WAVE DYNAMICS WITH APPLICATIONS IN OFF-SHORE WIND TURBINE DESIGN

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ABSTRACT: Advances have been made in the field of offshore extreme wave loading modeling. We present an overview of the current wave models in use and assess their relative advantages. The described method embeds existing nonlinear solutions for the kinematics of huge, regular waves into linear, irregular seas. While similar methodologies have been used in the past, the innovative methodology is shown to improve computing efficiency, reproducibility, and precision. By restricting the linear simulation with New Wave theory, the optimal fit with the big non-linear wave was attained. To examine the influence of these models on a basic 5 MW turbine mounted on a tripod support structure, GH Bladed was used.

KEYWORDS: Constrained, Non-linear, Waves, Offshore Wind Turbine and Design.

1. INTRODUCTION

The offshore environment presents a substantial opportunity for the generation of wind energy due to its higher mean annual wind speeds and reduced visual interference. However, waves should also be taken into account as another type of environmental loading. The nonlinearity of the governing equations makes water waves challenging for computer modelers to handle. Even though there exist fully non-linear computational models, engineering has not made much use of them. Currently, one of two fundamental assumptions is used to approximate wave loads:

- Every wave follows the same pattern, looking similar to the one that came before it. Within this constraint, there are well-established, extremely accurate computational solutions known as stream functions or regular non-linear waves. The method is frequently applied to high wave events since it is still effective as wave height increases. A example illustration of a surface's height is shown in Figure 1.
- There isn't any text available. There is a linear quality to the waves. Waves with different frequencies can be superimposed to create an irregular sea state. This approach assumes a sinusoidal surface elevation, which simplifies the waves utilized. This method can be used to calculate fatigue loads and is fairly accurate when the waves are moderately steep. Figure 2 shows a surface elevation sample. When exposed to strong waves, fixed offshore structures used in the oil and gas sector typically endure the highest levels of stress.
- Regular nonlinear wave models are frequently used to illustrate design requirements, and regular waves' deterministic nature is not seen as an issue. Because offshore wind turbines are so dynamic, they are more likely to experience extreme stresses brought on by a particular combination of big waves, rotor position, and wind gusts. It would be very beneficial to incorporate a stochastic component into a wave model that maintains accuracy even at high wave heights. As previously stated, models that specifically accomplish this are mainly limited to research uses.

An appendix to the IEC 61400-3 standard for offshore wind turbines provides various approaches for taking stochastic and non-linear factors into separate consideration. The first technique involves using a steady wind that has had its velocity increased over the target level using a gust reaction factor, together with periodic non-linear waves. An other suggested method entails combining a random sea and wind, followed by adding a non-linearity component to increase the loads. Later on, we will use this strategy to make comparisons.

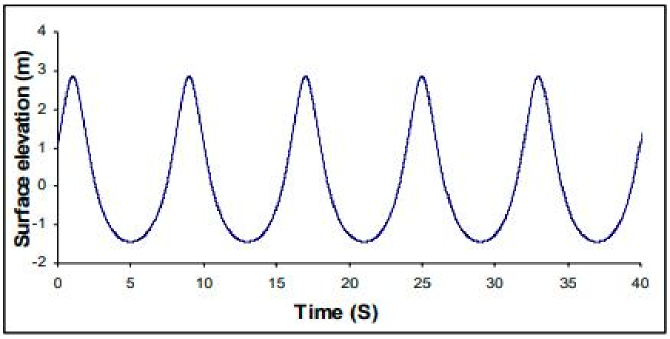

Figure 1. Non-linear regular waves

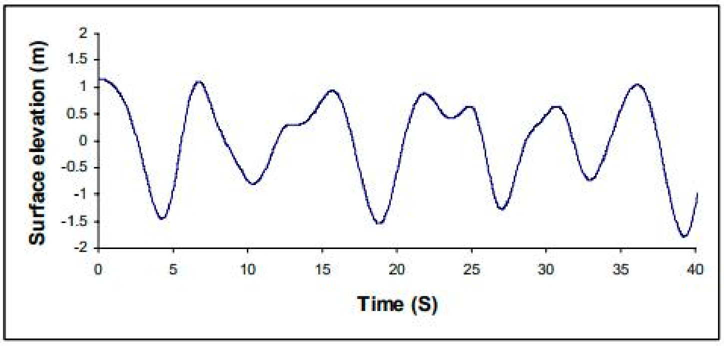

Figure2. Linear stochastic waves

2. EMBEDDED NON-LINEAR WAVES

According to IEC 61400-3, the third way involves "cutting and pasting" a large stream function wave into a stochastic, linear sea. This feature has the advantage of stochasticity, which allows for many simulations to study alternative combinations of waves and gusts. To account for the kinematics of the water surrounding the extreme wave, a realistic huge wave model is used. The extreme wave can be placed anywhere the modeler wants; pasting the stream function wave over a linear wave of similar height should result in a more realistic portrayal of the entire sea.

The two main challenges to applying this notion are determining an enormous wave to superimpose and continuously integrating the linear waves and stream function. This approach was previously used to pick an appropriate gigantic wave by doing long irregular wave simulations. After that, the huge wave would diminish and be replaced by a stream function wave. To prevent discontinuities, brief blending zones are used. In the blending region, all water parameters are calculated as a weighted average of the non-linear solution and the irregular linear sea. In water kinematics, the non-linear solution is used near the extreme crest. After a certain duration, the pure linear sea is used. The blending parameter, or weighting function, makes a progressive transition over the blending zone, starting at 100% at the crest and finishing at zero beyond a certain distance. Given the continuous nature of the resultant surface and its temporal derivative over the blending zone, the cosine function, as shown in Table 1, was chosen for implementation.

Time	Stream-function	Stochastic time history
$\lvert t-T_0\rvert > 0.75\times T$	0	1
$0.5\times T \le \lvert t-T_0\rvert \le 0.75\times T$	$0.5+0.5\cos\left(4\pi\left(\frac{\lvert t-T_0\rvert}{T}-0.5\right)\right)$	$0.5-0.5\cos\left(4\pi\left(\frac{\lvert t-T_0\rvert}{T}-0.5\right)\right)$
$\lvert t-T_0\rvert < 0.5\times T$	1	0

Table 1. Blending parameter for the stream-function solution, and the linear stochastic sea.

The relationship between the time period (T) of the extreme wave and the limited peak time (T0) is determined by the variable of time (t), which in turn affects the Blending parameter.

This technique is defective in two respects. Firstly, the task of identifying a suitably extensive linear wave is computationally inefficient. Extensive simulations are often required before a sufficiently large wave develops randomly. Furthermore, the colossal wave often exhibits asymmetry, indicating that the depth of the preceding trough varies from that of the subsequent one. Consequently, the mixing process is exceedingly disordered. Figure 3 displays a sample surface elevation that represents the non-linear regular wave, the linear sea, and the resulting combination of the two. The blended solution exhibits an unphysical discontinuity due to the significant disparity in size between the preceding dip and the non-linear wave. In order to address these two issues, we employed restricted wave frequencies.

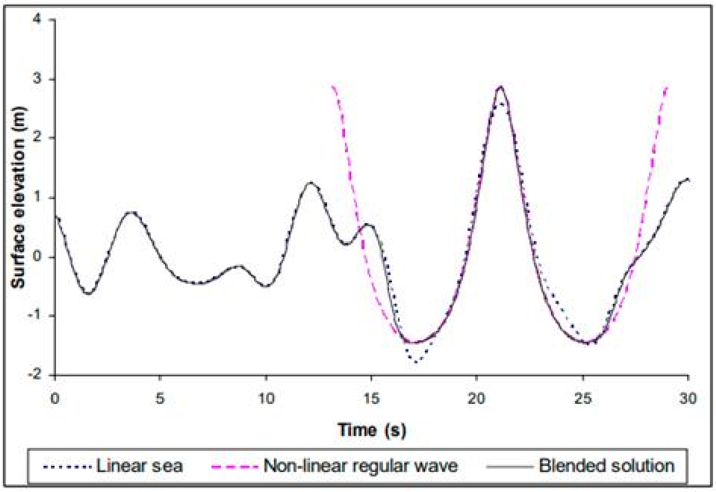

Figure 3. Embedded non-linear wave, previous method

Advancements in Wave Theory and Limited Waves One of the most basic and most researched types of stochastic processes is the Gaussian process, which includes linear sea states as an example. Although it's possible for the surface elevation to be anywhere at any one moment, it's much more probable to be close to the still water level than very above. Consequently, the surface elevation should follow a normal distribution, which is the probability distribution of the linear sea state, which is a Gaussian process. The probability distribution for a typical time series is overlayed in Figure 4, and the standard deviation is directly proportional to the significant wave height.

