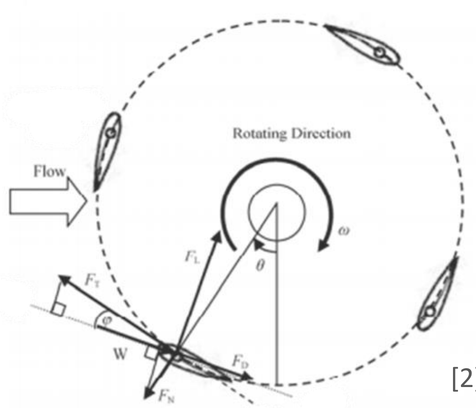

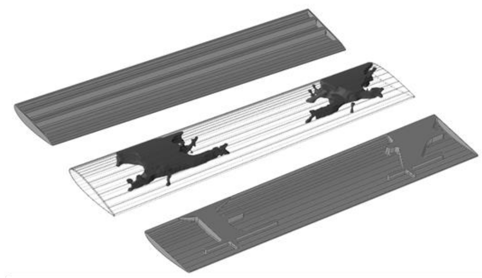

Topology Optimized Wind Turbine Blades Using Sustainable Biomaterials

TEAM MEMBERS

Alex Martinez alex.martinez@uwaterloo.ca
Sagar Patel sagar.patel@uwaterloo.ca
Pablo Enrique pablo.enrique@uwaterloo.ca

FACULTY ADVISOR

Mihaela Vlasea mihaela.vlasea@uwaterloo.ca

University of Waterloo, Waterloo, Ontario, Canada

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Market Appeal

The growing use of wind energy is part of a larger shift to reduce emissions by switching to renewable resources. Vertical axis wind turbines (VAWTs) provide higher efficiency in turbulent and/or low speed winds while having smaller design profiles than horizontal axis wind turbines (HAWTs) that make them suitable for use in high density population centers. The use of VAWTs to generate electricity or heat – especially in northern regions with lower solar exposure – provides an eco-friendly alternative to other sources of energy generation.

Current turbine blade materials are petroleum-based and difficult to recycle, which is detrimental when they reach their end-of-life. With wind energy expected to provide for a greater portion of energy demand in the future, the disposal of over 43.4 million tonnes of cumulative wind turbine waste is expected by 2050 [3]. One proposed solution is the fabrication of turbine blades with sustainable biomaterials instead of synthetic materials such as glass fibre reinforced polymers (GFRPs) [4].

We propose an alternative approach for additive manufacturing of small-scale VAWTs using direct ink writing (DIW), with significant improvements over traditional VAWTs through the use of a topology optimized design. Additionally, the use of a sustainable biomaterial addresses environmental issues associated with the disposal of turbine blades manufactured using synthetic materials. The benefits of the resulting design include a function-driven design, low material and processing costs, improved accessibility of affordable and reliable renewable energy, and mitigation of environmental concerns with turbine blade disposal.

Utilization of DDM Process

The use of DIW for manufacturing small-scale VAWTs could allow for inexpensive fabrication by anyone with access to a robotic dispensing setup similar to a fused filament fabrication (FFF) printer. Topology optimization of the internal structure for the blades – taking advantage of the freedom to design complex structures manufacturable by DIW – can improve the blade's durability by reducing cyclic loading by 70% (procedure summarized in Appendix). The resulting internal structure can be printed directly on a DIW printer. Each blade can be split up into 8 sections, each section with build dimensions of 160 by 270 by 120 mm, to fit a tabletop sized DIW printer and these sections can then be joined by using the biomaterial itself as the adhesive agent. The printed blade can then be manually coated with a thin layer of the biomaterial and subsequently polished (using sandpaper) to achieve the desired aerodynamic performance [5].

Design Innovation, Functionality and Durability

An important performance criterion for VAWTs is their durability, which depends on the maximum cyclic stress acting on the blades. The maximum cyclic stress was determined by considering the maximum Von Mises stress at the blade position with the highest applied pressure loads. We used topology optimization to obtain a 70% reduction in the maximum cyclic stress compared to a typical shear web design [6]. The optimization was performed in SolidThinking Inspire by sectioning the airfoil into multiple segments, which were subject to 44 individual pressure values from experimental data [2] at 4 different angles with respect to the freestream (the wind direction prior to contact with the blade). The optimization was done considering 4 loading cases (one of which is shown in Fig. 1), which approximate one complete revolution of the turbine, using multi-objective topology optimization. The relative wind pressure values used for optimizing the VAWT blades accord with an axial rotational speed of 128 RPM, corresponding to a tip speed ratio of 1.68 which is the optimum value for efficient operation of VAWT blades [2]. The simulation also considers rotational loads and gravity but does not account for span-wise pressure variations due to wingtip vortices. However, the current loading setup can be a good approximation if the blades are fitted with wing endplates (a simple type of winglet). The benchmark, topology optimized, and final CAD designs are shown in Fig. 2A, Fig. 2B, and Fig. 2C respectively.

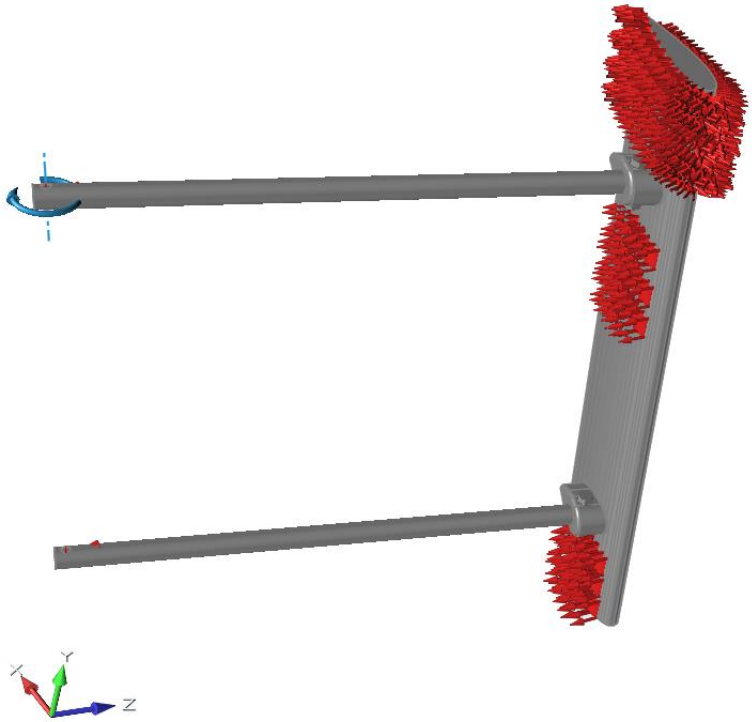

Fig. 1. Loading conditions applied to one quarter of the VAWT design. Al 6061-T6 was used for the tubing and the composite biomaterial was used for the blades and internal structure.

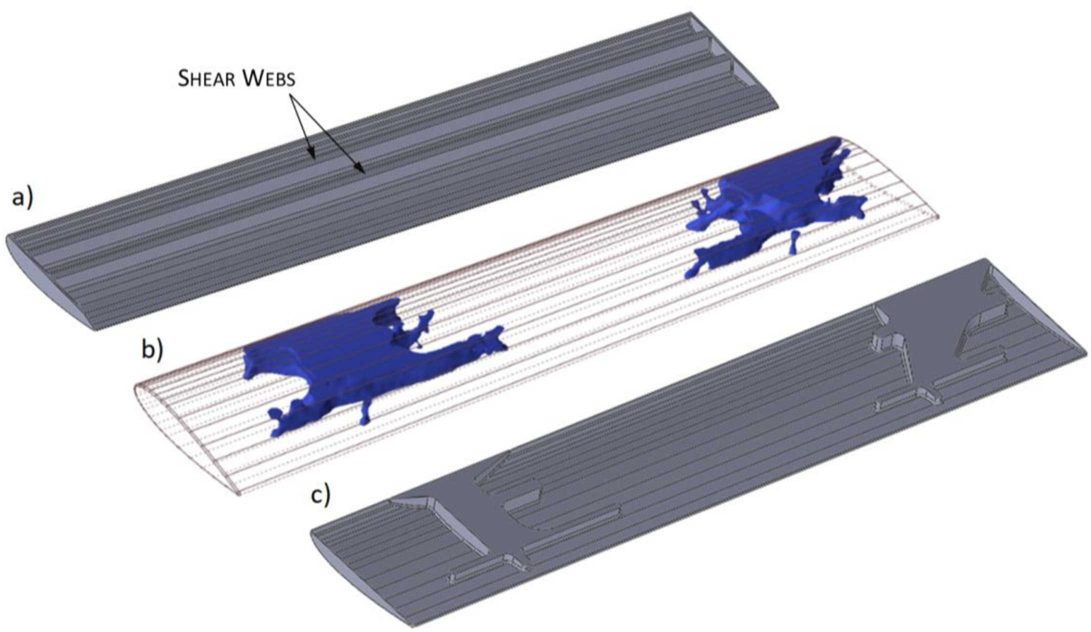

Fig. 2. Benchmark, topology optimized, and final CAD designs. a) Cross-section of the blade showing the benchmark shear webs. b) Transparent view of the blade showing the topology optimized internal support. c) Cross-section of the blade showing the final CAD design (simplified from the topology optimization result).

The optimized design achieves a 70% reduction in maximum stress by moving material towards the tube anchor points to increase their local stiffness. In the original design, the anchor points had the highest stress magnitudes. The obtained reduction in maximum stress will decrease the cyclic loading of the blades, thereby extending their working lifespan.

Utilization of DDM Materials and Cost Analysis

Our approach uses a composite biomaterial made from the two most common organic compounds on earth – cellulose and chitin – which has been shown to be printable using DIW [5]. This approach has the added benefits of low material costs ($2/kg compared to $4/kg for GFRPs), low material density (370 kg/m^3 compared to 1800 kg/m^3 for GFRPs), and potentially low processing costs (no need for a mold in DIW compared to resin infusion molding for GFRPs). Applying 3D-printable, cellulose-derived materials to small scale turbine blade development allows for distributed energy production at the household level, while mitigating the environmental impact of discarded wind turbines. The total material cost for printing one turbine blade (weight ≈ 2 kg) is approximately $4. The printing time for this blade is about 43 minutes assuming a 3 mm layer height, bead width of 13 mm and print rate of 1950 mm^3/s [5]. Due to the large size of the blade (4950 mm^3), a relatively coarser resolution offered by DIW is still adequate. This resolution could be improved by applying ultrasonic vibrations at the nozzle to decrease the effective viscosity of the cellulose-derived material [7].

Social and Environmental Impact

The development of low-cost and high-performance solutions, which can be implemented on an individual basis or through the development of local micro-grids rather than by large-scale utilities, has significant social and environmental impacts [8]. From a social perspective, the low manufacturing cost of the proposed solution increases access to affordable and reliable power. Additionally, the use of DIW as an additive manufacturing technology ensures the largest reach possible, considering the ease and frequency by which DIW can be used at home or at community centers such as libraries and universities. From an environmental perspective, the clearest impact is a reduced reliance on coal, oil, and gas for energy and heat generation. The distributed power generation aspect of VAWT use has additional benefits including shorter transmission distances (which reduces energy losses due to Joule heating in transmission lines), as well as an overall improvement in energy efficiency and power quality [8].

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