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New Remarks on Methodologies for Intact Stability Assessment

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Abstract
This paper provides new ideas on methodologies for intact stability assessment. An proposal of standard plan of physical model experiments based on a regule fàlsi method is presented with an example recently carried out at the seakeeping and manoeuvring basin of NRIFE. For the assessment with a numerical model, it is reported that the sudden change concept proposed at the first ship stability workshop was successfully applied to solve the initial-value dependence problem in intact stability. Moreover, it is numerically confirmed that an invariant manifolds analysis of a fixed point near a wave crest can be used for a stability assessment as an alternative to conventional numerical experiments for capsizing due to broaching.

Introduction

Rapid progress in ship design and heightening acceptable risk level of public make empirical criteria based on casualty statistics rather out-of-date. As a result, stability assessment with rational methods, namely, physical or numerical experiments, is highly expected. However, the methods of assessment for this purpose have not yet been fully established, while those for seakeeping or manoeuvring have almost been done. Thus, each research organisation is attempting stability assessment by trial and error.

Ship capsizing is a transition from a stable and nearly upright equilibrium to a stable and nearly upside-down one under external random excitation. Thus, a ship motion relating to ship stability is nonlinear and transient with undeterministic excitation. Therefore, the methodology for seakeeping, which deals with stationary ship motions with undeterministic excitation, or manoeuvring, which deals with transient motions mainly with deterministic excitation, cannot be directly applied to ship stability. For example, an initial condition can be easily specified for manoeuvring tests in calm water but it cannot be done in waves. While a steady motion dealt in seakeeping does not depend on initial conditions very much, ship stability crucially depends on the initial conditions. Although an actual ship meets short-crested irregular waves, its wave height and other particulars cannot be specified in advance. If a ship motion is almost linear like that relating in seakeeping, the value of wave height used in experiments is not very important. However, as capsizing is completely nonlinear, some philosophy to determine a wave height for stability assessment is essential.

NRIFE has engaged in intact stability assessment for various fishing vessels since

70's.[1] Among its activities the author found a possibility for standardisation of stability assessment with some new ideas. In this paper, he presents these new ideas for stimulating discussion among experts. More comprehensive report of the investigation based on these ideas will be published in separate publications.

Physical Model Experiments

So far capsizing model experiments have been carried out mainly in irregular waves. This is because there is a possibility that some nonlinear phenomena may occur only in irregular waves. Experiments in irregular waves should be repeated with so many different realisations to obtain statistically meaningful results. Number of realisation increases significantly when capsizing probability is reasonably small. And majority of actual ships are so. Thus, this kind of experiment is not appropriate for practical purpose. To avoid this difficulty, Takaishi [2] proposed the use of encounter group wave, which can be found when the ship velocity component is nearly equal to group velocity of principal wave energy, for capsizing experiments in irregular waves as worst scenario in irregular seas. In this situation, since the encounter wave profile tends to sinusoidal in time, capsizing experiments in irregular waves can be carried out in a rather deterministic way.

On the other hand, experimental results accumulated until now have not yet shown a clear evidence of a unique mode of capsizing in irregular waves. In the most of cases, if the maximum amplitude of the wavemaker is limited to be a certain value, capsizing in long-crested irregular waves occurs much more easily than that in short-crested waves and capsizing in regular waves occurs much more easily than that in irregular waves. [3] Takaishi's proposal is also based on the fact that capsizing due to regular excitation is more dangerous than that due to random excitation. Thus, the use of regular wave is not simply conservative and we should pay more attention to experiments in regular waves.

Considering the above, the author proposes an experiment plan as follows. First, we carry out capsizing model experiments in extremely steep regular waves. If the model does not capsize, we can presume that the possibility of capsize of this ship in any irregular waves is negligibly small. If the model capsizes, the possibility of capsize of this ship in certain irregular waves is unknown. Then, if necessary, we should carry out capsizing model experiments in irregular waves [4] or assessment based on stochastic theory [5-6]. As you see, the experiment in regular waves has an important role to minimise the size of whole assessment program. In case of relative assessment, critical wave steepness for capsizing can be used as an index, and can be determined with a set of capsizing model experiments in regular waves. Another problem is how to determine ship speed or heading angle. As widely accepted, the most dangerous operational condition is a run in quartering seas. Thus, it is obvious to test a model in quartering seas with lower wave steepness than in beam seas.

