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## **in rough seas Survival analysis of fishing vessels rolling**

I. Senjanovi, G. Cipri and J. Parunov

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# Survival analysis of fishing vessels<br>Folling in rough seas al analysis of fishing ves<br>rolling in rough seas

**Folling in rough seas**<br>By I. SENJANOVIĆ, G. CIPRIĆ AND J. PARUNOV<br>University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, *IANOVIC, G. CIPRIC AND J. PAR*<br>*Iaculty of Mechanical Engineering and*<br>*I. Lučića 5, 10000 Zagreb, Croatia* 

A new approach to the problem of predicting the safety of vessels rolling in rough<br>seas is described. It is based on the state of the art in nonlinear dynamics of a single-A new approach to the problem of predicting the safety of vessels rolling in rough<br>seas is described. It is based on the state of the art in nonlinear dynamics of a single-<br>degree-of-freedom system. The random wave excitat A new approach to the problem of predicting the safety of vessels rolling in rough<br>seas is described. It is based on the state of the art in nonlinear dynamics of a single-<br>degree-of-freedom system. The random wave excitat seas is described. It is based on the state of the art in nonlinear dynamics of a single-<br>degree-of-freedom system. The random wave excitation depends on sea state, vessel<br>speed and direction of wave propagation. The diffe degree-of-freedom system. The random wave excitation depends on sea state, vessel<br>speed and direction of wave propagation. The differential equation of rolling motion<br>is integrated by the harmonic acceleration method. The speed and direction of wave propagation. The differential equation of rolling motion<br>is integrated by the harmonic acceleration method. The procedure is illustrated for<br>the case of a typical fishing vessel. The roll respon is integrated by the harmonic acceleration method. The procedure is illustrated for<br>the case of a typical fishing vessel. The roll response of an intact and damaged vessel<br>is presented in the time and frequency domain. The the case of a typical fishing vessel. The roll response of an intact and damaged vessel<br>is presented in the time and frequency domain. The fractal erosion of the safe basin<br>in the initial-value plane is analysed. Finally, is presented in the time and frequency domain. The fractal erosion of the safe basin<br>in the initial-value plane is analysed. Finally, these results are used to determine the<br>probability of a vessel's survival as a function angle.

Keywords: fishing vessel; irregular waves; nonlinear rolling;<br>| roll energy spectrum: safe basin: probability of survival eywords: fishing vessel; irregular waves; nonlinear rolling;<br>roll energy spectrum; safe basin; probability of survival

#### 1. Introduction

 $\frac{1}{1}$ . Introduction<br>Vessels are designed in accordance with national and/or international rules. The<br>stability criteria prescribe the form and area under the righting-arm curve based on Vessels are designed in accordance with national and/or international rules. The<br>stability criteria prescribe the form and area under the righting-arm curve based on<br>experience (SNAME 1988) This is a rather conservative wa Vessels are designed in accordance with national and/or international rules. The stability criteria prescribe the form and area under the righting-arm curve based on experience (SNAME 1988). This is a rather conservative stability criteria prescribe the form and area under the righting-arm curve based on experience (SNAME 1988). This is a rather conservative way to preserve a vessel<br>of from capsizing, since a very important role of nonlin experience (SNAME 1988). This is a rather conservative way to preserve a vessel<br>from capsizing, since a very important role of nonlinear dynamic phenomena is not<br>taken into consideration (Cartmell 1990; Dimentberg 1988; Th from capsizing, since a very important role of nonlinear dynamic phenomena is not

taken into consideration (Cartmell 1990; Dimentberg 1988; Thompson 1993). The fact that many intact vessels were lost in rough seas confirms this statement (Dahle & Nisja 1984). Therefore, the state of the art in nonlinear fact that many intact vessels were lost in rough seas confirms this statement (Dahle  $\&$  Nisja 1984). Therefore, the state of the art in nonlinear dynamics should be used in stability analysis, and consequently new stabi Nisja 1984). Therefore, the state of the art in nonlinear dynamics should be used<br>stability analysis, and consequently new stability criteria should be established.<br>A vessel rolling in regular beam seas has been quite wel

in stability analysis, and consequently new stability criteria should be established.<br>A vessel rolling in regular beam seas has been quite well investigated, mostly<br>in the frequency domain, using relevant numerical methods A vessel rolling in regular beam seas has been quite well investigated, mostly<br>in the frequency domain, using relevant numerical methods (Cardo *et al.* 1984).<br>Nonlinear phenomena, such as amplitude jumping, superharmonic in the frequency domain, using relevant numerical methods (Cardo *et al.* 1984).<br>Nonlinear phenomena, such as amplitude jumping, superharmonic and subharmonic<br>response, symmetry breaking and period doubling, have been ana Nonlinear phenomena, such as amplitude jumping, superharmonic and subharmonic<br>response, symmetry breaking and period doubling, have been analysed (Senjanović<br>1994; Peyton Jones & Cankaya 1996). Transition from regular to response, symmetry breaking and period doubling, have been analysed (Senjanović 1994; Peyton Jones & Cankaya 1996). Transition from regular to chaotic motion is considered in the time domain (Senjanović & Fan 1994). It is an indication of possible vessel capsize (Thompson *et al.* 1990). Chaotic roll considered in the time domain (Senjanović & Fan 1994). It is an indication of possibly vessel capsize (Thompson *et al.* 1990). Chaotic rolling is partly and fully develope in the case of an intact and damaged vessel, res

ssel capsize (Thompson *et al.* 1990). Chaotic rolling is partly and fully developed<br>the case of an intact and damaged vessel, respectively (Kan & Taguchi 1991).<br>In reality, a vessel rolls in rough seas, and the linear ra in the case of an intact and damaged vessel, respectively (Kan & Taguchi 1991).<br>In reality, a vessel rolls in rough seas, and the linear random process valid for<br>small amplitude motion is solved by the spectral analysis ( In reality, a vessel rolls in rough seas, and the linear random process valid for small amplitude motion is solved by the spectral analysis (Price & Bishop 1974; Lloyd 1989; SNAME 1989). However, nonlinear response may be small amplitude motion is solved by the spectral analysis (Price & Bishop 1974;<br>Lloyd 1989; SNAME 1989). However, nonlinear response may be reliably determined<br>only by numerical simulation (Falzarano *et al.* 1995; Senjano Lloyd 1989; SNAME 1989). However, nonlinear response may be reliably determined<br>only by numerical simulation (Falzarano *et al.* 1995; Senjanović & Fan 1995*a*). The<br>explicit nonlinear phenomena caused by regular wave exc explicit nonlinear phenomena caused by regular wave excitation are coupled and<br>*Phil. Trans. R. Soc. Lond.* A (2000) 358, 1943-1965 (2000 The Royal Society



Figure 1. A typical fishing vessel.

Figure 1. A typical fishing vessel.<br>interferated in the case of a spectral excitation (Ochi & Bolton 1973). The definition<br>of deterministic chaos related to regular wave excitation can be extended to random interferated in the case of a spectral excitation (Ochi & Bolton 1973). The definition<br>of deterministic chaos related to regular wave excitation can be extended to random<br>chaos in the case of narrow hand spectral excitati interferated in the case of a spectral excitation (Ochi & Bolton 1973). The definitiof deterministic chaos related to regular wave excitation can be extended to rando<br>chaos in the case of narrow band spectral excitation ( of deterministic chaos related to regular wave excitation can be extended to random<br>chaos in the case of narrow band spectral excitation (Senjanović & Fan 1995b).<br>Taking the above facts into account, this article offers a

chaos in the case of narrow band spectral excitation (Senjanović & Fan 1995b).<br>Taking the above facts into account, this article offers a new, sophisticated, dynamic approach to the problem of determining a vessel's safet **MATHEMATICAL,<br>PHYSICAL<br>& ENGINEERING<br>& ENGINEES** Taking the above facts into account, this article offers a new, sophisticated, dynamic approach to the problem of determining a vessel's safety in rough seas. Vessel rolling is simulated by a single-degree-of-freedom (SDOF ic approach to the problem of determining a vessel's safety in rough seas. Vessel<br>rolling is simulated by a single-degree-of-freedom (SDOF) system. Nonlinear vis-<br>cous damping and restoring moment are taken into account. R rolling is simulated by a single-degree-of-freedom (SDOF) system. Nonlinear vis-<br>cous damping and restoring moment are taken into account. Random wave excita-<br>tion depends on the relevant wave slope energy spectrum for a g cous damping and restoring moment are taken into account. Random wave excita-<br>tion depends on the relevant wave slope energy spectrum for a given sea state and<br>encounter frequency. The governing differential equation of ro tion depends on the relevant wave slope energy spectrum for a given sea state and<br>encounter frequency. The governing differential equation of rolling motion is solved in<br>the time domain by the harmonic acceleration method. encounter frequency. The governing differential equation of rolling motion is solved in the time domain by the harmonic acceleration method. The safe basin in the initial-<br>value plane is determined for different sea states the time domain by the harmonic acceleration method. The safe basin in the initial-<br>value plane is determined for different sea states and values of encounter frequency.<br>The results obtained are used to predict the probabi value plane is determined for different sea states and values of encounter frequency.<br>The results obtained are used to predict the probability of a vessel's survival in rough<br>seas as a function of sea state, vessel speed a seas as a function of sea state, vessel speed and heading angle. The procedure is illustrated for the case of a typical fishing vessel, like the one shown in figure 1, in both intact and damaged conditions. trated for the case of a typical fishing vessel, like the one shown in figure 1, in both

## 2. Equation of rolling motion

A vessel in rough seas performs a complex motion consisting of six components: A vessel in rough seas performs a complex motion consisting of six components:<br>surge, sway, heave, roll, pitch, and yaw (Price & Bishop 1974; Lloyd 1989; SNAME<br>1989) Bolling motion is highly nonlinear. By neglecting coupli 1989). Rolling motion is highly nonlinear. By neglecting of six components:<br>1989). Rolling motion is highly nonlinear. By neglecting coupling (Falzarano *et al.* 1995), for the sake of simplicity, the vessel rolling is ana 1989). Rolling motion is highly nonlinear. By neglecting coupling (Falzarano *et al.* 1995), for the sake of simplicity, the vessel rolling is analysed by an SDOF system. The governing differential equation of motion expr

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Figure 2. Definition of heading angle.

and it reads

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$$
I\ddot{\varphi} + D(\dot{\varphi}) + R(\varphi) = M(t),
$$
\n(2.1)

 $I\ddot{\varphi} + D(\dot{\varphi}) + R(\varphi) = M(t),$  (2.1)<br>where *I* is the virtual moment of inertia, *D* is the damping moment, *R* is the restoring<br>moment. *M* is the wave-excitation moment and  $\varphi$  is the roll angle. where I is the virtual moment of inertia, D is the damping moment, R<br>moment, M is the wave-excitation moment and  $\varphi$  is the roll angle.<br>The virtual moment of inertia consists of the vessel's mass moment here I is the virtual moment of inertia, D is the damping moment, R is the restoring<br>oment, M is the wave-excitation moment and  $\varphi$  is the roll angle.<br>The virtual moment of inertia consists of the vessel's mass moment a

moment, M is the wave-excitation moment and  $\varphi$  is the roll angle.<br>The virtual moment of inertia consists of the vessel's mass moment and the added mass moment of surrounding water, i.e.

$$
I = Is + Iw.
$$
 (2.2)

The damping moment, consisting of wave radiation and viscous components, may The damping moment, consisting of wave radiation and viscous con<br>be approximated by a cubic polynomial as an analytical function

by  
normal as an analytical function  

$$
D(\dot{\varphi}) = D_w \dot{\varphi} + D_v \dot{\varphi} |\dot{\varphi}|
$$

$$
= D_1 \dot{\varphi} + D_3 \dot{\varphi}^3. \tag{2.3}
$$

The restoring moment is hydrostatic and is given by a nonlinear odd function. It The restoring moment is hydrostatic and is given<br>may be represented by a seventh-order polynomial a seventh-order polynon<br>  $R(\varphi) = K_1 \varphi + K_3 \varphi^3 + I$ 

$$
R(\varphi) = K_1 \varphi + K_3 \varphi^3 + K_5 \varphi^5 + K_7 \varphi^7.
$$
 (2.4)

 $R(\varphi) = K_1 \varphi + K_3 \varphi^3 + K_5 \varphi^5 + K_7 \varphi^7$ . (2.4)<br>Substituting the above formulae (2.2), (2.3) and (2.4) into (2.1), and dividing the<br>result by the virtual moment of inertia, the final form of the differential equation of  $r(\varphi) = \Lambda_1 \varphi + \Lambda_3 \varphi + \Lambda_5 \varphi + \Lambda_7 \varphi$ . (2.4)<br>Substituting the above formulae (2.2), (2.3) and (2.4) into (2.1), and dividing the<br>result by the virtual moment of inertia, the final form of the differential equation of<br>mo Substituting the aboresult by the virtual is<br>motion is obtained:

$$
\ddot{\varphi} + d_1 \dot{\varphi} + d_3 \dot{\varphi}^3 + k_1 \varphi + k_3 \varphi^3 + k_5 \varphi^5 + k_7 \varphi^7 = m(t),
$$
\n(2.5)

where

$$
d_i = D_i/I, \t i = 1, 3,\nk_i = K_i/I, \t i = 1, 3, 5, 7,\nm(t) = M(t)/I
$$
\n(2.6)

 $$\,m$$  are relative roll parameters.

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Exercise property as a function of ward of ward as a function of ward of ward of  $\bf{3.}$  Wave excitation

3. Wave excitation<br>The relative roll-excitation moment of a regular wave of beam sea may be presented<br>in the following form (Contento *et al.* 1996*a*): **is.** Wave excited<br>The relative roll-excitation moment of a regular<br>in the following form (Contento *et al.* 1996*a*): in the following form (Contento *et al.* 1996*a*):

$$
m(t) = \alpha_0 \omega_0^2 \pi \frac{h}{\lambda} \cos \omega t, \qquad (3.1)
$$

where  $\alpha_0$  is the effective wave slope coefficient (assumed constant), h is the wave where  $\alpha_0$  is the effective wave slope coefficient (assumed constant), h is the wave<br>height,  $\lambda$  is the wavelength of beam sea,  $\omega_0$  is the roll natural frequency, and  $\omega$  is the<br>wave frequency. Equation (3.1) may b where  $\alpha_0$  is the effective wave slope coefficient (assumed constant), h is the wave<br>height,  $\lambda$  is the wavelength of beam sea,  $\omega_0$  is the roll natural frequency, and  $\omega$  is the<br>wave frequency. Equation (3.1) may b height,  $\lambda$  is the wavelength of beam sea,  $\omega_0$  is the roll natural frequency, and  $\omega$  is the wave frequency. Equation (3.1) may be extended, taking vessel speed U and heading angle  $\chi$  into account. The heading angl wave frequency. Equation (3.1) may be extended, taking vessel speed U and angle  $\chi$  into account. The heading angle is the angle between the vessel and the direction of wave propagation at a celerity c (see figure 2). Th and the direction of wave propagation at a celerity  $c$  (see figure 2). Thus,

$$
m(t) = \alpha_0 \omega_0^2 \pi \frac{h}{\lambda} \sin \chi \cos(\omega_e t), \qquad (3.2)
$$

where  $\omega_e$  is the encounter frequency,

ency,  
\n
$$
\omega_{\rm e} = \omega - \frac{\omega^2 U}{g} \cos \chi.
$$
\n(3.3)

 $\omega_e = \omega - \frac{\cos \chi}{g}$ . (3.3)<br>The encounter frequency is single valued for beam seas and multi-valued for quar-<br>ring seas (as shown in figure 3) where The encounter frequency is single valued<br>tering seas (as shown in figure 3), where

$$
\omega_{\rm emax} = \frac{g}{4U\cos\chi} \tag{3.4}
$$

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Figure 4. Tabain's wave energy spectrum of the Adriatic Sea.

and <sup>g</sup> is the acceleration due to gravity. The encounter frequency may be positive or and g is the acceleration due to gravity. The encounter frequency may be positive or<br>negative. In the former case the waves overtake the vessel, and in the latter case the<br>vessel overtakes the waves If  $y \to 90^{\circ}$  then and g is the acceleration due to gravity. T<br>negative. In the former case the waves over<br>vessel overtakes the waves. If  $\chi \to 90^{\circ}$ , the Rough sea is presented by an irregular d g is the acceleration due to gravity. The encounter frequency may be positive or gative. In the former case the waves overtake the vessel, and in the latter case the ssel overtakes the waves. If  $\chi \to 90^{\circ}$ , then  $\omega_e$ 

vessel overtakes the waves. If  $\chi \to 90^{\circ}$ , then  $\omega_{\rm e} \to \omega$  and  $\omega_{\rm e \, max}$  -<br>Rough sea is presented by an irregular wave, i.e. as the sum of<br>so that the relative excitation moment (3.2) takes the form so that the relative excitation moment  $(3.2)$  takes the form

$$
m(t) = \alpha_0 \omega_0^2 \pi \sin \chi \sum_{n=1}^N \frac{h_n}{\lambda_n} \cos(\omega_{en} t + \varepsilon_n), \qquad (3.5)
$$

 $m(t) = \alpha_0 \omega_0^2 \pi \sin \chi \sum_{n=1}^{\infty} \frac{\cos(\omega_{en} t + \varepsilon_n)}{\lambda_n}$  (3.5)<br>where *n* is the index of wave component and  $\epsilon_n$  is the random phase angle in the<br>range  $0\text{--}2\pi$  whose probability of occurrence  $1/(2\pi)$  is uniformly dis where *n* is the index of wave component and  $\epsilon_n$  is the random phase angle in range 0-2 $\pi$ , whose probability of occurrence,  $1/(2\pi)$ , is uniformly distributed.<br>The wave height is obtained from the wave energy spectrum nere *n* is the index of wave component and  $\epsilon_n$  is the random phase angle in the nge 0–2 $\pi$ , whose probability of occurrence,  $1/(2\pi)$ , is uniformly distributed.<br>The wave height is obtained from the wave energy spectru

range 0–2 $\pi$ , whose probability of occurrence,  $1/(2\pi)$ , is uniformly distributed.<br>The wave height is obtained from the wave energy spectrum  $S(\omega)$  (Price & Bishop 1974; Lloyd 1989; SNAME 1989)

