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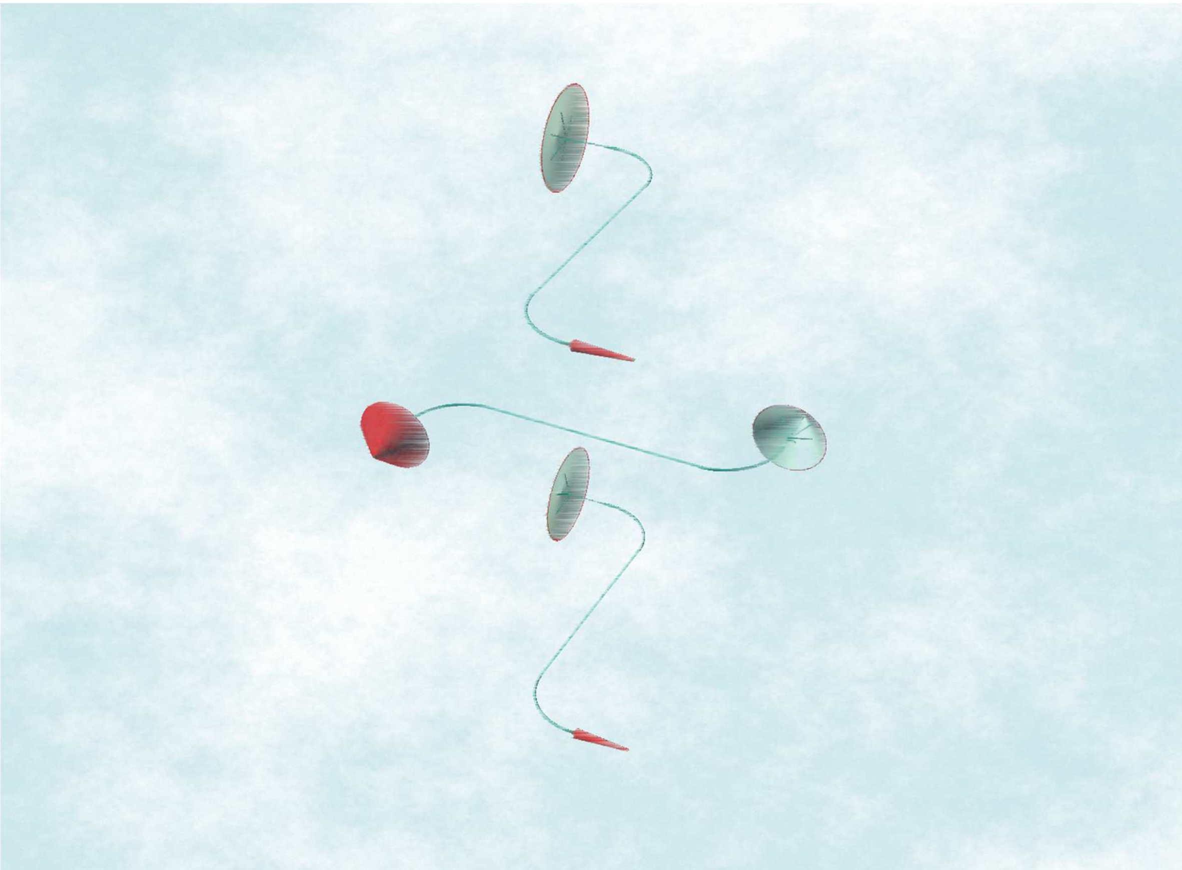
Final report

Developed Rotor of Lighter-Than-Air Wind Turbine

Modèle de rotor développé pour un nouveau système éolien plus léger que l'air



Graphic representation of flexible-blades operation in three stages of a drag-driven vertical rotor. The blades are passively folded in upwind motion and then passively deployed in downwind motion.

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List of abbreviations

AWE	Airborne Wind Energy
LTA	Lighter-Than-Air
VAWT	Vertical axis wind turbine

Résumé

La technologie Airbone Wind Energy (AWE) a pour but le développement de nouveaux systèmes qui permettent d'exploiter des vents forts à plusieurs centaines de mètres au-dessus du sol. À cette altitude, les courants de vent sont plus forts et bien plus constants que ceux plus proche du sol. Pour l'installation d'un système éolien à cette hauteur, un aérostat flottant à gaz est utilisé pour transporter un générateur électrique qui plane ensuite dans le ciel en étant connecté à la terre par câble. L'initiative AWE à Zarawind (spin-off à la Haute école spécialisée ZHAW) cherche à développer un nouveau système éolien plus léger que l'air pour exploiter les vents forts de haute altitude. Le système est compact, rentable et respectueux de l'environnement pour être utilisé dans les endroits reculés sans accès au réseau. Les travaux de recherche sur le développement de la partie rotor du système sont effectués par des simulations numériques, des essais en soufflerie et des tests sur les matériaux des pâles. Comparé à des rotors classiques, le nouveau concept de rotor présente une garantie de rendement pour un très bas rapport du poids/surface balayée. De plus, les tests sur les matériaux ont montré une capacité prometteuse de résistance des pâles contre la fatigue cyclique due à la charge du vent sous conditions météorologiques.

