Aerodynamic modeling of floating vertical axis wind turbines using the actuator cylinder flow method

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MARE-WINT new MAterials and REliability in offshore WINd Turbines technology

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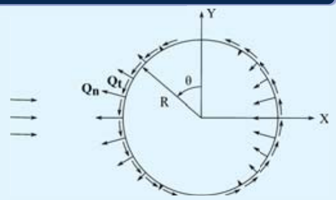
Abstract

Among the aerodynamic models of VAWTs, double multi-streamtube (DMST) and actuator cylinder (AC) models are two favorable methods for fully coupled modeling and dynamic analysis of floating VAWTs in view of accuracy and computational cost. This paper deals with the development of an aerodynamic code to model floating VAWTs using the AC method developed by Madsen (1982). It includes the tangential load term when calculating induced velocities, addresses two different approaches to calculate the normal and tangential loads acting on the rotor, and proposes a new modified linear solution to correct the linear solution. The effect of dynamic stall is also considered using the Beddoes-Leishman dynamic stall model. The developed code is verified to be accurate by a series of comparisons against other numerical models and experimental results. It is found that the effect of including the tangential load term when calculating induced velocities on the aerodynamic loads is very small. The proposed new modified linear solution can improve the power performance compared with the experiment data. Finally, a comparison of the developed AC method and the DMST method is performed and shows that the AC method can predict more accurate aerodynamic loads and power than the DMST method.

Actuator cylinder (AC) flow model

Considering a 2D quasi-static flow problem, the induced velocities are related to the volume force as well as the normal and tangential loads Qn and Qt, based on the continuity equation and Euler equation.

The final induced velocities can be divided into a linear part and a non-linear part.



Linear solution

$$w_x = -\frac{1}{2}\int_0^{2\pi} Q_n(\theta)\frac{-(x+\sin\theta)\sin\theta+(y-\cos\theta)\cos\theta}{(x+\sin\theta)^2+(y-\cos\theta)^2}d\theta - \frac{1}{2}\int_0^{2\pi} Q_t(\theta)\frac{-(x+\sin\theta)\cos\theta-(y-\cos\theta)\sin\theta}{(x+\sin\theta)^2+(y-\cos\theta)^2}d\theta$$

$$-\left(Q_n(\arccos y)\right)^{*}+\left(Q_n(-\arccos y)\right)^{**}-\left(Q_t(\arccos y)\frac{y}{\sqrt{1-y^2}}\right)^{*}-\left(Q_t(-\arccos y)\frac{y}{\sqrt{1-y^2}}\right)^{**}$$

$$w_y = -\frac{1}{2}\int_0^{2\pi} Q_n(\theta)\frac{-(x+\sin\theta)\cos\theta-(y-\cos\theta)\sin\theta}{(x+\sin\theta)^2+(y-\cos\theta)^2}d\theta - \frac{1}{2}\int_0^{2\pi} Q_t(\theta)\frac{(x+\sin\theta)\sin\theta-(y-\cos\theta)\cos\theta}{(x+\sin\theta)^2+(y-\cos\theta)^2}d\theta$$

Modified linear solution

It's relatively time-consuming to compute the nonlinear solution directly. A correction can be applied by multiplying the velocities from the linear solution with factor

$$k_a = \frac{1}{1-a} \quad \text{(Madsen et al., 2013)}$$

$$k_a = \begin{cases} \dfrac{1}{1-a}, & (a \le 0.15) \\ \dfrac{1}{1-a}\left(0.65+0.35e^{-4.5(a-0.15)}\right), & (a > 0.15) \end{cases} \quad \text{(Present)}$$

Aerodynamic modeling of a floating VAWT

Aerodynamic loads on a 2D VAWT

Approach I

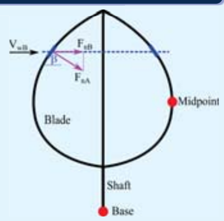
$$Q_t = \frac{BF_{tB}}{2\pi R\rho V_{wB}^2}$$

