Unsteady aerodynamics of attached flow for a floating wind turbine

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The dynamic response of a wind turbine is influenced by the aerodynamic loads, which are normally evaluated using the beam element momentum (BEM) method. This is an approach based on steady state conditions, and the unsteady aerodynamics are normally included by a semi-empirical model, e.g. Beddoes-Leishman method. The term unsteady aerodynamics is often used to describe dynamic stall, but the term also includes the unsteady conditions during attached flow. This study will focus on the unsteady aerodynamics during attached flow that occurs during normal operation of an offshore floating wind turbine.

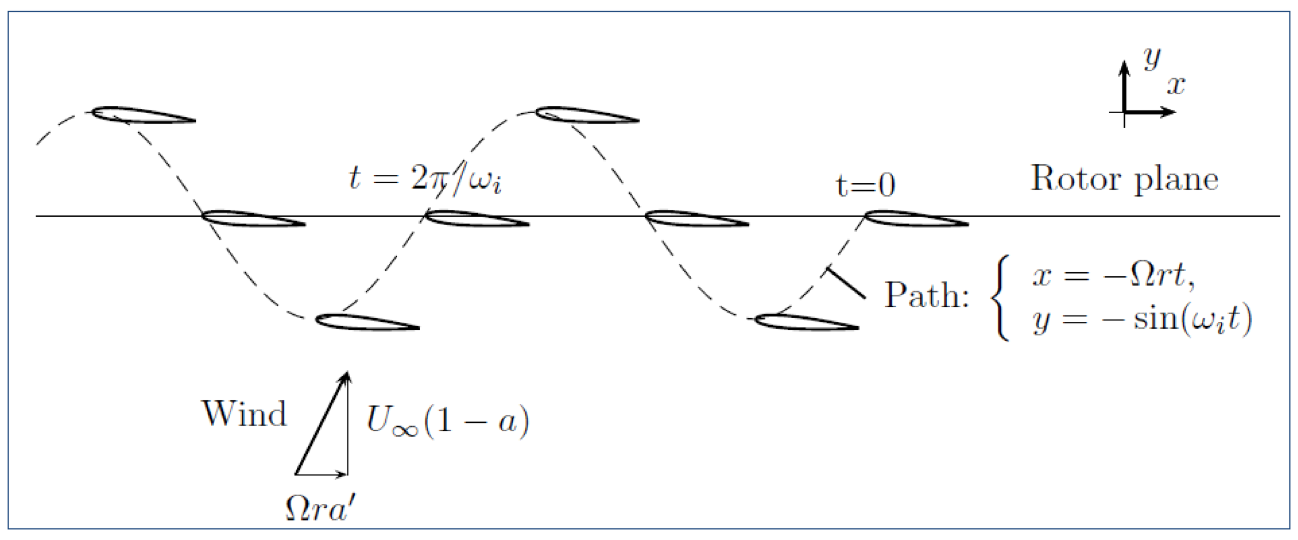

Figure 1: The oscillating path of a rotor blade.

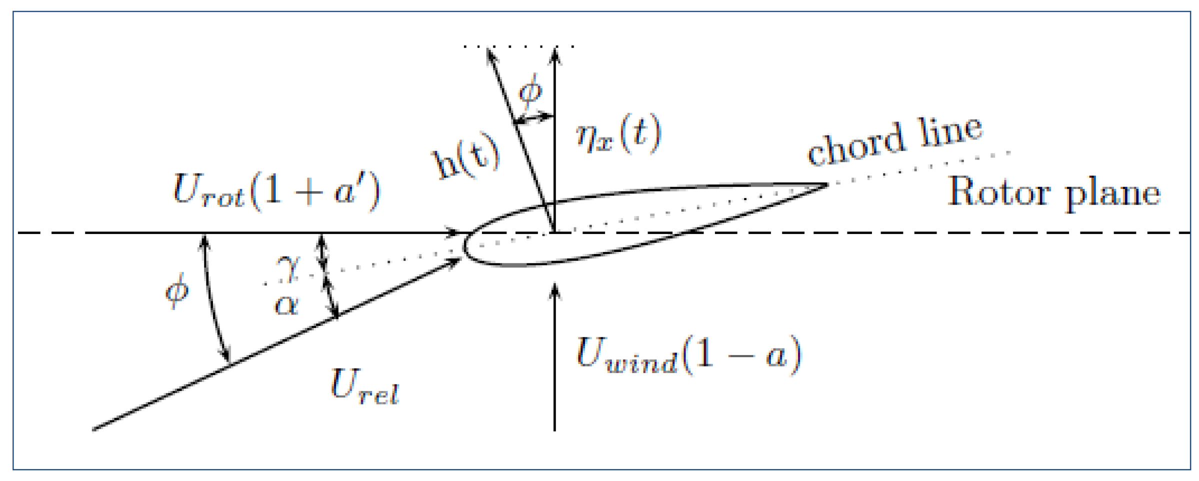

Figure 2: Angles and velocities relative to the airfoil and rotor plane

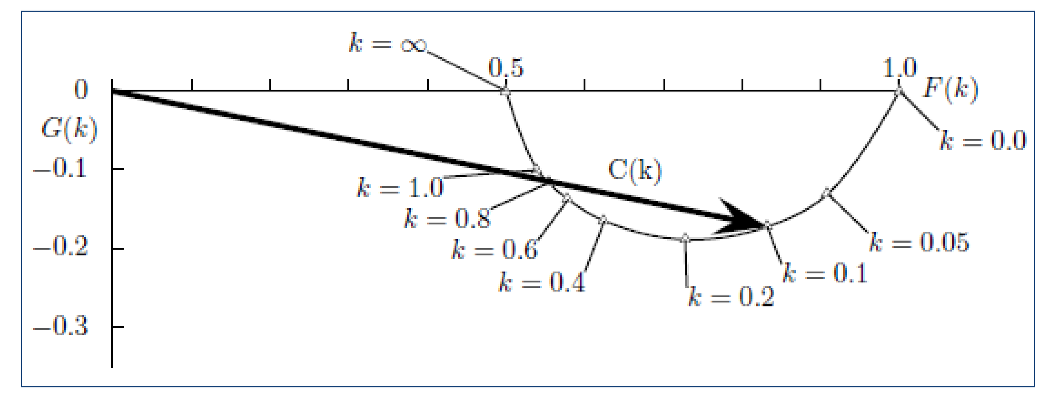

Figure 3: The imaginary and real part of the Theodorsen function.

Introduction

A floating wind turbine may have very long eigen-periods for the surge and pitch motions. These motions in the axial direction of the rotor are dominated by quasi-steady aerodynamics. However, the eigen-frequency of the first bending tower mode is significantly higher and similar to that of a fixed onshore wind turbine. Thus the unsteady aerodynamic effects may be important. Theodorsen derived the unsteady aerodynamic forces in frequency domain for a flat plate in 1925. The corresponding time-domain formulations have been adopted for wind turbine applications and are implemented in today's aero-elastic wind turbine codes. In the present work, the effect of the unsteady aerodynamics during attached flow conditions is evaluated in the context of the aerodynamic damping for an offshore floating wind turbine.

Method

The aerodynamic damping for a floating offshore wind turbine rotor oscillating in the axial direction is estimated using Theodorsen's solution and a vortex panel code. Theodorsen solution for the thin airfoil is formulated analytically in the frequency domain, and is computaionally efficient. On the other hand, the vortex panel method van be used to simulate flow around an arbitary shaped airfoil. They are both based on potential flow theory, and are limited to attached flow condition. The wind turbine studied is the OC3-Hywind wind turbine and the main properties are shown in Table 2. Details regarding distributed aerodynamic properties of the blade can be found in ref [1].

The unsteadiness is measured using the reduced frequency, k. This is defined as $k = \omega c/2U_{rel}$, where ω is the rotational frequency, c is the chord length and U_{rel} is the relative wind speed, see Figure 2. In Figure 4, k along the blade for three different wind velocities is shown. According to [3] the flow can be assumed steady when k<0.01. For increasing values of k, the unsteadiness of the aerodynamics is increasing.

In Figure 1, the circular path of a rotor blade segment is unfolded into a straight line and the rotor oscillations in the axial direction are represented as departures from the mean rotor plane. The damping coefficient is extracted from the resulting thrust load in phase with the axial velocity of the nacelle. In this study, the rotor is assumed rigid, and the velocity of the nacelle is therefore equal to the velocity of the airfoil in axial direction.

The panel vortex code is a time-domain method. Constant strength panel elements are used to model the flow. At the surface of the airfoil both sources and doublets are used, and in the wake, only doublets are applied. The track of doublets in the wake is a part of the solution. The airfoil is forced to move along the path shown in Figure 1.

Theodorsen function describes the lift as a function of the plunging motion in the frequency domain. The lift force is related to the thrust force of the wind turbine with the flow angle ϕ. The real part of the function is related to the mass or inertia, and the imaginary part is related to the damping:

$$T_{2d} = -[M_{a,2d}(i\omega)^2 + C_{a,2d}(i\omega) + K_{a,2d}]$$

In this presentation, only the damping is presented. The damping according to the Theodorsen function is:

$$C_{a,2d} = \rho c U_{rel} \pi F(k) cos^2\phi$$

Where U_{rel} is the relative wind (see Figure 2), ϕ is the flow angle (see Figure 2) and F(k) is the real part of the Theodorsen function illustrated in Figure 4. For steady state, k=1, F(k) is 1. The value decreases with increases reduced frequency.

Table 1: The oscillating path of a rotor blade.

Property	Angular frequency	Mass / inertial	Critical damping
Platform Pitch	0.21 rad/s	$5.8 * 10^{10}\ kg\ m^2$	$2.44 * 10^{10}$
1st elastic tower bending mode	2.95 rad/s	$3.9 * 10^5\ kg$	$2.31 * 10^6$

Table 2: Properties of OC-3 Hywind.

Property	Unit	Value
Rotor diameter	[m]	126
Nacelle mass	[Te]	240
Rotor mass	[Te]	110
Hub height	[m]	90

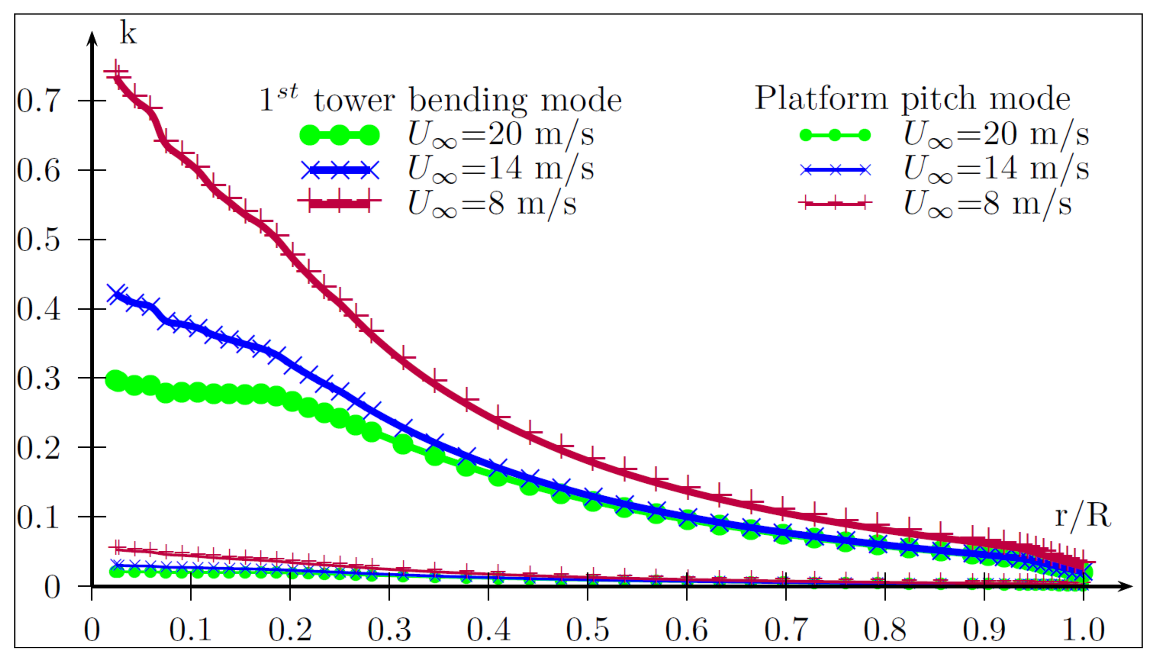

Figure 4: The reduced frequency relative to the radial position along the wind turbine blade.

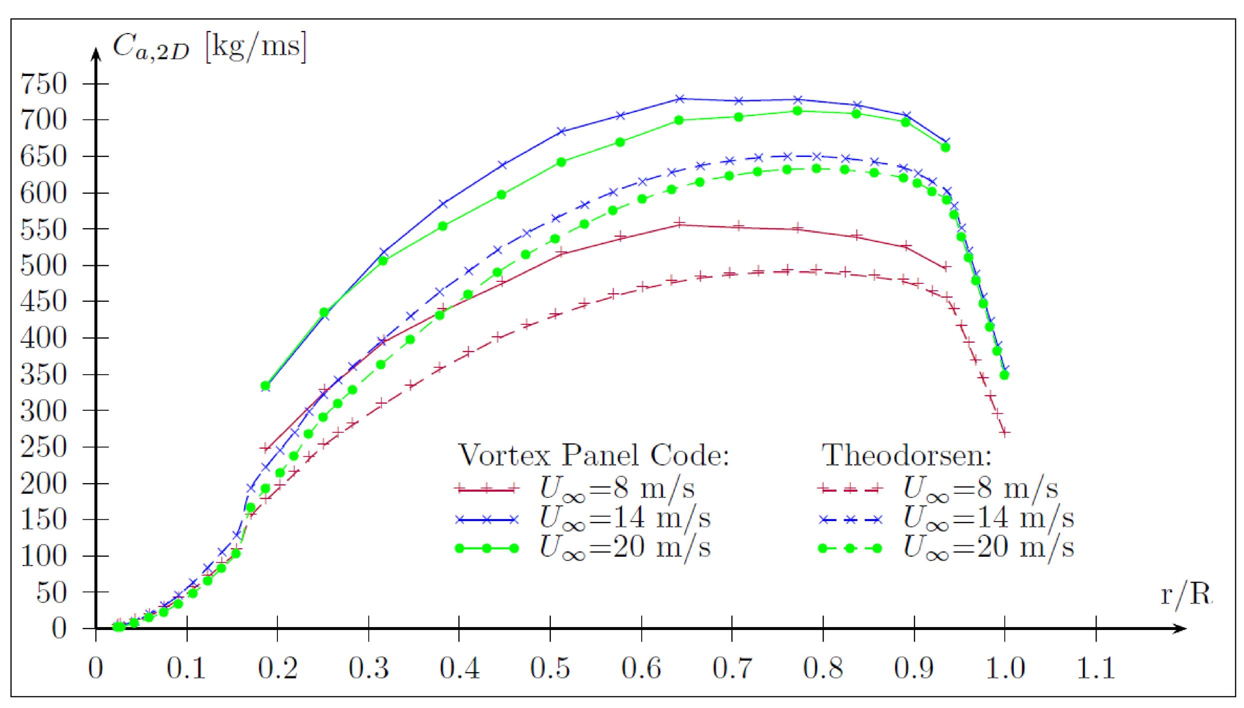

Figure 5: The local aerodynamic damping coefficient along the span of the blade for the platform pitch mode.

