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RELIABILITY-BASED COMBINATION OF ENVIRONMENTAL PARAMETERS FOR THE DESIGN OF NOVEL FLOATING STRUCTURES

Baidurya Bhattacharya*, Suqin Wang, Roger Basu, Kai-tung Ma and Balji Menon

Advanced Analysis Department
American Bureau of Shipping
16855 Northchase Drive, Houston, TX 77060, USA

ABSTRACT

Reliability-based design methods are attractive in the design of novel structures as they allow a systematic treatment of uncertainties and to set performance requirements in terms of explicit safety targets. The design of a novel floating structure may be complicated by the fact that the extreme dynamic response does not always occur at the individual maxima of the environmental parameters. The environmental contour method (ECM) is an elegant and efficient means for finding the most critical environmental combination for a given type of structural response subject to a specified probability of exceedance. However, in the presence of uncertainties in the response or in the structural capacity, an ECM analysis needs to be modified, and modifications based on the FORM (first order reliability method) omission sensitivity factors have been used in the literature. Determining the omission sensitivity factors, nevertheless, needs prior knowledge of structural behavior, which is difficult or even impossible for a novel or unique structure.

This paper presents a different approach in which the conditional distribution of the response as a function of the random environmental parameters is ascertained first, following which uncertainties are introduced in the analysis as well as in the structural capacity, and the unconditional reliability is obtained. The nominal design capacity and the environment corresponding to a specified target reliability can then be obtained iteratively. A numerical example applying the proposed method to the conceptual design of a very large floating structure is presented.

INTRODUCTION

The design of conventional marine structures usually follow prescriptive rules, standards or codes which have evolved over time, and which reflect both a history of successful design as well as occasional failures. Such approaches are difficult to apply in the case of novel structures. Performance-based design criteria, which can be expressed in terms of target safety levels, are attractive in these situations. Reliability-based design methods are a natural fit because they allow a systematic treatment of uncertainties and the setting of explicit safety targets.

Reliability-based analyses, however, become complicated when the structure responds dynamically, because the extreme dynamic response in a floating structure depends among others on the configuration and geometry of the structure, and does not always occur at the individual maxima of the environmental parameters. This is particularly of concern in novel structures without any operational history.

THE ENVIRONMENTAL CONTOUR METHOD

The environmental contour method or ECM (Winterstein et al, 1993) -- an application of the inverse first order reliability method (IFORM) -- is an elegant and efficient means for finding the most critical environmental combination for a given structural response category, subject to a specified probability of exceedance, *q*. IFORM switches the direction of optimization performed in classical (or "forward") FORM, and aims to maximize the structural response $G(\underline{X})$ subject to a fixed $\beta_q = \Phi^{-1}(1\text{-}q)$, where Φ is the normal distribution function (Madsen, 1988):

* Corresponding author, email: bbhattacharya@eagle.org,
fax: 281 877 5931

$$\max G(\underline{X}) \quad \text{where} \quad \underline{X} = T(\underline{z}) \quad \text{subject to} \quad \underline{z}^T \underline{z} = \beta_q \tag{1}$$

Here, $\underline{z}$ is the uncorrelated n-dimensional standard normal vector, and T is the mapping from the $\underline{z}$ space to the space of basic variables, $\underline{X}$. A necessary condition for ECM is that the response surface be convex with respect to the origin. The optimal point is $\underline{z}^*$, the corresponding design point is $\underline{x}^* = T(\underline{z}^*)$, and the maximum response is (Figure 1),

