ON THE PROBABILISTIC ANALYSIS OF NON-STATIONARY SHIP MANOEUVERING RESULTS FOR WATERWAY DESIGN

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ABSTRACT

Ship handling simulators have proven their value and role in design and operation of harbors and waterways. The results (swept paths and cross tracks) achieved from simulator are very useful and utmost important for the assessment of navigational risk in conjunction with waterway design. However, interpreting such results with respect to the navigational risk for entire waterway remains problematic. Conventionally the risk is considered for critical points of the waterway only. Such a practice can result in a waterway of questionable safety because of the missing information on the process of ship passage through the waterway. The total risk of entire waterway is not known.

The method of integrated risk assessment for entire waterway regarding the ship exceeding the waterway limits is presented in this paper. Assuming that trajectories of ship track or swept path are considered as the response ensemble of non-stationary random processes, the study then concentrates on estimating time - dependent spectral density function, $S(\omega,t)$, on the basis of the response ensemble. Time - dependent spectral moments, $m_i(t)$, can be obtained (by integrating $\omega^i S(\omega,t)$ over all frequencies) and used to determine the time - dependent mean crossing rate $\varpi(t)$. Finally, the extreme statistics of ship exceeding a level, b (cm), of the waterway limits during the period, T (sec), are determined using the so-called first passage problem. On basis of this result the entire risk assessment can be implemented, which amounts a straightforward use for optimal design of the waterway horizontals.

KEYWORDS: Response ensemble, spectral density function, non-stationary random processes, waterway

1. INTRODUCTION

Maritime simulators have been most frequently used as a highly technical and an indispensable tool in the design, operation and management of navigational waterways. The main application focuses essentially on waterway design to indicate the ship manoeuvrability and possible accident occurrence in relation to the human behavior and environmental conditions. The estimation of the probability of an accident in each zone of the waterway on the basis of ship track and swept path is something that has drawn much attention of researchers. Considerable efforts have been devoted and three main groups of research could roughly be categorized.

The most common methods are those that consider critical points of the waterway only. Such a practice can result in a waterway of questionable safety because of missing the information on the process of ship passage through the waterway. A relatively simple way of determining the risk level of the entire waterway is by dividing it in a few homogeneous parts then determining for each part the probability of the waterway border being exceeded. The length of an independent part relates to a half wavelength of the ships tracks in the waterway, which was estimated by Vrijling (1995) based on 4-5 ship length. Again, the critical point resides in the fact that the estimated wavelength of the ships tracks was defined simply by using judgment and expert rating based upon the simulation runs. The other method group using a different focus was demonstrated by Burger (1989). Essentially the principle of this method is based on the interdependence of successive passage sections, either using a linear regression model or Markov chains to determine the interdependency of transits in subsequent cross sections. However, this methodology still needs considerable effort to develop and it is also very costly because it requires the execution of a large number of the real time simulations; see PIANC (1992), Iribarren (1998), Gucma (2000).

A new method of integrated risk assessment for the entire waterway regarding the ship exceeding the waterway limits is presented in this paper.

1. ANALYSIS OF SHIP - PILOT BEHAVIOR

It was confirmed that trajectories of ship track and swept path can be viewed as a stationary random process for a certain environmental condition and a certain competence level of the mariner (Quy, 2006). In such a case the fluctuations of the ship track and swept path (the ship response) around the desired course line are maintained "stable" throughout the passage. However, there is a certain limit of environmental condition beyond which the response process of the ship becomes "unstable" or non-stationary. This can be explained by realizing that the trajectories of ship track and swept path could be non-stationary random process when the balance between the competence required by navigational environment and the mariner's competence can not be maintained along the passage. The output signals of the ship manoeuvering results should therefore be treated as a non-stationary random process. This phenomenon was observed where meteorological and hydrodynamic conditions vary so frequently and considerably along waterway, or a ship passes through a bend part. One example of non-stationary ship response process for the later case, as shown in Figure 1, has been used for this study. The method so-called "Reserve Arrangement Test" proposed by Bendat (1986) can be used as a useful tool for detecting stationarity or non-stationarity of any random process.

1. THE PROPERTIES OF A STATIONARY RANDOM PROCESS

Assume that a real time simulation is set up for a part of the waterway with the length L (m), a mariner completes the trail tests in the period T (sec), and $x_i(t)$ is the sample record (sample function) of the ship which is the ship position recorded at predetermined time interval, Δt (sec), during trial i-th. Let us assume that the ship rarely exceeds the channel border that successive up-crossings of a specified level are independent and can therefore be modeled as the Poisson process. Under these assumptions probability $P(b,T)$ that the response ensemble $\{x(t)\}$ (the symbol {} denotes an ensemble with the number of the sample records is n_s, we omitted ns to simplify the notation) will cross at level $x=b$ at least once during a period T given by Ochi (1973)

$$P(b,T) = 1 - \exp(-\nu_b T), \text{in which } \nu_b = \frac{1}{2\pi}\sqrt{\frac{m_{2x}}{m_{ox}}}\exp\left\{-\frac{1}{2}\left[\frac{(b-\bar{\mu}_x)^2}{m_{ox}}\right]\right\} \tag{1}$$

where ν_b is the mean rate of crossing with level b (b is considered as a half of the channel width); $\bar{\mu}_x$ is the ensemble mean value of $\{x(t)\}$; m_{ox} and m_{2x} represent respectively zero and second moments of the ensemble $\{x(t)\}$, which can be determined by the following equations:

$$m_{ox} = \int_0^\infty \bar{S}_{xx}(\varpi)d\varpi, \text{ and } m_{2x} = \int_0^\infty \varpi^2 \bar{S}_{xx}(\varpi)d\varpi \tag{2}$$

where $\bar{S}_{xx}(\varpi)$ is the power spectral density (PSD) which describes the distribution of the mean-square value of the ensemble $\{x(t)\}$ over the frequency domain. Based upon the ensemble $\{x(t)\}$, $\bar{S}_{xx}(\varpi)$ can be quickly determined by digital computer using the fast Fourier transform algorithm.

2. THE ANALYSIS OF A NON-STATIONARY PROCESS

Similarly to the analysis for response process $\{x(t)\}$ is stationary, the core of this approach is to determine the power spectrum for non-stationary process of the sample records $\{x(t)\}$ by using the Wigner distribution (*WD*). The analysis procedures of the *WD* for non-stationary processes have essentially the same type of physical interpretation as the spectra of the stationary processes, the main distinction being that whereas the spectra of a stationary process describes the power-frequency distribution for the whole process (i.e. over all time), the *WD* is time dependent and describes the local power-frequency distribution at each instant time, see Bendat (1986). The *WD* of a real signal $x(t)$ is given by Mecklenbrauker (1997)

$$W(t,\varpi) = \int_{-\infty}^{\infty} z(t+\tau/2) z^*(t-\tau/2) e^{j2\pi\varpi\tau} \mathrm{d}\tau \tag{3}$$

where $z(t)$ is the analytic signal associated with $x(t)$; $z^*(t)$ represents the complex conjugate of $z(t)$, which can by defined using the Hilbert and Fourier transform techniques, which are available in the Matlab Signal Processing Toolbox.

The response process $\{x(t)\}$ is a non-stationary when viewed as a whole. However, in the (t,ω) plane it may be possible to separate the non-stationary power spectral function into piecewise stationary segments. The location and the number of segments for separation can be found by detecting the *WD*, see Bendat (1986). So integration of $W(t,\omega)$ over any time interval gives the spectral density function of $\{x(t)\}$ at frequency ω. Also integration of $W(t,\omega)$ over all T gives the power spectral density function, $\bar{S}_{xx}(\varpi)$, of $\{x(t)\}$.

$$S_{xx}(t_1 \le t \le t_2, \varpi) = \int_{t_1}^{t_2} W(t,\varpi)\mathrm{d}t \tag{4}$$

Probability of the ship excursion from the borders for any part of the waterway as defined in Equation (1) with the parameters determined in Equation (2) will therefore be applicable to the present context. Equation (1) can be rewritten as Corotis (1972)

$$P(b, \Delta t = t_2 - t_1) = 1 - \exp\left\{-\int_{t_1}^{t_2} \nu_b(t)\mathrm{d}t\right\} \tag{5}$$

3. EXPERIMENTS AND RESULTS

A real case was used for the application of the foregoing approach. The real time simulations with the use of gas vessel were carried out at the Piastowski canal, in the Baltic Sea, which is composed of a double bend part and a straight one as shown in Figure 1. The first part of this canal named Paprotno Mielin bend was selected for this study. An ensemble of 30 trials of the ship passage handled in the simulated wind condition (wind speed 15m/s from West) was used for the analysis of its non-stationary power spectrum.

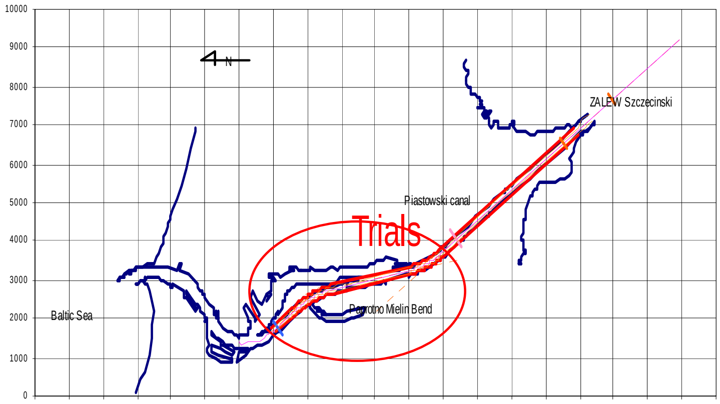

Figure 1: The layout and investigated bend part of the Piastowski canal, in the Baltic Sea

It was observed that almost the ship tracks went away from the referred line when the ship passed through the bend. This can also be seen in the analyzed result of the non-stationary power spectrum of the response ensemble as described in Figure 2, where the power spectrum density in the first part is much smaller than those in the latter part of the bend. The time axis, with zero value calculated at starting investigated point of the trials, is defined by ratios of the channel distance to the average ship speed. Figure 3 presented the final results of the probability function of ship excursion from a certain limit in both sides of the entire waterway, which were processed according to the presented method.

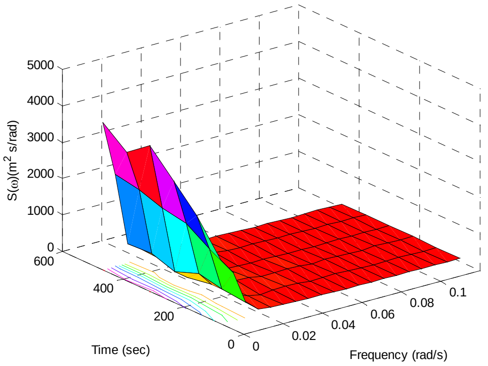

Figure 2: Time- dependent spectral density function of the response assemble (at Paprotno Mielin bend part)

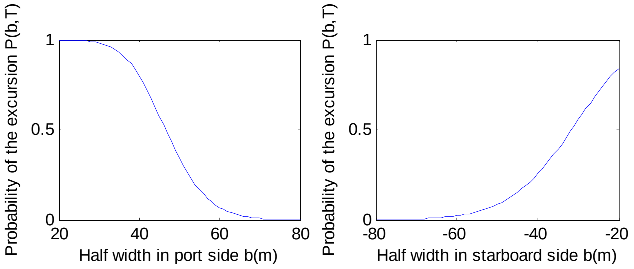

Figure 3: Probabilities of ship excursion for the entire bend part for various waterway widths

3. CONCLUSION

The ship trajectories obtained from real time simulations can be viewed as the ensemble of non-stationary process. Integrated risk of ship excursion from the waterway limits for entire or any part of the waterway can therefore be assessed by analysis of the ensemble of the non-stationary power spectral density with the aid of the probabilistic model. The method could also useful for the evaluation of how much the mariner competence can be adapted to the navigation condition by exploring behavior of power spectral density function of the manoeuvering results along the waterway.

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