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# Ship Seakeeping Operability, Motion Control, and Autonomy - A Bayesian Perspective

**Tristan Perez** *

* *School of Electrical Eng. and Comp. Sc., Queensland University of Technology, Australia. (e-mail: Tristan.Perez@qut.edu.au)*

**Abstract:** Ship seakeeping operability refers to the quantification of motion performance in waves relative to mission requirements. This is used to make decisions about preferred vessel designs, but it can also be used as comprehensive assessment of the benefits of ship-motion-control systems. Traditionally, operability computation aggregates statistics of motion computed over over the envelope of likely environmental conditions in order to determine a coefficient in the range from 0 to 1 called operability. When used for assessment of motion-control systems, the increase of operability is taken as the key performance indicator. The operability coefficient is often given the interpretation of the percentage of time operable. This paper considers an alternative probabilistic approach to this traditional computation of operability. It characterises operability not as a number to which a frequency interpretation is attached, but as a hypothesis that a vessel will attain the desired performance in one mission considering the envelope of likely operational conditions. This enables the use of Bayesian theory to compute the probability of that this hypothesis is true conditional on data from simulations. Thus, the metric considered is *the probability of operability*. This formulation not only adheres to recent developments in reliability and risk analysis, but also allows incorporating into the analysis more accurate descriptions of ship-motion-control systems since the analysis is not limited to linear ship responses in the frequency domain. The paper also discusses an extension of the approach to the case of assessment of increased levels of autonomy for unmanned marine craft.



*Keywords:* Ship performance assessment, probabilistic methods, motion control.

## 1. INTRODUCTION

Seakeeping theory studies the motion of surface vessels in waves, and seakeeping analysis is a procedure for computing vessel performance metrics related to the envelope of missions and environmental conditions in which the vessel is to operate (Lloyd, 1998). This analysis is often conducted during the vessel design stage, and the result is a number in the range from 0 to 1 called *Operability* ($O$) (NATO, 2000). This number is often given the interpretation of either a frequency, or the proportion of time that a vessel will remain operable. The metric $O$ is used, for example, by Navies as a tool for risk management during procurement to compare the merits of competing vessel designs against a prescribed performance standard—see for example RAN (2003). It has also been argued that increase on operability provides a key performance indicator of ship-ride control systems—attenuation of roll and pitch angles and accelerations (Crossland, 2000, 2003).

The interpretation of $O$ as a frequency attempts to attribute to nature—in this case the actual vessel behaviour—the result of a logical analysis of uncertainty. In this paper, we subscribe to the concept that probability is not a frequency, rather a measure of uncertainty or a state of knowledge (Jaynes, 2003). That is, probability allows us to do plausible reasoning in cases where we cannot reason with certainty. We consider an alternative framework for the assessment of operability. We pose $O$ as a hypothesis or proposition, namely a real property of the vessel, which can either be true or false and to which we seek to assign a probability of being true. The end result is the predictive probability of operability. That is, the probability that the vessel will attain the desired performance in one mission considering the envelope of likely environments and sailing conditions, namely, $P(O|D, I)$, where a proposition $D$ stands for data and $I$ stands for background information. This framework aligns with current trends in Bayesian reliability and risk analysis (Singpurwalla, 2006). This paper extends the previous work in Perez (2013) by using the method to assess increase in operability due to ride control. It also incorporates a discussion on the assessment of autonomy.

## 2. STANDARD OPERABILITY COMPUTATION

Standard seakeeping analysis considers long-term wave distributions, namely the joint distribution of probabilities $P(H_i, T_j)$ $(i = 1, \ldots, r; j = 1, \ldots s)$, where $H_i$ and $T_j$ are the following propositions [1] :

$$H_i : \{\underline{H}_i \le H_s \le \overline{H}_i\},$$
$$T_j : \{\underline{T}_j \le T \le \overline{T}_j\}.$$

[1] A proposition is a logic statement that can either be true or false.


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The propositions $H_i$ ($i = 1, \ldots, r$) establish that the significant wave height $H_s$ is in a particular range, whereas the propositions $T_j$ ($j = 1, \ldots, s$) establish that the zero-crossing wave period $T$ is in a particular range. The distribution $P(H_i, T_j)$ is tabulated in what are called scatter diagrams, which are available for different locations around the globe and times of the year.

The significant wave heigh and zero-crossing period are used to parameterise wave spectra $S_\eta(\omega, H_s, T)$, which under the assumption of deep water conditions characterise the Gaussian distribution of wave amplitudes for fully developed seas and for periods between 20 minutes to 3 hours (Haverre and Moan, 1985; Ochi, 1998). The wave spectra are then combined with vessel response operators (complex-valued frequency-response functions) $F_d(j\omega, U, \chi)$, for the different degrees of freedom $d = 1, 2, \ldots, 6$ computed under particular sailing conditions (vessel speed $U$ and wave encounter angle $\chi$) to obtain spectra of motion *displacements* relative to the vessel equilibrium condition:

$$S_d(\omega, U, \chi, H_s, T) = |F_d(j\omega, U, \chi)|^2 \, S_\eta(\omega, H_s, T),$$

with $d = 1, 2, \ldots, 6$. Note that the use of frequency response functions assumes linear ship response characteristics. This means that the effect of motion control systems used to reduce roll and pitch motion cannot be captured fully—neither adaptation of the control strategy to changes in environmental conditions, nor loss of performance due to actuator saturation is contemplated (Perez, 2005; Perez and Blanke, 2012).

The uncertainty associated with the sailing conditions is represented by the joint probability distribution of vessel speeds $U_k$ ($k = 1, \ldots, t$) and a wave encounter angles $\chi_l$ ($l = 1, \ldots, u$). For simplicity though, the speeds and encounter angles are assumed to be independent, namely, $P(U_k, \chi_l) = P(U_k)P(\chi_l)$. The distribution $P(U_k)$ is dictated by the operations the vessels conduct (transit, station keeping, equipment launch and recovery, etc.). Except for particular areas of operation in the globe, the distribution $P(\chi_l)$ is taken to be uniform in $[-\pi, \pi]$.

The motion spectra $S_d(\omega, U, \chi, H_s, T)$ ($d = 1, 2, \ldots, 6$) are used to compute ship-motion acceleration spectra and statistics (*e.g.* root mean square, single significant amplitude, double-significant amplitude) in the degrees of freedom of interest. These statistics are then mapped into performance indices $R_m$ ($m = 1, \ldots, v$) (for example, roll angle statistics, number of propeller emergences per hour, motion sickness index, slamming) which are compared with mission required threshold values (limits) and weighted according to their importance to determine a set of *operability coefficients* $W_{ijklm} \in [0, 1]$ associated with each scenario—wave height, wave period, speed, and encounter angle. It is very common to take $W_{ijklm}$ as a weighted membership function:

$$W_{ijklm} = k_m \, w(R_m),$$

where

$$w(R_m) = \begin{cases} 1 & \text{if } R_m \in \mathcal{R}_m, \\ 0 & \text{otherwise.} \end{cases}$$

and $\mathcal{R}_m$ is the set of values for which the performance is deemed satisfactory, and the coefficients $0 < k_m < 1$ weight the importance of the different performance indices—note the constraint $\sum_m k_m = 1$. Alternatives to the $w(R_m)$ above with a more gradual degradation as $R_m$ approaches the boundaries of $\mathcal{R}_m$ have also been proposed to reduce the sensitivity of $W_{ijklm}$ to small variations of $R_m$ close to set boundaries—see, for example, RAN (2003).

Once the operability coefficients are computed, the figure of merit of *operability* is computed as follows:

$$O = \sum_{i,j,k,l,m} W_{ijklm} \, P(H_i, T_j) \, P(U_k) \, P(\chi_l). \qquad (1)$$

The coefficient $O$ can be used a single figure of merit of a particular vessel, and the coefficients $W_{ijklm}$ can be used to assess performance in more detail.

For the assessment of ship-ride control systems, the measure of performance is the increase in operability due to the action of the ride control system (Crossland, 2000, 2003):

$$\Delta O = O_{cl} - O_{ol}, \qquad (2)$$

where subscripts *cl* and *ol* stand for closed loop and open loop respectively.

## 3. COMMENTS TO THE STANDARD APPROACH

Equation (1) mixes probabilities with weighting coefficients $W_{ijklm}$ that are deterministic in nature. By construction, the coefficient $O$ takes values in the range $[0, 1]$, and due to this, $O$ is then '*interpreted*' as a frequency or as percentage of time operable (Lloyd, 1998; NATO, 2000). One could also give (1) a decision-theoretic interpretation, where the coefficients $W_{ijklm}$ would represent a utility and $O$ would thus be a expected utility or risk (Lindley, 1991). To the best of the author's knowledge, this interpretation, has not been yet been discussed in the literature, and nor will it be discussed in this paper.

Although the metric $O$ serves the purpose of expressing performance in a cardinal scale, and when computed for different vessels, it allows one to make comparisons, the frequency interpretation is a rather far-fetched concept. The computations through (1) provide little support for such interpretation. A decision-theoretic interpretation may also be difficult to justify since no decision problem is alluded for the calculation of $O$. One could argue, however, that there is an underlying decision problem. Indeed, the purpose of seakeeping analysis is to infer $O$, and this used as key information for the associated with the decision problem which also requires the elucidation of the utilities of the decision maker. The latter, however, is a different, and harder, problem altogether; and therefore, it has been argued that inference should be separated from decision (Jaynes, 2003) (page 405).

Since we are dealing with uncertainty, and the end user will be using the information from the seakeeping analysis for making a decision under uncertainty, it would be, perhaps, more convenient to investigate the use of a procedure to compute $O$ that has its foundation in probability theory. Then, the seakeeping analysis would provide the probabilities that can be used as part of a subsequent decision problem (for example, to choose one vessel over another, or to accept a design *vs* requiring modifications and re-assessment).

To develop this approach using probability, we propose to consider the following hypothesis: