Title: **A lightweight approach for airborne wind turbine drivetrains**

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1. Introduction

Airborne wind turbine systems are gathering increasing attention. These devices are able to harness stronger winds at higher altitudes and with their automated and rapidly deployable system they are suited to niche applications such as emergency power generation. There are a plethora of different airborne wind turbine types, e.g. buoyant [1], flip-wing style (Mars) [2] and kite (SkySails power system) [3]. Buoyant airborne wind turbines are composed of a shell made of high performance fabric filled with helium that lifts a lightweight horizontal axis wind turbine up in the air. High strength tethers keep the turbine in place and send power to the ground station which comprises an autonomous control system and power conditioning equipment [1]. An example of such a system is the Altaeros turbine, shown in Figure 1.

Although much of the wind turbine technology for these systems is common with their ‘grounded’ cousins, these buoyant systems have some additional design constraints and the design has some extra objectives. One such limitation is the requirement for the wind turbine equipment to be lightweight. This paper concentrates on the drivetrain of the wind turbine and the different potential ways of reducing its mass.

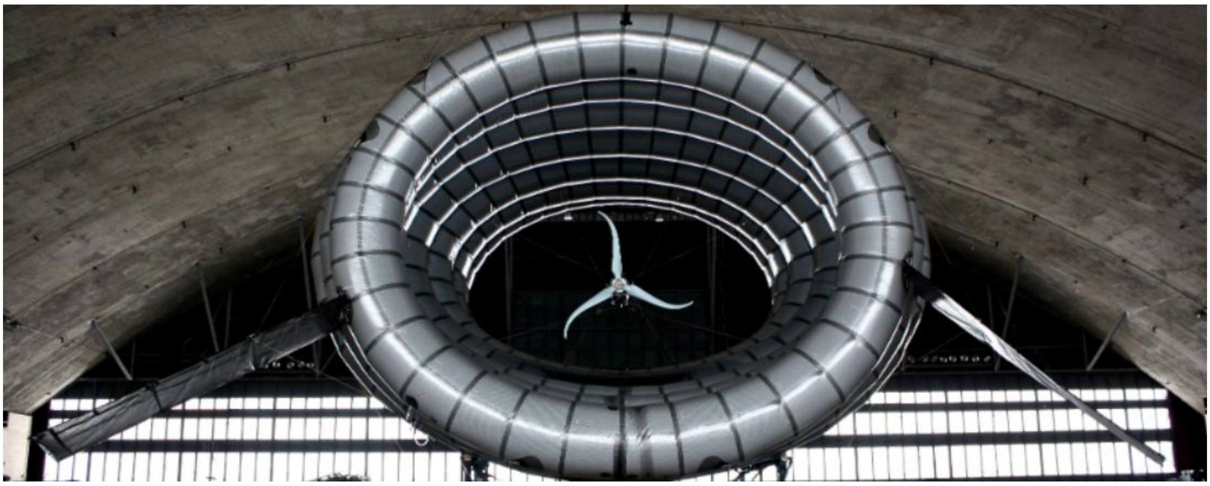


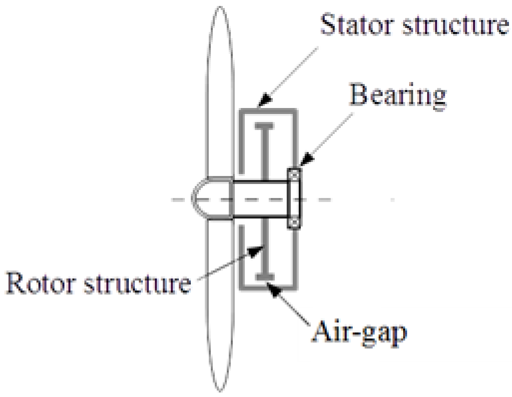
Figure 1. Buoyant airborne wind turbine (BAT) [1]

