Spectral response surfaces, designer waves and the ringing of offshore structures

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The purpose of this paper is to present a novel approach to offshore wave load analysis, the spectral response surface method, and demonstrate its application to the ringing problem. A distinguishing feature of the method is its ability to relate an extreme response to a particular ocean surface history, the "designer wave.".

We briefly overview the essential features of the method. A linear random sea can be represented by the sum of many un-correlated frequency components which obey a joint normal distribution. In many cases, a structural response (or an ocean surface property) can be expressed as a function of these frequency components and their Hilbert transforms (the same signal phase shifted by $\pi/2$). A constant value of the structural response defines a hyper-plane in the multi-dimensional space of the frequency components. Since, the statistics of the spectral components are joint normal, it is straightforward to estimate the combination of frequency components (and their phases) most likely to generate an extreme response and the probability of a response level being exceeded. We summarise the method and its application to the ringing problem more fully below.

Ringing might be described as a transient structural response which resembles that generated by an impulse excitation of a linear oscillator. The response exhibits a rapid build up and slow decay of energy concentrated around the natural frequency of the structure. It has been observed in model experiments on gravity base structures during the passage of steep wave crests. The ringing response contains frequencies that are relatively high compared to the dominant frequency of the wave field, indicating that non-linearity in the load process might determine its occurrence. In this study, Newman's long wave-length force-model [1] is used for calculating the wave loads on a column standing in a random sea. Diffraction is included in the analysis. The model allows non-linear wave forces up to the third-order to be calculated using linear wave theory as input.

We have re-formulated Newman's results in terms of the frequency components of the ocean surface elevation process and their Hilbert transforms. The frequency components are all standardised; that is transformed to unit variance and zero mean variables. By treating the structure as a single degree of freedom oscillator, the dynamic response of the structure can also be expressed in terms of the standardised variables. Using these expressions, it is possible to generate surfaces of constant response level for both static and dynamic response in the space of the spectral components of the ocean surface.

A random sea can be described by the superposition of a finite number of spectral components; these are the standarised variables each multiplied by a standard deviation to match an appropriate surface energy spectrum. Each component is narrow banded (a pure harmonic modulated by a slowly varying amplitude) and is normally distributed. As the spectral components and their Hilbert transforms are un-correlated, linear processes, they obey a joint normal distribution with zero cross correlation. Surfaces of constant probability density are concentric spheres in the space of the standardised variables representing the spectral components of the ocean surface. The probability density is highest at the origin and falls montonically as a function of distance from the origin that is independent of direction. Under these circumstances, it is straightforward to treat the response surfaces as limit states in a FORM (first order reliability method) type of analysis. The point on a surface of constant response where the distance to the origin is shortest is called the "design point." The design point is, to a good approximation, the point on the surface where a maximum is most likely to be found. The accuracy of the approximation increases as the severity of the response increases and, in consequence, the distance of the design point from the origin increases.

The design point defines the amplitude and phase of the standardised variables at the instant when the extreme occurs. Thus, it allows us to deduce the time histories of the response and related variables around the time of the extreme. These histories are the ones that are the ones most likely to be associated with a response maximum of the chosen level. Thus, in the case of the ringing problem, we can identify if ringing occurs or not; that is if ringing determines the extreme response. It allows us to identify the type of applied load history that excites a ringing response. In addition, it provides the surface history (the "designer wave") that generated the applied load and the response. Finally, we can estimate the exceedance probabilities of extreme ringing responses very efficiently. We achieve this by calculating the probability of finding a maximum above a hyper-plane tangent to the response surface at the design point.

We studied the case of a 10 m diameter column in a sea of significant wave height of 12 m and a zero crossing period of 13.5 s that obeys a JONSWAP spectrum. The water depth is 300 m. The dynamics are modelled by an oscillator with a natural frequency of 1.57 rad/s, while the peak of the surface energy spectrum is approximately 0.36 rad/s. We investigated the effects of using the Newman load model to first order, to second order and to third order and drew the following conclusions:

1. The method is tractable.
2. The non-linear terms in Newman's model have a much greater effect on dynamic response than on applied load.
3. Some ringing effects can be found in the response with only second order excitation.
4. The third order terms lead to a double impulse (positive impulse followed immediately by a negative impulse) loading that excites a strong ringing type of response. The double impulse is associated with a wave crest; the positive impulse immediately precedes it and the negative impulse follows it. Apart from the isolated

double impulse the third order excitation is insignificant. The response time series is shown in Figure 1, the associated surface history in Figure 2 and the third order component of load in Figure 3.

5. For the sea state studied, the non-linear effects and consequent ringing, lead to much larger responses for exceedance probabilities of order 1/100 and rarer.
6. The method is many times faster than random time domain simulation.

As well as presenting the ringing study and results, the paper discusses the general merits of this approach to structural analysis. The method generates ocean surface histories that generate extreme responses, "designer waves," very quickly and easily. This is potentially of great practical value since designer waves can be used to provide the type of information that would otherwise involve many hours of time domain simulation. As such, the method may be of value in engineering design as well as in general analysis.