1974; Lloyd 1989; SNAME 1989)  
\n
$$
h_n = 2\sqrt{2\tilde{\omega}S(n\tilde{\omega})},
$$
\nwhere  $\tilde{\omega}$  is the step of wave frequency, i.e.  $\omega_n = n\tilde{\omega}$ . The wavelength is given by

cy, i.e. 
$$
\omega_n = n\tilde{\omega}
$$
. The wavelength is given by  
\n
$$
\lambda_n = \frac{2\pi g}{(n\tilde{\omega})^2}.
$$
\n(3.7)

 $\lambda_n = \frac{2ng}{(n\tilde{\omega})^2}$ . (3.7)<br>Furthermore, following (3.3), the encounter frequency for a wave component takes Furthermore<br>the form

$$
\omega_{en} = n\tilde{\omega} - \frac{(n\tilde{\omega})^2 U}{g} \cos \chi.
$$
\n(3.8)

The wave energy spectrum depends on ocean statistics (Price & Bishop 1974; Lloyd The wave energy spectrum depends on ocean statistics (Price & Bishop 1974; Lloyd 1989; SNAME 1989). In this analysis, it is assumed that the vessel is exposed to the Adriatic Sea environment. For this closed sea, a specif The wave energy spectrum depends on ocean statistics (Price & Bishop 1974; Lloyd 1989; SNAME 1989). In this analysis, it is assumed that the vessel is exposed to the Adriatic Sea environment. For this closed sea, a specif Adriatic Sea environment. For this closed sea, a specific wave energy spectrum (see figure 4) has been defined on the basis of observations and measurements (Tabain 1977),

$$
S(\omega) = 0.862 \frac{0.0135 g^2}{\omega^5} \exp\left[-\frac{5.186}{\omega^4 h_{1/3}^2}\right] 1.63^p,
$$
 (3.9)

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Figure 5. Hull form of the fishing vessel.

where  $h_{1/3}$  is the significant wave height. The remaining quantities are defined as follows:

$$
p = \exp\left[-\frac{(\omega - \omega_{\rm m})^2}{2\sigma^2 \omega_{\rm m}^2}\right],
$$
  
\n
$$
\omega_{\rm m} = 0.32 + \frac{1.80}{h_{1/3} + 0.6},
$$
  
\n
$$
\sigma = \begin{cases} 0.08 & \text{if } \omega < \omega_{\rm m}, \\ 0.10 & \text{if } \omega > \omega_{\rm m}. \end{cases}
$$
\n(3.10)

(0.10 if  $\omega > \omega_{\rm m}$ .)<br>The units in these formulae are m for  $h_{1/3}$  and rad s<sup>-1</sup> fo for  $\omega$ .

#### 4. Time integration of the roll equation

4. Time integration of the roll equation<br>In linear roll analysis, which is valid for small roll amplitudes, spectral analysis is<br>applied (Price & Bishop 1974: Lloyd 1989: SNAME 1989). The wave slope energy In linear roll analysis, which is valid for small roll amplitudes, spectral analysis is<br>applied (Price & Bishop 1974; Lloyd 1989; SNAME 1989). The wave slope energy<br>spectrum defined in the wave frequency domain has to be t applied (Price & Bishop 1974; Lloyd 1989; SNAME 1989). The wave slope energy spectrum defined in the wave frequency domain has to be transformed into the encounter frequency domain. The same is done with the appropriate r spectrum defined in the wave frequency domain has to be transformed into the spectrum defined in the wave frequency domain has to be transformed into the<br>encounter frequency domain. The same is done with the appropriate roll transfer<br>function. Then, the roll energy spectrum is obtained by multiplyi encounter frequency domain. The same is done with the appropriate roll transfer<br>function. Then, the roll energy spectrum is obtained by multiplying each spectral<br>ordinate by the square of the roll transfer function. Finall function. Then, the roll energy spectrum is obtained by multiplying each spectral<br>ordinate by the square of the roll transfer function. Finally, the roll energy spectrum<br>may be transformed from the encounter frequency doma ordinate by the square of the roll transfer function. Finally, the roll energy spectrum<br>may be transformed from the encounter frequency domain to the wave frequency<br>domain. In this procedure, the grouping of the wave slope may be transformed from the encounter frequency domain to the wave frequency<br>domain. In this procedure, the grouping of the wave slope spectrum in the encounter<br>frequency domain is obvious in the case of multi-valued encou domain. In this procedure, the grouping of the wave slope spectrum in the encounter<br>frequency domain is obvious in the case of multi-valued encounter frequency (see<br>figure 3). If the excitation energy is concentrated close frequency domain is obvious in the case of multi-valued encounter frequency (see figure 3). If the excitation energy is concentrated close to the vessel's roll natural frequency, large roll amplitudes occur and the capsizi

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Relative restoring moment for the intact and damage (dotted line represents real, solid line approximate).



A vessel rolling with large amplitudes is a nonlinear problem and has to be analysed A vessel rolling with large amplitudes is a nonlinear problem and has to be analysed<br>by nonlinear dynamics. Time-domain calculation is preferable, since only in that way<br>may a complete response be obtained, especially for A vessel rolling with large amplitudes is a nonlinear problem and has to be a<br>by nonlinear dynamics. Time-domain calculation is preferable, since only in<br>may a complete response be obtained, especially for a random excitat nonlinear dynamics. Time-domain calculation is preferable, since only in that way<br>ay a complete response be obtained, especially for a random excitation.<br>The governing differential equation of rolling motion (2.5) is inte

may a complete response be obtained, especially for a random excitation.<br>The governing differential equation of rolling motion  $(2.5)$  is integrated by the harmonic acceleration method (Senjanović & Lozina 1993). For this The governing differential equation of rolling mot<br>harmonic acceleration method (Senjanović & Lozir<br>equation is transformed into a pseudo-linear form, equation is transformed into a pseudo-linear form,

$$
\ddot{\varphi} + 2\xi\omega_c\dot{\varphi} + \omega_c^2\varphi = \Psi(t),\tag{4.1}
$$

 $\frac{1}{0}$  where

ere  
\n
$$
\Psi(t) = m(t) + (2\xi\omega_c - d_1)\dot{\varphi} - d_3\dot{\varphi}^3 + (\omega_c^2 - k_1)\varphi - k_3\varphi^3 - k_5\varphi^5 - k_7\varphi^7
$$
\n(4.2)

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ourier coefficients of relative excitation<br>  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup>,  $\chi = 60^{\circ}$ . re excitation<br>  $\chi = 60^{\circ}$ .



is the pseudo-excitation, and  $\xi$  and  $\omega_c$  are the assumed integration damping coef-<br>ficient and integration frequency respectively. These parameters are introduced in is the pseudo-excitation, and  $\xi$  and  $\omega_c$  are the assumed integration damping coef-<br>ficient and integration frequency, respectively. These parameters are introduced in<br>order to improve convergence (Senianović & Lozina is the pseudo-excitation, and  $\xi$  and  $\omega_c$  are the assumed integration damping coef-<br>ficient and integration frequency, respectively. These parameters are introduced in<br>order to improve convergence (Senjanović & Lozina ficient and integration frequency, respectively. These parameters are introduced in order to improve convergence (Senjanović  $\&$  Lozina 1993). The step-by-step iteration integration algorithm reads as

s as  
\n
$$
\{Y\}_{i+1}^{k+1} = [T]\{Y\}_i + \{L\}\Psi_{i+1}^k,
$$
\n(4.3)

 ${Y}_{i+1}^{k+1} = [T] {Y}_i + {L} \Psi_{i+1}^k,$  (4.3)<br>where Y is the response vector, which includes  $\varphi$ ,  $\dot{\varphi}$  and  $\ddot{\varphi}$ , [T] is the transfer matrix,<br> ${L}$  is the load vector, *i* and *k* are the time and iteration steps, where Y is the response vector, which includes  $\varphi$ ,  $\dot{\varphi}$  and  $\ddot{\varphi}$ , [T] is the transfer matrix,<br>{L} is the load vector, i and k are the time and iteration steps, respectively. The<br>quantities [T] and {L} are spec  $\{L\}$  is the load vector, *i* and *k* are the time and iteration steps, respectively. The quantities [T] and  $\{L\}$  are specified in Senjanović & Lozina (1993).

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y spectrum of relative excitation moment,  $h_{1/3} = 2.5$  is (solid line represents  $\chi = 60^{\circ}$ , dashed line  $\chi = 90^{\circ}$ ). ion moment,  $h_{1/3} = 2.5$  i<br>, dashed line  $\chi = 90^{\circ}$ ).