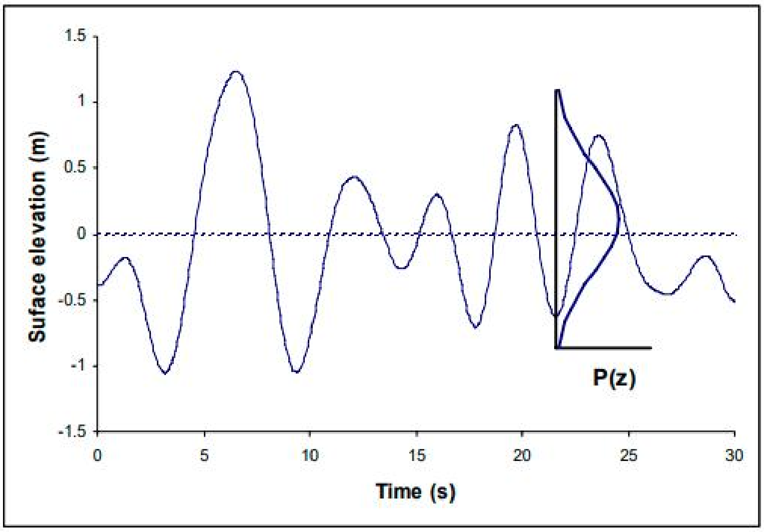

Figure 4. Probability distribution of the surface elevation is a linear stochastic sea.

After a brief amount of time, the sea surface is expected to be substantially closer to the given elevation rather than zero when it is at a specific elevation above the mean water level at one point (notably less than the duration of a typical wave period). Unlike the original normal distribution, the significant wave height and the frequency content of the sea state will determine the conditional probability distribution of the new surface elevation (assuming the surface has passed through the defined elevation). The New Wave theory, as shown in Figure 5, was developed by analyzing the surface elevation surrounding a massive crest and determining the conditional probability distribution, which consists of the surface elevation's mean and standard deviation, assuming that a stationary point of elevation X existed at time T.

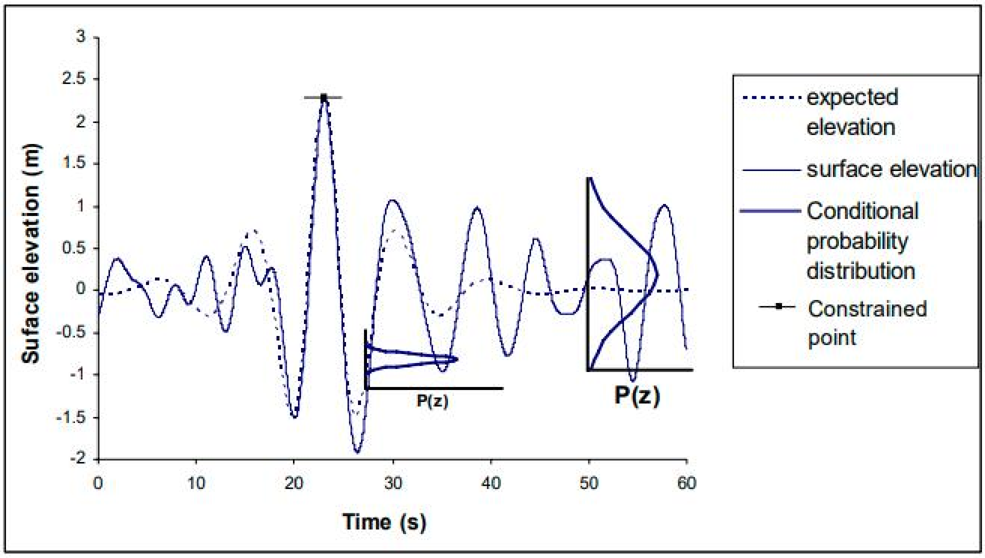

Figure 5. Conditional probability distribution for a constrained linear sea.

This not only allows for the determination of the most probable form of a large crest, but it also facilitates the execution of a restricted simulation. Linear sea state computer simulations can be adjusted to conform to the conditional probability distribution and maintain a fixed point at any specified height and period. This method can serve as an alternative to doing many simulations in order to find a wave with the appropriate height, hence conserving substantial computational resources.