$$r_{\max} = G(\underline{x}^*) \tag{2}$$

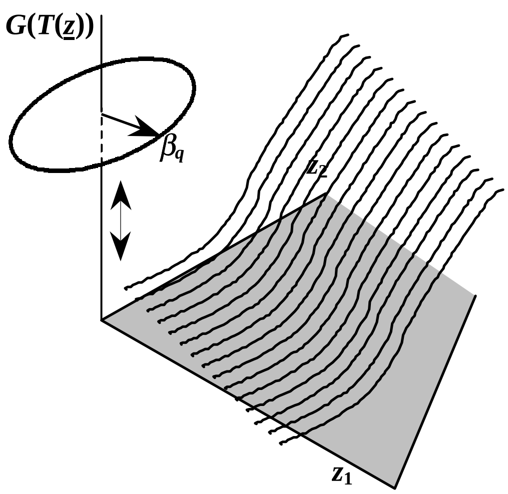

Figure 1 : Searching for maximum response

The maximum response, $r_{\max}$, obtained this way is the design response with a probability of exceedance q (subject to the limitations of FORM), and the corresponding environmental parameters, $\underline{x}^*$, is the design combination. By confining the set of all possible environmental parameters to only a contour, ECM can significantly reduce the total number of combinations used to determine the response with a specified probability of exceedance.

PRESENCE OF UNCERTAINTY

If the response is deterministic (i.e., $G(\underline{X})$ given $\underline{X} = \underline{x}$ is a non-random function) and the structural capacity is non-random, then designing for the most critical response, $r_{\max}$, ensures a reliability of 1-q. However, several sources of uncertainty (intrinsic as well as extrinsic) may exist in the analysis and design, causing a reduction in the reliability. In such situations, an *inflated contour* or an *inflated response* or a combination of the two have been incorporated in the existing literature to compensate for the added uncertainty (Winterstein et al, 1996; Niedzwecki et al, 1998) in order to retain the above ECM-based procedure. Such contour or response inflation procedures are based on FORM omission sensitivity factors (Madsen, 1988).

Computation of omission sensitivity factors, however, requires the "unreduced" limit state function, which in turn requires prior and reasonably accurate knowledge of the behavior of the structure under consideration. For a novel and complex structure in its design stages, the limit state function may be difficult, or even impossible, to ascertain, especially in closed-form.

This paper presents a different method in which the conditional distribution of the response as a function of the random environmental parameters are ascertained first, following which uncertainties are introduced in the analysis as well as in the structural capacity, and thus the unconditional reliability is obtained. The (nominal) design capacity and the environment corresponding to a specified target reliability can then be obtained iteratively. A numerical example of the proposed method, applied to a novel structure, is presented.

PROPOSED APPROACH

Let the vector $\underline{B}$ of random variables denote uncertainties in structural modeling and response calculation, and let the vector $\underline{\Theta}$ represent the randomness in structural strength or capacity. The conditional reliability, $L(c,\underline{b},\underline{\theta})$, of the structure designed for the maximum response $r_{\max}$, is [re eqs (1) and (2)],

$$L(c,\underline{b},\underline{\theta}) = P\left[G(\underline{X}) \le c \mid c(\underline{\Theta}) = r_{\max}, \underline{B} = \underline{b}\right] = 1 - q \tag{3}$$

where c is the nominal structural capacity. Note that eq (3) also provides the conditional cdf (cumulative distribution function) of $G(\underline{X})$.

It is possible to perform the ECM-based procedure k times for k exceedance probabilities q_i ($i=1,2,\ldots,k$), and the corresponding set of design responses, $r_{\max_i}$, may be obtained. The conditional cdf of $G(\underline{X})$ is then readily evaluated at $r_{\max_i}$:

$$F_{G(\underline{X})}\left(r_{\max_i} \mid \underline{B} = \underline{b}\right) = 1 - q_i\,, \quad i = 1,2\ldots,k \tag{4}$$

The unknown conditional statistics and the unknown conditional probability distribution of $G(\underline{X})$ may now be obtained from the k point estimates in eq (4). If the statistics of modeling error $\underline{B}$ can be established, the unconditional distribution of $G(\underline{X})$ can be obtained as:

$$F_{G(\underline{X})}(r) = \int \ldots \int \; F_{G(\underline{X})}\left(r \;\middle|\; \underline{B} = \underline{b}\right) f_{\underline{B}}(\underline{b}) \;\; d\underline{b} \qquad (5)$$

Furthermore, if resistance uncertainties are known, the unconditional reliability can be determined as:

$$L = \int \ldots \int \; P\left[G(\underline{X}) \le c(\underline{\Theta}) \mid \underline{\Theta} = \underline{\theta}\right] f_{\underline{\Theta}}(\underline{\theta})\, d\underline{\theta} \qquad (6)$$

For the same nominal capacity, the unconditional reliability is generally less than 1- q [eq (3)]. A higher nominal capacity, depending on the modeling and capacity uncertainties, is required to raise the reliability to the target of 1- q.

