Aerodynamic models

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The most commonly used model for calculating the loads and performance of wind turbines is the Blade Element Momentum model (BEM), since it is extremely fast compared to more advanced aerodynamic models, and thus well suited for optimisation and time true aeroelastic simulations. The text starts with the classical BEM method as described in (Glauert, 1935) and continues with an extended BEM including various engineering models to enable simulations in the time domain.

Classical BEM

The classical BEM model from (Glauert, 1935) is an extension of the momentum theory in the sense that global wake is divided into a number of strips and that the loads affecting the strips are found from considering the flow locally at the blade at the radial position of the strip. Each strip has an infinitesimal height of, *dr*, and is positioned at a radial distance from the rotational axis, *r*, as shown in Figure 1.

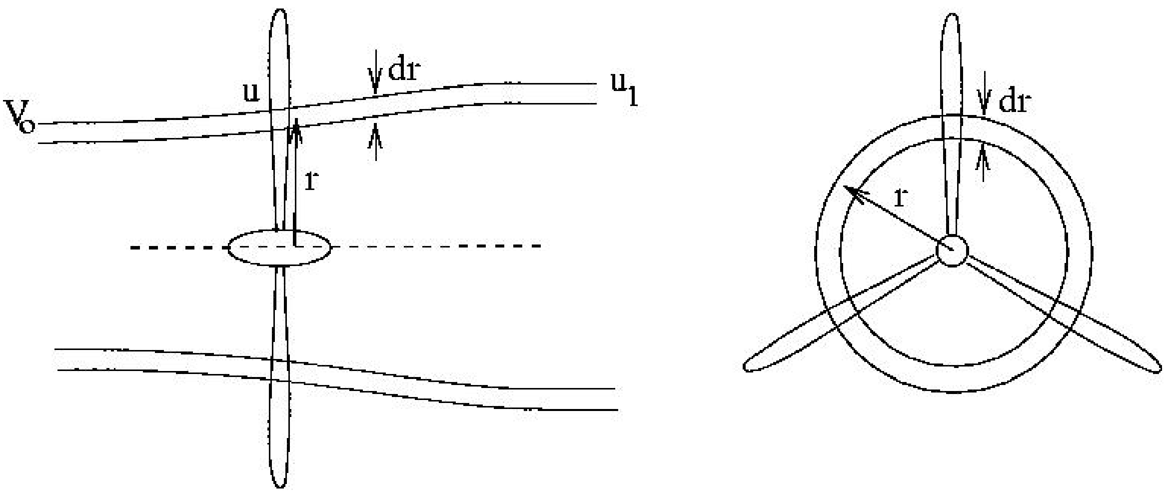

Figure 1: A strip at radial position, r, and with thickness, dr, as applied in the BEM method

It is assumed that a strip is independent of the other strips and that the net pressure force in the flow direction on the lateral side of the strip is zero. And since the pressure far up- and downstream is the ambient pressure there is no pressure force on the strip. The velocity entering the strip is the undisturbed wind speed, V_o, the velocity in the wake is denoted, u_1, and u is the velocity at the rotor plane, and is often given by the axial induction factor a:

$$u = (1 - a)V_o \qquad (1)$$

Further the tangential velocity in the wake is defined through the tangential induction factor as:

$$C_\theta = 2a'\omega r \qquad (2)$$

and the result from 1-D momentum theory is applied:

$$u_1 = (1 - 2a)V_o \qquad (3)$$

The linear and angular momentum equations for the control volume comprised by the strip are:

$$dT = (V_o - u_1)d\dot{m} = \rho u 2\pi r dr (V_o - u_1) = 4\rho\pi r V_o^2 a(1 - a)dr \qquad (4)$$

and

$$dM = rC_\theta d\dot{m} = r2a'\omega r \rho u 2\pi r dr = 4\pi r^3 \omega V_o a'(1 - a)dr \qquad (5)$$

where *dT* and *dM* are the thrust force and torque acting from the blades on the control volume, and these can be estimated from the local flow around the blades and using 2-D airfoil data as:

$$dT = Bp_N dr = B(L\cos\phi + D\sin\phi)dr \qquad (6)$$

$$dM = Brp_T dr = Br(L\sin\phi - D\cos\phi)dr \qquad (7)$$

p_N and p_T denote the normal and tangential load [N/m] for one blade and is found by projecting the lift and drag to a direction normal and tangential to the rotor plane, respectively, see Figure 2 and *B* is the number of blades. ϕ denotes the flow angle and is the angle between the rotor plane and the relative velocity and can be estimated geometrically from Figure 2 as: