Fatigue loading on a 5MW offshore wind turbine due to the combined action of waves and current

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Abstract. In the design of an offshore wind turbine the natural frequencies of the structure are of importance. In the design of fixed offshore wind turbine support structures it cannot be avoided that the first eigenmode of the structure lies in the frequency band of wave excitation. This study indicates that wave-current interaction should be taken into account for support structure design load calculations.

Wave-current interaction changes the shape of the wave spectrum and the energy content in the wave frequency range of 0.2 - 0.35Hz. This is in the range of natural frequencies fixed offshore wind turbine structures are designed for. The waves are affected by the current in two ways. First there is a frequency shift, Doppler effect, for the fixed observer when the wave travels on a current. Second the shape of the wave is modified in case the wave travels from an area without current into an area with current. Due to wave-current interaction the wave height and wave length change. For waves on an opposing current the wave energy content increases, while for waves on a following current the wave energy content slightly reduces.

Simulations of normal production cases between cut-in and cut-out wind speed are performed for a 5MW wind turbine in 20m water depth including waves with 1) a following current, 2) an opposing current and 3) no current present. In case of waves having an opposing current, the 1Hz equivalent fore-aft tower bending moment at the seabed is about 10% higher compared to load cases with waves only.

1. Introduction
In 1988 Peters and Boonstra [1] reported about the fatigue loading on the Europlatform due to combined action of waves and currents. The Europlatform is a monopile platform located 60km offshore 'Hoek van Holland' in 32m water depth. Measurement of the horizontal accelerations at the platform showed that the accelerations were larger than expected during design. A strong relation was observed between the value of the horizontal accelerations and the variations in the tide. Since the majority of offshore wind turbines installed in the North Sea have a monopile as a support structure it was decided to investigate the effect of combined action of waves and current on a 5MW offshore wind turbine.

In offshore wind turbine design stochastic linear waves are used for the estimation of fatigue. Wave-current interaction changes the shape of the wave spectrum and the energy content in the wave frequency range of 0.2 - 0.35Hz. This is in the range of natural frequencies fixed offshore wind turbine structures are designed for. Before the fatigue life due to combined waves and current can be determined a wave model is needed to include the effect of currents on waves.
The wave-current model applied is a uniform current on a linear wave (Hedges [2]). This model can be implemented relatively easily in existing stochastic linear wave models (Hedges [3]).

The fatigue loading is calculated using metocean data from the IJmuiden shallow water site [4]. Simulations of normal production cases between cut-in and cut-out wind speed are performed for a 5MW wind turbine in 20 water depth including waves with 1) a following current, 2) an opposing current and 3) waves only (no current). Also normal production cases without waves (wind only) are calculated.

2. Theory of wave-current interaction

The theory of water waves is described in several text books on hydrodynamics for instance [5] and [6]. Here the focus is on the theory behind the modelling of a linear wave and an uniform current. The theory behind the modelling of random waves together with a uniform current is based on papers by Hedges [7, 3, 2].

For the modelling of the combined action of wave and current two coordinate systems are defined. One fixed reference frame (Figure 1) with subscript \(a\) for the apparent wave properties and a moving reference frame (Figure 2) with the subscript \(i\) moving with current velocity \(U_c\). The wave properties appear different for a stationary observer (fixed structure) than for an observer moving with the current velocity \(U_c\). The moving reference frame is defined because the wave properties in the moving reference are the same as for a wave in quiescent water i.e. without current.

![Figure 1. Fixed reference frame with wave and current.](image1)

![Figure 2. Reference frame moving with current speed \(U_c\) and waves only.](image2)

Two wave-current models are distinguished:
- Waves travelling on a steady uniform current;
- Waves propagating from an area without current into an area with a steady uniform current.

The wave-current interaction model.

In the first model with waves travelling on a steady uniform current the apparent wave frequency as seen by a stationary observer (or fixed structure) is taken into account (Doppler-effect). The wave properties are determined in the moving reference frame and transformed to the fixed frame. In this model the wave height and wave length are the same in both frames (systems).

