AEROELASTIC STABILITY ANALYSIS OF OFFSHORE WIND TURBINE BLADES AT STANDSTILL CONDITION CONSIDERING UNSTEADY AERODYNAMICS

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This paper deals with aeroelastic stability analysis of offshore wind turbine blades at standstill condition considering unsteady aerodynamics focusing on the stall flutter of a coupled flap-and-edgewise bending motion. Taking an example of a 7MW offshore wind turbine, it was investigated that dynamic stall effect on the aeroelastic damping covering the whole regions of angle of attack and direction of blade vibration. To conduct the analysis, state space modeling was applied, which consists of linearized unsteady aerodynamic model as well as 1 DoF blade vibration model. According to the analysis, it was revealed that unsteady aerodynamics could alleviate aeroelastic instabilities to different but great extents for each region defined based on angle of attack and direction of blade vibration.

Keyword: wind turbine, aeroelastic stability, unsteady aerodynamics, stall flutter

1. INTRODUCTION

Wind power is one of the most widely installed renewable energies around the world – in particular, offshore wind is drawing growing interest in recent years as more powerful and boundless energy resources. To reduce the offshore wind cost, there is a clear design trend that offshore wind turbines are getting bigger and bigger in size (rotor diameter) and capacity (rated power) with much longer and even more slender rotor blades, whereby aeroelastic investigation of offshore wind turbine blades is becoming more important.

Aeroelastic instability problems for wind turbine blades can be classified into two types[1)]. The first is a torsional flutter (or simply called flutter) in rotating condition. In extremely high tip speed region, especially in case of the over speed situation, pitching motion would be coupled with edgewise motion and could become unstable in some cases, however, it is considered that there is still a margin for the flutter speed as long as the turbine is operated within normal tip speed region. The second is a stall-induced flutter at standstill condition. A coupled flap-and-edgewise motion would become unstable when at least one of the blades would be exposed to an oblique strong wind inflow with angles of attack in deep stall region, which could take place during offshore transportation, assembly and maintenance at the site.

This paper deals with aeroelastic stability analysis focusing on the stall-flutter, taking an example of a 7MW offshore wind turbine, MWT167/7.0, which was developed by Mitsubishi Heavy Industries, Ltd., of which blades are the longest (81.6m) among all wind turbines in operation as of now. Unsteady aerodynamic model as well as quasi-steady aerodynamic model was used in order to investigate the dynamic stall effect on the aeroelastic damping, which was required to be investigated covering the whole regions of angle of attack and direction of blade vibration. In this study, state space representation was applied to model unsteady aero-dynamics consisting of an effect of shed vorticity from the trailing edge based on Theodorsen's theory[2)] and an effect of dynamics (time-lag) of separation point based on Leishman's formulation[3-4)]. According to the analysis, it was revealed that unsteady aerodynamics could alleviate aeroelastic instabilities to different but great extents for each region defined based on angle of attack and direction of blade vibration.

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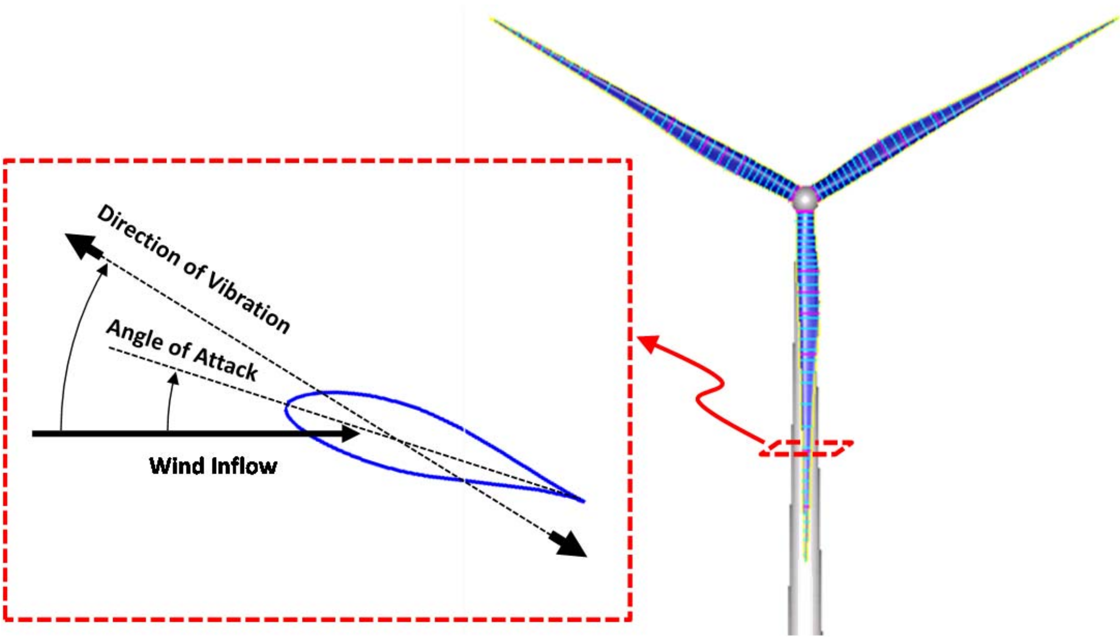

Figure 1: Schematic of the stall-induced flutter analysis of offshore wind turbines

2. UNSTEADY AERODYNAMIC MODEL

Unsteady lift and drag coefficient represented aerodynamic derivatives

$$\Delta C_L^{dyn} = C_{L\alpha}^{dyn} \cdot \Delta\alpha + C_{LX_1}^{dyn} \cdot \Delta x_1 + C_{LX_2}^{dyn} \cdot \Delta x_2 + C_{LX_4}^{dyn} \cdot \Delta x_4 \tag{1}$$

$$\Delta C_D^{dyn} = C_{D\alpha}^{dyn} \cdot \Delta\alpha + C_{LX_1}^{dyn} \cdot \Delta x_1 + C_{LX_2}^{dyn} \cdot \Delta x_2 + C_{LX_4}^{dyn} \cdot \Delta x_4 \tag{2}$$

State space representation of aerodynamic variables by one dimensional displacement of a blade section

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & T_p & 0 \\ 0 & 0 & 0 & T_f \end{bmatrix} \begin{bmatrix} \Delta\dot{x}_1 \\ \Delta\dot{x}_2 \\ \Delta\dot{x}_3 \\ \Delta\dot{x}_4 \end{bmatrix} = \begin{bmatrix} -b_1 \cdot \frac{2u_0}{c} & 0 & 0 & 0 \\ 0 & -b_2 \cdot \frac{2u_0}{c} & 0 & 0 \\ C_{L\alpha}^p & C_{L\alpha}^p & -1 & 0 \\ 0 & 0 & f_{\alpha 0}/C_{L\alpha}^p & -1 \end{bmatrix} \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta x_3 \\ \Delta x_4 \end{bmatrix} + \begin{bmatrix} -A_1 \cdot b_1 \cdot \frac{2}{c} \cdot \sin\theta \\ -A_2 \cdot b_2 \cdot \frac{2}{c} \cdot \sin\theta \\ -C_{L\alpha}^p (1 - A_1 - A_2) \\ 0 \end{bmatrix} \Delta\dot{x} \tag{3}$$

3. EQUATIONS OF MOTION

One dimensional equation of motion

$$m\ddot{x} + 2m\zeta_n \omega_n \dot{x} + m\omega_n^2 x = F_X \tag{4}$$

External force represented by lift coefficient and drag coefficient

$$F_X = L\sin(\theta-\Delta\varphi) - D\cos(\theta-\Delta\varphi) = \frac{1}{2}\rho c u^2 \cdot \left[C_L \sin(\theta-\Delta\varphi) - C_D \cos(\theta-\Delta\varphi)\right] \tag{5}$$

State space representation

$$\begin{bmatrix}\Delta\dot{x}\\ \Delta\ddot{x}\end{bmatrix} = \begin{bmatrix}0 & 1\\ -\omega_n^2 & -2\zeta_n\omega_n\end{bmatrix}\begin{bmatrix}\Delta x\\ \Delta\dot{x}\end{bmatrix} - \begin{bmatrix}0\\ \Delta F_X/m\end{bmatrix} \tag{6}$$

$$\Delta F_X = F_{\dot{X}}\cdot\Delta\dot{x} + F_{\ddot{X}}\cdot\Delta\ddot{x} + F_{X_1}\cdot\Delta x_1 + F_{X_2}\cdot\Delta x_2 + F_{X_4}\cdot\Delta x_4 \tag{7}$$

4. AEROELASTIC ANALYSIS

State space representation for equations of motion and unsteady aerodynamic model

$$\begin{bmatrix}1&0&0&0&0&0\\0&1&0&0&0&0\\0&0&1&0&0&0\\0&0&0&1&0&0\\0&0&0&0&T_p&0\\0&0&0&0&0&T_f\end{bmatrix}\begin{bmatrix}\Delta\dot{x}\\ \Delta\ddot{x}\\ \Delta\dot{x}_1\\ \Delta\dot{x}_2\\ \Delta\dot{x}_3\\ \Delta\dot{x}_4\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0 & 0 & 0\\ -\omega_n^2 & -2\cdot\left(\zeta_n\omega_n + \frac{\rho c u_0}{4m}\cdot\eta^{dyn}\right) & -F_{X_1}/m & -F_{X_2}/m & 0 & -F_{X_4}/m\\ 0 & -A_1 b_1\cdot\frac{2}{c}\cdot\sin\theta & -b_1\cdot\frac{2u_0}{c} & 0 & 0 & 0\\ 0 & -A_1 b_1\cdot\frac{2}{c}\cdot\sin\theta & 0 & -b_2\cdot\frac{2u_0}{c} & 0 & 0\\ 0 & C_{L\alpha}^p(1-A_1-A_2)\cdot\left(-\frac{\sin\theta}{u_0}\right) & C_{L\alpha}^P & C_{L\alpha}^P & -1 & 0\\ 0 & 0 & 0 & 0 & f_{\alpha 0}/C_{L\alpha}^p & -1\end{bmatrix}\begin{bmatrix}\Delta x\\ \Delta\dot{x}\\ \Delta x_1\\ \Delta x_2\\ \Delta x_3\\ \Delta x_4\end{bmatrix} \tag{8}$$

Calculating conditions:
Air density = 1.225kg/m3
Wind speed = 20m/s
Natural frequency = 0.8Hz (1st mode)
Structural damping delta = 0.03
Spanwise station = 0.84Radius
Chord length = 1.447m
Mass per length = 113.5kg/m
Unsteady aerodynamic model parameters:
A1 = 0.165, A2 = 0.335, b1 = 0.0455, b2 = 0.3000, Tp = 0.35, Tf = 0.35

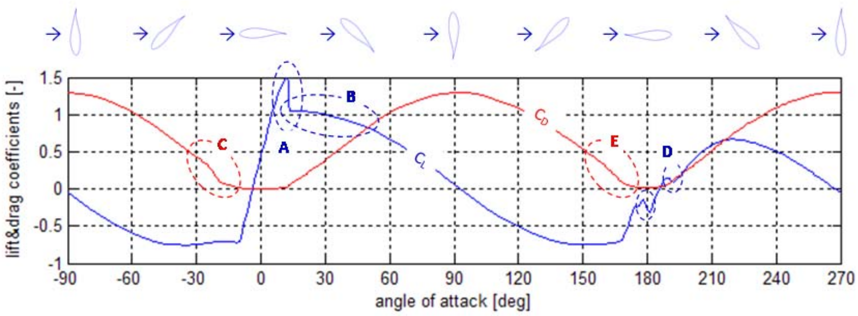

Figure 2: Static (quasi-steady) lift and drag coefficients of representative blade section (r/R=0.84) for the whole angle-of-attack range from -90deg to +270deg

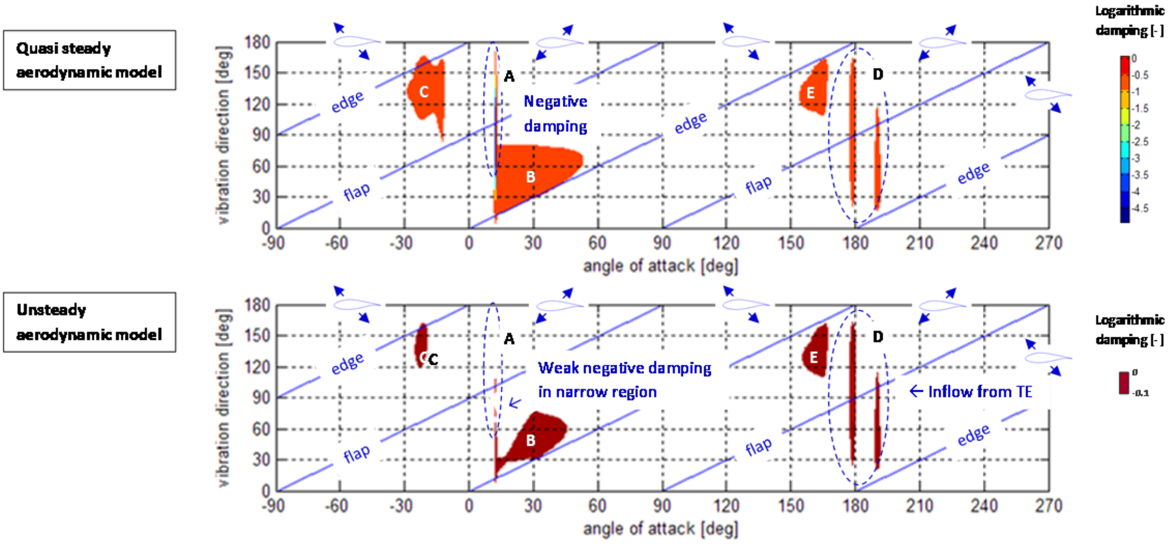

Figure 3: Results of aeroelastic analysis of the representative blade section (r/R=0.84) using quasi-steady aerodynamic model (to the top) and unsteady aerodynamic model (to the bottom) for the whole angle-of-attack range from -90deg to +270deg

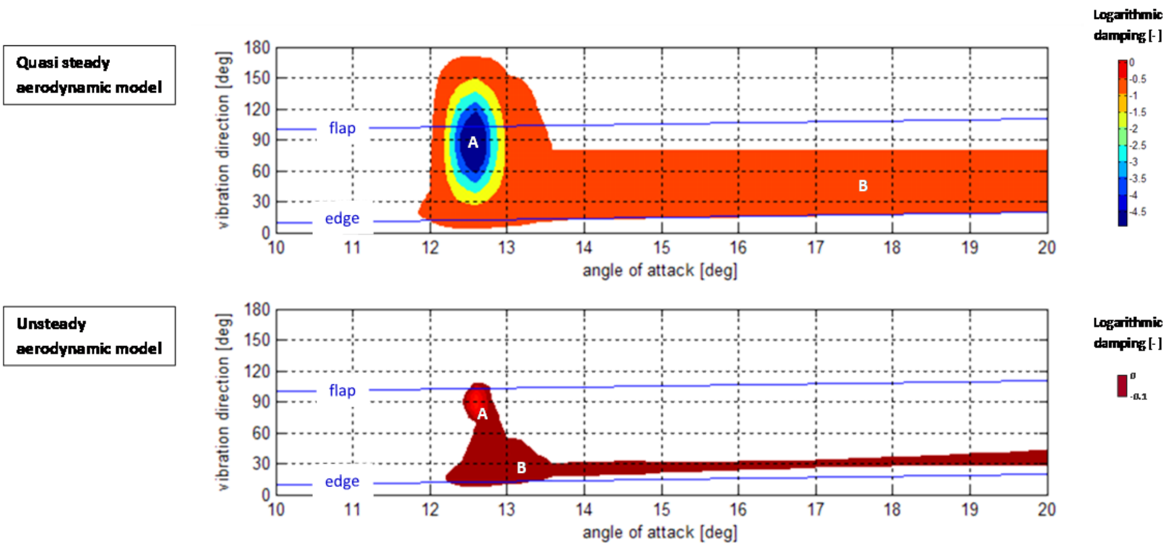

Figure 4: Results of aeroelastic analysis of the representative blade section (r/R=0.84) using quasi-steady aerodynamic model (to the top) and unsteady aerodynamic model (to the bottom) at angles of attack in the range of 10deg to 20deg

5. CONCLUSIONS

In this paper, aeroelastic stability analysis of offshore wind turbine blade (81.6m length) at standstill condition was carried out using quasi-steady aerodynamic model and linearized unsteady aerodynamic model, covering the whole regions of angle of attack and direction of blade vibration. According to quasi-steady analysis, it was found that the coupled flap-and-edgewise motion would become unstable when at least one of the blades would be exposed to strong wind inflow with angle of attack in the following five regions; (A) post stall region where flapwise motion would become deeply unstable due to steep negative lift slope, (B) deep stall region where edgewise motion would become slightly unstable for wider angle-of-attack region somewhere between 12deg to 45deg due to gradual negative lift slope, (C) negative angle of attack region of around -20deg where the coupled flap-edgewise motion would become slightly unstable due to negative lift coefficient with negative drag slope, (D) angle of attack from 180deg to 190deg (reverse flow condition) where the flapwise or the coupled flap-edgewise motion would become slightly unstable due to negative lift slope and (E) angle of attack around 160deg where edgewise motion would become unstable due to negative slope of lift and drag curves. Based on the analysis that was subsequently conducted considering unsteady aerodynamics, it was revealed that unsteady aerodynamics could greatly alleviate aeroelastic instabilities for each region, especially, the region A was the region most affected by unsteady dynamics, in other words, dynamic stall in the post stall region. It was finally concluded that the region B should be avoided during offshore transportation, assembly and maintenance at the site because, even when unsteady aerodynamics was considered, the region B would remain unstable for wider angle-of-attack region.

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