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Ringing loads on tension leg platform wind turbines

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ABSTRACT

The present work identifies realistic wave (and associated wind) conditions which could induce ringing responses in tension leg platform wind turbines (TLPWTs). The simulation results show the importance of ringing forces, the effects of turbine operation, and the sensitivity of the ringing response to platform stiffness and viscous damping. To model the ringing loads, the second order quadratic transfer function and a bandwidth-limited summation formulation for the third order wave forces were implemented. The chosen formulation avoids the spectrum cut-off dependency and the low-frequency components of a direct implementation of the irregular wave Faltinsen, Newman, Vinje (FNV) formula. Depending on the natural period and damping, the difference between a direct implementation and this formulation was 5–25%. Ringing-type responses were simulated for 50-year wind and wave conditions. Various hydrodynamic models were used to isolate physics in different approaches. For platforms with 14–18 m diameters, ringing loads resulted in larger extreme loads and increased short-term fatigue damage in the tendons and tower. Ringing effects were particularly severe for platforms with a pitch/bending natural period of 3–4 s. The viscous damping coefficient had a negligible influence on the ringing response, while aerodynamic damping could be important in damping the oscillations following the initial maximum.

1. Introduction

Tension leg platform wind turbines (TLPWTs) hold promise for capturing offshore wind energy in intermediate (45–150 m) and deep (>150 m) water. TLPWT designs with diameters in the range 5–18 m and pitch natural periods of 1.5–4.5 s have been presented in the literature (Matha, 2009; Henderson et al., 2010; Bachynski and Moan, 2012; Stewart et al., 2012). Marine structures with structural periods in the range of 1–5 s are known to be susceptible to "ringing" responses in severe seas: "transient structural deflections at frequencies substantially higher than the incident wave frequencies" (Faltinsen et al., 1995). In contrast to the more steady-state "springing" response to sum-frequency wave effects, ringing is characterized as a transient event, generally following a high, steep wave (Gurley and Kareem, 1998). The present work seeks to identify environmental conditions that could induce ringing responses in TLPWTs and evaluate their effects.

Ringing of offshore oil and gas tension leg platforms (TLPs) is known to occur in steep wave conditions (Faltinsen et al., 1995). Ringing responses were first observed on the Hutton platform, and were subsequently seen in Heidrun and Snorre model tests (Natvig, 1994). Studies of the hydrodynamic loading which drives these responses provided significant theoretical development in the 1990s. Some of the hydrodynamic criteria for ringing loads that have been described in the previous studies (Faltinsen et al., 1995; Tromans et al., 2006) include:

1. Presence of surface-piercing columns.
2. Low Keulegan–Carpenter number ($KC = 2\pi U/\omega D$, where U is the fluid particle velocity amplitude, ω is the wave period, and D is the diameter) (fluid loading dominated by inertial loads): $KC < 5$.
3. Low diameter-wavelength (D/λ) ratio (linear diffraction is not significant): $D/\lambda < 0.2$. (Alternatively: $ka < 0.63$, where $k = 2\pi/\lambda$ and $a = D/2$).
4. Wave height comparable to cross-sectional structure dimensions.

TLPWT platforms, particularly single column designs with relatively large diameters, may meet the given criteria for certain wave conditions. In order to model these forces, a model of the nonlinear forces (third order and higher) on cylindrical columns is required.

The well-known Faltinsen, Newman, Vinje (FNV) long-wave formulation (Faltinsen et al., 1995) for the horizontal forces on a

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Nomenclature

a	radius
C_D	drag coefficient
D	diameter
$d\omega$	frequency bandwidth
D_{RFC}	fatigue damage
F_t	tendon pretension
$F_x^{FNV(3)}$	third order long-wave horizontal force
Fr	Froude number
FNV	Faltinsen, Newman, Vinje force formulation
g	acceleration due to gravity
h	draft (of cylinder for force calculation)
H_s	significant wave height
K	material parameter (SN curves)
k	wave number ($k=2\pi/\lambda$)
KC	Keulegan–Carpenter number
K_I	integral control coefficient
K_P	proportional control coefficient
m	SN curve slope
M_{FA}	fore-aft tower base bending moment
S	stress range
T_1	downwind tendon tension
T_p	peak period
TLP	tension leg platform
TLPWT	tension leg platform wind turbine
u	wave particle horizontal velocity
U_w	mean wind speed
w	wave particle vertical velocity
β	function representing finite cylinder depth
$\Phi^{(i)}$	velocity potential (ith order)
ζ	wave amplitude
λ	wavelength
ρ	water density
Ψ_1 and Ψ_2	non-dimensional spatially varying functions
ω	wave frequency
ω_p	peak wave frequency
$\omega_{\psi n}$	controller natural frequency

vertical cylinder due to the third order potential was extended to irregular waves by Newman (1996b). While the second order component of the long-wave excitation force has been shown to compare well to full second-order diffraction only up to approximately $ka=0.1$, the third order FNV formulation is known to compare well to full third order diffraction theory up to $ka=0.4$ (Krokstad et al., 1998).