Summary

The technology of Airborne Wind Energy (AWE) aims to develop new systems that operate to harvest strong wind power at several hundred meters above ground level. At that altitude, wind currents are stronger and much more consistent than those close to the ground. For the installation of the wind power system at that elevation, a buoyant gas aerostat is used to carry an electrical generator which hovers in the sky with a cable-tether connection to the earth. The AWE initiative at Zarawind (spin-off at the school of engineering at ZHAW, Zürich University of Applied Sciences), aims to develop a new Lighter-Than-Air (LTA) Wind Power Turbine for the harvesting of the high-altitude strong-wind power. The system is compact, cost-effective and eco-friendly to be used in remote off-grid locations. Research works are conducted on the development of the rotor part of the system through numerical simulations, wind tunnel experiments and blade material tests. Compared to classical rotors, the new rotor concept has been shown insuring a power performance at very low weight-to-swept-area ratio. Moreover, the material tests have shown a promising ability of the blades to stand for cyclic fatigue wind loading under weathering conditions.

1 Introduction

This project supported by SFOE the Swiss Federal Office of Energy, contributes further developments to a new Airborne Wind Energy System (AWES). Specifically, it aims to develop a new rotor installed in a novel Lighter-Than-Air (LTA) wind turbine for the generation of the electrical power at high altitude. The floating rotor-generator is carried in the sky by a strong lifting aerostat and is connected to the ground by a cable-tether attachment. One of innovative concepts in the new system is the first implementation of a vertical rotor operating with flexible blades. Indeed the soft-shell concept of power kite is incorporated in the rotor's design. Thus flexible-blade shell are deployed when moving downwind to allow more swept area for the incident wind. The flexible-blades are folded again when moving upwind to reduce drag-losses. Note that such an alternating deployment-folding deformation is passively performed by the blade through its interaction with the wind (without using active control instruments like sensors, actuators or other control devices). This allowed an enhanced power performance of the rotor and an increased efficiency of the system at reduced payloads.
The implemented concept of LTA wind power turbine uses a drag-driven vertical rotor. This allows the tethered floating system to perform an omni-direction stable operation accepting wind from all directions. With flexible blade design, the rotor features a very low weight-to-swept-area ratio. Furthermore, the reduced drag resistance associated with flexible-blade operation, allows the tethered system to keep a high lift-to-drag ratio. Therefore the floating rotor-generator system hovers in the sky at controlled blow-down angle (zenith) between the vertical and the tether attachment to the ground. This feature allows a reliable operation of the rotor by keeping a quasi-vertical pose for an efficient harvesting of the strong wind power at high altitude.

The accomplishments in this project belong to three principal work packages handled by three teams at the School of Engineering at ZHAW, Zürich University of Applied Sciences:

- Numerical simulations are conducted at ICP, Institute of Computational Physics.
- Wind tunnel tests are performed at ZAV, Center of Aviation.
- Material tests are performed at IMPE Institute of Material Process and Engineering.

2 Numerical simulation works

2.1 Turbulence model

Different turbulence models have been applied by solving RANS Reynolds Average Navier Stokes equations. This include: k-Epsilon, KKL-Omega, k-omega SST (Shear Stress Transport). The open-source package “OpenFoam” has been used.

2.2 Deformed mesh development

A Mathematica module has been implemented as an interface for an advanced mesh generation in OpenFoam. This routine facilitates controlling the quality of the mesh generation with specific geometrical requirements. It allows the user to conduct the simulations of the rotor and the blades with rotating conditions in both two-dimensional (2D) and three-dimensional (3D) cases, Figure 1.

2.3 Single blade aerodynamics

A model of single blade aerodynamics has been set up firstly in two-dimensional (2D), and later, in three-dimensional (3D) test cases. The simulations have been performed with different wind speed values and reproduced with different azimuth angles of the blade deviation from the wind direction.
The conditions for internal flow case (simulation with the wind tunnel test conditions) and external flow case (simulation with open-field test conditions) are considered in the computational model.

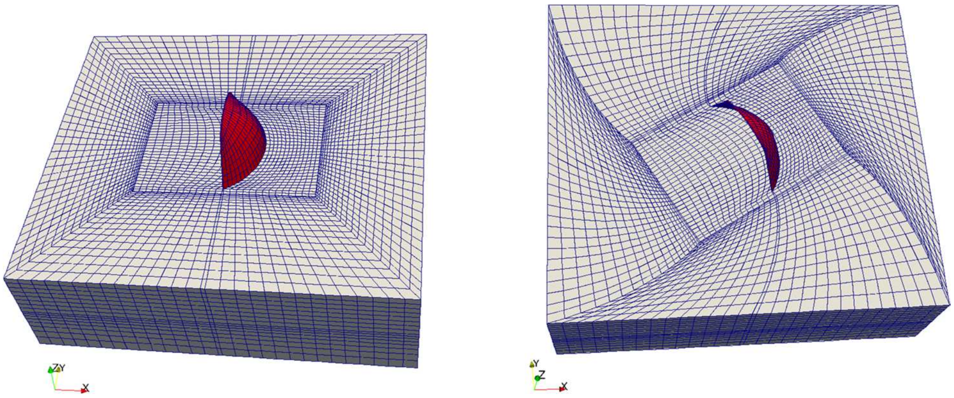
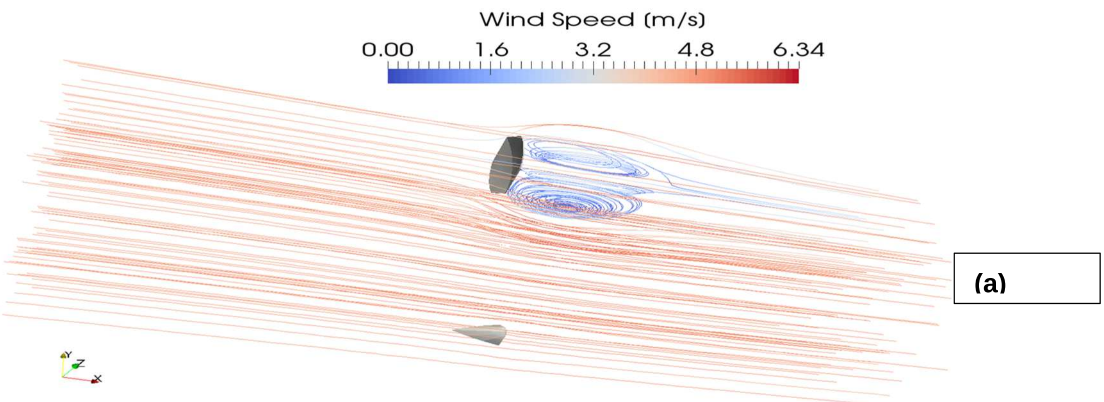


