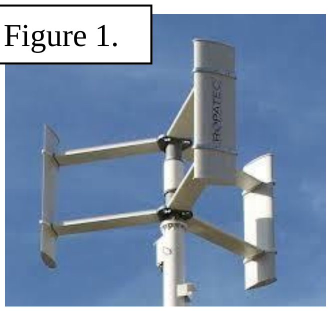
Submission via Blackboard. Deadline: Friday 28 March, 6 pm (Teaching week 9)

## Overview

Figure 1.



This coursework aims to simulate a vertical-axis wind turbine (VAWT): specifically an H-rotor design (Fig. 1). The cross-section is uniform, so, if end effects are ignored, the aerodynamic torque on the rotor can be investigated using a 2-d simulation.

The geometry is divided into 2 parts (Fig. 2): a stationary outer domain, with an interface to a rotating inner domain. The latter contains the rotor: a number of identical blades spaced equally around a circle, each with an unpitched symmetric NACA0021 aerofoil profile. In a simple model, support struts and central axis are not included.

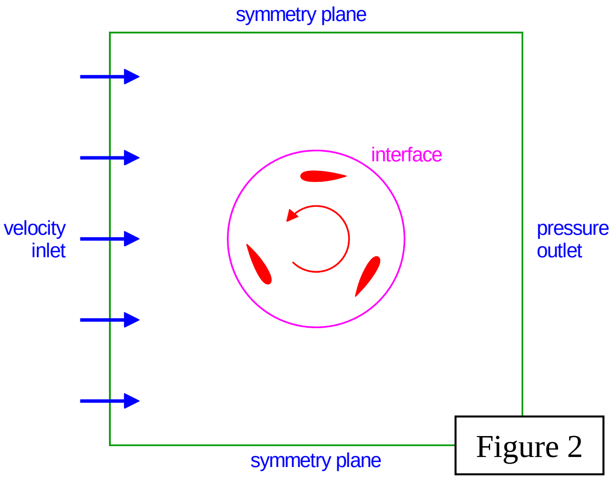



Figure 2

The following performance parameters are defined:

tip-speed ratio (tsr): $$\lambda = \frac{\Omega R}{U_0}$$

moment coefficient: $$C_M = \frac{M_z}{\frac{1}{2}\rho U_0^2 AR}$$

power coefficient: $$C_P = \frac{M_z \Omega}{\frac{1}{2}\rho U_0^3 A} = C_M \lambda$$

solidity: $$\sigma = \frac{n_b c}{D}$$

where $\Omega$ is the angular velocity of the rotor, $M_z$ is the axial moment or torque, $U_0$ is the onset wind speed, $A$ is the swept area normal to the onset wind, $R$ is the radius of the rotor (distance from axis to a blade), $c$ is aerofoil chord length and $n_b$ is the number of blades. In two dimensions the swept area per unit depth is $A = D$, where $D$ $(= 2R)$ is the diameter of the rotor.

The calculation will be performed in non-dimensional units, based on $D$, $U_0$ and $\rho_0$ as reference length, velocity and density. STAR-CCM+ does not recognize non-dimensional inputs, so you will have to make the following associations when entering data:

$$D \rightarrow 1\ \text{m}$$
$$U_0 \rightarrow 1\ \text{m s}^{-1}$$
$$\rho_0 \rightarrow 1\ \text{kg m}^{-3}$$
$$\mu \rightarrow \frac{1}{\text{Re}}$$

Set the last two values in `Continua > Physics > Models > Gas` sub-properties.

Simulations here should use $\text{Re} = 10^5$ (for which you will have to adjust the dynamic viscosity $\mu$) and tip speed ratios $\lambda = 3$ (for which you will have to set the angular velocity).

## Geometry – CAD

- Start the CAD module and import the NACA0021 aerofoil profile from file `NACA0021.csv`. Choose `3D Curves`, select the file, `Import as Polyline` (not the default Spline, which doesn't scale well).
- Extrude to form a 3-d body and rename all its faces as "Aerofoil-1".
- Scale this body by factor 0.08 to obtain a chord-diameter ratio of $c/D = 0.08$.
- Translate this aerofoil so that its aerodynamic centre (the ¼-chord position) is at $x = 0$, $y = R = 0.5D$. Angular position $\theta$ will be measured from here (Figure 3).
- Duplicate the aerofoil body $n_b - 1$ times, and rotate the duplicates about (0,0) by the requisite number of degrees to create a rotationally-symmetric $n_b$-bladed rotor. Rename all the faces of the duplicated bodies "Aerofoil-2".
- Create a cylindrical body of radius $0.75D$ and subtract the aerofoils to form the rotating inner domain. (Note that the earlier scaling of the aerofoil will affect its extrusion distance). Name any remaining boundaries.
- Create an outer square domain centred at (0,0) and with side lengths $10D$. Extrude this to form a 3-d body.
- Subtract the rotor from the outside block, <u>retaining</u> the inner part. After deleting any unnecessary body parts you should be left with (i) an outer stationary block and (ii) an inner cylindrical part containing the rotor.
- Name all boundaries. It is useful to give inner and outer interfaces the same name.