References

[1] Newman, J.N. (1996) "Non-linear scattering of long waves by a vertical cylinder," published in "Waves and non-linear processes in hydrodynamics," pp 91-102, J. Grue et al (editors), Kluwer, The Netherlands.

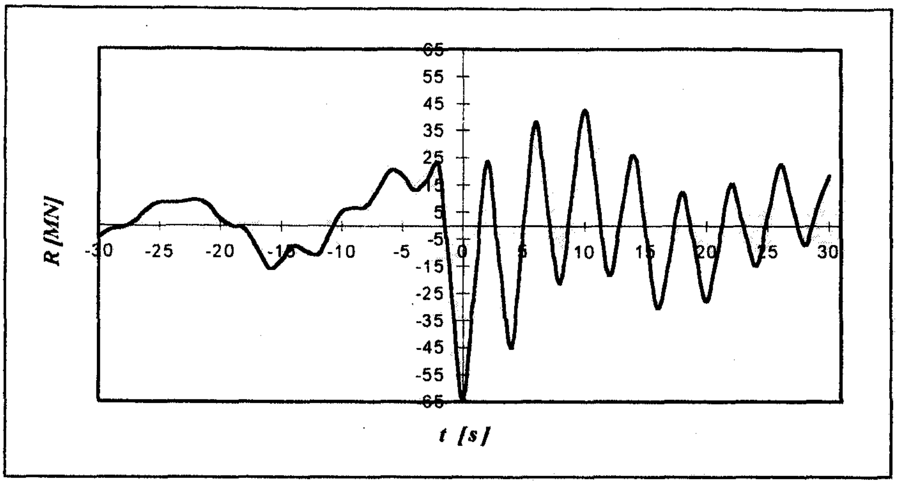

Figure 1: Negative dynamic response with first, second and third-order excitation

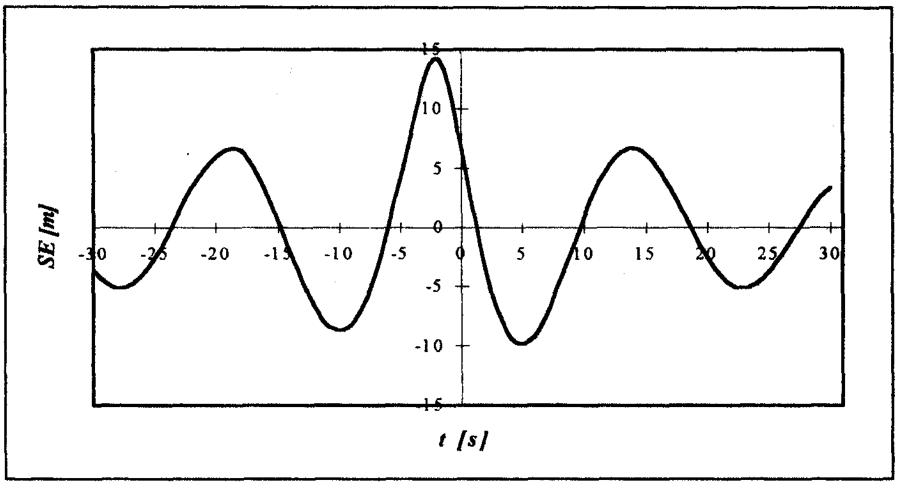

Figure 2: Surface elevation generating the response time series in Figure 1

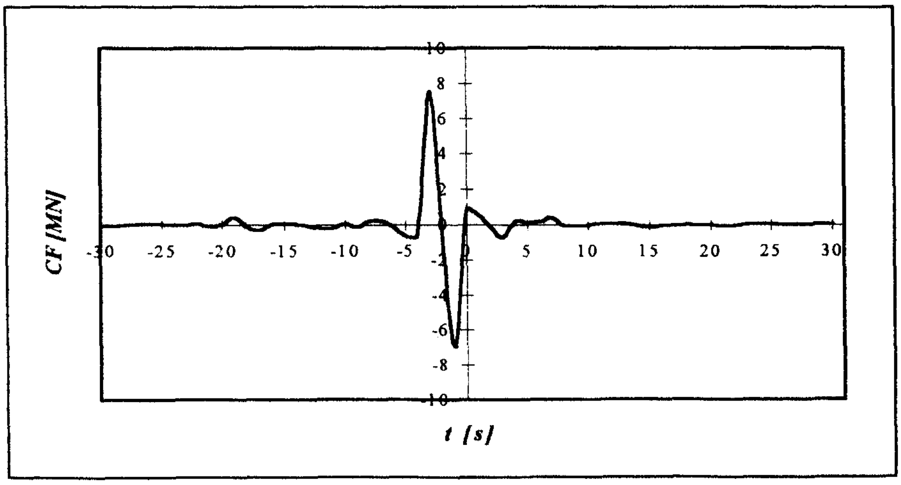

Figure 3: Third-order component of the force excitation