Time-Domain Aeroelastic Loads and Response of Wind Turbine Blades in Gusty Wind: Prediction and Experimental Validation

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The traditional method of flutter analysis of wind turbine blades employs a mixed-domain (frequency- and time-domain) formulation for self-excited aerodynamic loads, because flutter derivatives are functions of reduced frequencies. However, a time domain formulation for self-excited and buffeting loads allows the equations of motion to be continuously solved for response time histories of wind turbine blades below flutter speed and captures the transient response in gusty and turbulent winds. The rational function coefficients and buffeting indicial function coefficients that appear in the time domain formulation were previously extracted for the NREL S830 airfoil, a low-noise and high lift to drag ratio airfoil with 21% thickness to chord ratio used in wind turbine blades, using section model tests in a wind tunnel. The objective of the current study is to evaluate how well these experimentally extracted coefficients can predict the aerodynamic loads on a blade in different wind conditions, through a separate set of tests conducted on a much larger (3.3 times) section model of the blade in a larger wind tunnel than originally used. The tests were performed for different upstream wind conditions (stationary, ramp-down gust, low turbulence and high turbulence) and the loads (lift and moment) were validated by simulating them in time domain using the measured displacements and comparing them with the measured ones. The amplitudes and pattern of the simulated aerodynamic loads compared reasonably well with those measured, even in gusty and more turbulent wind environment.

Keyword: Wind Turbine blades1, Time-domain2, Aeroelastic load prediction3, Gusty wind4

1. INTRODUCTION

Traditional analysis for calculating response of a slender structure such as a wind turbine blade subject to aerodynamic loads employs a frequency-domain formulation of the loads which works on the assumption that the incident wind is stationary and the response of the blade is sinusoidal or near-sinusoidal, neither of which is true. A frequency-domain formulation of the aerodynamic loads on a wind turbine blade uses Theodorsen functions1 that are theoretically-derived functions for thin airfoils (thickness to chord ratio less than 10%)2,3,4 or uses experimentally-derived flutter derivatives, both of which are functions of reduced frequency5. The dynamic equations of motion for the wind turbine blade then becomes a mixed-domain (frequency- and time-domain) formulation because the aerodynamic loads are formulated in mixed domain. To utilize this formulation, some authors use the pseudo-steady formulation6,7,8 of the flutter derivatives which uses approximate expressions of the flutter derivatives in terms of the static force coefficients for the airfoil sections and their derivatives with respect to angle of attack at zero degree angle of attack. Wind turbine blades consist of thick airfoils operating at non-zero angles of attack, questioning the applicability of these approximations. Alternately and preferably, flutter derivatives of the airfoil sections9,10 of the wind turbine blades can be extracted from wind tunnel tests, however, these frequency-domain formulations cannot be used to continuously predict the response of wind turbine blades in real time. Therefore, time-domain formulations for aerodynamic loads11,12,13,14 were proposed and investigated because these are more suitable for gusty or non-stationary incident wind, finite element modeling, feedback-dependent structural control, and fatigue-life prediction. Cao

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and Sarkar\(^{15}\) developed an algorithm to experimentally extract time-domain rational function coefficients for a section model while Chang and Sarkar\(^{16}\) developed a method to experimentally extract the time-domain buffeting indicial functions. A time-domain procedure for predicting the loads and response which uses both the rational function coefficients and the buffeting indicial functions, was also developed and validated\(^{17}\). Sauder and Sarkar\(^{18}\) employed these methods to extract the rational function (RF) coefficients and the buffeting indicial functions for a thick, asymmetric wind turbine blade airfoil corresponding to different mean angles of attack. 

In the current paper, these time-domain RF and buffeting indicial function coefficients are used to predict the total aeroelastic loads acting on an airfoil section model that was subjected to stationary wind, ramp-shaped gusty wind, and turbulent wind. The predictions are compared to the measured loads to validate the procedure.