2. Approach

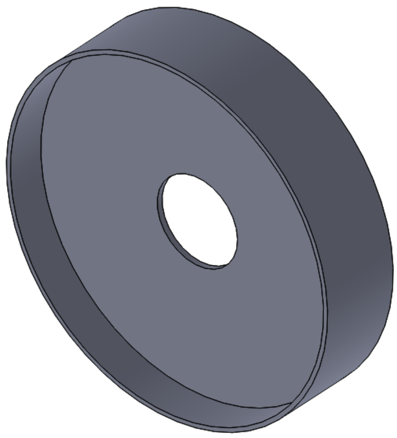
For this research, a 100kW airborne wind turbine with different types of drivetrains has been analysed in order to find the lightest arrangement.

In the initial stage of the study, the make-up of the drivetrain is constrained to a permanent magnet generator with a gearbox or no gearbox (direct drive). For the gearbox driven generator the gear ratio is a free variable; generally as the gear ratio increases the gearbox mass increases but the generator mass can be reduced. Gearbox masses are based on catalogue data for commercially available parallel and planetary gearbox units. Generator masses are based on basic electromagnetic design and scaling, with the addition of modelling the mechanical design to cope with forces within the generator. This first part of the study finds a minimal drivetrain mass subject to efficiency constraints based on conventional technology.

The second part of the study investigates the design of the electrical generator with a focus of using composite materials in the supporting structures for the generator rotor and stator. In a gearless drivetrain, the heaviest component is the electrical generator. Nonetheless, that weight can be substantially reduced by changing the current material (typically cast iron or steel) by using materials with a higher ratio of Young's Modulus to density such as composites. In this investigation, a disc structure with a mosaic pattern fibre orientation [4] has been assumed for the electrical generator.



(a)



(b)

Figure 2. (a) Generator structure [5]**; (b) Rotor structure made of steel.**

3. Main body of abstract

This investigation is based on a 100kW buoyant airborne wind turbine with a swept area of 93.5m^2 and 5.5m rotor radius. With a rotor speed of 140rpm, the low speed shaft nominal torque is 6.8kNm. As explained, the turbine drivetrain must be as light as possible to be lifted up in the air. Bearing this in mind, a particular number of layouts – comprising gearless and conventional geared with several ratios – have been studied so as to find out the lightest possible arrangement. In the calculation of the drivetrain mass, the gearbox (if needed) and the generator masses have been considered. The electrical generator mass involves the mass of winding copper, permanent magnets, steel (rotor and stator yokes, stator teeth), supporting structure and others (casing, bearings, mountings). The breakdown of masses for the 100kW direct drive generator is shown in Figure 3.