## 5. Vessel particulars and roll parameters

 $\Box$  Rolling motion and survival analysis are illustrated in the case of a fishing vessel with the following particulars and roll<br>with the following particulars (Cardo *et al.* 1994):

g particulars (Cardo <i>et al.</i> 1994):	
length overall	$L_{\text{oa}} = 30.70 \text{ m},$
length between perpendiculars	$L_{\rm pp} = 25.00$ m,
$^{\rm breadth}$	$B = 6.90$ m,
$\text{depth}$	$H = 4.96$ m,
draught	$T = 2.67$ m,
displacement	$\Delta = 195$ t.

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ourier coefficients of the intact vessel's<br>  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup>,  $\chi = 60^{\circ}$ . tact vessel's  $, \chi = 60^{\circ}.$ 

The roll parameters are determined by the model test for a model on a scale<br>1.12.5 Most of the results are taken from Cardo *et al.* (1994) and recalculated The roll parameters are determined by the model test for a model on a scale<br>of 1:12.5. Most of the results are taken from Cardo *et al.* (1994) and recalculated<br>for the full scale. The virtual mass moment of inertia  $I = 1$ The roll parameters are determined by the model test for a model on a scale<br>of 1:12.5. Most of the results are taken from Cardo *et al.* (1994) and recalculated<br>for the full scale. The virtual mass moment of inertia  $I = 1$ of 1:12.5. Most of the results are taken from Cardo *et al.* (1994) for the full scale. The virtual mass moment of inertia  $I = 1078$  metacentric height  $\overline{GM} = 0.962$  m. The roll natural frequency

$$
\omega_{\text{o}} = \left[\frac{g\Delta\overline{GM}}{I}\right]^{1/2} = 1.32 \text{ rad s}^{-1}.
$$
 (5.1)

For the given vessel form shown in figure 5 and for the vertical coordinate of the centre of gravity,  $KG = 2.62$  m.

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Figure 15. Fourier coefficients of the intact vessel's roll angle,  $h_{1/3} = 2.5$  m,  $\chi = 90^{\circ}$ .<br>The relative restoring moment reads as

The relative restoring moment reads as

$$
r(\varphi) = \frac{R(\varphi)}{I} = \frac{g\Delta \overline{GZ}}{I},\tag{5.2}
$$

 $r(\varphi) = \frac{\partial \varphi}{I} = \frac{\partial \varphi}{I}$ , (5.2)<br>where  $\overline{GZ}$  is the righting arm. The moment is shown by the dotted lines in figure 6 for<br>the intact and damaged yessel. It is assumed that the engine room is flooded and the where  $\overline{GZ}$  is the righting arm. The moment is shown by the dotted lines in figure 6 for<br>the intact and damaged vessel. It is assumed that the engine room is flooded and the<br>permeability coefficient is 0.75 (figure 1) where  $GZ$  is the righting arm. The moment is shown by the dotted lines in figure 6 for<br>the intact and damaged vessel. It is assumed that the engine room is flooded and the<br>permeability coefficient is 0.75 (figure 1). Fur the intact and damaged vessel. It is assumed that the engine room is flooded and the permeability coefficient is  $0.75$  (figure 1). Furthermore, the moment is approximated by a polynomial (solid lines in figure 6). The co permeability coefficient is 0.75 (figure 1). Furthermore, the moment is apply a polynomial (solid lines in figure 6). The coefficients of the fifth- a order polynomial for the intact and damaged vessel, respectively, are formal footh lines in figure 6). The coolidents of the linear and lost<br>
lynomial for the intact and damaged vessel, respectively, are<br>  $k_1 = 1.7737 \text{ s}^{-2}$ ,  $k_3 = -0.518291 \text{ s}^{-2}$ ,  $k_5 = 0.0306808 \text{ s}^{-2}$ 

$$
k_1 = 1.7737 \text{ s}^{-2}
$$
,  $k_3 = -0.518291 \text{ s}^{-2}$ ,  $k_5 = 0.0306808 \text{ s}^{-2}$ 

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bll energy spectra of the intact vessel,  $h_{1/3} = 2.5$  m, *U* (solid line represents  $\chi = 60^{\circ}$ , dashed line  $\chi = 90^{\circ}$ ). (solid line represents  $\chi = 60^{\circ}$ , dashed line  $\chi = 90^{\circ}$ ).



Figure 17. Legend of time-intervals to capsize.

$$
k_1 = 1.63824 \text{ s}^{-2}
$$
,  $k_3 = -0.829256 \text{ s}^{-2}$ ,  
\n $k_5 = 0.14776 \text{ s}^{-2}$ ,  $k_7 = -0.00923174 \text{ s}^{-2}$ .

 $k_5 = 0.14776 \text{ s}^{-2}$ ,  $k_7 = -0.00923174 \text{ s}^{-2}$ .<br>The damping-moment coefficients are assumed to be the same in both cases, i.e. for e intact and damaged vessel  $k_5 = 0.14776$ <br>The damping-moment coefficies<br>the intact and damaged vessel vessel<br>  $d_1 = 0.0208 \text{ s}^{-1}$ ,

$$
d_1 = 0.0208 \text{ s}^{-1}, \qquad d_3 = 0.01648 \text{ s}.
$$

The damping-moment coefficients are assumed to be the same in both cases, i.e. for<br>the intact and damaged vessel<br> $d_1 = 0.0208 \text{ s}^{-1}$ ,  $d_3 = 0.01648 \text{ s}$ .<br>The effective wave slope coefficient  $\alpha_0 = 0.729$  is taken from  $a_1 = 0.62$ <br>The effective wave slope coefficies<br>all harmonic wave components.<br>The yessel's roll analysis is ne ne effective wave slope coefficient  $\alpha_0 = 0.729$  is taken from Cardo *et al.* (1994) for harmonic wave components.<br>The vessel's roll analysis is performed for one sea state given by the significant we height  $h_{3/2} = 2.5$ 

all harmonic wave components.<br>The vessel's roll analysis is performed for one sea state given by the significant<br>wave height  $h_{1/3} = 2.5$  m, three vessel speeds  $U = 0$ , 2, 4 m s<sup>-1</sup>, and the heading<br>angle  $0^{\circ} \le \chi \le 18$ The vessel's roll analysis is performed for one sea state given by the significant<br>wave height  $h_{1/3} = 2.5$  m, three vessel speeds  $U = 0, 2, 4$  m s<sup>-1</sup>, and the heading<br>angle  $0^{\circ} \le \chi \le 180^{\circ}$ , with discrete interval wave height  $h_{1/3} = 2.5$  m, three vessel speeds  $U = 0, 2, 4$  m s<sup>-1</sup>, and the heading angle  $0^{\circ} \le \chi \le 180^{\circ}$ , with discrete intervals  $\Delta \chi = 10^{\circ}$ . The wave energy spectrum, shown in figure 4, up to the frequency shown in figure 4, up to the frequency  $\omega_1 = 3$  rad s<sup>-1</sup> is taken into account. This is the maximum value obtained by the formula

$$
\omega_1 = \left[\frac{2\pi g \sin \chi}{B}\right]^{1/2},\tag{5.3}
$$

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Figure 18. Safe basin of the intact vessel.

Figure 18. Sare basin of the intact vessel.<br>which follows from the assumed condition  $\lambda \sin \chi > B$  for the wave slope excitation<br>contribution and from the relation (3.7). The frequency step  $\tilde{\omega} = 0.025$  rad s<sup>-1</sup> is which follows from the assumed condition  $\lambda \sin \chi > B$  for the wave slope excitation contribution and from the relation (3.7). The frequency step  $\tilde{\omega} = 0.025$  rad s<sup>-1</sup> is chosen so that the total number of harmonic waves contribution and from the relation (3.7). The frequency step  $\tilde{\omega} = 0.025$  rad s<sup>-1</sup> is which follows from the assumed condition  $\lambda \sin \chi > B$  for the wave slope excitation contribution and from the relation (3.7). The frequency step  $\tilde{\omega} = 0.025$  rad s<sup>-1</sup> is chosen, so that the total number of harmonic wave chosen, so that the total number of harmonic waves forming an irregular wave pattern<br>is  $N = \omega_1/\tilde{\omega} = 120$ .

