RISK-BASED DECISION SUPPORT FOR OFFSHORE WIND TURBINE INSTALLATION AND OPERATION & MAINTENANCE

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Agenda

- Research Motivation
- Description of the software tool in question.
- Short term validation input. Weather and vessel model.
  - Position
  - Input variables
  - Hywind Rotor-Lift installation phases
  - Limit states under consideration
- Types of limit states
- Procedure for estimating Probabilities of Failed Operations
- Proof of concept. DEMO
- Probability based Decision Making.
  - Limit State Probabilities of Failure
  - Operation Failure rate
  - Weather window estimation
- Long term validation for summer 2014.
- Risk Based Decision Making
- Conclusions and discussion
Motivation

State-of-the-art in assessing whether a weather sensitive offshore operation is safe to commence is only based on significant wave height $H_s$ and wind speed at the location in question. The actual limitations of installation are mostly physical:

- strength of the installation equipment used - crane cable loads, tug wire tensions, etc.
- Limits on the equipment being installed – maximum acceleration limits on wind turbine nacelle/rotor components.
- safe working environment conditions – motions and accelerations at the height/location of the installation limiting or prohibiting the installation crews work.

Transition from limits on weather conditions to limits on physical response criteria in decision making would improve the predictions of weather windows for installation and potentially reduce the cost of energy.

Operation phase input (cranes, vessels, lifting equipment, etc.) → Hydrodynamic multibody motion simulator → Time series of relevant responses (equipment loads, motions) → Operational Acceptance limits (maximum crane loads, allowable motions) → STATISTICAL MODEL → Estimates of Probability of Operation Failure → Decision making based on combination of Costs and Probabilities of failed operations.
DECOFF – Example test case

Hywind Rotor-Lift Operation

Phase 1  Phase 2  Phase 3  Phase 4  Phase 5  Phase 6
Transition to field 8 hours  Preparation for lift 3 hours  Rotor lift up 0.2 hours  Rotate rotor 0.2 hours  Lift-up close to nacelle 0.4 hours  Connecting rotor to nacelle 0.3 hours

Total duration 12.1 hours

Test case:
- Phases 3-6 – barge is at the installation position, rotor is lifted up and bolted to the nacelle.
Limiting operational parameters

Hywind Rotor-Lift Operation

Phase 1: Transition to field
- 8 hours

Phase 2: Preparation for lift
- 3 hours

Phase 3: Rotor lift up
- 0.2 hours

Phase 4: Rotate rotor
- 0.2 hours

Phase 5: Lift-up close to nacelle
- 0.4 hours

Phase 6: Connecting rotor to nacelle
- 0.3 hours

Phase 3 Operation Limits
- Crane Load
- Lift Wire Tension
- Tug Wire Tension
- Airgap between blades and waves
- Rotor acceleration
- Rotor rotational acceleration
- Rotor Sway motion
- Rotor Surge motion

Phase 6 Operation Limits
- Relative yaw angle between rotor and special tool
- Relative tilt angle between rotor and special tool
- Relative axial velocity
- Relative radial velocity
- Airgap between blade 3 and tower
Short term Validation. Simulation input - weather

Location: 7 ° W 55.25 ° N
FINO 3 site
Forecast: ECMWF 2013
2013-08-06

51 ensemble members containing up to 250 hours lead time forecast.

- Wind speed and direction.
- Sig wave height and peak and direction.
- Swell sig wave height and mean period and direction.
Short term Validation. Simulation input - weather
Types of limit states

Non-exceedance limit state. The response has to be above the acceptance limit (no slack in lifting cables, tug wires, tower clearance etc.).

Exceedance limit state. The response has to be below a certain acceptance limit (maximum motions, loads on lifting equipment etc.).

Evaluation of non-exceedance function at acceptance limit $R_{\text{max}}$.

\[ P_{F,\text{ens}} = F_{\text{non-exc,ens}}(R_{\text{max}}) \]

Evaluation of exceedance function at acceptance limit $R_{\text{max}}$.

\[ P_{F,\text{ens}} = P_{\text{exc,ens}}(R_{\text{max}}) \]
Types of limit states continued

**Deterministic limit state.** Defined by a single value of acceptance/ failure limit.

**Non-deterministic limit state.** Defined by a distribution of the acceptance limit.

Evaluation of CDF at the acceptance limit $R_{max}$.

\[ P_{F,ens} = P_{F,exc,ens}(R_{max}) \]

Integral of response CDF multiplied with “strength” PDF within acceptance limit range.

\[ P_{F,ens} = \int P_{exc,ens}(R) \cdot f(R|\mu_{ln}, \sigma_{ln})dR \]
Types of limit states continued

**Deterministic limit state.**
Defined by a single value of acceptance/failure limit.

**Non-deterministic limit state.**
Defined by a distribution of the acceptance limit.

Evaluation of CDF at the acceptance limit $R_{max}$.

$$P_{F,ens} = P_{F,exc,ens}(R_{max})$$

Integral of response CDF multiplied with “strength” PDF within acceptance limit range.

$$P_{F,ens} = \int P_{exc,ens}(R) \cdot f(R|\mu_{ln}, \sigma_{ln})dR$$
Procedure of Failure Probability estimation

Weather forecasts are passed through hydro-elastic simulator and response time series are analysed statistically in order to obtain Probabilities of Failed operations:

1. Peak Over Threshold method is applied to extract extreme values of relevant responses (R) (with $E(R) + 1.4 \cdot \sqrt{VAR(R)}$ threshold and 5 response cycles time separation).
Procedure of Failure Probability estimation

2. Weibull or Normal distribution (adjusted for number of peaks after POT) is fitted to the extremes using Maximum Likelihood parameter estimation.

3. Steps 1-2 are repeated for 51 forecast ensembles.

4. The Probability of Failure for one limit state is an average over 51 ensembles. Combining up all the limits states in one phase gives Probability of failure within an operation phase.

\[
P_{F,\text{Lim State}} = \frac{\sum_{i=1}^{N} P_{F,\text{Ensemble}}}{\text{number of ens}}
\]

\[
P_{F,\text{Operation}} = 1 - \prod_{i=1}^{N_{\text{Lim States}}} (1 - P_{F,\text{Lim State},i})
\]

\[
P_{F,\text{Operation}} = 1 - \prod_{i=1}^{N_{\text{Phases}}} (1 - P_{F,\text{Phase},i})
\]
Proof of Concept. Short Term Validation
Combination of Limit state Probabilities of Failure

Hywind Rotor-Lift Operation

Phase 1: Transition to field 8 hours
Phase 2: Preparation for lift 3 hours
Phase 3: Rotor lift up 0.2 hours
Phase 4: Rotate rotor 0.2 hours
Phase 5: Lift-up close to nacelle 0.4 hours
Phase 6-7: Connecting rotor to nacelle 0.3 hours

\[ P_{F, \text{Crane Load}, \text{Ph 3}} + P_{F, \text{Crane Load}, \text{Ph 4}} + P_{F, \text{Crane Load}, \text{Ph 5}} = \]

\[ P_{F, \text{Air Gap Blade Water}, \text{Ph 2}} + P_{F, \text{Air Gap Blade Water}, \text{Ph 2}} = \]

\[ P_{F, \text{Rotor Sway}, \text{Ph 3}} + P_{F, \text{Rotor Sway}, \text{Ph 4}} + P_{F, \text{Rotor Sway}, \text{Ph 5}} = \]

\[ P_{F, \text{Acceleration}, \text{Ph 3}} + P_{F, \text{Acceleration}, \text{Ph 4}} + P_{F, \text{Acceleration}, \text{Ph 5}} = \]

\[ P_{F, \text{Operation}} = 1 - \prod_{i=1}^{N_{\text{Limit States}}} (1 - P_{F, \text{Limit State}, i}) \]
Limit state Probabilities of Failure
5. A sum over all the phases gives the total Operation failure rate. Based on $P_{F,Op}$ weather windows, suitable for installation, could be found.