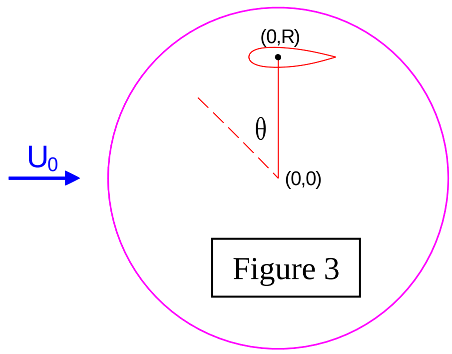


Figure 3

## Mesh

- Convert the CAD model to geometric parts. It should pick up separate inner and outer.
- Select both geometric parts simultaneously and assign to regions. Ensure that you have one region for each part and individual named surfaces remain separate. An internal interface connecting the resulting two regions should appear automatically.
- Set boundary types for region boundaries (Fig. 2). Top and bottom are irrelevant. Make both sides of the interface anything other than a wall to prevent prism layers there.
- `Geometry > Operations > New > Mesh > Badge for 2D Meshing`, applying to both parts, so that any 2-d mesh will be created on the $z = 0$ plane.
- `Geometry > Operations > New > Mesh > Automated Mesh (2D)`, applying to both parts:
  - select models: `Quadrilateral Mesher` and `Prism Layer Mesher`
  - default controls: `Base Size` $0.1D$, `Surface Growth Rate` 1.05, `Prism Layer Total Thickness` 4% of base; `Number of Prism Layers` 15; `Prism Layer Stretching` 1.2;
  - a `Volumetric Control`, comprising inner part: `Custom Size` 10% of base;
  - a `Surface Control` comprising all aerofoils: `Target Surface Size` 1% of base, `Minimum Surface Size` 0.1% of base.

## Equations and Boundary Conditions

For this coursework uncheck the "`Auto-select`" box and use the following model physics:

- Two Dimensional;
- Implicit Unsteady;
- Gas;
- Coupled Flow;
- Constant Density;
- Turbulent / Reynolds-Averaged Navier-Stokes (RANS) / K-Epsilon Turbulence;
- K-Epsilon Turbulence / Realizable K-Epsilon Two-Layer / Two-Layer All-y+ Wall …

- Set density and dynamic viscosity correctly for your non-dimensional variables.
- In `Continua – Physics 1 – Initial Conditions` set velocity to [1,0].
- Check that the inflow boundary has turbulence intensity 0.01, turbulent viscosity ratio 10 and velocity magnitude $U_0$ fudged as $1 \text{ m s}^{-1}$, equivalent to dimensionless input.

## Rotation

- Under `Tools – Motions` create a new `Rotation`, and set its axis as the $z$ axis and its non-dimensional angular velocity for the desired tip speed ratio $\lambda$.
- Apply this `Motion` to the rotating inner region.
- Calculate the corresponding period of rotation $T$ and set the timestep $\Delta t = T/180$ in the `Solvers > Implicit Unsteady` properties. Also, change the temporal discretisation to 2nd-order.

## Reports

- Create a moment coefficient (+ monitor + plot) to output the moment coefficient for one blade ("Aerofoil-1"). Make sure that you set `Reference Radius`.
- Create a second moment coefficient (+ monitor) to output the coefficient for the whole rotor. Add this monitor as a second data series to the plot above.
- You may find it convenient to create some scenes for your final output at this stage.

## Stopping Criteria

- Disable `Maximum Steps`. Increase the `Maximum Inner Iterations` to 10 and set the `Maximum Physical Time` to that of 6 complete rotations.

## Run

- Set initial conditions (`Solution > Initialize Solution`)
- Run the simulation for 6 complete rotations. (This could take some time!) A steady oscillation in torque and a full wake should have built up by this time.

## **Main Submission** (One PDF file please)

For a three-bladed rotor, with tip-speed ratio $\lambda = 3$, provide plots of:

(1) Mesh
(2) Pressure coefficient
(3) Velocity magnitude
(4) Streamlines passing through the rotor.

**Your scenes should focus on the rotor, not the whole domain.** Use your judgement about what is important. You will be marked on common sense and quality, not number, of figures. You are expected to improve on default settings, particularly for colour scales and viewport.

Output the following line graphs, drawn either in STAR-CCM+ or other software.

(5) Streamwise-velocity profile 1D downstream the wake of the rotor.
(6) Moment coefficients (single-blade and whole-rotor on the same graph) against time.
(7) Power coefficient for one blade as a function of angle $\theta$ for one fully-developed cycle.

(8) Find the mean power coefficient for the whole rotor (3 blades; $\lambda = 3$) for one fully-developed cycle.

The following items are **deliberately more open**: you will be marked on the basis of **initiative and sound scientific analysis**, **not length**.

(9) Investigate (for tip-speed ratio $\lambda = 3$), the effect of having 2, 3 or 4 blades.
(10) Comment on the physical behaviour exhibited by your simulations and the implications for the design of a VAWT. Also suggest, beyond having different numbers of blades, other parametric investigations that could be carried out for a VAWT.

## **Secondary Submission** (Convert to a second PDF file please)

(11) The StarCCM+ Summary Report at the end of your computation for items 1-8.