2. TIME-DOMAIN EQUATIONS FOR AEROELASTIC LOADS

For wind turbine blades, it is sufficient to consider only the vertical and torsional modes of vibration because airfoils are designed to have low drag coefficients. For other structures, it might be necessary to consider the along-wind motion as well. In this paper, only the self-excited and buffeting loads are included because vortex-induced loads are not typically a problem for current wind turbine blades. The equations of motion can be written as

\[
m\dddot{h} + 2\zeta_h\omega_h \dot{h} + \omega_h^2 h = L_{ae} = L_b + L_{se} \\
I\dddot{\alpha} + 2\zeta_\alpha\omega_\alpha \dot{\alpha} + \omega_\alpha^2 \alpha = M_{ae} = M_b + M_{se}
\]

where \(m\) is the mass per unit length; \(I\) is the mass moment of inertia about the centroidal axis per unit length; \(h(t,x), \alpha(t,x)\) are the vertical (cross-wind) and torsional displacements, respectively; \(\zeta_h, \omega_h\) are the damping ratio and the natural frequency for the vertical mode; \(\zeta_\alpha, \omega_\alpha\) are the damping ratio and the natural frequency for the torsional mode; \(\dot{} = \frac{d}{dt}\); \(\dddot{} = \frac{d^3}{dt^3}\); \(L_{ae}\) is the total aeroelastic lift; \(M_{ae}\) is the total aeroelastic moment; \(L_{se}\) is the self-excited lift; \(M_{se}\) is the self-excited moment; \(L_b\) is the buffeting lift component; and \(M_b\) is the buffeting moment component.

(1) Self-excited loads

The self-excited lift and moment for a wind turbine blade section in time-domain, as obtained by transforming the rational function formulation from Laplace domain, can be written as

\[
L_{ae}(t) = \frac{1}{2} \rho U^2 \frac{1}{c} \begin{cases} 
(A_{11})_{11} \hat{h} + (\hat{E})_{11} \hat{h} + \frac{\hat{h}}{U} (A_{11} \frac{\lambda L}{c}) \int_s \left[ \frac{U}{c} e^{-\lambda L (t-\tau)} \right] h(\tau) d\tau \\
+ ((A_{11})_{12} \frac{\lambda L}{c}) \alpha + ((A_{12})_{11} \frac{\lambda L}{c}) \alpha - (\hat{E})_{11} \frac{\lambda L}{c} \int_s \left[ \frac{U}{c} e^{-\lambda L (t-\tau)} \right] \alpha(\tau) d\tau
\end{cases}
\]

(3)

\[
M_{ae}(t) = \frac{1}{2} \rho U^2 \frac{1}{c} \begin{cases} 
((A_{11})_{12} \frac{\lambda L}{c}) \hat{h} + ((A_{12})_{12} \frac{\lambda L}{c}) \hat{h} - (\hat{E})_{12} \frac{\lambda L}{c} \int_s \left[ \frac{U}{c} e^{-\lambda L (t-\tau)} \right] h(\tau) d\tau \\
+ ((A_{12})_{12} \frac{\lambda L}{c}) \alpha + ((A_{12})_{11} \frac{\lambda L}{c}) \alpha - (\hat{E})_{12} \frac{\lambda L}{c} \int_s \left[ \frac{U}{c} e^{-\lambda L (t-\tau)} \right] \alpha(\tau) d\tau
\end{cases}
\]

(4)

where \(\rho\) is the air density; \(U\) is the mean velocity; \(c\) is the chord length; \(A_{ij}, A_i\) are the stiffness and damping matrix, respectively; \(\hat{E}\) is the lag matrix, all of order 2 x 2, and \(\lambda_L\) and \(\lambda_M\) are the lag coefficients. The elements of \(\Delta_{1i}, A_i\) and \(E\) matrices and \(\lambda_L\) and \(\lambda_M\) are known as the Rational function coefficients.

(2) Buffeting Loads

In time domain, buffeting lift and moment for a wind turbine blade section can be formulated using the buffeting indicial functions in terms of non-dimensional time, \(s = Ut/c\), as follows:
where \( u \) and \( w \) are the longitudinal and vertical components of wind turbulence fluctuations and \( \phi'_L \) and \( \phi'_M \) are the derivatives of the buffeting indicial functions \( \phi_L \) and \( \phi_M \) with reduced time. \( C_L \), \( C_D \), and \( C_M \) are the static force coefficients for lift, drag, and moment, respectively, and \( C_L' \) and \( C_M' \) are the derivatives with respect to angle of attack.