3. OUR METHOD

We successfully integrated our innovative wave modelling technique with GH Bladed. GH Bladed, an integrated software suite, allows users to do full performance and loading calculations required for the design and certification of onshore and offshore wind turbines. Bladed offers complete hydroelastic and aeroelastic modeling to determine combined wind and wave loading.

Our system relies heavily on replicating a suitably sized wave in the background sea conditions with a small number of linear waves. The simulated wave is then partially replaced by a non-linear regular wave. We have increased our usage of limited waves to address the problem of merging the linear sea into typical wave settings. Furthermore, we feel we are pioneers in integrating this approach into a wind turbine design tool. Constraints are positioned in the depressions on both sides, requiring the water surface to reach a certain peak. The desire to investigate peaks drove the development of new wave theory. However, from a mathematical standpoint, the theory merely states that the time derivative of surface elevation is zero at the point of interest. Thus, the same approaches can be used to create a confined channel, with the exception of showing a considerably low surface height.

In GH Bladed, the user can set the wave height, period, and occurrence time limits. The elevation of the troughs is obtained by first running the nonlinear regular wave model. The next step is to define six constraints, which consist of three surface elevations and three zeros of the surface elevation time derivative. The linear sea state model is then developed using the same manner as in the previous approach and combined with the nonlinear wave. Despite the same blending technique, the trough limitations ensure a high degree of conformity between the linear sea state and the nonlinear wave in the blending zones. Without the blending, the surface elevation model would not account for the water's velocities, accelerations, and pressures across the whole water column. Mixing is still required because these components were not included in the limiting phase. Figure 6 shows the resulting time history.

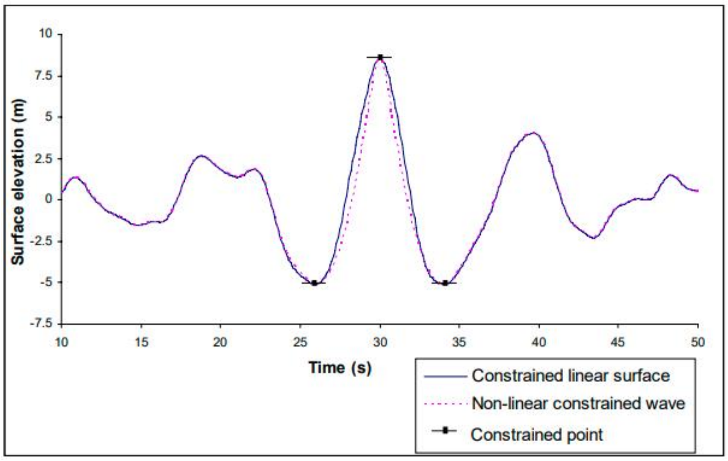

Figure6. Non-linear wave embedded in stochastic linear sea using the new method of constraining the linear sea at three points.

The The advantages of limiting the deep valleys of the powerful wave become evident when comparing the vertical patterns of water particle movements in the linear sea and the non-linear wave. The blending process initiates at the low points of the non-linear wave, hence improving accuracy due to the matching velocity profile of the linear sea at that specific moment. Figure 7 depicts vertical profiles of the horizontal velocity of water particles. The velocity profiles presented were derived using the stream function solution and six constrained linear simulations incorporating the nonlinear wave. Three of the linear seas were exclusively located at the highest point, while three were additionally restricted at neighboring low points. The image demonstrates that incorporating additional restricted points leads to simulations with velocity profiles that exhibit a significantly higher degree of alignment with the stream function solution.