$$P_{F,Operation} = 1 - \prod_{i=1}^{N_{Limit\ States}} (1 - P_{F,Limit\ State,i})$$
Risk based decision making

\[ C_{total} = C_{\text{waiting}} + C_{\text{equipment}} + \sum_{i=1}^{N_{\text{phases}}} \left( \sum_{j=1}^{N_{\text{LS}}} P_{\text{LS},i,j} C_{\text{LS},i,j} \right) \]

Having Probabilities of Failure related to a particular limit state and combining those with monetary consequences of failure with particular limit state Risk Based decision making is possible.

What is needed:

- Cost in NOK (€) related to Operation Failure with a particular limit state.
- Cost in NOK (€) of complete Operation Failure for less detailed analysis (one failure results in loss of all equipment and complete Operation Failure).
Long term validation. Input

- **Location:** 7° W 55.25° N FINO 3 site.
- **Forecast:** ECMWF May 1st to August 1st 2014.
  measurements @FINO3.
- **Parameters used:**
  - Wind speed and direction.
  - Significant wave height and peak and direction.
  - Swell sig wave height and mean period and direction.
- **Hydrodynamic model:** Hywind Rotor Lift operation.
- **Benchmarking:** The proposed method is validated against a standard “Alpha-Factor” from DNV-HS-101.
- **Different benchmarking cases:**
  - Tabulated Alpha-Factors from DNV-HS-10.
  - Site specific Alpha-Factors for FINO3 site according to DNV-HS-10.
  - DECOFF method with ECMWF forecasts @FINO3.
  - DECOFF method with measurements @FINO3.
Long term validation. Alpha-Factor method

Weather limits for Hywind Rotor Lift operation:
• \( H_s = 1.5 \text{m}, T_p = 5 \text{s}, W_s = 7 \text{m/s}. \)

<table>
<thead>
<tr>
<th>Case</th>
<th>( \alpha_{Hs} ) for ( H_s = 1.5 \text{m} )</th>
<th>( \alpha_{Tp} ) for ( T_p = 5 \text{s} )</th>
<th>( \alpha_{Ws} ) for ( W_s = 7 \text{m/s} )</th>
<th>Quantile</th>
</tr>
</thead>
<tbody>
<tr>
<td>T 4-1. WFQ = C</td>
<td>0.705</td>
<td>inf</td>
<td>0.78</td>
<td>1</td>
</tr>
<tr>
<td>T 4-2. WFQ = B</td>
<td>0.740</td>
<td>inf</td>
<td>0.78</td>
<td>1</td>
</tr>
<tr>
<td>T 4-3. WFQ = A+M</td>
<td>0.780</td>
<td>inf</td>
<td>0.78</td>
<td>1</td>
</tr>
<tr>
<td>T 4-4. WFQ = A+C</td>
<td>0.925</td>
<td>inf</td>
<td>0.78</td>
<td>1</td>
</tr>
<tr>
<td>T 4-5. WFQ = A+M+C</td>
<td>0.925</td>
<td>inf</td>
<td>0.78</td>
<td>1</td>
</tr>
<tr>
<td>FINO3 measurements</td>
<td>0.810</td>
<td>inf</td>
<td>0.78</td>
<td>1</td>
</tr>
</tbody>
</table>

T x-y – table indicator for reference in DNV-HS-10;
WFQ – weather forecast quality class A, B or C.
+M – meteorologist on site, +C – calibrated based on measurement data.
Long term validation. Alpha-Factor method

Weather limits for Hywind Rotor Lift operation:
- $H_s = 1.5\text{m}$, $T_p = 5\text{s}$, $W_s = 7\text{m/s}$.