3. EXPERIMENTAL SET-UP

The experimental tests presented here were performed on a larger section model in order to show that the coefficients extracted on the smaller section model could be used to predict the loads on a model of a larger scale. This allows the functions to reasonably be extended to predict the loads on an actual wind turbine blade.

(1) Description of Wind Tunnel Used

The experiments described here were performed in the Aerodynamic and Atmospheric Boundary Layer (AABL) wind and gust tunnel located in the Wind Simulation and Testing Laboratory (WiST Lab) in the Department of Aerospace Engineering at Iowa State University. This wind tunnel has an aerodynamic test section of 2.44 m (8.0 ft) width \( \times \) 1.83 m (6.0 ft) height, an atmospheric boundary layer test section of 2.44 m (8.0 ft) width \( \times \) 2.21 m (7.25 ft) height, and a designed maximum wind speed of 53 m/s (173.9 ft/s) in the aerodynamic section. An active gust generator was developed and implemented by Haan et al.\(^6\) in this wind tunnel. The gust generator works by diverting air to and from the main duct to a bypass duct which allows the flow velocity in the test section to be increased or reduced in a short duration.

(2) Model

A profile view of the National Renewable Energy Laboratory (NREL) S830 (21% thickness to chord ratio) airfoil is shown in Fig. 1. This airfoil is part of the S-series family of airfoils that are thick (high thickness to chord ratio), generate low-noise during operations and aerodynamically efficient with high lift-to-drag ratio, for use in 20-25 m wind turbine blades.

![Figure 1: Non-dimensionalized profile of the NREL S830 airfoil.](image)

The section model used for the experiment is shown in Fig. 2. The model is constructed out of a rectangular wooden spar with foam airfoil sections mounted over the top. The length \( L \), chord length \( c \), and thickness \( t \) of the model are about 1.52, 0.508, and 0.107m, making this model 3.3 times larger than the section model used to extract the rational function and buffeting indicial function coefficients. The two-DOF model suspension...
system used in this experiment is also shown in Fig. 2. The suspension system enables vertical (h) and torsional (α) motions using 12 linear helical springs, six at each end of the model. Free vibration tests were completed prior to the wind tests to determine the two uncoupled stiffness coefficients of the two-DOF system for each DOF, calculated as $K_h = 2,233.5 \text{ N/m}$ and $K_\alpha = 103.72 \text{ Nm/\text{rad}}$, respectively. The natural frequencies were also measured in the free vibration tests as $f_h = 1.98 \text{ Hz}$ and $f_\alpha = 3.43$ and the mechanical damping ratios of the system as $\zeta_h = 0.24\%$ and $\zeta_\alpha = 0.45\%$. To induce coupling and hence vibration in the model, two C-clamps were added as lumped masses, one on each side of the model span at a distance of 0.25 m downstream of the model shaft. The mass and the mass moment of inertia of the entire dynamic system were $M = 14.88 \text{ kg}$ and $I = 0.0059 \text{ kg/m}^2$.

(4) Rational and Indicial Functions for the S830 airfoil

A section model ($c = 152.4 \text{ mm}$, $t = 32 \text{ mm}$, $L = 450 \text{ mm}$) of the NREL S830 airfoil with end plates was placed in the Bill James Wind Tunnel (0.915 m width by 0.762 m height), an open return tunnel in the Wind Simulation and Testing Laboratory at Iowa State University, for the extraction of the rational function coefficients and the buffeting indicial functions with two separate sets of experiments. In these experiments four angles of attack were used (0, 3, 6, 9 deg), but the validation effort presented here corresponds to the 3 degree angle of attack (AOA). The rational function coefficients and the derivatives of the buffeting indicial functions for 30 AOA, as extracted in Sauder and Sarkar, are given below:

$$
\Delta_0 = \begin{bmatrix}
-8.2582 \\
1.2395
\end{bmatrix}, \quad \Delta_1 = \begin{bmatrix}
-7.0203 \\
1.2396
\end{bmatrix}, \quad \Delta_2 = \begin{bmatrix}
-14.2616 \\
5.4781
\end{bmatrix};
$$