$$Q_n = \frac{BF_{nB}}{2\pi R\rho V_{wB}^2}$$

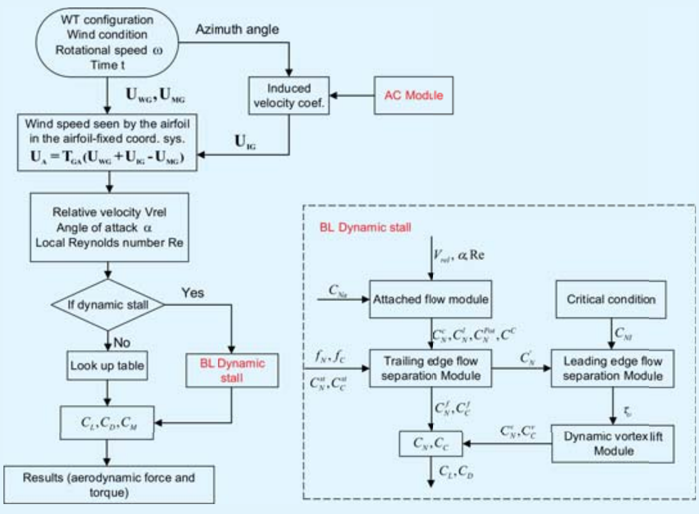
Approach II

$$Q_t = \frac{BF_{tA}}{2\pi R\rho V_{wB}^2 \sin\beta}$$

$$Q_n = \frac{BF_{nA}}{2\pi R\rho V_{wB}^2 \sin\beta}$$



Aerodynamic modeling of a floating VAWT



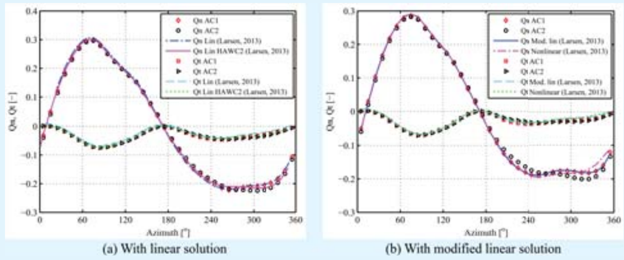
Flow chart of aerodynamic modeling of a floating VAWT using the AC method

Verifications and discussions

The developed AC code can be categorized into AC1, AC2, AC3 and AC4.

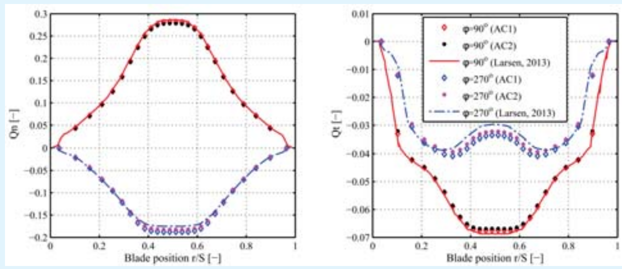
	Approach for Qn and Qt	Qt term in linear solutions	Modified linear solution
AC1	I	Neglected	Madsen et al., 2013
AC2	I	Included	Madsen et al., 2013
AC3	II	Included	Madsen et al., 2013
AC4	II	Included	Present

Verification of AC1 and AC2



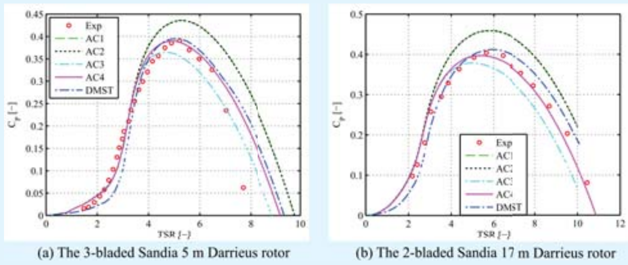
(a) With linear solution (b) With modified linear solution

Distribution of Qn and Qt at midpoint of the blade at different azimuth angle



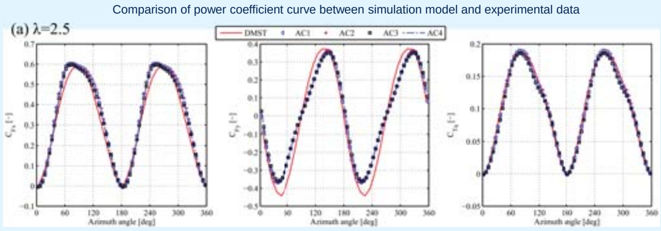
Distribution of Qn and Qt along the blade at azimuth angle of 90 and 270.

Verification of AC3 and AC4 & Comparison of AC and DMST methods



(a) The 3-bladed Sandia 5 m Darrieus rotor (b) The 2-bladed Sandia 17 m Darrieus rotor

Comparison of power coefficient curve between simulation model and experimental data



Coefficients of thrust, side force and torque for the Sandia 17 m Darrieus rotor as a function of the azimuth angle

Conclusions

- The effect of tangential load on the aerodynamic loads when calculating the induced velocities is found to be relatively very small.
- Calculating the normal and tangential loads using approach II which considers more physical phenomena predicts better aerodynamic loads than approach I.
- The modified linear solution proposed in this study gives prediction of good aerodynamic power compared with experimental data.
- The developed code AC4 can predict more accurate aerodynamic power and aerodynamic loads than the DMST method.
- This AC code can be integrated with the computer codes SIMO-RIFLEX to form a fully coupled simulation tool, i.e. SIMO-RIFLEX-AC (Cheng et al., 2016), which is capable of performing the aero-hydro-servo-elastic time-domain analysis for onshore bottom-fixed or floating VAWTs.

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