An application highlighting the key features of the proposed method is presented next. The floating structure selected is novel and unique in many ways: there are significant modeling uncertainties, and the structural response is not available in closed-form.

APPLICATION TO NOVEL STRUCTURES

The example presented in the following concerns wave-induced axial loads in an inter-module connector of a Mobile Offshore Base (MOB). The MOB, currently undergoing feasibility studies under the auspices of the Office of Naval Research, is conceived as a mile-long, multi-module floating structure (Remmers et al, 1998). No validated design, fabrication or operational experience exist for such a structure, and a MOB may be responsive to environmental phenomena in ways that are beyond the scope of current analysis and prediction procedures. Such novel and complex floating structures are likely to have a greater modeling uncertainty than usual, and an ECM-based estimation of its design response needs to be modified according to eqs (5) and (6).

Hydrodynamic modeling

A five-module MOB with hinged connectors is adopted for this example (Wu and Mills, 1996). Each MOB module is a semi-submersible hull with port/starboard and fore/aft symmetry. The main particulars of the module are given in Table 1, and a hydrodynamic panel model is shown in Figure 2. Between a pair of adjacent modules, two connectors are placed symmetrically 50m from the MOB center-line at the deck level (43m above center of gravity). The connectors allow only one rotational degree of freedom about the transverse horizontal axis. The maximum axial connector load has been found to occur when the relative wave heading is around 75 degrees, which is used in this analysis. The response parameter under consideration is the axial load on one connector between the second and the third modules in a fully connected configuration.

The modules are hydrodynamically modeled using a three-dimensional linear diffraction-radiation analysis code, in which the wetted surface of the single module is represented by 1760 quadrilateral and triangular elements (re Figure 2). The response of the connected modules is obtained on the assumption that the hydrodynamic interaction between the modules is not significant.

Upper hull dimensions	280m x 150m x 24.6m
Lower hull dimensions	260 m x 38m x 16m
Transverse spacing	100m
Column dimensions	21m x 21m
Operating draft	39.0m
Displacement	337000 tonne
Longitudinal center of gravity (from amidships)	0
Transverse center of gravity (from center-plane)	0
Vertical center of gravity	26.87m
Water plane area	3452m^2
Vertical center of buoyancy (from baseline)	13.1 m
Transverse metacenter from baseline	40.1 m
Longitudinal metacenter from baseline	66.0 m
Roll radius of gyration	55.8 m
Pitch radius of gyration	93.2 m
Yaw radius of gyration	97.1 m

Table 1: Main particulars of one MOB module

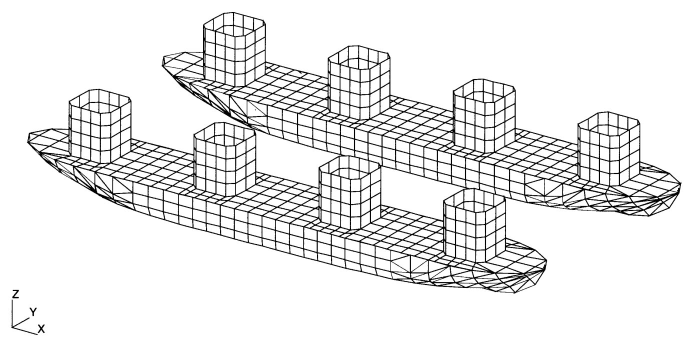

Figure 2: Hydrodynamic panel model of one MOB module

Environmental description

For illustration purposes, the area of operation is assumed to be Northern North Sea. The long term joint probability distribution of the significant wave height (H_s) and peak wave period (T_p),

$$F_{H_s,T_p}(h,t) = F_{H_s}(h)\, F_{T_p|H_s}(t \mid h) \qquad (7)$$

is given by (Haver and Nyhus, 1986):