$$
F_0 = \begin{bmatrix}
6.9796 \\
-0.8657
\end{bmatrix}, \quad F_1 = \begin{bmatrix}
8.9027 \\
-4.9014
\end{bmatrix}, \quad F_2 = \begin{bmatrix}
-0.8657 \\
-4.9014
\end{bmatrix};
$$

$$
\lambda_L = 0.0157; \quad \lambda_M = 0.282
$$

$$
\phi_L' = 0.016 \cdot e^{-0.0367s} + 0.088 \cdot e^{-0.167s}
$$

$$
\phi_M' = 0.0031 \cdot e^{-0.0326s} + 0.189 \cdot e^{-0.211s}
$$

In these tests, the static force coefficients were also measured as follow: $C_L = 0.66$, $C_L' = 5.29$, $C_D = 0.02$, $C_M = -0.26$, $C_M' = 1.63$.

(3) Instrumentation

In this experiment, wind velocity time histories were measured by a Cobra Probe (Turbulent Flow Instrumentation) placed immediately upstream of the airfoil section model. The sampling rate was set at 312.5 Hz. The vertical and torsional displacement of the model was measured by measuring the elastic force in each of four helical springs, which are connected to the model at one end and a strain gauge force transducer at the other end, as show in Fig. 2. The LabVIEW program was used for data acquisition and the sampling rate was set to 625 Hz. The aerodynamic pressures were also recorded in the experiment to determine the aeroelastic loads for comparison with those obtained through numerical simulation. The pressures were measured through 24 pressure taps placed along the upper and lower surface at the centerline of the model. A 64-channel pressure module (Scanivalve ZOC33/64 Px) was used to measure the pressures. The sampling rate was 312.5 Hz and
Scanivalve’s Scantel was used for data acquisition. Data synchronization was accomplished using an external trigger to begin data acquisition for all three instruments.

4. RESULTS AND DISCUSSION

In the wind tunnel tests, the wind speed was increased until the model was on the edge of divergent flutter and both the model displacement and pressures were recorded during the vibration. Tab. 1 shows the predicted flutter speed and the measured flutter speed for this section model. The measured model displacements \( h(t) \) and \( \alpha(t) \), their first derivatives \( \dot{h}(t) \) and \( \dot{\alpha}(t) \) were calculated using finite difference method, and the previously extracted rational function coefficients were input into Eqs. 3 and 4 to simulate the self-excited lift and moment at each time step. Similarly, the time history of the turbulent wind velocity (both \( u \) and \( w \)) was input into Eqs. 5 and 6 to simulate the buffeting lift and moment at each time step. Four cases were considered: stationary wind (Turbulence Intensity TI = 0.27%), ramp-down gust, low turbulence (TI = 0.85%) and high turbulence (TI = 11.7%) to evaluate the predictions in time-domain.

<table>
<thead>
<tr>
<th>Table 1: Error in original flutter speed prediction for the airfoil prediction</th>
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<tr>
<td>Predicted Flutter Speed</td>
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<tr>
<td>11.42</td>
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(1) Load Prediction for Stationary Wind Case

For the stationary wind case, the aeroelastic loads were predicted and measured at a mean wind speed of about 11.35 m/s, as can be seen in the velocity time history show in Fig. 3(a). The measured turbulence intensity by the Cobra Probe was 0.27% and, therefore, this flow condition can be classified as smooth flow which limits the effect of the buffeting loads. Figs. 3(b) and 3(c) show the time histories for the vertical (cross wind, \( h \)) and torsional (\( \alpha \)) displacements that were used in the prediction of the aeroelastic loads. Finally, Figs. 3(d) and 3(e) show the comparison of the measured and simulated non-dimensionalized lift and moment, respectively.
As can be observed from the lift and moment comparison plots, the moment coefficient time history prediction matches well with the experimental results for both amplitude and phase angle. While the amplitude of the lift coefficient was predicted well, the predicted phase angle was slightly different from that of the measurement. Cao and Sarkar\(^{17}\) saw a similar shift, but in the moment coefficient. It was theorized that it was due to an error in the extracted rational function coefficients that are related to the flutter derivative $A_2^*$. Another reason for this slight error in the predictions could be attributed to the current formulation that used only one lag term for lift or moment, whereas additional lag term(s) could be used to improve the predictions that will be examined in the future.