The relative excitation moment is calculated by the formula (3.5), employing (3.6), (3.7) and (3.8), within the time-interval equal to the period of the lowest excitation harmonic, i.e.  $T = 2\pi/\tilde{\omega} = 250$  s. Also, the Fourier transform is performed in the (3.7) and (3.8), within the time-interval equal to the period of the lowest excitation harmonic, i.e.  $\tilde{T} = 2\pi/\tilde{\omega} = 250$  s. Also, the Fourier transform is performed in the encounter frequency domain. Interesting resu harmonic, i.e.  $T = 2\pi/\tilde{\omega} = 250$  s. Also, the Fourier transform is performed in the encounter frequency domain. Interesting results for  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup> and  $\chi = 60$  and 90<sup>°</sup> are obtained and shown in fi encounter frequency domain. Interesting results for  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup> and  $\chi = 60$  and 90° are obtained and shown in figures 7–10. The grouping of the harmonic waves is evident in the case  $\chi = 60^{\circ}$  at  $\$  $\chi = 60$  and 90° are obtained and shown in figures 7–10. The grouping of the harmonic<br>waves is evident in the case  $\chi = 60^{\circ}$  at  $\omega_e = 1.2$  rad s<sup>-1</sup> (see figure 8), since, according<br>to figure 2, their uniformly distrib waves is evident in the case  $\chi = 60^{\circ}$  at  $\omega_e = 1.2$  rad s<sup>-1</sup> (see figure 8), since, accord to figure 2, their uniformly distributed frequencies are transformed into the encourance frequencies of almost equal values.  $\Omega$  frequencies of almost equal values. The Fourier coefficients in the case  $\chi = 90^{\circ}$  follow to figure 2, their uniformly distributed frequencies are transformed into the encounter<br>frequencies of almost equal values. The Fourier coefficients in the case  $\chi = 90^{\circ}$  follow<br>a smooth line because  $\omega_e = \omega$ , and thei frequencies of almost equal values. The Fourier coeffic<br>a smooth line because  $\omega_e = \omega$ , and their total numbe<br>wave energy ordinates, i.e.  $N = 120$  (see figure 10).<br>In order to compare the wave excitations for  $y = 60$ smooth line because  $\omega_e = \omega$ , and their total number is equal to the number of the wave energy ordinates, i.e.  $N = 120$  (see figure 10).<br>In order to compare the wave excitations for  $\chi = 60$  and  $90^\circ$ , the energy spectru wave energy ordinates, i.e.  $N = 120$  (see figure 10).<br>In order to compare the wave excitations for  $\chi = 60$  and  $90^{\circ}$ , the energy spectrum

of the relative excitation moment is determined by the formula,

$$
S_{\rm m}(\omega_{\rm e}) = \frac{m_n^2}{2\tilde{\omega}},\tag{5.4}
$$

 $S_{\rm m}(\omega_{\rm e}) = \frac{n}{2\tilde{\omega}},$  (5.4)<br>and shown in figure 11. The grouping of component waves energy is very pronounced<br>in the former case and shown in figure 1<br>in the former case. *Phil. Trans. R. Soc. Lond.* A (2000)

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#### 6. Roll analysis of intact vessel

 $\bullet$ . Roll analysis of intact vessel<br>The differential equation of rolling motion (2.5) is integrated by the harmonic acceler-<br>ation method taking the integration frequency close to the excitation spectrum peak The differential equation of rolling motion (2.5) is integrated by the harmonic acceleration method, taking the integration frequency close to the excitation spectrum peak frequency for beam seas i.e.  $\omega_z = 1$  rad  $s^{-1}$  The differential equation of rolling motion (2.5) is integrated by the harmonic acceleration method, taking the integration frequency close to the excitation spectrum peak frequency for beam seas, i.e.  $\omega_c = 1$  rad  $s^{-1}$ ation method, taking the integration frequency close to the excitation spectrum peak<br>frequency for beam seas, i.e.  $\omega_c = 1 \text{ rad s}^{-1}$ , and damping coefficient  $\xi = d_1/(2\omega_o) =$ <br>0.007 88. The initial conditions  $\varphi(0) = \varphi_0$ frequency for beam seas, i.e.  $\omega_c = 1$  rad s<sup>-1</sup>, and damping coefficient  $\xi = d_1/(2\omega_o) = 0.007 88$ . The initial conditions  $\varphi(0) = \varphi_0$  and  $\dot{\varphi}(0) = \dot{\varphi}_0$  are assumed so that the vessel stability is preserved within 0.007 88. The initial conditions  $\varphi(0) = \varphi_0$  and  $\dot{\varphi}(0) = \dot{\varphi}_0$  are assumed so that the vessel stability is preserved within the time-interval  $t = 300$  s, where the time-step is  $\Delta t = 0.025$  s. This includes 50 s t vessel stability is preserved within the time-interval  $t = 300$  s, where the time-step is  $\Delta t = 0.025$  s. This includes 50 s to reduce possible transient response caused by initial conditions, and the period of the lowest

Among a large number of the calculated cases for one sea state, three vessel speeds tial conditions, and the period of the lowest excitation harmonic  $T = 2\pi/\tilde{\omega} = 250$  s.<br>Among a large number of the calculated cases for one sea state, three vessel speeds<br>and 19 heading angles (as stated in  $\S 5$ ), the Among a large number of the calculated cases for one sea state, three vessel speeds<br>and 19 heading angles (as stated in §5), the realization of the roll angle and its<br>Fourier transform for  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup> and 19 heading angles (as stated in §5), the realization of the roll angle and its<br>Fourier transform for  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup> and  $\chi = 60$  and 90° are shown in<br>figures 12–15. Comparing these diagrams with those Fourier transform for  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup> and  $\chi = 60$  and 90° are shown in figures 12–15. Comparing these diagrams with those for the wave excitation (figures 8 and 10), some subharmonic response may be notic figures  $12-15$ . Comparing these diagrams with those for the wave excitation (figures 8 and 10), some subharmonic response may be noticed. Also, stationary response is not achieved in a deterministic sense. and  $10$ , some subharmonic response may be noticed. Also, stationary response is

To be able to compare the vessel's response obtained for various conditions, the roll energy spectrum is determined according to the definition

$$
S_{\varphi}(\omega_{\rm e}) = \varphi_n^2 / 2\tilde{\omega}.\tag{6.1}
$$

 $S_{\varphi}(\omega_{\rm e}) = \varphi_n^2/2\tilde{\omega}.$  (6.1)<br>The roll spectrum for  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup> and  $\chi = 60$  and 90<sup>°</sup> is shown in<br>figure 16 Roll energy presented by a zero statistical moment is much larger in the The roll spectrum for  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup> and  $\chi = 60$  and  $90^{\circ}$  is shown in figure 16. Roll energy, presented by a zero statistical moment, is much larger in the former than in the latter case The roll spectrum for  $h_{1/3} = 2$ .<br>figure 16. Roll energy, presented<br>former than in the latter case. *Phil. Trans. R. Soc. Lond.* A (2000)

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The safety of the vessel rolling in rough seas may be analysed in the initial-value The safety of the vessel rolling in rough seas may be analysed in the initial-value plane as a control space. For this purpose, the differential equation of motion (2.5) is integrated for a different combination of the in The safety of the vessel rolling in rough seas may be analysed in the initial-value<br>plane as a control space. For this purpose, the differential equation of motion (2.5)<br>is integrated for a different combination of the in plane as a control space. For this purpose, the differential equation of motion (2.5) is integrated for a different combination of the initial conditions  $\varphi(0) = \varphi_0$  and  $\dot{\varphi}(0) = \dot{\varphi}_0$ , where  $-3 \le \varphi_0 \le 3$  rad an  $\dot{\varphi}(0) = \dot{\varphi}_0$ , where  $-3 \leq \varphi_0 \leq 3$  rad and  $-3 \leq \dot{\varphi}_0 \leq 3$  rad s<sup>-1</sup>. Also, two sea states<br>*Phil. Trans. R. Soc. Lond.* A (2000)

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Figure 1. The damaged vessel  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup>,  $\chi = 56^{\circ}$ . raged vessel's<br>  $, \chi = 56^{\circ}.$ 



Figure 23. Roll angle of the damaged vessel,  $h_{1/3} = 2.5$  m,  $\chi = 90^{\circ}$ .<br>given by the significant wave height  $h_{1/3} = 0$  and 2.5 m, three vessel speeds  $U = 0$ ,<br>2 and 4 m s<sup>-1</sup> and 10 values of hooding angles  $0 \le \chi \le$ given by the significant wave height  $h_{1/3} = 0$  and 2.5 m, three vessel speeds  $U = 0$ ,<br>2 and 4 m s<sup>-1</sup>, and 19 values of heading angles  $0 \le \chi \le 180^{\circ}$ , with discrete heading<br>intervals  $\Delta v = 10^{\circ}$  are taken into acco given by the significant wave height  $h_{1/3} = 0$ <br>2 and 4 m s<sup>-1</sup>, and 19 values of heading angle<br>intervals  $\Delta \chi = 10^{\circ}$ , are taken into account.<br>Some interesting results are shown in figures and  $4 \text{ m s}^{-1}$ , and 19 values of heading angles  $0 \le \chi \le 180^{\circ}$ , with discrete heading<br>servals  $\Delta \chi = 10^{\circ}$ , are taken into account.<br>Some interesting results are shown in figures 18-20, with a resolution of  $200 \times 2$ 

intervals  $\Delta \chi = 10^{\circ}$ , are taken into account.<br>Some interesting results are shown in figures 18–20, with a resolution of  $200 \times 200 = 40\,000$  grid points. According to the legend given in figure 17, the black area is t Some interesting results are shown in figures 18–20, with a resolution of  $200 \times 200 =$  40 000 grid points. According to the legend given in figure 17, the black area is the safe basin, since the vessel survives within the basin, since the vessel survives within the whole period  $T$ . The bright area represents the capsize domain where the vessel capsizes at the very beginning of rolling motion, basin, since the vessel survives within the whole period T. The bright area represents<br>the capsize domain where the vessel capsizes at the very beginning of rolling motion,<br> $0 < t/\tilde{T} < \frac{1}{5}$ . The remaining shades denote the capsize domain where the vessel capsizes at the very beginning of rolling motion,<br> $0 < t/\tilde{T} < \frac{1}{5}$ . The remaining shades denote some transition time-intervals to capsize.<br>In the case of calm sea ( $h_{1/3} = 0$  m), the  $0 < t/T < \frac{1}{5}$ . The remaining shades denote some transition time-intervals to capsize.<br>In the case of calm sea  $(h_{1/3} = 0 \text{ m})$ , the safe basin is compact with a smooth capsize boundary (see figure 18). For rough seas, th *Phil. Trans. R. Soc. Lond.* A (2000)