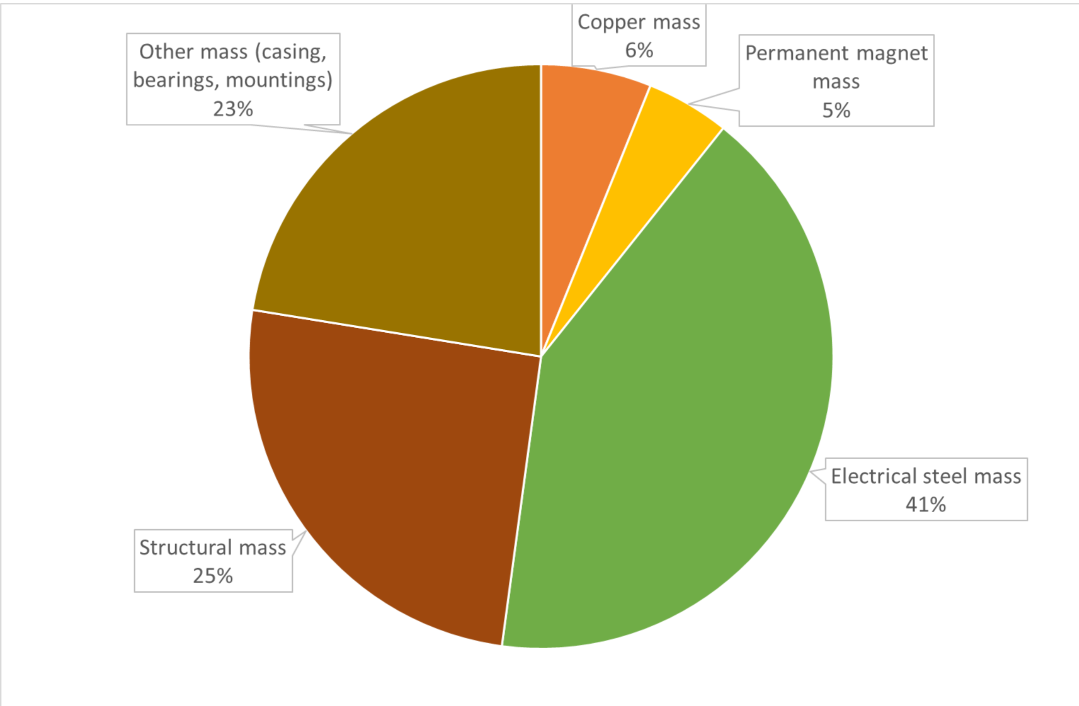


Figure 3. Breakdown of mass for the direct drive generator.

The structure of the generator must be able to:

- Transmit and react torque
- Maintain a clearance between rotor and stator subject to a magnetic force of attraction between the magnets on the rotor and the steel on the stator
- Maintain that clearance subject to the radial expansion due to rotation

A generator supporting structure is assumed to be made with discs. For all generators, the structure was modelled in ANSYS and the major dimensions were varied so as to reduce structural mass while meeting deflection criteria.

Gearbox masses – where used – were found from [6]. Results for overall drivetrain (generator and gearbox) mass are given in Figure 4.

