The Aero-elastic-wake Coupling Behavior for a Two-wind-turbines Case with Power Control Process

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Abstract. This study focuses on the aero-elastic-wake coupling behavior of wind turbines. A newly developed code called FALM (Flexible Actuator Line Model), which combines the wake simulation ability of the actuator line method (ALM) and the structural simulation ability of the flexible multibody dynamics method, was employed to achieve these simulations. The power output and thrust, the natural frequency and deformation and the wake characteristics of a single NREL 5MW wind turbine were studied to validate this code. It shows that nonlinear effects such as spin softening and stress stiffening were fully considered by FALM and it can also guarantee a reliable prediction of power and thrust of wind turbines. Furthermore, a case of two-wind-turbines with the inlet wind speed of 14m/s (exceeding the rated wind speed) were carried out to study the aero-elastic-wake coupling behavior in a wind farm. It shows that FALM is able to simulate multiple wind turbines with power control system involved. The pitch control process of the upstream wind turbine was predicted and the dynamic loads of the downstream wind turbine caused by the wake effect were studied. These results will contribute to the study of reducing the fatigue load caused by wake effect.

Key words: Actuator line method; flexible multibody dynamics; aero-elastic-wake coupling behavior; wind turbine simulation

1. Introduction
With the development of wind industry, wind turbines are heading to larger scale and offshore. A conceptual 5MW wind turbine with rotor diameter of 126m was published by NREL in 2009[1] and the diameter of the largest wind turbine nowadays, which is built by Vestas with rated power of 9.5MW, has reached 164m. However, larger wind turbines are more unsteady and more susceptible to large wind loads and large deflections. The wake effect is also important since it will dramatically affect the power output and the structural load of the downstream wind turbines in a wind farm[2]. As the main reference in the design phase, wind turbine simulation tools are facing new challenges.

Blade element momentum (BEM) theory is the most widely used method in wind turbine analysis for its low computational cost and its accuracy in power prediction. However, BEM theory can hardly simulate wake characteristics of wind turbines. Actuator line method (ALM) was proposed in 2002 by Sørensen and Shen[3] to overcome this disadvantage of BEM. By combining the computational fluids dynamics and the blade element theory, ALM can simulate the power and wake characteristics of wind turbines simultaneously. Nowadays this method has become the most potential method in wind farm simulation due to its wake simulation ability and low computational cost.
The wind turbine structure is a typical flexible multi-body system, which is composed of blades, nacelle and tower. The deformation of wind turbines is significant due to the slender structure of blades and tower. Furthermore, the coupling behavior of the rigid motion and the deformation is significant due to the wind turbine rotation. In this study, flexible multibody dynamics was chosen as the structural analysis method, because of its accuracy in the motion-deformation coupling analysis[4].

In this paper, a new method called FALM (Flexible Actuator Line Method) based on ALM and flexible multibody dynamics was developed to study the aero-elastic-wake coupling behavior of wind turbines. Simulations of a NREL 5MW wind turbine with uniform inlet of 8m/s and 14m/s were carried out to validate this new method. The two-wind-turbines case with atmospheric boundary layer (ABL) inlet of 14m/s (which is over the rated wind speed) was studied. The power control process was considered to simulate the real dynamic response of the downstream wind turbine.

2. Approach

The FALM introduced in this paper is mainly composed of two parts: the aerodynamic part which is based on the actuator line method, and the structural part which is based on the flexible multibody dynamics. Figure 1 shows the diagram of the FALM approach. The details of the realization of FALM will be introduced in this section.

\begin{equation}
\frac{\partial \rho \pi_i}{\partial x_i} = 0
\end{equation}

\begin{equation}
\rho \frac{\partial \pi_i}{\partial t} + \rho \frac{\partial (\pi_i \pi_j)}{\partial x_j} = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial \pi_i}{\partial x_j} + \frac{\partial \pi_j}{\partial x_i} \right) \right] + \frac{\partial r_{ij}}{\partial x_j} + f
\end{equation}

Figure 1. The diagram of the FALM approach.

2.1. Actuator line method

The actuator line method is a computational fluid dynamics (CFD) based approach. Regardless of the resolved shape, actuator line method represents wind turbine blades by source term. The governing equations used in FALM is shown as Eq. (1) and Eq. (2)
where $\bar{u}$ is the filtered velocity vector field, $p$ is the scalar field of pressure, $\mu$ is a scalar represent the kinematic viscosity, $\tau_{ij}^s = -\rho(\bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j)$ is called the subgrid-scale (SGS) Reynolds stress, and the standard Smagorinsky SGS model is employed in this study.