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l energy spectra of the damaged vessel,  $h_{1/3} = 2.5$  m,<br>(solid line represents  $\chi = 56^{\circ}$ , dashed line  $\chi = 90^{\circ}$ ). (solid line represents  $\chi = 56^{\circ}$ , dashed line  $\chi = 90^{\circ}$ ).

with the sea roughness, as may be seen in Senjanović *et al.* (1996). It also depends with the sea roughness, as may be seen in Senjanović *et al.* (1996). It also depends<br>on vessel speed and heading angle. In the case considered, where  $h_{1/3} = 2.5$  m and<br> $U = 4$  m s<sup>-1</sup>, the crosion at  $\chi = 90^{\circ}$  is ver with the sea roughness, as may be seen in Senjanovic *et al.* (1996). It also depends<br>on vessel speed and heading angle. In the case considered, where  $h_{1/3} = 2.5$  m and<br> $U = 4$  m s<sup>-1</sup>, the erosion at  $\chi = 90^{\circ}$  is ver on vessel speed and heading angle. In the case considered, where  $h_{1/3} = 2.5$  m and  $U = 4 \text{ m s}^{-1}$ , the erosion at  $\chi = 90^{\circ}$  is very small, while at  $\chi = 60^{\circ}$  it is at a maximum. This is due to the influence of th  $U = 4 \text{ m s}^{-1}$ , the erosion at  $\chi = 90^{\circ}$  is very small, while at  $\chi = 60^{\circ}$  it is a maximum. This is due to the influence of the encounter frequency on the group of the harmonic component waves close to the natural % of the harmonic component waves close to the natural frequency of vessel roll.<br>7. Roll analysis of damaged vessel

7. Roll analysis of damaged vessel<br>In a similar way, the rolling of the damaged vessel for the same sea state, vessel speeds<br>and heading angles are analysed. The change of the excitation moment (3.5) due to In a similar way, the rolling of the damaged vessel for the same sea state, vessel speeds<br>and heading angles are analysed. The change of the excitation moment (3.5) due to and heading angles are analysed. The change of the excitation moment (3.5) due to<br>*Phil. Trans. R. Soc. Lond.* A (2000)

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Figure 26. Safe basin of the damaged vessel.<br>Table 1. *Minimum probability of a vessel's survival, sea state*  $h_{1/3} = 2.5$  m

	vessel $U \text{ (m s}^{-1})$ $\chi$ (deg) $p$		
intact	$\theta$	90	0.99
	$\overline{2}$	60	0.79
	4	60	0.10
damaged	$\theta$	90	0.98
	$\overline{2}$	50	0.86
	4	56	0.16

different values of roll natural frequency  $\omega_o$  is not taken into account. In order to find<br>the maximum roll response, the heading angle in an interval  $50 < y < 60^\circ$  is varied different values of roll natural frequency  $\omega_0$  is not taken into account. In order to find<br>the maximum roll response, the heading angle in an interval  $50 < \chi < 60^\circ$  is varied<br>by a step of  $\Delta v = 1^\circ$ . For  $h_{\lambda/2} = 2.5$ different values of roll natural frequency  $\omega_o$  is not taken into account. In order to find<br>the maximum roll response, the heading angle in an interval  $50 < \chi < 60^{\circ}$  is varied<br>by a step of  $\Delta \chi = 1^{\circ}$ . For  $h_{1/3} = 2$ the maximum roll response, the<br>by a step of  $\Delta \chi = 1^{\circ}$ . For  $h_{1/3}$ <br>at  $\chi = 56^{\circ}$ , while at  $\chi = 90^{\circ}$  th<br>the time and frequency domain the heading angle in an interval  $50 < \chi < 60^{\circ}$  is varied  $\gamma_3 = 2.5$  m and  $U = 4 \text{ m s}^{-1}$ , large rolling is obtained the roll angle is somewhat lower, as may be seen from in presentation of the realization in figures 2 by a step of  $\Delta \chi = 1^{\circ}$ . For  $h_{1/3} = 2.5$  m and  $U = 4 \text{ m s}^{-1}$ , large rolling is obtained<br>at  $\chi = 56^{\circ}$ , while at  $\chi = 90^{\circ}$  the roll angle is somewhat lower, as may be seen from<br>the time and frequency domain pre at  $\chi = 56^{\circ}$ , while at  $\chi = 90^{\circ}$  the roll angle is somewhat lower, as may be seen from<br>the time and frequency domain presentation of the realization in figures 21–24. The<br>corresponding roll energy spectra are shown the time and frequency domain presentation of the realization in figures 2<br>corresponding roll energy spectra are shown in figure 25. The zero statistics<br>of the roll spectrum for  $\chi = 56^{\circ}$  is much larger than that for s 21–24. The<br>ical moment<br>. Comparing<br>spectively it. corresponding roll energy spectra are shown in figure 25. The zero statistical moment<br>of the roll spectrum for  $\chi = 56^{\circ}$  is much larger than that for  $\chi = 90^{\circ}$ . Comparing<br>the diagrams in figures 16 and 25 for the in of the roll spectrum for  $\chi = 56^{\circ}$  is much larger than that for  $\chi = 90^{\circ}$ . Comparing the diagrams in figures 16 and 25 for the intact and damaged vessel, respectively, it is evident that the corresponding statistica the diagrams in figures 16 and 25 for the intact and damaged vessel, respectively, it<br>is evident that the corresponding statistical moments are larger in the latter than in<br>the former case.

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Figure 27. Capsize boundary of the damaged vessel,  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup>,  $\chi = 56^{\circ}$ .<br>Furthermore, the safe basin for calm sea (with  $h_{1/3} = 0$  m) and its erosion for  $u_3 = 2.5$  m  $U = 4$  m s<sup>-1</sup> and  $\chi = 56$  Furthermore, the safe basin for calm sea (with  $h_{1/3} = 0$  m) and its erosion for  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup> and  $\chi = 56$  and  $90^\circ$  are determined and shown in fig-<br>ures 26–27 and 28 respectively Comparing these fig Furthermore, the safe basin for calm sea (with  $h_{1/3} = 0$  m) and its erosion for  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup> and  $\chi = 56$  and  $90^{\circ}$  are determined and shown in figures 26, 27 and 28, respectively. Comparing these  $h_{1/3} = 2.5$  m,  $U = 4$  m s<sup>-1</sup> and  $\chi = 56$  and  $90^{\circ}$  are determined and shown in figures 26, 27 and 28, respectively. Comparing these figures for the damaged vessel with the corresponding figures 18-20 for the intact ures 26, 27 and 28, respectively. Comparing these figures for the damaged vessel with<br>the corresponding figures  $18-20$  for the intact vessel, one may see that the safe basin<br>is reduced by  $ca. 17\%$  and more eroded in the the corresponding figures 18–20 for the intact vessel, one may see that the safe basin