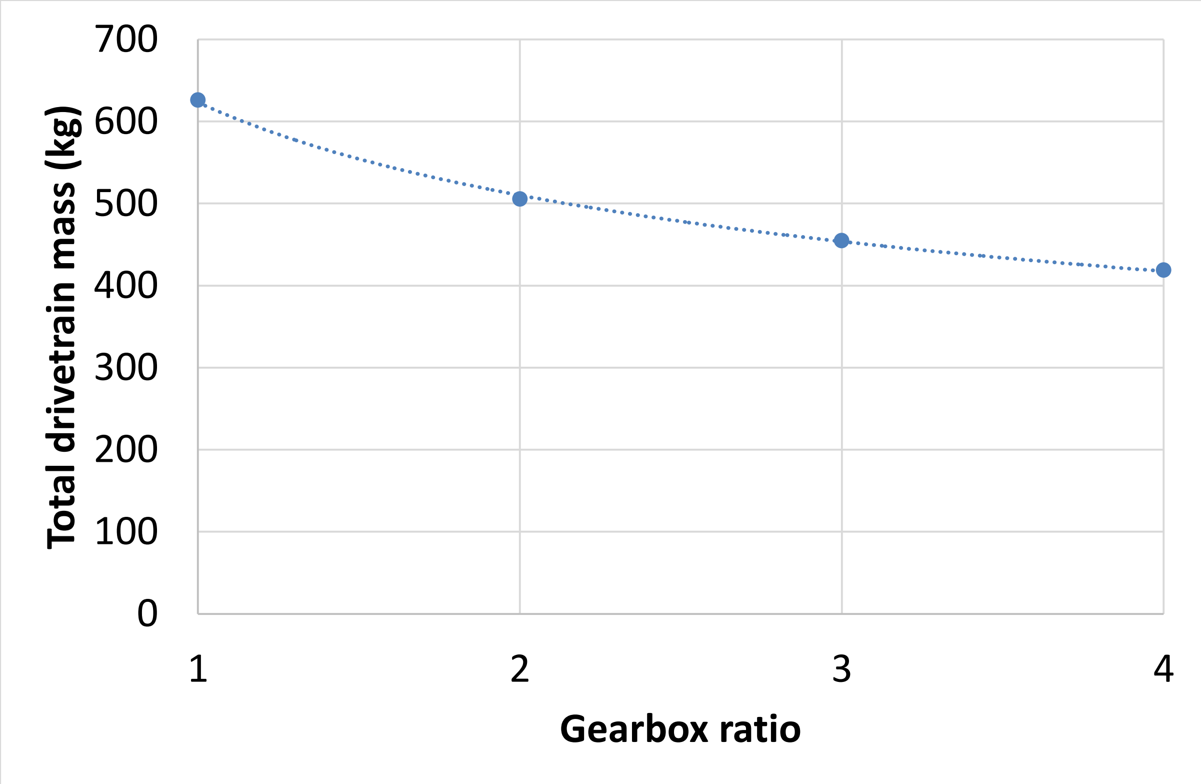
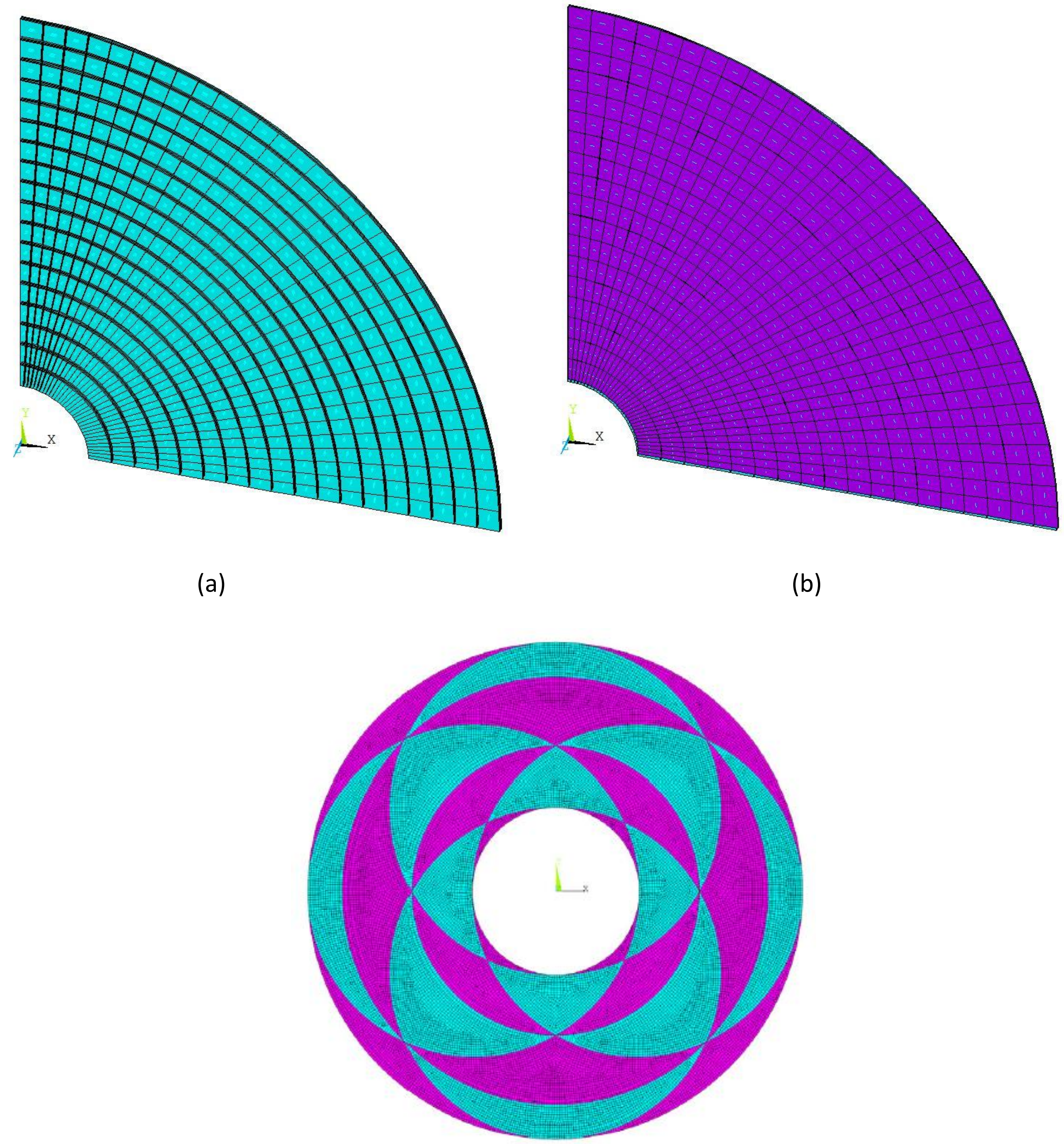