$f$ is the source term which represents the wind turbine blade in ALM and it can be calculated based on the blade element theory, as shown in Eq. (3). Here, $v$, $c$ and $L$ are the inlet velocity, chord length and element length, respectively, of each blade element, $C_l$ and $C_d$ are the lift and drag coefficient of the airfoil and $\rho$ is the air density.

$$f_{\text{element}} = (dL, dD) = \left( \frac{1}{2} \rho v^2 c C_l L, \frac{1}{2} \rho v^2 c C_d L \right)$$

(3)

The forces calculated by Eq. (3) are point forces and a regularization kernel must be employed to avoid a numerical singular, as shown Eq. (4) and Eq. (5). Here, $\epsilon$ is Gaussian width which adjusts the strength of this regularization kernel.

$$f = \sum f_{\text{element}} \otimes \eta_{\epsilon}$$

(4)

$$\eta_{\epsilon} = \frac{1}{\epsilon \pi^{3/2}} e^{-\left(\frac{r_{\epsilon}}{\epsilon}\right)^2}$$

(5)

2.2. Flexible multibody dynamics

In this study, flexible multibody dynamics method with floating frame of reference formulation were employed as the structural model. The position of a point in the flexible body is represented by eq.(6)

$$\mathbf{P} = \mathbf{r} + \mathbf{A} (\mathbf{u}_0 + \mathbf{S} \mathbf{q})$$

(6)

Where $\mathbf{r}$ is the vector from the origin of the inertial frame to the floating frame, $\mathbf{A}$ is the transformation matrix from the floating frame to inertial frame, $\mathbf{u}_0$ is the initial position before the deformation, $\mathbf{S}$ is the shape function and $\mathbf{q}$ is the node deformation.

Therefore, the kinetic energy and potential energy could be calculated using Eq. (6) and the motion of the multibody system could be depicted according to the Hamilton’s theory, shown as Eq. (7). The details of the derivation could be found in Shabana’s book[5].

$$\begin{bmatrix} I & -\mathbf{A} \mathbf{\dot{u}} G \\ -G^T \mathbf{\ddot{u}}^T \mathbf{\ddot{u}} G & \mathbf{A} \mathbf{S} \\ \mathbf{sym} & \mathbf{S}^T \mathbf{S} \end{bmatrix} \begin{bmatrix} \mathbf{\ddot{r}} \\ \mathbf{\ddot{\theta}} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & K_s + K_o \end{bmatrix} \begin{bmatrix} \mathbf{r} \\ \mathbf{q} \end{bmatrix} + C_0^T \lambda = Q_e + Q_v$$

(7)

Here, $K_{ff}$ is the stiffness matrix, $Q_e$ and $Q_v$ are generalized external forces and quadratic velocity vector, respectively. $C$ represents the constraint of the multibody system and $C_0$ is the Jacobian matrix of constraint equations.

$K_s$ is the stress stiffening term and it must be taken into consideration because it will significantly affect the natural frequency of the wind turbine structure[6]. This increment of stiffness is related to the tightening stress which is mainly caused by the centrifugal force of the blade rotation in wind turbine analysis.

2.3. Wind turbine model and control system

The power control system of NREL 5MW wind turbine was modeled in FALM. This control system is composed of three main parts: the low-pass filter, the generator controller, and the pitch controller. The control process of NREL 5MW wind turbine is as follow:

(1) Read the generator speed and apply a low-pass filter to obtain the input value for controllers.

(2) If the input is lower than the rated speed, enable the generator controller to control the generator torque.

(3) If the input is higher than the rated speed, enable the generator-torque controller and the blade-pitch controller to control the generator torque and the pitch angle, respectively.
All the parameters used in the control system is derived according to the definition of NREL 5MW [1].

3. Results

3.1. Validation

Table 1 compared the aerodynamic performance of a NREL 5MW wind turbine predicted by FALM and previous studies. In this study, two typical inlet velocity, 8m/s and 14m/s, were chosen. It shows that the rotor power calculated by FALM agrees well with previous studies. The rotor thrust calculated by FAST is obviously higher but results of other studies including FALM agrees well with each other. In summary, FALM provides reliable simulations of the aerodynamic performance of NREL 5MW wind turbine.

Table 1. Contrast of power and thrust results between previous results and FALM

| Inlet velocity | FAST[1] | HAWC2 | Li[7] | Jeong[8] | Ponta[9] | FALM |
|---------------|---------|-------|-------|----------|----------|------|
| 8m/s          | Power(MW) 1.856 | 1.928 | 1.865 | 2.242    | 1.817    | 1.840 |
|               | Thrust(kN) 466   | 391   | 389   | 410      | 340      | 388  |
| 14m/s         | Power(MW) 5.296  | No data | No data | 5.249     | 5.088    | 5.259 |
|               | Thrust(kN) 541   | No data | No data | 433      | 408      | 491  |

Table 2. compared the simulation results of tip deflections. Oopdefl represents the out of plane deflection and IPDefl represents the in-plane deflection. The deflection result of FALM with and without nonlinear effect are both listed to make a fully comparison. It’s clear that the simulation results of FALM agree with FAST and Li’s result when the nonlinear effect are neglected and agree with Yu’s study, which also simulated the nonlinear effect of wind turbine blade, when the nonlinear effect are involved. It could be concluded that FALM provides reliable simulations of the wind turbine deflection.

Table 2. Contrast of tip deflection results between previous results and FALM

| Inlet velocity(m/s) | FAST[1] | Li[7] | Yu[10] | FALM linear | FALM nonlinear |
|---------------------|---------|-------|--------|-------------|---------------|
| OoPDefl(m)          | 3.22    | 3.592 | 2.958  | 3.637       | 2.938         |
| IPDefl(m)           | -0.350  | -0.345| No data| -0.257      | -0.255        |
| 8                   |         |       |        |             |               |
| OoPDefl(m)          | 3.10    | No data| 3.195  | 4.275       | 3.01          |
| IPDefl(m)           | -0.739  | No data| No data| -0.793      | -0.696        |
| 14                  |         |       |        |             |               |

Figure 2. shows the results of natural frequency vs. rotating speed of the wind turbine rotor. It should be noticed that the difference of the natural frequency of two 2nd flapwise waving mode is calculated by FALM and this agrees with the results of ADAMS when rotating speed is zero. It’s clear that FALM provides a better simulation than FAST of this frequency difference. Furthermore, the nonlinear effect such as the spin softening and stress stiffening is fully considered by FALM. The natural frequency calculated by FALM varies with the rotating speed because of the nonlinear effects. The stress stiffening mainly affects the flapwise mode and there is a dramatic increment of the natural frequency when the rotating speed goes up. However, the natural frequency of rotor torsion and tower waving mode will decrease when the rotating speed goes up. It’s clear that neglecting of the nonlinear
effect will cause a big simulation error for a rotating wind turbine and FALM is suitable for these simulations.

![Image](image_url)

**Figure 2.** The natural frequency vs. rotating speed of the wind turbine rotor calculated by FAST, ADAMS and FALM. Results of the first 10 modes were plotted.

### 3.2. Two-wind-turbines study

A two-wind-turbines case were studied using FALM. Figure 3 shows the calculation domain of the simulation. D represents the diameter of the NREL 5MW wind turbine, which is 126m. the gap between the upstream wind turbine and the downstream wind turbine is 6D. The inlet wind speed is 14m/s which is over the rated wind speed of NREL 5MW. The atmospheric boundary layer (ABL) inlet condition and the power control process were considered to simulate the real dynamic responses of the downstream wind turbine. The results (Figure 4) showed that:

1. The pitch angle of the downstream wind turbine will drop and reach zero with oscillation. This is caused by the power control process and the pitch motion will also cause an oscillation to the aerodynamic power and blade tip deflection.

2. The rotor thrust of the downstream wind turbine is much higher than the upstream wind turbine because the pitch angle not only reduces the rotor power but also reduces the rotor thrust.

3. The rotor power of the downstream wind turbine is significantly lower than the Jensen model’s prediction, which is a widely used wake model of wind turbines. This is mainly caused by the difference of velocity distribution between the FALM simulation and the Jensen model.

4. The atmospheric boundary layer (ABL) inlet will cause an oscillation on the tip deflection of wind turbines. However, this unbalance of blade tip deflection caused by ABL inlet are receded due to the velocity recovery in the wake region of the upstream wind turbine.
Figure 3. Calculation domain of the two-wind-turbines simulation

![Calculation Domain](image)

Figure 4. The simulations results for the upstream wind turbine and the downstream wind turbine. (a) the pitch angle, (b) the rotor thrust (c) the generator power (d) the tip deflection

The velocity distribution (as shown in Figure 5.) and vorticity distribution (as shown in Figure 6.) along the wind direction are extracted. As shown in Figure 5., the x axis represents the Longitude coordinate behind the upstream wind turbine and a grid in x axis also represent the inlet velocity of 14m/s. The dash line represents the velocity distribution of ABL inlet condition and the solid lines represent the velocity distribution in the wake region. Therefore, the difference between the solid lines and the dash line represents the wake effect (loss of velocity) of the wind turbine. As shown in Figure 6., the dash line represents the vorticity distribution of ABL inlet condition and the solid lines represent the vorticity distribution in the wake region.
The wake results showed that:
1. The loss of velocity is mainly caused by wind turbine blades and the vorticity is mainly caused by the tip and the root of wind turbine blades. The wake effect in upper wake region is higher than the lower region.
2. The velocity of the wake region of the downstream wind turbine is much lower than the upstream one and the vorticity of the downstream wind turbine is much higher than the upstream one.
3. The wake region of the downstream wind turbine is larger than the upstream one and the velocity recovery is better.

4. Conclusion
In this paper, a new validated simulation method for the aero-elastic-wake coupling behavior of wind turbine was developed and a two-wind-turbines case with power control process and over-rated inlet were studied. The conclusion is as followed:
1. The FALM method is validated by the results of the uniform inlet of 8m/s and 14m/s. The rotor power, rotor thrust, tip deflection and natural frequency result calculated by FALM agrees well with previous studies.
2. The wake of the upstream wind turbine and pitch motion will apply an oscillation to the aerodynamic and structural performances of the downstream wind turbine.

3. The wake region of the downstream wind turbine is larger than the upstream one, with lower velocity, high vorticity and better velocity recovery.

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