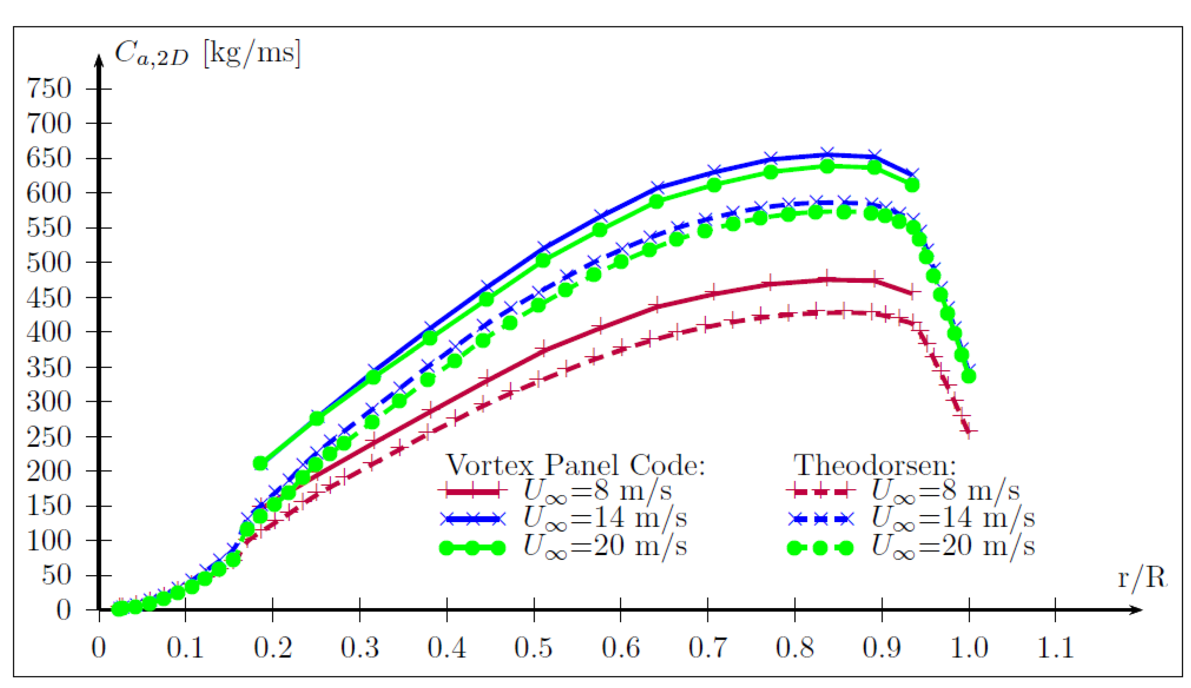

Figure 6: The local aerodynamic damping coefficient along the span of the blade for the 1st elastic tower bending mode.

Results

The local damping coefficients at the different blade sections for three different wind speeds are shown in Figure 5 and Figure 6. By summing up the damping coefficient along the blade and including the modal properties, the damping coefficient is estimated. For the platform pitch the top mass is multiplied by the squared distance to the water line, and the first is multiplied with the modal displacement. The ratio between the aerodynamic damping and the critical damping is the damping ratio, ξ. The results are listed in Table 3.

Discussion

The level of unsteadiness is measured using the reduced frequency, k, shown in Figure 4. The 1st tower mode is the most unsteady and the platform pitch has almost steady aerodynamic behaviour. The difference between the vortex panel method and the Theodorsen method, should only be related to the effect that the vortex panel code includes the thickness of the airfoil. This will have an influence on the slope of the lift curve, which is an important factor for steady aerodynamic damping.
In these simulations the panel vortex method shows higher damping relative to the Theodorsen method. The highest wind speed has the most steady aerodynamics, but also the largest difference in damping between the methods.

The most unsteady aerodynamics is for the 1st tower bending mode with the lowest wind speed. The local damping has the same trend, and the difference is so small that it is not visible in the damping ratio.

Conclusion

The aim of this study is to investigate the unsteady effects of attached flow. The main effect of increasing unsteadiness is reduced aerodynamic damping. The Theodorsen method and the vortex panel code give relative similar results.

Table 3: The aerodynamic damping results

	Wind speed [m/s]	Panel vortex method		Theodorsen method	
		C_a	ξ	C_a	ξ
Platform Pitch	8	$2.20 * 10^9 kg\ m^2/s$	9%	$2.09 * 10^9 kg\ m^2/s$	8.5%
	14	$2.92 * 10^9 kg\ m^2/s$	12.0%	$2.74 * 10^9 kg\ m^2/s$	11.2%
	20	$2.82 * 10^9 kg\ m^2/s$	11.6%	$2.60 * 10^9 kg\ m^2/s$	10.7%
1st elastic tower bending mode	8	$5.17 * 10^4 kg\ /s$	2.2%	$5.16 * 10^4 kg\ s$	2.2%
	14	$7.21 * 10^4 kg\ /s$	3.1%	$7.09 * 10^4 kg\ s$	3.1%
	20	$7.01 * 10^4 kg\ /s$	3.0%	$6.82 * 10^4 kg\ s$	3.0%

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