$$F_{H_s}(h) = \begin{cases} \Phi\left(\frac{\ln h - 0.836}{0.613}\right); & h \le 3.27 \\ 1 - \exp\left(-(h/u)^{\alpha}\right); & h > 3.27 \end{cases} \quad (8)$$

$$F_{T_p|H_s}(t \mid h) = \Phi\left(\frac{\ln t - \mu}{\lambda}\right)$$

where h is in meters, t is in seconds, u = 2.822, α = 1.547 and Φ is the standard normal distribution. The parameters of the conditional distribution of T_p are given by:

$$\mu = 1.59 + 0.42\ln(h+2)$$
$$\lambda^2 = 0.005 + 0.085\exp(-0.13 + h^{1.34}) \quad (9)$$

Four environmental contours, corresponding to four exceedance probabilities, 0.1, 0.01, 0.001 and 0.0001, are constructed (Figure 3). Discrete points along each environmental contour are input to the hydrodynamic model to determine the corresponding connector axial loads. The combination H_s* - T_p* producing the highest axial load is identified for each contour (Figure 3). The numerical values are listed in Table 2.

It is observed that T_p* in each case is around 16 seconds. The inter-module connectors have been modeled as infinitely rigid in this analysis, consequently they do not absorb any energy. This assumption produces connector loads that are conservative and relatively insensitive to the wave period. Flexible connectors will be considered later in this task and will be the subject of a future paper.

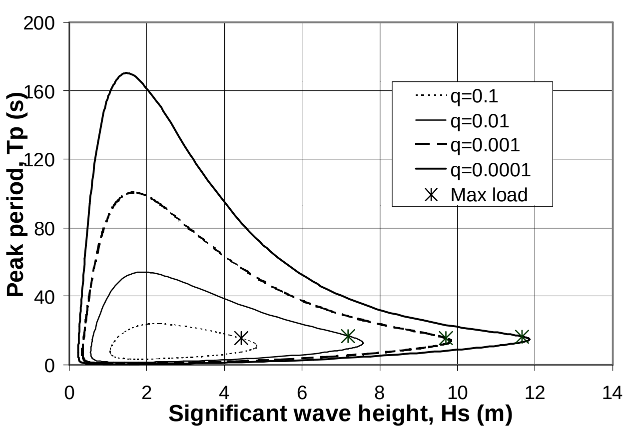

Figure 3: Hs-Tp contours and locations of maximum connector axial load

Exceedance Probability	Maximum axial load, S (kN)	H_s* (m)	T_p* (s)
0.1	2.23×10^5	4.44	15.50
0.01	3.77×10^5	7.18	16.80
0.001	4.93×10^5	9.70	15.72
0.0001	6.09×10^5	11.67	16.47

Table 2: Maximum axial load and design environment for four contours

Connector reliability and modeling uncertainties

Assume that the upper tail of the conditional cdf of the connector load, S, can be fitted to a lognormal distribution. From the four point estimates of the conditional cdf of S [re. eq (4)] in Table 2, a least-square analysis of the data yields the following parameters of the distribution:

$$E[\ln S \mid \underline{B}] = 11.82$$
$$\mathrm{var}[\ln S \mid \underline{B}] = 0.169 \quad (10)$$

which yields the conditional median and variance of S as 1.36×10^5 kN and 43%, respectively.

The modeling uncertainty in a hydrodynamic load analysis can be decomposed into three independent sources: pressure calculation (B_p), motion calculation (B_m) and load-effects calculation (B_l). Each of these sources of uncertainties in turn has three aspects: analytical, discretizational and numerical, with the analytical aspect having the largest contribution. For a hydrodynamic analysis of a MOB, the pressure calculation is expected to have little bias but a relatively large uncertainty (attributable mainly to linearization assumptions); the motion calculation (given the pressures) is expected to mildly overpredict with relatively low uncertainty; and the load-effect calculation (given the motions) is also expected to mildly overpredict with relatively low uncertainty. The three modeling uncertainty variables are assumed statistically independent and lognormally distributed, with parameters listed in Table 3.

Type of uncertainty	Median	cov	Distribution
Pressure calculation (B_p)	1.0	20%	Lognormal
Motion calculation (B_m)	0.975	5%	Lognormal
Load-effects calculation (B_l)	0.975	5%	Lognormal

Table 3: Uncertainties in hydrodynamic analysis

The unconditional distribution of the connector axial load is therefore also lognormal, with median and coefficient of variation (cov), respectively, as:

$$m_S = 1.36\text{x}10^5 \text{ x } 1.0 \text{ x } 0.975 \text{ x } 0.975 = 1.29 \text{ x}10^5 \text{ kN}$$

$$V_S = \sqrt{[(1+0.43^2)(1+0.20^2)(1+0.05^2)(1+0.05^2) - 1]} = 49\ \% \quad (11)$$

Three independent sources of uncertainty are likely to exist in estimating the axial load capacity of one connector: analytical (θ_a), material (θ_m) and fabrication (θ_f). Table 4 lists the assumed statistical properties for the three strength modeling uncertainties.

Type of uncertainty	Median	cov	distribution
analytical (θ_a)	1.05	10%	Lognormal
material (θ_m)	1.0	5%	Lognormal
fabrication (θ_f)	1.0	5%	Lognormal

Table 4: Uncertainties in connector capacity

The connector axial load capacity, C, is therefore lognormally distributed with median $1.05C_n$ and cov 12%, where C_n is the nominal capacity of the connector.

The unconditional failure probability of the connector is,

$$L = P[C \leq S] \quad (12)$$

Figure 4 shows the unconditional failure probability as a function of the nominal connector capacity. It also plots the effect of ignoring uncertainties in connector load and capacity, by selecting the nominal capacity equal to the maximum response (Table 2). For example, given a maximum permissible failure probability of 0.001, a nominal connector load capacity of $4.9\text{x}10^5$ kN would be deemed sufficient if modeling uncertainties were ignored. However, the analysis presented in this paper shows that this would in fact lead to an unacceptable failure probability of 0.004, and that the nominal capacity should be upgraded by 20% to about $6.0\text{x}10^5$ kN to achieve the desired target reliability. The nominal design environment corresponding to the permissible failure probability of 0.001 can be obtained by linear interpolation from Table 2 as,

$$H_s^* = 11.52\,m \qquad T_p^* = 16.41\,s \quad (13)$$

This combination is different from the critical point located on the contour corresponding to $q = 0.001$.

The connector target reliability of 0.999 in the preceding paragraph is for illustration purposes only. Target reliabilities for various MOB limit states are currently under investigation as part of the development of the MOB Classification Guide (Bhattacharya et al, 1999).

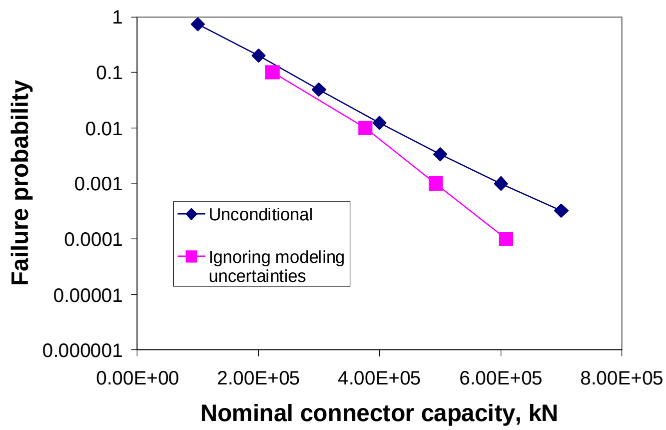

Figure 4: Connector failure probability

CONCLUSIONS AND RECOMMENDATIONS

This paper presented a computationally efficient method for finding the design capacity of a novel floating structural component subject to a specified target reliability. The method is particularly suitable if: (i) the response is not obtainable in closed-form and, (ii) in addition to environmental uncertainties, significant response and capacity uncertainties exist. While implementing this method, it is recommended that the range of exceedance probabilities (of the family of environmental contours used in the analysis) includes the target structural reliability. Subject to the limitations of computational resources, a reasonable number of environmental contours should be analyzed. The uncertainties in response and capacity modeling should be estimated by model tests wherever possible.

ACKNOWLEDGMENTS

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