Figure 1: Rotating mesh generation in a developed Mathematica-OpenFoam routine. Cut view is showing the lower half of the mesh surrounding the blade. Azimuth angle 90 degree (left) and 60 degree (right)

Single-blade blade simulations have facilitated further understanding of the flow aerodynamics around the blade domain, identification of the zones of low pressure flow acceleration and high pressure flow stagnation, analyzing the effects of the blade deformation on the drag forces.

2.4 Rotor with passive flexible blades

A model of rotor with both flexible and rigid blade cases is set up, Figure 2 (a, b). The simulations are performed for a first step in 2D, and later, in 3D test cases with static rotor conditions.



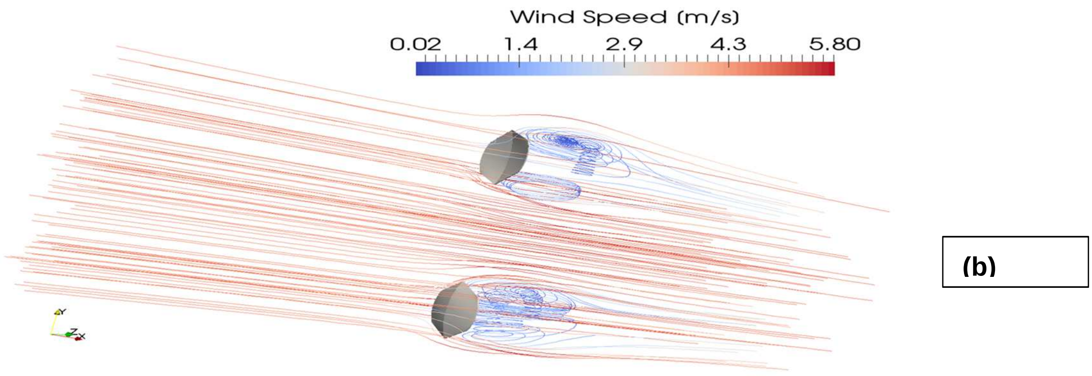


Figure 2: Streamline of wind flow around two-blade rotor. The inlet (free stream) wind flow is in x-direction. (a) Flexible blade passively folded-upwind and deployed-downwind. (b) Rigid blades model.

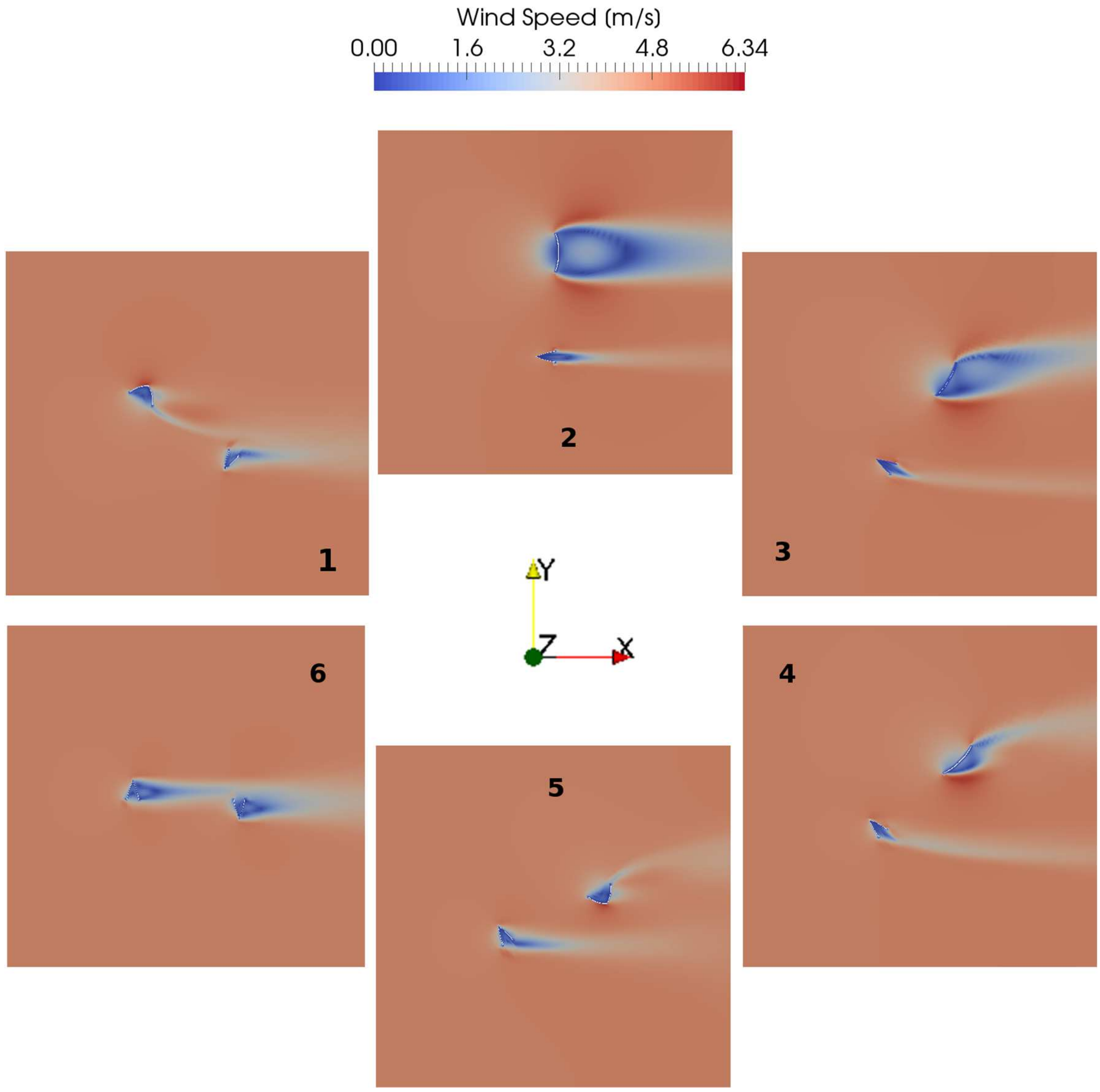


Figure 3: Two-blade rotor is exposed to free stream wind flow along x-axis direction. Magnitudes of wind speed are shown for different azimuth angles of rotation around rotor axis with poses numbering from 1 to 6. Wind is flowing around flexible blades that are passively folded in upwind and passively deployed in downwind. (Simulation using OpenFoam and visualization using Paraview)

The implemented rotor model is suitable to represent both internal and external flow cases. The simulations results have facilitated the analysis of the effects of the blade flexibility on the flow hydrodynamics. The distribution of stagnation and flow acceleration zones around blade can be tracked for different azimuth angles of rotation around rotor axis as shown in Figure 3. The velocity magnitudes shown in Figure 3, have been obtained on a two-dimensional cross-sectional cut through the blade and the fluid region. Note that the solution was, in fact, fully three-dimensional.

Furthermore, a comparison of the torque applied on the rotor body has been conducted with a series of tests on both flexible and rigid blade. The rotor model is considered with different azimuth angles with respect to the free stream wind flow. The simulation results have shown an advantageous torque generation with the flexible blades against rigid-blades.

On the other hand, since the lighter-than-air wind power turbine is designed with a vertical rotor, the system maintains the efficiency of generated power when the rotor assumes a quasi vertical position (the tether attachment between aerostat and ground fixation keeps a controlled blow-down angle). This requires that system should not be driven with a strong drag forces acting on the floating components. An interesting aspect of the obtained results is showing a quantified an advantageous role of the passive deformation of the flexible blade in saving the high-lift-to-drag ratio of the system. Indeed, the flexible blades exhibit a decreased global drag field applied on the rotor in comparison with flexible blades.

2.5 Model validation

The numerical model has been validated by the comparison of the computational results with respect to the measured values obtained from wind tunnel tests. For an example, a model of internal wind flow (wall confinement flow) over a static single blade has been computationally implemented. Drag forces are obtained for different wind speed at a fixed azimuth of 90 degree where the blade is directly exposed to the downwind flow. As shown in Figure 4, at controlled blockage effects, simulations results fit the wind tunnel measurements.

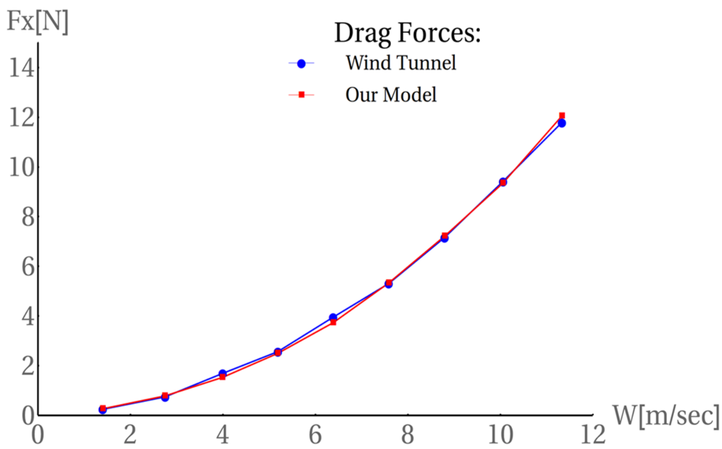


Figure 4: A small scale model of single blade in wind tunnel. Drag forces with respect to wind speed from simulations and measurements.

Another validation example is a small-scale model of a rotor with two flexible blades that has been studied with internal flow simulation (wall confinement flow). Torques have been measured for a static installation of the rotor in the wind tunnel with an azimuth angle of 90 degree from wind direction. The measurements have been conducted at different wind speed where the deployed blade is directly exposed to downwind flow and the folded blade is upwind oriented. The same setting up has been reproduced computationally with RANS model and the simulation have been performed using OpenFoam package. As shown in Figure 5, the torque values with respect to the vertical axis resulting from the simulations fit those obtained from the wind tunnel measurements.