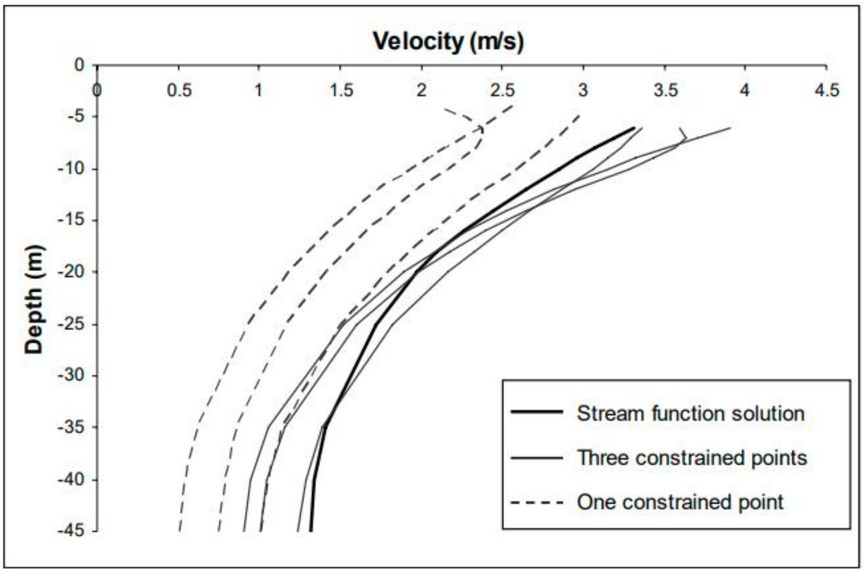

Figure 7. Comparison of velocity profiles at trough of constrained wave.

An examination in contrast to the wave non-linearity factor approach to quantifying non-linearity.

Both the "cut and paste" method and the wave non-linearity factor approach conserve time by employing a reduced quantity of waves. As per the proposed IEC 61400-3 standard, the simulation must operate for a minimum of six one-hour periods for any combination of extremely tumultuous wind speed and extremely stochastic sea state. However, the number of simulations can be reduced to six 600-second trials through the use of limited waves. This results in a significant reduction of 600% in computation time.

Design load case simulations were conducted using GH Bladed for a basic 5 MW turbine affixed to a tripod support structure. The extreme wave was represented using two distinct approaches: our newly developed constrained non-linear wave method and the wave non-linearity factor approach, which incorporates constrained linear waves.

The results indicated that elevated structural loads were frequently attributable to linear severe wave models. Initially, this result may appear unexpected, but it actually exposes a potential flaw in the application of constrained linear wave models. Uneven in elevation, the two troughs adjacent to the highest crest of the linear confined wave do not coincide. When the vertical distance between the crest and the mean of the two adjacent trough levels is used to define the height of an extreme wave, it is common for one side of the wave to appear considerably taller than the other, and in some cases, considerably taller. Greater tensions may result from the kinematics of the water particles on the upper side of the wave compared to a wave height that is more precisely controlled in the model. Determining the height of a wave using the taller of two wave faces would constitute a non-conservative approach. The application of the new method results in the limited non-linear wave exhibiting symmetry, thereby eliminating any ambiguity pertaining to the height of the wave.

It is recommended, according to IEC 61400-3, to multiply the ultimate loads by the appropriate wave non-linearity factors when utilizing the linear restricted wave. To ascertain this, conventional wave simulations that encompass both linear and non-linear waves are employed. Divide the greater loads in the non-linear example by the loads in the linear case to determine the non-linearity factor. The factor is applied to the final loads obtained from the linear constrained wave simulation. It is necessary to independently compute these parameters for every burden component. It is imperative to bear in mind that the utmost load typically applies to each load component at a distinct moment. As a result, it is necessary to conduct two simulations for each load component to accurately determine the non-linearity factor, which considers the wind speed and wave height that contribute to the final load. As a consequence, the computation time for structures featuring tripod and jacket designs is significantly prolonged. Accurately determining the wind speed and wave height at the location of maximum tension is also more difficult than it may appear. The subsequent burdens experienced by a dynamic structure are influenced by the historical pattern of external loads from a specific point in time. Subsequent to the cessation of the tremendous external loads that induced them, the ultimate load consequences typically manifest. Nevertheless, our non-linear restricted wave method eliminates the requirement for additional load factor calculations.

4. CONCLUSIONS

A novel approach to simulating the adverse marine conditions necessary for the construction of offshore wind turbines is introduced in this study. The suggested approach presents a straightforward and practical means of simulating turbulent sea conditions through the integration of a non-linear steep wave model into a stochastic sea environment. The stream function solution for the strongest wave, as described by the NewWave theory, was limited to the highest point and adjacent lowest point heights by employing a linear stochastic wave train. By utilizing an appropriate blending function, the stream function wave can be incorporated into the current sea condition. Utilizing limited pulses provides two benefits. To detect significant waves in the background sea condition, long-term simulations are unnecessary. Furthermore, the integration of the stream function wave with the underlying sea condition is enhanced. In contrast to established methodologies, the novel approach provides substantial time and effort savings in computer programming and design.

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