg, B., Papuga, K., Müller, N.**, "Novel Compressor using woven/wound composite impeller", *ASME-Paper IMECE2006-13342*.
2. **Holden, N., Müller, N.**, "Optimal Impeller-Wheel Diameter Design for a Water-Vapor (R-718), Axial, Compressor", *ASME-Paper IMECE2006-14039*.
3. **Rosner, R.** *MacMillan Encyclopedia of Physics*. **4**, Simon & Schuster, New York, 1996, 1545.
4. **Galiński, C.**, "Key problems in design of micro-planes and entomopters," (in Polish) *Oficyna Wydawnicza Politechniki Warszawskiej*, Warszawa 2006.
5. **Green, M.A., Emery, K., King, D.L., Igari, S., Warta, W.,** "Solar cell efficiency tables (version 23)," *Progress in Photovotlaics*, **13**, 2003, 55-62.
6. **Mouland, M.**, **Müller, N.**, "Preliminary Design Considerations for Integrating a Composite Impeller in a Brushless Permanent Magnet Motor", *ASME-Paper IMECE2006-13904*.
7. **Broussely, M., Archdale, G.**, "Li-ion batteries and portable power source prospects for next 5-10 years" *Journal of Power Sources*, **136**, 2004, 386-394.

8 **Epstein A.**, "Millimeter-scale, MEMS gas turbine engines", *Proc. ASME Turbo Expo 2003*, Atlanta, USA, GT-2003-38866.

9. **Piechna, J., Akbari, P., Iancu, F., Müller, N.**,"Radial-Flow Wave Rotor Concepts, Unconventional Designs and Applications", *ASME Paper IMECE2004-59022*.
10. **Iancu F., Piechna, J., Dempsey E., Müller N.**, "Ultra-Micro Wave Rotor Investigations" *5th International Workshop on Micro Nanotechnology for Power Generation and Energy Conversion Application, PowerMEMS*, Tokyo, Nov. 2005.
11. **Iancu F., Müller N.**, "Efficiency of Shock Wave Compression in a Microchannel" *Journal of Microfluidics and Nanofluidics*, 2005, **2**/1, 50-63.
12. **Iancu, F.**," Integration of a wave rotor to an Ultra-micro gas turbine (UμGT)", *PhD Dissertation, Michigan State University*, 2005
13. **Iancu, F., Müller, N.**, "Radial Ultra-Micro Wave Rotors (UμWR): Design and Simulation", *ASME-Paper IMECE2006-13721*.
14. **Piechna J.**, 2006, "Feasibility study of the wave disk micro-engine operation", *Journal of Micromechanics and Microengineering*, **16** (2006), 270–S281
15. **Piechna J.**, "Wave Disk Jet Micro-Engine Idea", 2006, http://www.imrt.ethz.ch/news/Piechna_Feb2006_ETHZ.pdf