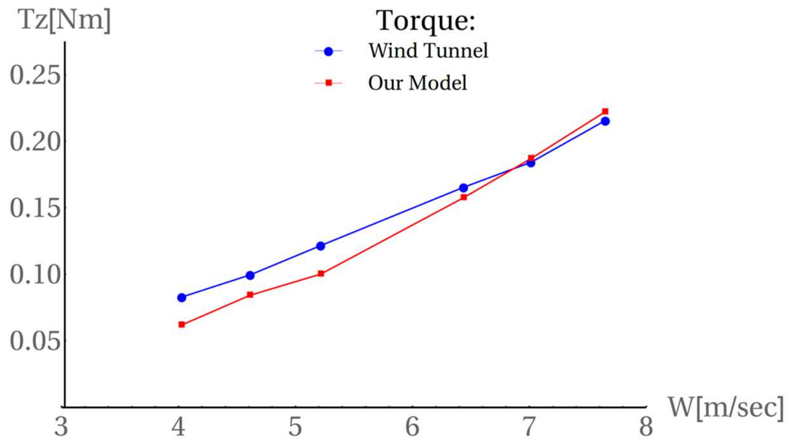


Figure 5: A small scale model of one-stage rotor with two flexible blades. Torque is obtained for azimuth angle 90 degree with respect to wind speed.

It is worth to note that the forces on the blades obtained from both numerical simulations and wind tunnel measurements has been used as guiding estimation for those applied in material test works.

3 Wind tunnel experiments

3.1 Aerodynamic characterization of the single static blade

A model of single blade is set up for static tests in the wind tunnel. The torques produced by the single blade, are measured with respect to a vertical mounting axis in the wind tunnel. However, the measured torques and forces values are readily post-processed to estimate the torque that blade effectively produces on the axis of a rotor handling that blade at a given arm length form rotor axis. This transformation has been analytically obtained through a splitting of the torque-arm vector multiplying the measured forces in the integral formulation of the torque. Note that with single-blade model we have insured further control on the blockage effects in the wind tunnel, and then, allowed further validation of the rotor-torque measured data (next section) through aforementioned transformation.

3.2 Aerodynamic characterization of static rotor

A model of vertical rotor is set up for a static testing (without rotation) in the wind tunnel. A static installation of the rotor has been conducted at different azimuth angles and with different wind speed values. The tests have been performed with one and two-stage rotor model for different number of blades per stage and for different shift-angle between stages.

Outcomes:

Beside the validation of computational simulation, the measurements have shown a promising role in the perspective of the engineering development of the rotor design. This includes:

i- For a given swept area, a two-stage rotor design with 90 degree shift angle is advantageous compared to that with one stage design. Although that former doesn't promote a considerable increased static torque compared to the later (for the same swept area), it insures a enhanced self-starting capability.

ii- In case of one-stage rotor, an advantageous torque generation is shown with 4 blades design against the design with lower number of blades. Indeed in the present model, there is a large radial gap between the blade and the vertical axis. This makes the effective drag surface clearly smaller than the swept area of the rotor. However, an arrangement of several blades insures a global drag surface in down-wind motion that covers the conventional swept area (productive half section of the rotor in the side of deployed blades). This should enhance the performance of the rotor in consistency with the observed increase of the measured torque at higher blades number as explained in Figure 6.

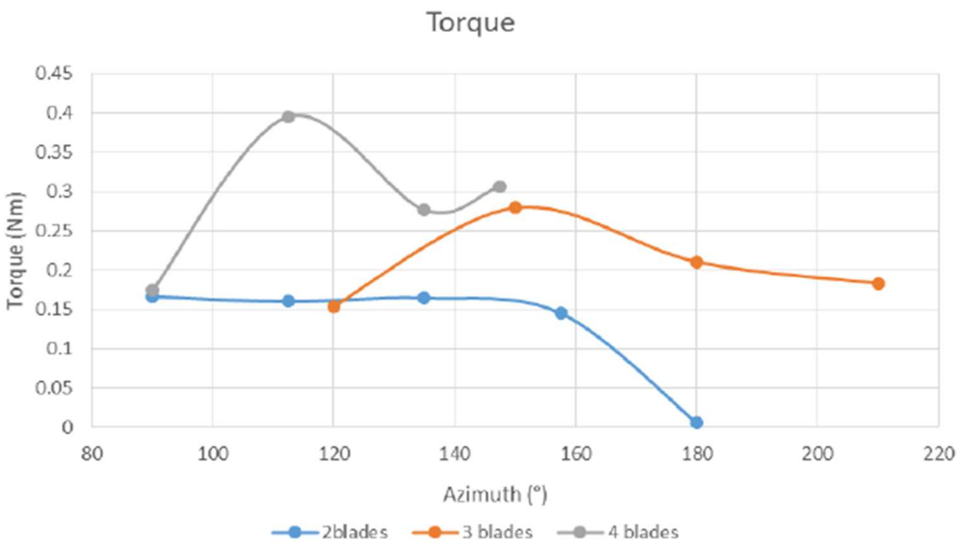


Figure 6: Torque measured for model of one-stage rotor with different number of blades. Wind speed 6.5 m/Sec

3.3 Aerodynamic characterization of dynamic rotor

A bachelor work of students (M. Jansen and R. Schelbert) from the aviation program at ZHAW has been conducted on the aerodynamic of the rotor in lighter-than-Air turbine. For the testing of dynamic rotor in the wind tunnel, new installations of sensor device and other equipments have been accomplished. This includes the following tasks:

– Incorporation of a new dynamic torque sensor (Datum Electronics, M425 Torque Transducer)

– Mounting construction (basement, rollers, shaft, coupling....)