#### 8. Probability of survival

The ratio between the areas of the safe basin obtained for and without wave excitation **The ratio between the areas of the safe basin obtained for and without wave excitation** may be used as the probability of the vessel's survival (Senjanović *et al.* 1996, 1997). Such diagrams constructed for the intact an The ratio between the areas of the safe basin obtained for and without wave excitation<br>may be used as the probability of the vessel's survival (Senjanović *et al.* 1996, 1997).<br>Such diagrams constructed for the intact and may be used as the probability of the vessel's survival (Senjanović *et al.* 1996, 1997).<br>Such diagrams constructed for the intact and damaged vessel, and for the considered<br>sea state  $h_{1/3} = 2.5$  m, are shown in a PC ra Such diagrams constructed for the intact and damaged vessel, and for the considered<br>sea state  $h_{1/3} = 2.5$  m, are shown in a PC radar map in figures 29 and 30. The<br>vessel speed  $U = 0$ , 2 and 4 m s<sup>-1</sup> is a parameter, and See state  $h_{1/3} = 2.5$  m, are shown in a PC radar map in figures 29 and 30. The vessel speed  $U = 0$ , 2 and 4 m s<sup>-1</sup> is a parameter, and the heading angle is variable.<br>The minimum values of the probability function for t vessel speed  $U = 0$ , 2 and 4 m s<sup>-1</sup> is a parameter, and the heading angle is variable.<br>The minimum values of the probability function for the considered cases are listed in table 1. The probability of survival of the flo The minimum values of the probability function for the considered cases are listed in table 1. The probability of survival of the floating vessel,  $U = 0 \text{ m s}^{-1}$ , is minimum for beam seas, and it is larger for the intact table 1. The probability of survival of the floating vessel,  $U = 0$  m s<sup>-1</sup>, is minimum for beam seas, and it is larger for the intact than for the damaged condition. Quartering seas are very dangerous for the stability o beam seas, and it is larger for the intact than for the damaged condition. Quartering seas are very dangerous for the stability of a voyaging vessel. In spite of the fact that the probability of survival is somewhat larger seas are very dangerous for the stability of a voyaging vessel. In spite of the fact<br>that the probability of survival is somewhat larger for the damaged vessel than for<br>the intact one, it is so drastically reduced in both that the probability of survival is somewhat larger for the damaged vessel than for<br>the intact one, it is so drastically reduced in both cases that such situations have to<br>be avoided. It is obvious that the vessel at quart the intact one, it is so drastically reduced in both case<br>be avoided. It is obvious that the vessel at quartering<br>and/or change direction in order to avoid capsizing. *Phil. Trans. R. Soc. Lond.* A (2000)

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#### 9. Conclusion

**MATHEMATICAL,<br>PHYSICAL<br>& ENGINEERING<br>SCIENCES** A vessel at sea is an autonomous system exposed to many hazardous situations.<br>However, the vessel's capsizing has catastrophic consequences since it results in the<br>loss of the vessel and possibly heavy human losses. Insuff A vessel at sea is an autonomous system exposed to many hazardous situations. A vessel at sea is an autonomous system exposed to many hazardous situations.<br>However, the vessel's capsizing has catastrophic consequences since it results in the<br>loss of the vessel and, possibly, heavy human losses. Ins However, the vessel's capsizing has catastrophic consequences since it results in the loss of the vessel and, possibly, heavy human losses. Insufficient stability is a very frequent cause of fishing vessel losses (Dahle & loss of the vessel and, possibly, heavy human losses. Insufficient stability is a very frequent cause of fishing vessel losses (Dahle  $\&$  Nisja 1984). The reason is that stability criteria, given by national and internat quent cause of fishing vessel losses (Dahle & Nisja 1984). The reason is that stability<br>criteria, given by national and international rules, are rather conservative, prescrib-<br>ing the form and area under the restoring mom criteria, given by national and international rules, are rather conservative, prescribing the form and area under the restoring moment curve. In this way it is ensured that the work of the restoring moment in calm sea is l that the work of the restoring moment in calm sea is larger than the work of a possible heeling moment. Many vessels capsize in rough seas in spite of the fact that that the work of the restoring moment in calm sea is larger than the work of a pos-<br>sible heeling moment. Many vessels capsize in rough seas in spite of the fact that<br>they satisfy stability criteria. This is due to the fac sible heeling moment. Many vessels capsize in rough seas in spite of the fact that<br>they satisfy stability criteria. This is due to the fact that the nonlinear phenomena<br>of vessels rolling are not taken into account. Theref of vessels rolling are not taken into account. Therefore, in order to improve vessel safety, it is necessary to analyse vessel rolling in rough seas as a nonlinear random process.

process.<br>In this paper a contemporary approach employing a sophisticated numerical method<br>and recent knowledge of nonlinear dynamics is described. The problem is reduced<br>to an SDOF system with a nonlinear damping and resto In this paper a contemporary approach employing a sophisticated numerical method and recent knowledge of nonlinear dynamics is described. The problem is reduced to an SDOF system with a nonlinear damping and restoring mome In this paper a contemporary approach employing a sophisticated numerical method and recent knowledge of nonlinear dynamics is described. The problem is reduced<br>to an SDOF system with a nonlinear damping and restoring moment. The wave<br>energy spectrum is used to determine random roll excitation. An i to an SDOF system with a nonlinear damping and restoring moment. The wave<br>energy spectrum is used to determine random roll excitation. An intact vessel and<br>a damaged vessel are considered in different conditions specified energy spectrum is used to determine random roll excitation. An intact vessel and<br>a damaged vessel are considered in different conditions specified by sea state, vessel<br>speed and heading angle. The final result is the dete a damaged vessel are considered in different conditions specified by sea state, vessel<br>speed and heading angle. The final result is the determination of the probability<br>function of vessel survival depending on these three speed and heading angle. The final result is the determination<br>function of vessel survival depending on these three parameters.<br>voyage in quartering seas is very dangerous for vessel stability. p *Phil. Trans. R. Soc. Lond.* A (2000)

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Figure 29. Probability of the intact vessel's survival,  $h_{1/3} = 2.5$  m.

The intention of this paper is to point out the need for analysing vessel stability The intention of this paper is to point out the need for analysing vessel stability<br>through nonlinear rolling and capsizing. This new approach requires application of<br>the stability criterion based on the probability functi The intention of this paper is to point out the need for analysing vessel stability<br>through nonlinear rolling and capsizing. This new approach requires application of<br>the stability criterion based on the probability functi through nonlinear rolling and capsizing. This new approach requires application of<br>the stability criterion based on the probability function of vessel survival. In this<br>way, non-permissible voyage conditions may be specifi the stability criterion based on the probability function of vessel survival. In this way, non-permissible voyage conditions may be specified. In the meantime, such survival diagrams like those shown in figures 29 and 30 m way, non-permissible voyage conditions may be specified. In the meantime, such survival diagrams like those shown in figures 29 and 30 may be used onboard to avoid experience. In disastrous situations. At the present time, this is left to the captain's assessment and experience.<br>In order to increase vessel safety in rough seas, this new approach for stabil-

experience.<br>In order to increase vessel safety in rough seas, this new approach for stabil-<br>ity estimation should be improved by investigating coupled motion, hydrodynamic<br>coefficients reliable wave excitation, sloshing ef In order to increase vessel safety in rough seas, this new approach for stability estimation should be improved by investigating coupled motion, hydrodynamic coefficients, reliable wave excitation, sloshing effect for dam ity estimation should be improved by investigating coupled motion, hydrodynamic<br>coefficients, reliable wave excitation, sloshing effect for damaged vessels, etc. (ITTC<br>1996; Contento *et al.* 1996*b*; Francescutto & Conten coefficients, reliable wave excitation, sloshing effect for damaged vessels, etc. (ITTC 1996; Contento *et al.* 1996*b*; Francescutto & Contento 1997). Finally, experimental verification is also very important (Oh *et al.* 

#### References

**References**<br>Cardo, A., Francescutto, A. & Nabergoj, R. 1984 Nonlinear rolling response in a regular sea.<br>Int. Shinhuilding Prog. 31, 204–208. *Int. Shipbuilding Prog.* 31, 204–208. *Int. Shipbuilding Prog.* **31**, 204–208.<br>*Phil. Trans. R. Soc. Lond.* A (2000)

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Cardo, A., Contento, G., Francescutto, A., Copola, C. & Penna, R. 1994 On the nonlinear ship roll damping components. In *Int. Symp. on Ship and Marine Research, Rome, 1994*, vol. 1. Cardo, A., Contento, G., Francescutto, A., Copola, C. & Penna, R. 1994 On the nonlinear ship<br>roll damping components. In *Int. Symp. on Ship and Marine Research, Rome, 1994*, vol. 1.<br>Cartmell, M. 1990 *Introduction to line* roll damp<br>rtmell, M<br>& Hall.<br>rtente G & Hall.<br>Contento, G., Francescutto, A. & Piciullo, M. 1996a On the effectiveness of constant coefficients

roll motion equation. *Ocean Engng* 23, 597-618. Contento, G., Francescutto, A. & Piciullo, M. 1996a On the effectiveness of constant coefficients<br>roll motion equation. Ocean Engng 23, 597–618.<br>Contento, G., Francescutto, A. & Piciullo, M. 1996b On the effectiveness of

roll motion equation. *Ocean Engng* 23, 597–618.<br>
ntento, G., Francescutto, A. & Piciullo, M. 1996b C<br>
roll motion equation. *Ocean Engng* 23, 597–618.<br>
ble F. A. & Nicie G. E. 1984 Intest and democration roll motion equation. Ocean Engng 23, 597–618.<br>Dahle, E. A. & Nisja, G. E. 1984 Intact and damaged stability of small crafts with emphasis on

design. In *Proc. Int. Conf. on Design Considerations of Small Craft*. London: RINA. Dahle, E. A. & Nisja, G. E. 1984 Intact and damaged stability of small crafts with emphasis c<br>design. In *Proc. Int. Conf. on Design Considerations of Small Craft*. London: RINA.<br>Dimentberg, M. F. 1988 *Statistical dynamic* 

design. in *Proc. Int. Conf. on Design Considerations of Small Craft.* London: KINA.<br>Dimentberg, M. F. 1988 *Statistical dynamics of nonlinear and time-varying systems*. Wiley.<br>Falzarano, J. M., Esparza, I. & Taz Ul Mulk, Falzarano, J. M., Esparza, I. & Taz Ul Mulk, M. 1995 A combined steady-state and transient approach to study large amplitude ship rolling motion and capsizing. *J. Ship Res.* **39**, 213–224. Falzarano, J. M., Esparza, I. & Taz Ul Mulk, M. 1995 A combined steady-state and transient<br>approach to study large amplitude ship rolling motion and capsizing. *J. Ship Res.* **39**, 213–224.<br>Francescutto, A. & Contento, G.