The approach used by Krokstad et al. (1998) was therefore followed here: the full second order sum-frequency quadratic transfer function (QTF) forces were included in all degrees of freedom, and the third order sum-frequency horizontal forces according to the FNV formulation were added. The explicit expression for the pitch moment based on Marthinsen et al. (1996) was not included in the present formulation. The expression for the ringing moment is not fully consistent, and is expected to be less important than the moment about the center of gravity induced by the horizontal force applied at the still water level.

Even using the second order QTF rather than the second order FNV component, Krokstad et al. (1998) found that the FNV formulation slightly overpredicted the high-frequency loads on a stationary cylinder. The overprediction was steepness-dependent, with steeper waves leading to larger overprediction. Stansberg (1997) presented experimental results for the first, second, and third order loads on fixed cylinders of different diameters. Although similar overprediction of the forces was observed, the FNV model was shown to correctly predict the trends in the third order force with regard to wave number.

An alternative implementation of the FNV formulation for irregular waves was presented by Johannessen (2012). This implementation addresses two of the challenges associated with a direct implementation of FNV: the spectrum cut-off dependency and the presence of low-frequency components. FNV includes terms that do not decay at high frequency, which implies that nonphysical wave components can be amplified, and the resulting force can be altered based on the input wave spectrum. Additionally, a direct implementation of the irregular FNV formula includes undesired difference-frequency components (Newman, 1996a).

In the present work, two methods of computing the ringing force were considered: a direct implementation of Newman's irregular wave formulation (Newman, 1996b), and Johannessen's bandwidth-limited, sum-frequency-only implementation (Johannessen, 2012). After comparing the computed forces and examining the response of a single degree-of-freedom model, Johannessen's formulation was chosen for use in the time-domain coupled simulations of several TLPWT models, as it removes some of the overconservatism of the direct implementation while preserving the desired terms.

Neither of the aforementioned approaches can capture the secondary loading cycle that was experimentally observed as early as 1993 by Grue et al. (1993). This loading cycle, which was documented for moderately steep waves and relatively large radii ($k\zeta > 0.3$, $0.1 < ka < 0.33$, $3.8 < KC < 7$ and $Fr > 0.4$, where $Fr = \omega A/\sqrt{gD}$), takes place approximately one quarter wave period after the main force peak (Grue and Huseby, 2002). This phenomenon may also affect TLPWTs with very large diameters, but cannot be modeled by current numerical methods and is not considered here.

Although ringing forces on TLPWTs have not been studied until now, nonlinear shallow water wave effects on bottom-fixed monopile offshore wind turbines have been investigated. Rogers (1998) examined breaking wave effects on monopiles and observed ringing-type responses. Significant harmonic structures up to the 5th order in the wave forces on a monopile during focused wave experiments have been observed, even in the absence of breaking waves (Zang et al., 2010). Furthermore, several authors have investigated the effects of nonlinear models. Veldkamp and van der Tempel (2005) observed 5–10% differences in the predicted fatigue damage on monopiles due to the use of second order or fully nonlinear waves, and more recent irregular wave simulations of a monopile wind turbine indicated that severe sea states contribute more significantly to the fatigue damage using nonlinear wave forcing compared to linear wave forcing (Schløer et al., 2013).

In the present work, the hydrodynamic developments from TLPs are applied to TLPWTs and the responses, including the wind turbine, are considered. The different ringing force formulations are introduced in Section 2. The computational tool, environmental conditions, TLPWT models – including a modification to the control system – and fatigue damage estimation method are presented in Section 3, while results for the baseline designs, softened designs, and variations in turbine operational status and viscous damping are shown in Section 4.

2. Third order ringing force formulations

Two methods of computing the ringing force are described in Sections 2.1 and 2.2: a direct implementation of Newman's