– Micro motor

– Speed controller

– Dealing with both software and hardware setting up.

The dynamic tests have been performed on one-stage rotor with different blade numbers at a range of RPM (Rotation Per Minute) of the rotor and free stream wind speed values.

<u>Outcomes :</u>

Considering the wide room of improvements in term of blade number, blade arrangement, the blade area and blade shape, the present dynamic wind tunnel measurements confirm the expected potential of the new rotor concept to perform efficient power generation i.e. Cp > 25% at very low weight-to-swept ratio. This makes the new rotor concept very suitable of the Airborne Wind Energy applications.

3.4 Improved rotor skeleton materials for wind tunnel model

In order to set up a wind tunnel model with a reliable operation of the sensor devices measurements, it was necessary to avoid the vibrational noises coming from the rotor structure under wind loading. Therefore, the rotor has been installed in wind tunnel with rigid structure including vertical shaft and arms. Moreover, different materials have been investigated for the rotor skeleton. This includes arms and shaft fabricated with wood, aluminum and carbon materials.

3.5 Aerostat model

A wind tunnel investigation of aerostat that combines the aerodynamic and the buoyancy lift capability has been started at ZAV (Center of Aviation, ZHAW). This is to evaluate the lift-to-drag ratio of the tethered system and then to establish an experimental estimation of the rotor inclination (blow-up angle). A model of aerostat of type Helikite has been fabricated for this purpose, Figure 7. This to allow a preliminary prediction of the power performance of system when a strong-lifting aerostat is used to maintains a quasi vertical installation of the rotor in the strong wind

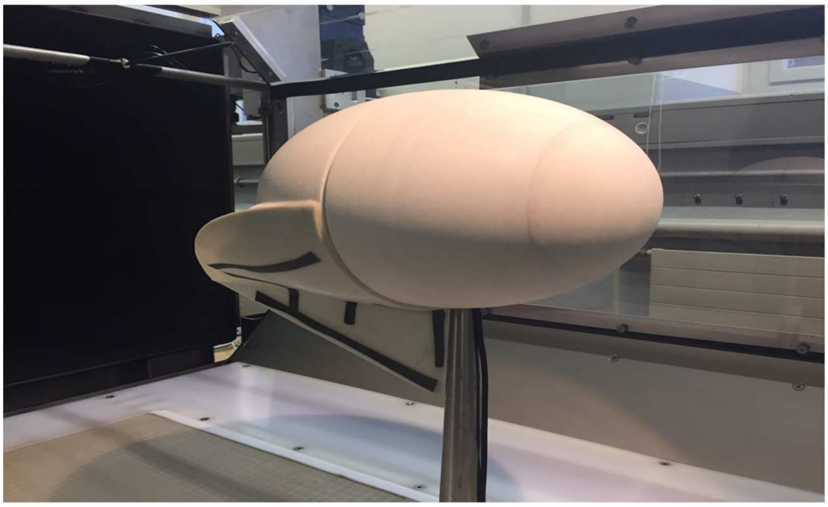


Figure 7 : A model of strong lifting aerostat of type Helikite installed in the wind tunnel.

Furthermore in the framework of bachelor project (students: K. Baur and P. Kaelin) in aviation program at ZAHW. A computational study of aerodynamic of the Helikite aerostat has been achieved, Figure 8. The work was planned with the following steps:

a. Testing different turbulence models that are available in the commercial package ANSYS CFX. This includes approaches like K-Epsilon, K-Omega and K-SST with testing of different solving schemes.

b. Validation of the computational model with respect to the wind-tunnel tests. This covers different cases of aerostat installation with different pitch and Yaw angles at different wind speed applied in the wind tunnel tests.

c. Use the validated model to provide a computational assessment of the aerodynamic performance of the Helikite. Suggestion of developments from an aerospace engineering point of view. based on the simulations results.

The simulations have been performed with ANSYS using parallel computations with 2 processor for each case with simulation time of 168 hours and a memory utilization of order 80 GB. The results have shown a consistent the distribution of velocity and the pressure around the aerostat