In the second wave-current model, where waves from quiescent water move into an area with current, the interaction between the waves and the current results in a change in wave height and wave length. Again the wave properties are determined in the moving reference frame and
need to be transformed to the fixed frame. In this fixed frame the apparent wave period \( T_a \) is not changed by the current. In case of an opposing current the waves get steeper due to an increasing wave height and a shortening wave length. When the waves and current travel in the same direction the wave height decreases and the wave length increases.

First the wave-current models are explained for regular waves followed by the application of the models to the random wave situation.

2.1. Regular wave-current model

First the transformation from the moving frame to the fixed frame will be described followed by the wave-current interaction when the wave propagates from quiescent water into an area with a current. In a two dimensional \( x,z \) plane the position \( x_i \) of the moving frame with respect to the fixed frame is given by:

\[
x_i = x_0 + U_c t
\] (1)

Here \( x_0 \) is the position of the origin of the moving frame at time \( t = 0 \).

The velocity of the wave crest in the fixed frame, the apparent celerity \( C_a \), is the sum of the wave celerity \( C_i \) in moving frame and the current velocity \( U_c \).

\[
C_a = C_i + U_c
\] (2)

For a fixed frame with a co-existing wave and steady uniform current the wave length \( L \) has the same length in both the fixed frame and the moving frame. The wave celerity \( C_i \) and the apparent celerity \( C_a \) can be expressed by the wave length and their corresponding period, respectively \( T_i \) and \( T_a \).

\[
C_i = \frac{L}{T_i}
\]

\[
C_a = \frac{L}{T_a}
\] (3)

Multiplying both left and right hand side of Eq. (2) with the wave number \( k = \frac{2\pi}{L} \) yields the apparent angular frequency \( \omega_a \)

\[
\omega_a = \omega_i + kU_c
\] (4)

Here \( \omega_i \) is the relative or intrinsic wave angular frequency.

Since in the moving frame general wave theory applies as is the case in quiescent water, \( \omega_i \) can be expressed by the dispersion relation:

\[
\omega_i^2 = gk \tanh(kd)
\] (5)

Here \( g \) is the acceleration due to gravity and \( d \) is the water depth.

For a given apparent period \( T_a \) (or \( \omega_a \)), water depth \( d \) and current velocity \( U_c \) Eq. (6) can be solved for \( k \) after substitution of \( \omega_i \) from Eq. (4) in Eq. (5).

\[
(\omega_a + kU_c)^2 = gk \tanh(kd)
\] (6)

Once the wave number \( k \) and the wave frequency \( \omega_i \) are solved the wave kinematics can be calculated in the moving frame of reference. The free surface elevation given by linear wave theory is:
\[ \zeta = \frac{H}{2} \cos(kx_i - \omega_i t) \]  

Using equation (1) and (4) gives the free surface elevation in the fixed frame.

\[ \zeta = \frac{H}{2} \cos(kx_0 - \omega a t) \]  

For the apparent wave in the fixed frame with the co-existing wave and current and the wave in the moving frame the wave number \( k \) is the same.

In the second wave current model where the wave travels from quiescent water into an area with current, the wave height \( H \) and the wave length \( L \) change due to wave current interaction.

In a fixed frame the apparent wave period \( T_a \) does not change when a wave propagates from an area without current into an area with current. For the wave in the fixed frame of reference without current the subscript '0' is used (see Figure 3). For the fixed and moving frame with current the subscript 'a' and 'i' are used respectively.