**T x - y - table indicator for reference in DNV-HS-10;**

**WFQ - weather forecast quality class A, B or C.**

+M - meteorologist on site, +C - calibrated based on measurement data.
Long term validation. Results

Alpha-Factor method

DECOFF method with ECMWF

Total of 12 Weather Windows

Total of 18 Weather Windows
Long term validation. Results

Alpha-Factor method

DECOFF method with FINO3 measurements
Long term validation. Results

Number of weather windows

- **αₚ = 1**
- **αₚ = 0.79**

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of Weather Windows</th>
</tr>
</thead>
<tbody>
<tr>
<td>T.4-1</td>
<td>23</td>
</tr>
<tr>
<td>T.4-2</td>
<td>22</td>
</tr>
<tr>
<td>T.4-3</td>
<td>22</td>
</tr>
<tr>
<td>T.4-4(5)</td>
<td>22</td>
</tr>
<tr>
<td>FINO3 Data</td>
<td>14</td>
</tr>
<tr>
<td>DECOFF FINO3</td>
<td>31</td>
</tr>
<tr>
<td>DECOFF ECMWF</td>
<td>17</td>
</tr>
</tbody>
</table>
Long term validation. Results

Total Length of weather windows

- $\alpha_{fp} = 1$
- $\alpha_{fp} = 0.79$

<table>
<thead>
<tr>
<th>Source</th>
<th>Total Length of Weather Windows, ['']</th>
</tr>
</thead>
<tbody>
<tr>
<td>T.4-1</td>
<td>400</td>
</tr>
<tr>
<td>T.4-2</td>
<td>230</td>
</tr>
<tr>
<td>T.4-3</td>
<td>250</td>
</tr>
<tr>
<td>T.4-4(5)</td>
<td>230</td>
</tr>
<tr>
<td>FINO3 Data</td>
<td>100</td>
</tr>
<tr>
<td>DECOFF FINO3</td>
<td>200</td>
</tr>
<tr>
<td>DECOFF ECMWF</td>
<td>90</td>
</tr>
</tbody>
</table>
Long term validation. Results

Length X Number of weather windows

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Num Windows X Length Windows, [L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T.4-1</td>
<td>9000</td>
</tr>
<tr>
<td>T.4-2</td>
<td>5000</td>
</tr>
<tr>
<td>T.4-3</td>
<td>5000</td>
</tr>
<tr>
<td>T.4-4(5)</td>
<td>5000</td>
</tr>
<tr>
<td>FINO3 Data</td>
<td>5000</td>
</tr>
<tr>
<td>DECOFF FINO3</td>
<td>5000</td>
</tr>
<tr>
<td>DECOFF ECMWF</td>
<td>5000</td>
</tr>
</tbody>
</table>

Legend:
- $\alpha_T^p = 1$
- $\alpha_T^p = 0.79$
Conclusions and discussion

- After extensive testing it can be concluded that the procedure for estimation of Probability of Failed Operations produces consistent results and could be used to assist in decision making for Offshore Wind Turbine installation.

- The proposed new DECOFF method performs better or at least as good as the standard “Alpha-factor” method (when number of windows x total window length measure is used).

- Weather forecast uncertainty plays a central role in predicting weather windows. With increasing uncertainty the length and number of weather windows decreases. This is on par with the standard “Alpha-factor” method.

- Using better, less uncertain, weather forecasts (calibrated weather forecasts, downscaling etc.) would be very beneficial in the performance of DECOFF method.

- Easy extension to Oil and Gas and other relevant industries.
Possible future work would include but should not be limited to:

- Updating the model with Structural Reliability techniques in order to reduce the demand on a lot of simulations necessary to obtained reliable results.
- Splitting the limit states in Serviceability and Ultimate.
- Including Costs of Failure to produce a “Risk-Based” aspect allowing to evaluate different weather windows in terms of expected Risk rather than just Probability of Failure.
- Improving the accuracy of weather forecasts.
- Extending the methodology to more general Offshore Operations (Oil and Gas, Wind turbine installation on monopoles/jackets etc.).
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ANY QUESTIONS? COMMENTS?

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