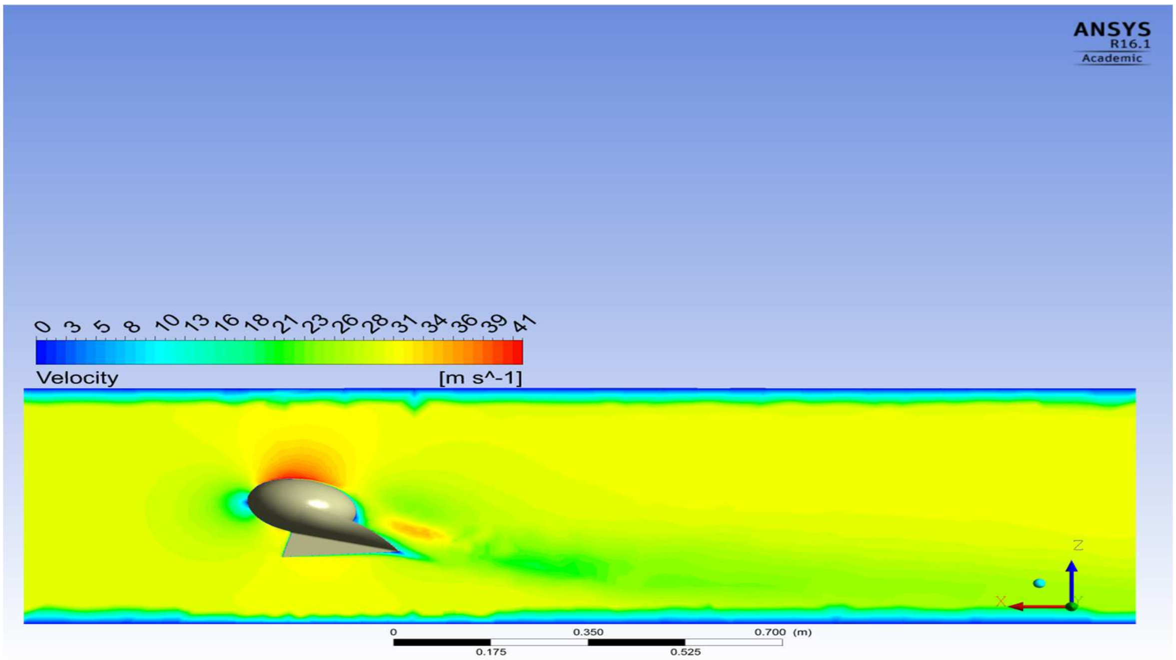


Figure 8: Wind velocity distribution around aerostat in wind-tunnel model

4 Material tests

The rotor at high-altitude is exposed to complex loading histories combining cyclic thermal/humidity and mechanical loading. Such loading patterns cause damage in the materials that lead to functional integrity problems (reduced rotor performance or turbine cutting out) or structural integrity problems like, for instance, the detachment of the blade's parts. The operational conditions of the rotor at high-altitudes require dealing with options for reliable materials under different loading and environmental effects. In this project, tests have been conducted on different material types.

Firstly the material has been investigated with optical microscopy Figure 9 and infrared spectroscopy Secondly, the dynamic behavior of the material has been measured by DMA analysis Figure 10 at different temperatures 20 ºC Figure 11 and -25 ºC Figure 12.