Figure 4. Total drivetrain mass (mass of gearbox and generator) plotted against gearbox ratio.

Figure 4 shows that as a gearbox is introduced the drivetrain mass is reduced (although there is additional mass for the gearbox, the reduction in generator mass is greater). The gearbox does have disadvantages though: additional failure modes and potentially worse reliability along with losses in the gearbox. In order to further reduce the mass of the generator, further investigation of the structure is needed.

The said structure can be made of different materials. Cast iron and steel are commonly applied. However, less dense materials such as composites can also be used. If so, a significantly lighter structure can be obtained. Nevertheless, as the composite structure must be able to withstand all the loads present during machine's operation, a specific design is needed. Considering an allowable structural deflection of less than 10% of the airgap size, various approaches have been studied. The first one was the so called conventional approach where the disc owns 4 plies with circumferential fibre orientation. The second one was the conventional approach with the 4 plies reinforced (smear reinforcement) and finally, the third was the 4 unit disc [4] where the fibres follow a mosaic pattern. See Figure 5. It was noticed that the last two models were capable of supporting the loads. Nonetheless, the 4 unit disc with mosaic pattern fibre orientation was selected for the analysis since it was also able to spread out the stress concentrations in the structure due to the fibres interlacing.

If a comparison between generator structure masses is made, it can be easily seen that the composite structure has better features. Looking at the gearless case, the mass of a steel structure is around 105kg, whereas the mass of the composite structure is only 22kg. This gives us a reduction of about 80% of the generator mass and supposes a 20% drop in drivetrain mass.



(a) (b)

(c)

Figure 5. (a) Conventional approach showing circumferential fibre orientation; (b) Conventional approach showing fibre orientation of reinforcing elements; (c) 4-unit disc (mosaic pattern fibre orientation) [4]**.**

4. Conclusion

In this paper, different arrangements for airborne wind turbine drivetrains, from gearless to conventional geared approaches with variable gear ratios, have been described and analysed. Due to the drivetrain weight limitations that this type of turbines presents, the electrical generator supporting structure mass has been reduced using low density materials such as composites. Designs already utilised for other applications, for instance energy storage flywheels, have been slightly modified to be employed in the generator structure. It has been demonstrated that by making of use of the mosaic pattern 4-unit disc model, all the structural requirements including the airgap deflection limit, can be matched. At the same time, a significant reduction in the generator structural mass, see the gearless case, of up to 80% can be achieved. This accounts for more than 20% of the total drivetrain mass. The full paper will show the analysis of various drivetrain arrangements, as well as the FE results obtained for the composite disc structures of their generators with different fibre orientations and mosaic patterns and how these configurations affect the structural design of the electrical machine.

5. Learning objectives

This paper will enable the reader to:

- Understand how new devices, such as buoyant airborne wind turbines, work and their limitations
- Identify the different options available for buoyant airborne wind turbine drivetrains and how the alternatives affect drivetrain mass
- Appreciate that the use of materials with a higher ratio of Young's Modulus to density can be used to reduce the mass of the electrical generator
- Categorize the distinct approaches that can be followed to meet the structural requirements of an electrical generator disc structures made of composites

6. References

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