Details of our standard test plan is shown in Table 1. First, a model is adjusted to have a specified metacentric height, GM, as well as a specified freeboard and gyro radius in pitch or yaw. Then a natural roll period and damping coefficients are measured with roll decay tests. (I&II) Next, the relationship between the propeller revolution and ship speed is obtained by model runs in still water. Or it can be obtained by standard propulsion tests. (III) The turning test in still water with the maximum rudder angle and maximum speed is recommended. If the model capsized, the rudder angle or ship speed should be limited not to capsize only due to a turning motion. (IV) Next step is experiments in regular waves. Wave period is equal to or slightly longer than the natural roll period and wave steepness, H/λ, is specified to be 1/7 as critical one. Because of wave breaking, measured wave steepness can be smaller than 1/7 but should be larger than 1/10. The model drifts in these waves with an idling propeller. If the hull form is longitudinally symmetric or nearly so, the model meets waves from side. If the model capsizes, experiment is repeated with sufficiently small wave steepness to find a periodic attractor. It is obvious that a capsizing boundary exists between these two wave steepness. Thus, the critical wave steepness for capsizing can be determined within a required accuracy by repeating experiments with a regule falsi method, which is often used in the numerical analysis. (V) If the natural roll period is twice as long as the natural heave or pitch period, it is recommended that a similar procedure should be applied for the wave period corresponding to the natural heave or pitch period. Then we conduct model runs in regular head waves, whose steepness is slightly smaller than the critical one for capsizing with an idling propeller. The wave length to ship length ratio, λ/L, is set to be about 1.5 because ship motions become significant in this wave condition. Since wave steepness is extremely large, the ship speed cannot be so large even with the maximum propeller revolution, and not so crucial for capsizing. If we observe capsizing, the critical wave steepness for capsizing in head seas can be determined again with the regule falsi method. (VI) Finally model runs in quartering seas should be commanded. The wave steepness is set to be slightly lower than the critical one for capsizing with an idling propeller. The wave length to ship length ratio should cover the range between 1.0 and 1.5. Before a generated water wave train propagates enough, the model is kept near the wavemaker without propeller revolution. Then at a certain moment we command to immediately increase the propeller revolution up to the specified one and to make the auto pilot active for the specified course. Repeating these model runs, the critical combination of the nominal Froude number, Fn, and auto pilot course, χ_c, or the critical wave steepness for capsizing in quartering seas can be identified. (VII)

Table 1 Standard programme of capsizing model experiment at NRIFE

(I)	Preparing Model (Weighting, Ballasting, Measuring Gyro Radius)
(II)	Inclining Test & Roll Decay Test
(III)	Speed Trial in Calm Water
(IV)	Turning Test in Calm Water
(V)	Capsizing Test without Forward Velocity in Regular Waves
(VI)	Capsizing Test with Forward Velocity in Regular Head Waves
(VII)	Capsizing Test with Forward Velocity in Regular Following/ Quartering Waves

As an example of experimental assessment based on the above scheme, this paper presents the conclusions of intact stability assessment for a 34.5 m-long Japanese purse seiner, as follows.

1) Under the condition, (GM=0.75m in full scale) , that does not satisfy the IMO Intact Stability Code, the model capsized in beam, head and quartering seas. The critical wave steepness for capsizing in quartering seas is the lowest among them.

2) Under the condition, (GM=1.00m), that critically satisfies the IMO Code, no capsizing was observed in beam and head seas but capsizing occurred in quartering seas with the wave steepness 1/9.2 and the nominal Froude number 0.43. The capsizing modes were either the loss of stability on wave crest or broaching. The time series for capsizing due to broaching are presented in Fig. 1. The coordinate systems used throughout this paper are shown in Fig. 2.

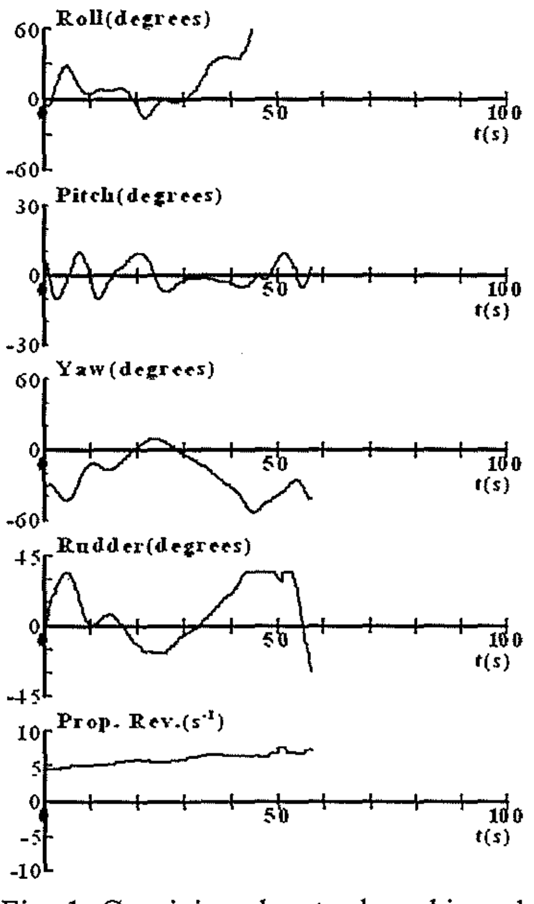

Fig. 1 Capsizing due to broaching observed in physical model experiments. (H/λ=1/9.2, λ/L=1.5, χ_c=-10 degrees, Fn=0.43, GM=1.0m, rudder again K_P=1; in full scale.)

