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"High runs" of a ship in multi-chromatic seas

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ABSTRACT

When a ship operates in steep irregular waves, it can attain, in intermittent time intervals, abnormally high speed, due to waves' effect. Such events may occur in following seas and they will be called hereafter "high runs". Investigations have been carried out for this peculiar type of ship motion, in three directions: firstly, the statistics of high runs are calculated by numerical simulation, exploring, in particular, their dependence on the wave spectrum and the sea state. Secondly, a rather neglected up to now analytical method, proposed in the 60 s by Grim, for the quantification of the probability of high run occurrence, is assessed, against a direct numerical approach. Finally, the actual velocity of a ship in high run incidents is investigated. Suitable metrics are applied on the difference between characteristic velocity values associated with wave's form, and surge velocity, during high runs.

1. Introduction

In an irregular sea, a realisation of surf-riding is perceived as a prolonged high speed run of the ship, occurring in a time interval when the waves, in the vicinity of the ship, maintain sufficient steepness to enable the phenomenon. A statistical approach for calculating the probability of surf-riding of a ship through numerical modelling and simulation, in reference to an environment of extreme irregular waves, could be then based on the direct counting of those special time intervals in which her speed is maintained consistently above the normally expected range of speed fluctuation in waves. Any individual realisation of such behaviour will be called hereafter "a high run". It can be considered as the generalisation of surf-riding, for a multi-frequency wave environment, including also transitory and unclassified phenomena which, from a dynamics perspective, may not be exactly surf-riding. Whilst the mechanism of inception of such phenomena requires deep consideration of system's phase-space, empirically, it can be recognised by the up-crossing of an appropriate surge velocity threshold, such as *the instantaneous wave celerity*. The concept of instantaneous wave celerity, and its phenomenological connection with high run events in irregular seas, has been discussed in Spyrou et al. (2014a).

A high-run's temporary end may be, similarly, defined by the down-crossing of a suitable threshold. For this however, as will be discussed later, there is no clear consensus on its definition.

Literature on the topic is scarce. However, in a pioneering (but rather oversighted) work, Grim had attempted to determine how a ship could be accelerated by waves and then maintain a speed higher than her mean speed, for extended time intervals, in irregular seas (Grim, 1963). He had called such phenomena "long-runs". By a string of eloquent, and yet quite plain, analytical approximations, he had produced statistical estimates of their existence and duration, based on up-crossings of a speed level that he had considered as critical.

The term "high-run" is often used in oceanography to indicate the realisation of a sequence of nearly regular high waves (Longuet-Higgins, 1984). Use of such a concept has been made in the past for assessing ship stability in irregular stern quartering seas (e.g. Takaishi et al., 2000). In the present context, however, the meaning of the term is very different, referring to a ship's unintended high speed motion and not to wave phenomena. In fact, use of the term "long-run" could be ambiguous here, because sometimes, the addressed extreme motions are not characterised by a velocity plateau as was Grim's assumption.

The aim of our study was the examination of the probabilistic properties of high run events. It is well-known that, the longer a ship maintains a speed higher than normal, the more likely it is to experience the broaching-to instability (Spyrou, 1995). The importance of the topic is thus prevalent. The adopted approach is developed as follows: firstly, a campaign of numerical simulations with direct recording of the high run intervals was performed.

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Targeted quantities were: a) the mean duration of high run; and b) the mean time between successive high runs. This has produced the statistical dependence of the phenomenon on the characteristics of the wave field. Then, the key elements of Grim's method were implemented, taking advantage however of the modern numerical calculation capability. Thus, alternative probability figures were derived which were contrasted against those obtained by direct counting. Our final goal was to figure out which characteristic wave velocity definition conforms best with surge velocity during high run incidents. We selected as initial candidates: a) the instantaneous wave celerity at the position of the ship on the wave (this is a quantity that is varied in time-space, hence it should be calculated at every step); and b) the celerity that corresponds to the peak frequency of the spectrum (receiving, thus, a constant value during simulation runs deriving from a certain spectrum). The distance of these celerities from surge velocity during high runs was systematically assessed, on the basis of suitable metrics.

2. High run statistics

2.1. Mathematical model

The mathematical model of surge motion in following seas was written for an earth-fixed observer, as follows:

$$(m - X_{\dot{u}})\ddot{\xi} - \left(\tilde{\tau}_2\dot{\xi}^2 + \tilde{\tau}_1 n\,\dot{\xi} + \tilde{\tau}_0 n^2\right) + \left(r_1\dot{\xi} + r_2\dot{\xi}^2 + r_3\dot{\xi}^3\right) - \sum_{i=1}^{N} F_{xi}\,\sin\left(k_i\xi - \omega_i t + \varepsilon_i + \varepsilon_{fi}\right) = 0 \quad (1)$$

where ξ is the longitudinal position of the ship and m, $X_{\dot{u}}$ are her mass and "surge added mass" respectively. In the summation term denoting wave force, k_i, ω_i and ε_i stand respectively for the i harmonic's wave number, frequency and random phase. F_{xi} denotes the amplitude, and ε_{fi} the phase, of the i harmonic wave force component. Also, n is the propeller rate and r_i, $\tilde{\tau}_i$ are polynomial coefficients appearing in the resistance and thrust force expressions, respectively.

2.2. "High run" definition

An apparent choice of a velocity threshold whose up-crossing would signal a high run, is the instantaneous wave celerity. Yet, it is known that attraction towards surf-riding is very likely to have started from a slightly earlier time (and thus from a lower velocity). If this early stage is neglected, a small underestimation of the probability should be expected. As down-crossing threshold was set, as first step, the nominal speed. This lower threshold is not very likely to be crossed by speed fluctuations occurring during a high-run. The nominal speed is a safe choice from this point of view, although a conservative one, possibly contributing to a slight overestimation of probability. This may be statistically cancelled out, at least partly, with the underestimation linked with the beginning of the high run. As an extra condition, we request, the surge velocity to be always higher than the nominal speed, in order to exclude, for relatively short wave lengths and mild wave height conditions, cases that, qualitatively, should not be counted as high runs. In Fig. 1 are shown time segments of high run in accordance to the presented definition. It is desired to obtain the statistics of 'high runs' duration, as well as of the time interval between successive occurrences. The mean duration is obtained by summing up all individual durations; and then dividing by the number of occurrences:

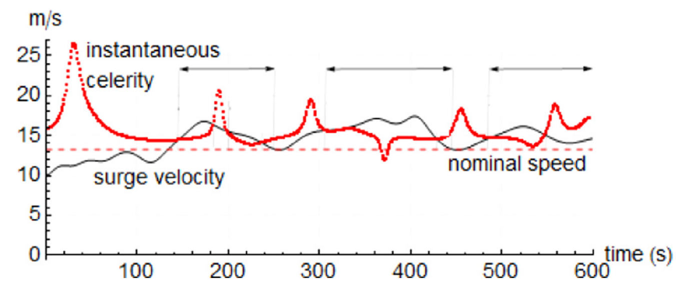

Fig. 1. Schematic definition of high run.

$$\bar{t}_{high\ \ run} = \frac{\sum_{i=1}^{N} t_{high\ \ run}^{(i)}}{N} \quad (2)$$

A similar formula is applied for the mean time between high runs.

2.3. Simulation settings

The ship selected for applying the calculation schemes is an ONR "tumblehome topside", well-known from several previous studies (for example, Spyrou et al., 2014a). A JONSWAP spectrum is considered, discretized by applying a fixed frequency increment $\delta\omega = 2\pi/t_{sim}$ where $t_{sim} = 300$s is the so-called "basis simulation time". The total simulation time was set to a selected multiple of the basis time (up to $40 \times t_{sim}$). Four ranges (from narrow to broad) around spectrum's peak were separately examined, containing the wave frequencies participating in the simulations. In Fig. 2 are indicated the wave amplitudes obtained from the spectrum, considering frequency ranges $0.2\,\omega_p$ and $0.4\,\omega_p$. A different choice would have been to modify the wave amplitude so that the variance remains constant. In that case the wave amplitudes obtained would be considerably higher (see again Fig. 2). In the current study wave realisations were produced according to the first method, meaning that, the increase of the frequency range increased also the energy.

Lastly, in Table 1 appear the values of the remaining simulation parameters. Sensitivity studies, in relation to sea state, narrowness of spectrum and simulation time, were carried out. We run 100 wave realisations per parameters' setting. The nominal and the initial speed of the ship, in each scenario, were not changed (for extra explanations see Spyrou et al., 2014b).

2.4. Results

In Fig. 3 appear characteristic high run durations, predicted through simulation. Vast differences are noticed, some high runs

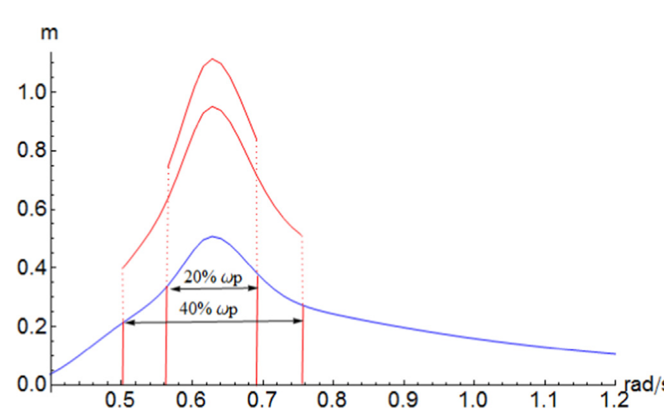

Fig. 2. Wave amplitudes for 2 frequency ranges and their modified values when the variance is kept constant. $H_S = 6$ m and $T_P = 10$ s.