![Figure 3. Definition sketch for random waves in water of finite depth.](image)

The change in wave height \( H \) or wave amplitude \( \zeta_a \) is determined from the principle of wave action conservation [8].

\[ \frac{\partial}{\partial t} \left( \frac{E}{\omega_i} \right) + \frac{\partial}{\partial t} \left[ \frac{E (U_c + C_{gi})}{\omega_i} \right] = 0 \]  

Here \( C_{gi} \) is the relative group velocity of the waves and \( E \) is the wave energy density.

\[ C_{gi} = \frac{1}{2} C_i \left( 1 + \frac{2kd}{\sinh 2kd} \right) \]  

\[ E = \frac{1}{8} \rho g H^2 = \frac{1}{2} \rho g \zeta_a^2 \]  

For a steady wave and current equation (9) reduces to.

\[ \frac{\partial}{\partial t} \left[ \frac{E (U_c + C_{gi})}{\omega_i} \right] = 0 \]  

For waves travelling from quiescent water into a current this means that the wave action for both flow systems is equal.

\[ \frac{E_0 C_{g0}}{\omega_a} = \frac{E (U_c + C_{gi})}{\omega_i} \]  

Where \( E_0 \) and \( C_{g0} \) are
\begin{equation}
E_0 = \frac{1}{2} \rho g H_0^2 = \frac{1}{2} \rho g \zeta_0^2
\end{equation}

\begin{equation}
C_{g0} = \frac{1}{2} C_0 \left( 1 + \frac{2k_0d}{\sinh 2k_0d} \right)
\end{equation}

Substitution of equation (11) and (14) in equation (13) gives an expression for the wave amplitude \( \zeta_a \):

\begin{equation}
\zeta_a = \zeta_0 \sqrt{\frac{\omega_i C_{g0}}{\omega_a (U_c + C_{gi})}}
\end{equation}

2.2. Stochastic wave-current model

The wave spectrum and uniform current are defined in the fixed frame (see Figure 1). This is convenient since offshore the wave spectrum will be measured with a current present. The wave spectrum together with the equations of the regular wave-current model are used to generate random waves. Hedges [2] gives a formulation for the effect of currents on wave spectra

\begin{equation}
S_C(\omega, U) = S_C(\omega) \frac{\omega_i^2}{\omega_a^2} \frac{1}{1 + \frac{2U \omega_i}{g}}
\end{equation}

The wave spectrum together with the modified complex receptances \( H_u \) and \( H_a \) [6] for the horizontal velocity \( u \) and horizontal acceleration \( a \) give the velocity and acceleration spectra.

\begin{equation}
H_u(\omega_{im}) = \omega_{im} \frac{\cosh k(d+z)}{\sinh(kd)}
\end{equation}

\begin{equation}
H_a(\omega_{im}) = -i \omega_{im}^2 \frac{\cosh k(d+z)}{\sinh(kd)}
\end{equation}

Here \( \omega_{im} \) is the intrinsic wave frequency and wave number \( k \) is found by solving the dispersion equation (5).

The velocity spectrum \( S_u(\omega, U) \) is

\begin{equation}
S_u(\omega, U) = |H_u(\omega)|^2 S_C(\omega, U) = \omega_i^2 \frac{\cosh^2 k(d+z)}{\sinh^2(kd)} S_C(\omega, U)
\end{equation}

and the acceleration spectrum

\begin{equation}
S_a(\omega, U) = |H_a(\omega)|^2 S_C(\omega, U) = \omega_i^2 S_u(\omega, U)
\end{equation}

The effect of the current on the spectra with and without wave-current interaction is shown in Figure 4, 5, 6 for the following conditions.

(i) No current;
(ii) \( U_c = 0.8 \text{ m/s} \), no wave-current interaction;
(iii) \( U_c = -0.8 \text{ m/s} \), no wave-current interaction;
(iv) \( U_c = 0.8 \text{ m/s} \), with wave-current interaction;
(v) \( U_c = -0.8 \text{ m/s} \), with wave-current interaction.
The input wave spectrum has the following input $H_s = 1.5m$, $T_p = 5s$ and $\gamma = 3.3$. The effect of an adverse current on the acceleration spectra is clearly visible.

Figure 4 shows that the wave spectrum changes when wave-current interaction is applied. This corresponds with the results presented by Hedges [2] (Figure 10). Figure 5 and Figure 6 show the effect of the current on the horizontal water particle velocity and acceleration spectra. The effect of the combined action of wave and current is clearly visible for wave frequencies above 0.2Hz. This is the same frequency range the frequency of the first eigenmode is active 0.2-0.35Hz. The changes in the wave kinematics due to the current can cause changes to the drag an inertia load on offshore structures [7].