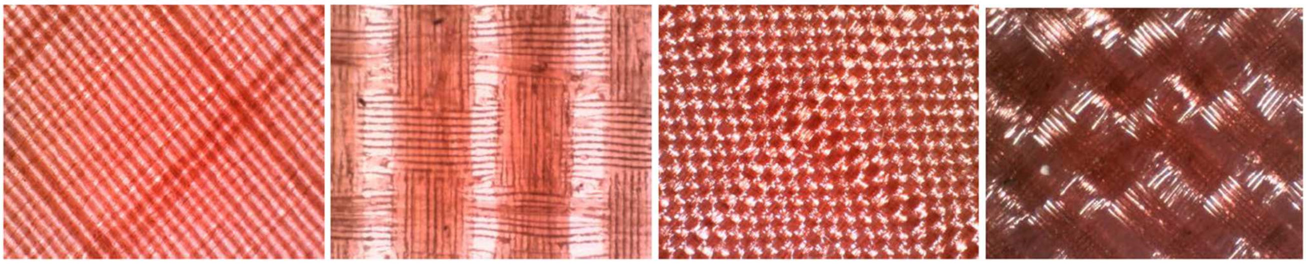


Figure 9: Optical microscopy investigation

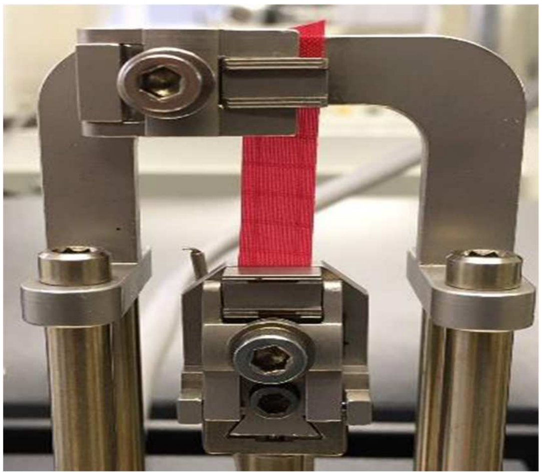


Figure 10: Foil clamp DMA Q800 TA Instruments, picture only for visualization

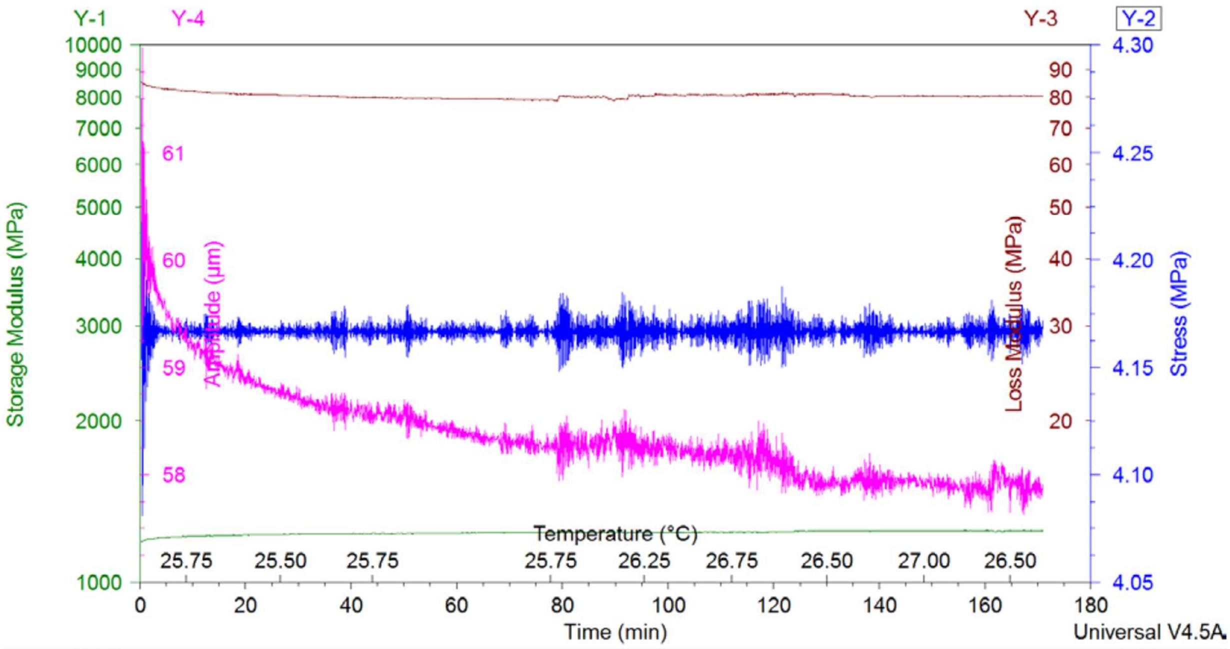


Figure 11: DMA tests at temperature of 20 ºC

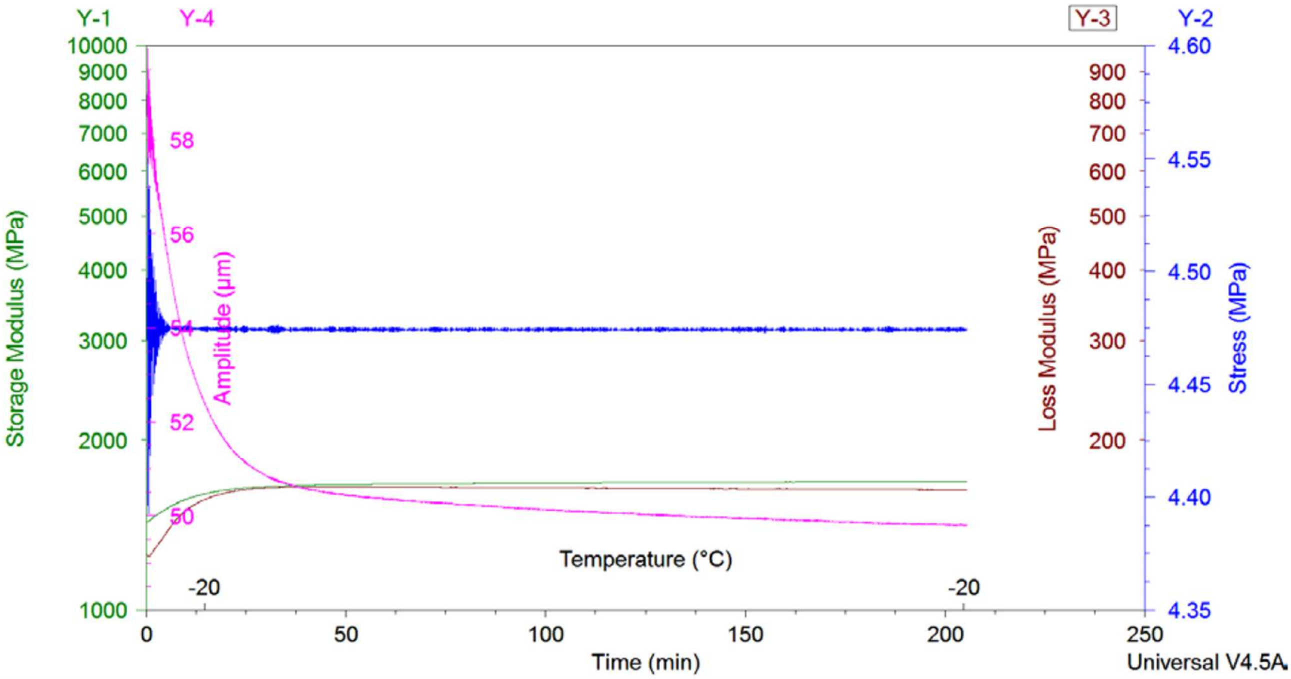


Figure 12: DMA tests at low temperature -25 ºC

According to the rotor operational specifications, the material should show a mechanical stability for 40 Million cycles at an average loading of around 400 N/m² (0.0004 MPa). The loading in the DMA test was around 10’000 times higher than expected under real conditions. Both tests are indicating that the material holds at least 1.1 x 10^6 cycles (120 Hz during 160 min) with a stress of slightly higher than 4 MPa.

A slow decrease of the amplitude is shown for both tests which indicates a slight stiffening or align-ment of the fabric material. This is also shown in a slight increase of the storage modulus. As ex-pected, storage and loss moduli are slightly higher at low temperature, but the differences are small. It is expected that tested materials could be candidates as material for the blade.