approach to study large amplitude ship rolling motion and capsizing. *J. Ship Res.* **39**, 213–224.<br>ancescutto, A. & Contento, G. 1994 An experimental study of the coupling between roll motion<br>and sloshing in a compartment. *Japan, 1994*. *Phil. Trans. R. Soc. Lond.* A (2000)

**MATHEMATICAL,<br>PHYSICAL<br>& ENGINEERING<br>SCIENCES** 

**MATHEMATICAL,<br>PHYSICAL<br>& ENGINEERING<br>SCIENCES** 

THE ROYAL

**PHILOSOPHICAL**<br>TRANSACTIONS  $\overline{\delta}$ 

- Francescutto, A. & Contento, G. 1997 An investigation on the applicability of simplified mathematical models to the roll-sloshing problem. In *7th Int. Offshore and Polar Engineering*<br>Conference, Honolulu, Hawaii, 1997. *Francescutto, A. & Contento, G. 1997 An investigation on the applicability of simplified mathematical models to the roll-sloshing problem. In 7th Int. Offshore and Polar Engineering Conference, Honolulu, Hawaii, 1997.*<br>GH
- Conference, Ho<br>IS 1993 Generi<br>Systems, Inc.<br>TC 1996 Bener GHS 1993 *General Hydrostatics, version 6.10, user's manual*. Port Townsend, WA: Creative Systems, Inc.<br>ITTC 1996 Report of the Seakeeping Committee for the 21st International Towing Tank Con-<br>ference (ITTC)
- Systems, Inc.<br>TC 1996 Report of<br>ference (ITTC).<br>In M & Taguchi Kan, M. & Taguchi, H. 1991 Chaos and fractals in capsizing of a ship. In *Proc. NADMAR91*.<br>Lloyd, A. R. J. M. 1989 *Seakeeping: ship behaviour in rough weather*. Chichester: Ellis Horwood.<br>Cobi. M. K. & Bolton. W. E. 1973
- 
- 
- Nan, M. & Tagueni, H. 1991 Chaos and ractas in capsizing of a sinp. In *Proc. NADMAR91*.<br>Lloyd, A. R. J. M. 1989 *Seakeeping: ship behaviour in rough weather*. Chichester: Ellis Horwood.<br>Ochi, M. K. & Bolton, W. E. 1973 St Ochi, M. K. & Bolton, W. E. 1973 Statistics for prediction of ship performance in a seaway. *Int.* Shipbuilding Prog. 222, 27-54; 224, 89-121; 229, 346-373.
- Oh, I., Nayfeh, A. & Mook, D. 1992 Theoretical and experimental study of the nonlinear cou-Shipbuilding Prog. 222, 27–54; 224, 89–121; 229, 346–373.<br>
1, I., Nayfeh, A. & Mook, D. 1992 Theoretical and experimental study of the nonlinear coupled heave, pitch and roll motions of a ship in longitudinal waves. In *9t Hydrodynamics, Seoul, Korea, 1992* Theoretical and experimental study of the nonlinear coupled heave, pitch and roll motions of a ship in longitudinal waves. In *9th Symp. on Naval Hydrodynamics, Seoul, Korea, 1992.*<br>Peyt
- *d Hydrodynamics, Seoul, Korea, 1992.*<br> **depending 1998** Generalized harmonic analysis of nonlinear ship roll dynamics. *J. Ship Res.* 40, 316–325. Peyton Jones, J. C. & Cankaya, I. 1996 Generalized harmonic analysis of nonlinear ship roll<br>dynamics. *J. Ship Res.* 40, 316–325.<br>Price, W. G. & Bishop, R. E. D. 1974 *Probabilistic theory of ship dynamics*. London: Chapma
	- dynamics<br>ice, W. G<br>& Hall.<br>nianović Senjanovi¶c, I. 1994 Harmonic analysis of nonlinear oscillations of cubic dynamical systems. *J.*
	- *Ship Res.* **38**, 225-238.
	- Senjanović, I. & Fan, Y. 1994 Transition from regular to chaotic oscillations of cubic dynamical systems. In 1st Congress of Croatian Society of Mechanics, Pula, 1994. Senjanović, I. & Fan, Y. 1994 Transition from regular to chaotic oscillations of cubic dynamical<br>systems. In *1st Congress of Croatian Society of Mechanics, Pula, 1994*.<br>Senjanović, I. & Fan, Y. 1995a Numerical simulation
	- *Congress of Croatian*<br> *Chaos Solitons Fractals* 5, 727–737.<br> *Chaos Solitons Fractals* 5, 727–737.<br> **Chaos Solitons Fractals** 5, 727–737. Senjanović,I. & Fan, Y. 1995*a* Numerical simulation of a ship capsizing in irregular waves.<br> *Chaos Solitons Fractals* 5, 727–737.<br>
	Senjanović, I. & Fan, Y. 1995*b* Deterministic and random chaotic oscillations. *Machine*
	- Chaos Solitor<br>njanović, I. &<br>4, 125–129.<br>njanović, I. &
	- 4, 125–129.<br>Senjanović, I. & Lozina, Ž. 1993 Application of the harmonic acceleration method for nonlinear dynamic analysis. *Comp. Struct.* 47, 927–937. Senjanovič,I., & Lozina, Z. 1993 Application of the harmonic acceleration method for nonlinear dynamic analysis. *Comp. Struct.* 47, 927–937.<br>Senjanović, I., Ciprić, G. & Parunov, J. 1996 Nonlinear ship rolling and capsi
	- *Brodogradnja* 44, 19–24.<br>*Brodogradnja* 44, 19–24.<br>*Brodogradnja* 44, 19–24. Senjanovič, I., Ciprič, G. & Parunov, J. 1996 Nonlinear ship rolling and capsizing in rough sea.<br> *Brodogradnja* 44, 19–24.<br>
	Senjanović, I., Parunov, J. & Ciprić, G. 1997 Safety analysis of ship rolling in rough sea. *Chao*
- *IATHEMATICAL,<br>'HYSICAL<br>k ENGINEERING<br>CIENCES Brodogradnja* 44, 19–24.<br>njanović, I., Parunov, J. & Cipr<br>*Solitons Fractals* 8, 659–680.<br>14 ME 1988. *Prinsinks of navo* Senjanović, I., Parunov, J. & Ciprić, G. 1997 Safety analysis of ship rolling in rough sea. *Chaos*<br>Solitons Fractals 8, 659–680.<br>SNAME 1988 *Principles of naval architecture*, vol. I. *Stability and strength* (ed. E. V. L
	- Solitons Fractals 8, 659–68<br>JAME 1988 Principles of n<br>Jesey City, NJ: SNAME.<br>LAME 1989 Principles of n SNAME 1988 *Principles of naval architecture*, vol. I. *Stability and strength* (ed. E. V. Lewis).<br>Jesey City, NJ: SNAME.<br>SNAME 1989 *Principles of naval architecture*, vol. III. *Motions in waves and controllability* (ed.
	- Jesey City, NJ: SNAME.<br>IAME 1989 *Principles of naval architect*<br>E. V. Lewis). Jersey City, NJ: SNAME. SNAME 1989 *Principles of naval architecture*, vol. III. *Motions in waves and controllability* (ed. E. V. Lewis). Jersey City, NJ: SNAME.<br>Tabain, T. 1977 *Temporary navy standard for sea state at the Adriatic*. Zagreb: Br
	- Tabain, T. 1977 Temporary navy standard for sea state at the Adriatic. Zagreb: Brodarski Insti-
	- Thompson, J. M. T. 1993 Basic concepts of nonlinear dynamics. In *Proc. IUTAM Symp. on Nonlinearity and Chaos in Engineering Dynamics, London, July 1993.*<br> *Nonlinearity and Chaos in Engineering Dynamics, London, July 1993.*<br> *Nonlinearity and Chaos in Engineering Dynamics, London, July 1993.*<br> *Nonlinearit*
	- Nonlinearity and Chaos in Engineering Dynamics, London, July 1993.<br>nompson, J. M. T., Rainey, R. C. T. & Soliman, M. S. 1990 Ship stability criteria base<br>chaotic transients from incursive fractals. *Phil. Trans. R. Soc. Lo*

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**PHILOSOPHICAL**<br>TRANSACTIONS ō

*Phil. Trans. R. Soc. Lond.* A (2000)