**Figure 4.** Wave spectra with and without current and/or wave-current interaction.

**Figure 5.** Spectra of horizontal velocity with and without current and/or wave-current interaction.

**Figure 6.** Spectra of horizontal acceleration with and without current and/or wave-current interaction.

3. Definition of ART 5MW offshore wind turbine and the fatigue load cases
For the calculation of the fatigue life ECN’s Aerodynamic Reference wind Turbine (ART 5MW) is used together with metocean data based on the IJmuiden shallow water site as defined in work packages 4 of the UPwind project [4].

The ART 5MW is the NREL 5MW wind turbine [9] with the aerodynamic blade and controller redesigned by ECN [10]. For the ART 5MW wind turbine the blade design is derived from the 62.6m long blade designed in the DOWEC-project [11]. A summary of the main parameters of
the ART 5MW is given in Table 1. The support structure is the monopile and tower as defined in the OC3-project [12] with the soil stiffness as derived by Passon [13]. The water depth is 20m. The wave loads are calculated with Morison equation [14] with drag coefficient $C_d = 0.7$ and inertia coefficient $C_m = 2.0$. For the application of the wave-current model on a floating structure applying potential flow theory the interested reader is referred to Wichers [15].

The fatigue life is calculated for normal production wind speeds from 6m/s to 24m/s. The environmental data, wind and wave conditions, used is presented as lumped scatter diagram in Table 2. A tidal current $U_c = 0.8$m/s is used for all cases, where a positive current velocity $U_c$ means a following current and a negative current velocity $U_c$ is an opposing current. In total six wind, wave-current conditions are considered:

(i) No waves (wind only);
(ii) Waves only (no current);
(iii) Waves $U_c = 0.8$m/s;
(iv) Waves $U_c = -0.8$m/s;
(v) Waves + interaction $U_c = 0.8$m/s;
(vi) Waves + interaction $U_c = -0.8$m/s;

Each wave-current conditions consist of ten simulations. One simulation for each wind speed and its associated sea state. For comparison reasons for each wind speed the same wind field is applied for all wave-current conditions. Each wind speed having its own random seed. Also for each sea state the same random seed is used. The duration of each simulation is 3600s. The simulations are performed with ECN’s aeroelastic code PHATAS [16].

The fatigue loads are calculated by rainflow count for 64 bins filtering the ranges smaller than 10% of the maximum range. The 1Hz equivalent fatigue load is calculated in the support structure for a slope of the S-N curve $m = 3$.

Table 1. Summary of the main parameters of the ART 5MW wind turbine.

| Rating       | 5MW                             |
|--------------|---------------------------------|
| Wind regime  | IEC61400-3(Offshore) Class1B    |
| Cut in/out wind speed | 4m/s - 25m/s                |
| Rotor orientation | Upwind                        |
| Rotor diameter/ Hub diameter | 128.4m/ 3m                  |
| Hub height   | 90m                             |
| Rated rotor speed | 12.1rpm                      |
| Control      | Variable speed, collective pitch|
| Maximum pitch acceleration | 12deg/m²                   |
| Maximum pitch speed | 6deg/s                    |
| pitch angle range | 0 to 90deg                 |

4. Results
The 1Hz equivalent fatigue load of the fore-aft overturning moment at the seabed is determined. The fatigue analysis is done first for the fatigue of the individual one hour simulations. Table 3 shows the 1Hz equivalent load for each wind speed. The wind, wave-current condition with waves only (no current) is taken as reference (100%) for the other conditions.
Table 2. Lumped scatter diagram of the given offshore site (sorted Wind bins). See Table 18 of the Upwind report [4].

| V [ms] | TI [%] | Hs [m] | Tp [m] | peakness | occ./year | hrs |
|--------|--------|--------|--------|----------|-----------|-----|
| 2      | 29.2   | 0.91   | 5.83   | 3.3      | 0.04839   | 423.9 |
| 4      | 20.4   | 0.97   | 5.65   | 3.3      | 0.13541   | 1186.2 |
| 6      | 17.5   | 1.03   | 5.46   | 3.3      | 0.16407   | 1437.3 |
| 8      | 16.0   | 1.14   | 5.39   | 3.3      | 0.15875   | 1390.7 |
| 10     | 15.2   | 1.33   | 5.5    | 3.3      | 0.15748   | 1379.5 |
| 12     | 14.6   | 1.57   | 5.79   | 3.3      | 0.11817   | 1035.2 |
| 14     | 14.2   | 1.84   | 6.15   | 3.3      | 0.08157   | 714.6 |
| 16     | 13.9   | 2.2    | 6.64   | 3.3      | 0.06080   | 532.6 |
| 18     | 13.6   | 2.56   | 7.0    | 3.3      | 0.03455   | 302.6 |
| 20     | 13.4   | 2.96   | 7.41   | 3.3      | 0.02098   | 183.8 |
| 22     | 13.3   | 3.34   | 7.86   | 3.3      | 0.01059   | 92.8 |
| 24     | 13.1   | 3.63   | 8.21   | 3.3      | 0.00412   | 36.1 |
| 26     | 12.0   | 4.14   | 8.7    | 3.3      | 0.00185   | 16.2 |
| 28     | 11.9   | 4.32   | 8.95   | 3.3      | 0.00056   | 4.9 |
| 30     | 11.8   | 4.59   | 9.05   | 3.3      | 0.00020   | 1.8 |
| 32     | 11.8   | 5.09   | 9.54   | 3.3      | 0.00006   | 0.5 |
| 34-42  | 11.7   | 4.82   | 9.42   | 3.3      | 0.00003   | 0.3 |

Table 4 gives the 1Hz fatigue load for a 20-year fatigue life. Using the probability of occurrence for each of the ten wind speeds as given in Table 2. Again the results of the different wind, wave-current conditions are shown.

Table 3. 1Hz Equivalent fatigue load of fore-aft moment at seabed for every wind speed

| Wind speed m/s | No waves 100% | Waves only Uc = 0.8 m/s | Waves Uc = -0.8 m/s | Waves + interaction Uc = 0.8 m/s | Waves + interaction Uc = -0.8 m/s |
|----------------|----------------|--------------------------|----------------------|---------------------------------|----------------------------------|
| 6.0            | 57%            | 9.02E+06                 | 97%                  | 104%                            | 86%                              |
| 8.0            | 68%            | 1.06E+07                 | 97%                  | 104%                            | 88%                              |
| 10.0           | 73%            | 1.20E+07                 | 98%                  | 102%                            | 91%                              |
| 12.0           | 87%            | 1.93E+07                 | 99%                  | 105%                            | 96%                              |
| 14.0           | 86%            | 2.19E+07                 | 98%                  | 102%                            | 97%                              |
| 16.0           | 86%            | 2.46E+07                 | 98%                  | 99%                             | 94%                              |
| 18.0           | 88%            | 2.69E+07                 | 99%                  | 101%                            | 95%                              |
| 20.0           | 89%            | 3.06E+07                 | 99%                  | 102%                            | 96%                              |
| 22.0           | 91%            | 3.37E+07                 | 99%                  | 100%                            | 98%                              |
| 24.0           | 92%            | 3.75E+07                 | 99%                  | 101%                            | 99%                              |
| 26.0           | 93%            | 4.15E+07                 | 100%                 | 102%                            | 101%                             |
| 28.0           | 93%            | 4.55E+07                 | 100%                 | 103%                            | 102%                             |
| 30.0           | 94%            | 4.95E+07                 | 101%                 | 104%                            | 103%                             |
| 32.0           | 94%            | 5.35E+07                 | 101%                 | 105%                            | 104%                             |
| 34.0           | 95%            | 5.75E+07                 | 102%                 | 106%                            | 105%                             |
| 36.0           | 96%            | 6.15E+07                 | 102%                 | 107%                            | 106%                             |
| 38.0           | 96%            | 6.55E+07                 | 103%                 | 108%                            | 107%                             |
| 40.0           | 97%            | 6.95E+07                 | 103%                 | 109%                            | 108%                             |
| 42.0           | 97%            | 7.35E+07                 | 104%                 | 110%                            | 109%                             |
| 44.0           | 98%            | 7.75E+07                 | 104%                 | 111%                            | 110%                             |
| 46.0           | 98%            | 8.15E+07                 | 105%                 | 112%                            | 111%                             |
| 48.0           | 99%            | 8.55E+07                 | 105%                 | 113%                            | 112%                             |
| 50.0           | 99%            | 8.95E+07                 | 106%                 | 114%                            | 113%                             |
| 52.0           | 99%            | 9.35E+07                 | 106%                 | 115%                            | 114%                             |
| 54.0           | 100%           | 9.75E+07                 | 107%                 | 116%                            | 115%                             |
| 56.0           | 100%           | 1.02E+08                 | 107%                 | 117%                            | 116%                             |
| 58.0           | 100%           | 1.06E+08                 | 108%                 | 118%                            | 117%                             |
| 60.0           | 100%           | 1.10E+08                 | 108%                 | 119%                            | 118%                             |
Table 4. 1Hz Equivalent fatigue load of fore-aft moment at seabed for a 20-year fatigue life.