### (2) Load Prediction for Ramp-Down Gusty Wind Case

To ultimately validate the feasibility of the time domain formulation for this airfoil in a non-stationary wind environment, the wind tunnel tests were carried out in a ramp-down gusty wind. The horizontal wind velocity time history is shown in Fig. 4(a) and the corresponding displacement and force coefficient time histories are plotted in Figs. 4(b) to 4(e).
Figure 4: (a) Measured wind speed for gusty wind case; (b) Measured vertical (cross-wind) displacement; (c) Measured torsional displacement; (d) Comparison of the numerically simulated lift with measured; (e) Comparison of numerically simulated moment with measured.

For this gusty wind case, it is observed that the amplitudes of the load coefficients are predicted well for the first half of the time intervals. However, in the later part of the time histories the lift coefficient is over predicted and the moment coefficient is slightly under predicted. Moreover, the phase shift between the simulated and measured results is still present in both lift and moment. Given intrinsic errors in the pressure measurements, errors in extracting the time-domain coefficients and errors in the numerical differentiation and integration procedures used, the comparison seems quite encouraging.

(3) Load Prediction for Turbulent Wind Cases

Two turbulent wind cases were examined to evaluate this prediction procedure in more complex scenarios. The first, or low turbulence, case has a measured turbulence intensity of 0.85%. This turbulence was generated by placing 4in roughness elements in the diffuser section of the wind tunnel (following the fan section). This use of roughness elements resulted in the nearly sinusoidal wind velocity in both the along wind (u) and the vertical (w) components of velocity. Fig. 5(a) shows the along-wind measured velocity. Figs. 5(b) to 5(e) show the measured displacements and comparison of the simulated and the measured lift and moment coefficients. There are slight errors in the predicted amplitudes at certain moments in time, but the overall prediction is quite good given that it was turbulent wind.
Figure 5: (a) Measured wind speed for low turbulence wind case; (b) Measured vertical (cross-wind) displacement; (c) Measured torsional displacement; (d) Comparison of the numerically simulated lift with measured; (e) Comparison of numerically simulated moment with measured.

The second turbulent wind case that was evaluated is considered a high turbulence case with a turbulence intensity of 11.7%. This turbulence intensity is much lower than the Lower Turbulence wind classes set by the IEC 61400-1 standard for wind developers, but has a good representation of how this time domain formulation would work for an actual wind turbine operating in the field. The turbulence in this case was generated using 4 spires (0.13m base and 1.17m height). These spires were placed 2.5m upstream of the model.

The horizontal wind velocity generated in this case is shown Fig. 6(a) and the comparison of the measured and the simulated load coefficients are shown in Fig. 6(b) and 6(c). The amplitudes here are
occasionally over predicted or under predicted, however the overall pattern and standard deviation between the two compare well with a 7.3% and a 11.0% error in the standard deviation of the lift and moment coefficients, respectively. Given this information, this procedure seems to hold up even in a high turbulence situation.

![Graph](image_url)

Figure 6: (a) Measured wind speed for the high turbulence wind case; (b) Comparison of the numerically simulated lift with measured; (c) Comparison of numerically simulated moment with measured.

5. CONCLUSIONS AND FUTURE WORK

In order to validate the time domain formulation for predicting aerodynamic loads on a wind turbine blade airfoil at a non-zero angle of attack, experiments were carried out for four different wind inputs (stationary, ramp-down gust, low turbulence and high turbulence). In each case, the amplitudes and pattern of the simulated aerodynamic loads (lift and moment) compared well with those measured, however, there was a slight phase shift in the time histories. This shows that this formulation and procedure to predict aerodynamic loads in real time using the incident wind information will be very useful for structural health monitoring applications and hence preventive maintenance and also for the evaluation of the fatigue life of wind turbine blades. Future work will include a second lag term in the self-excited load formulation using rational function coefficients to improve the phase shift error and evaluate this procedure when blade rotation is added.

ACKNOWLEDGMENTS

This work is supported by Grant # 13-02 from the Iowa Energy Center; their support is gratefully acknowledged. The author is supported under the U.S. National Science Foundation Grant No. 1069283 which supports the activities of the Integrative Graduate Education and Research Traineeship (IGERT) in Wind Energy Science, Engineering and Policy (WESEP) at Iowa State University.
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