| Case                              | Equivalent Fore-aft OTM [NmHz] | percentage |
|-----------------------------------|--------------------------------|------------|
| No Waves                         | 0.1581E+08                     | 86%        |
| Waves only                        | 0.1844E+08                     | 100%       |
| Waves Uc = 0.8 m/s               | 0.1818E+08                     | 99%        |
| Waves Uc = -0.8 m/s              | 0.1878E+08                     | 102%       |
| Waves + interaction Uc = 0.8 m/s | 0.1757E+08                     | 95%        |
| Waves + interaction Uc = -0.8 m/s| 0.2038E+08                     | 111%       |

5. Discussion
The 1Hz fatigue loads of the one hour simulations in Table 3 show that the fatigue of the overturning moment at the seabed is dominated by the wind loads. Cases with combined action of wave and current show an increase in fatigue load in case of an opposing current and a reduction in case of a following current. This is valid both for the case with wave-current interaction and for the case without wave-current interaction. Without current-interaction the effect of the current is a few percent. In case the wave-current interaction is included the reduction and increase in fatigue load is largest. For the below rated wind speed with opposing current the increase is more than 20%. Above rated the increase is about 8%.

In Table 4 the fatigue loads for a 20-year life time show that without wave-current interaction the difference in fatigue load is small, a 1% reduction for following current and a 2% increase for opposing current. In case of wave-current interaction this is 5% and 11% respectively.

6. Conclusions
In this paper the fatigue loading on the ART 5MW due to combined action of waves and current is studied. Two effects of an uniform current on waves are modelled. First there is a frequency shift, Doppler effect, for the fixed observer when the wave travels on a current. Second, the shape of the wave is modified in the cases where the wave travels from an area without current into an area with current, the so-called wave-current interaction.

The following can be concluded:

- For a 5MW turbine in 20m water depth, wind contributes most to the fatigue load in case of normal productions 57% - 92% with increasing wind speed;
- The wave-current loads due to the Doppler-effect only (without interaction) show for a one hour simulation a reduction of 2% and an increase of maximum 5% in the fatigue load;
- Wave-current interaction gives for a one hour simulation a fatigue load reduction (max 14%) in the case of following current and an increase (max 33%) in the case of opposing current;
- The effect of wave-current interaction is largest for below rated wind speeds;
- For the 20-year fatigue life the case with wave-current interaction shows a reduction of 5% and an increase of fatigue load of 11 % without wave-current interaction the change in 20-year fatigue life is negligible.

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