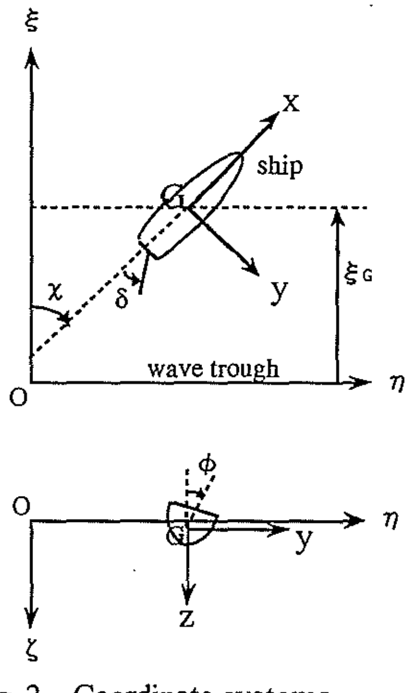

Fig. 2 Coordinate systems.

ξ_G: londitudinal position of centre of gravity from a wave trough. It can be nondimensionalised with a wave length.
u: surge velocity. v: sway velocity. These can be nondimensionalised with a wave celerity,c. χ: heading (or yaw) angle from a wave direction. r: yaw rate. It can be nondimensionalised with the surge velocity and ship length. ϕ: roll angle. p: roll rate. It can be nondimensionalised with the surge velocity and ship length. δ: rudder angle.

3) In case of GM=1.25m, only capsizing due to broaching was observed. When we further increased GM up to 1.46m, no capsizing occurred but broaching without capsizing was still observed.
To obtain the above conclusions, about 300 model runs were made in the seakeeping and manoeuvring basin. The details of these experiments will be published with comparisons with nonlinear dynamics.

Numerical Experiments

Since capsizing is nonlinear, whether capsizing occurs or not depends on the initial condition. Therefore, it is essential in physical or numerical experiment to properly choose the initial condition. In particular, we can input any initial conditions for numerical models but stability assessment only for a certain initial condition is not useful. Although numerical experiments for all possible initial condition sets can be carried out for an uncoupled roll model [7], it is practically impossible to do so for capsizing in quartering seas. Because, the initial value space of the surge-sway-yaw-roll-auto pilot model is at least eight dimensional. As a result, numerical experiments have often been carried out for the "worst initial condition" for capsizing. For example, Vassalos [8] or Munif and Hamamoto [9] proposed that the wave crest at the midship is the "worst initial condition" as a result of some pilot runs. However, since a complete search for the worst initial condition cannot be done, these proposals must be limited in their applicability.

Considering the above and reminding that all initial conditions do not have same practical meanings, the author proposed the "sudden change concept" at the first ship stability workshop.[10] In this concept, first the ship is assumed to be in a certain stable steady state under a certain set of control variables, such as propeller revolution and auto pilot course, and then we suddenly change these control variables, in a way of the step function, as shown in Fig. 3. By a numerical model in time domain we observe how the ship tends to new steady state. These sudden change of the control variables corresponds to actual operational practice at sea. If the preceding state is periodic, the phase lag of the operational command to a wave is not unique. Thus we have to repeat numerical integration from 0 to 2π as the phase lag of the operational command to a wave. However, since the initial value set of phase space is limited to be one dimensional and the set of the initial control valuable is two dimensional, the procedure is still applicable for practical purpose . Later on Spyrou made a similar proposal to this "sudden change concept".[11]

In this paper, to provide a way to terminate the "worst initial condition" problem, numerical results based on the "sudden change concept" with the purse seiner used in the physical experiments are presented. The preceding steady state is a harmonic periodic motion for the nominal Froude number, Fn, 0.1 and the auto pilot course, χ_c, 10 degrees, shown in Fig. 4. Because of symmetry, all lateral motions are zero. With a certain phase lag of the operational command to a wave, in other words, a certain initial longitudinal condition of the ship centre to a wave trough, $(\xi_G/\lambda)_0$, the nominal Froude number and the auto pilot course are suddenly changed to the specified value and 10 degrees, respectively. Fig. 5 shows the results of this numerical experiments; the abscissa is the initial longitudinal position and the ordinate is the new nominal Froude number. In case of the nominal Froude number is smaller than 0.3247, the ship tends to new periodic attractor as a result of change in control variables. In case of the nominal Froude number is larger than 0.3248, the ship experiences unstable surf-riding, broaching and capsizing. Here it is noteworthy that the boundary between the two does not depend on initial longitudinal condition at all. As far as initial condition is set to be a steady state under the previous control variables, the results of change in the control variables do not depend on the initial conditions of the state variables. This suggests that the "sudden change concept" is much more efficient for numerical experiment than the "worst initial condition" approach. Furthermore, this fact justifies the procedure of physical model experiments that described in the previous section because a sudden change method is also used in the physical experiments . For operational practice, it is important that commands for auto pilot course or engine telegraph may be given anytime under a periodic motion.

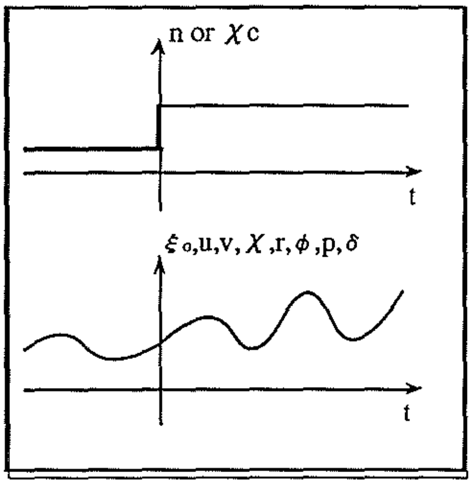

Fig. 3 Sudden change concept

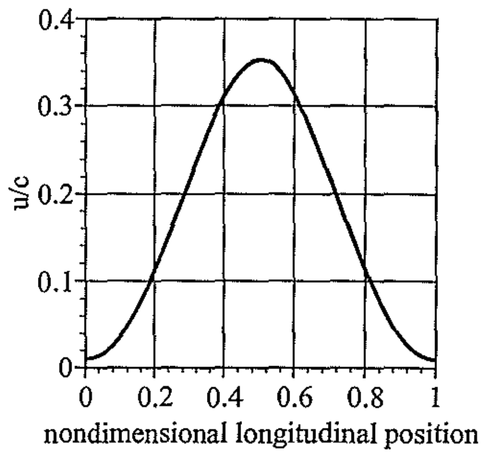

Fig. 4 Periodic motion (H/λ=1/9.2, λ/L=1.5, Fn=0.1, χ_c=0 degrees)

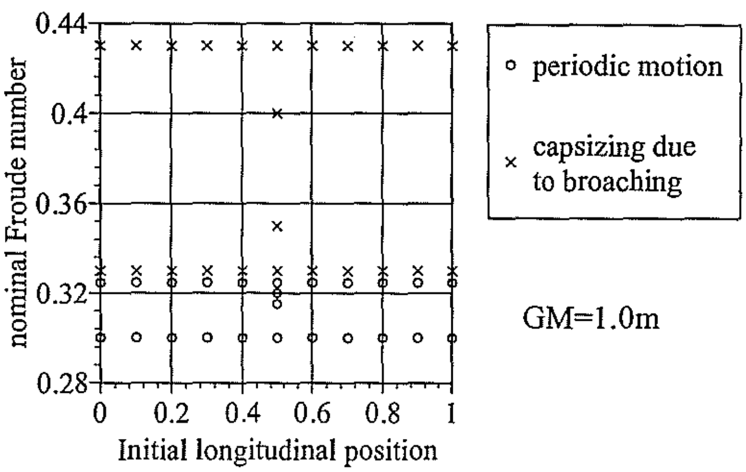

Fig. 5 Results of numerical experiments based on sudden change concept (H/λ=1/9.2, λ/L=1.5, K_P=1; from Fn=0.1, χ_c=0 degrees to χ_c=10 degrees)

The periodic attractor for the new nominal Froude number 0.3247, shown in Figs. 6-8, is not sinusoidal, although the periodic attractor for the nominal Froude number 0.1 is. When the ship centre situates on downslope near wave crest, $\xi_G/\lambda \sim 0.59$ or -0.41, the trajectory behaves like a saddle. Here the relative velocity of the ship to a wave is almost zero and the ship spends on a wave crest for longer time duration than a wave trough. This phenomenon is known as "riding on crest"[12], and is completely different from surf-riding, which occurs on downslope near a wave trough.[13] It is interesting that superharmonic roll motion, in which three cycles of motion are found within one cycle of excitation, exists here.

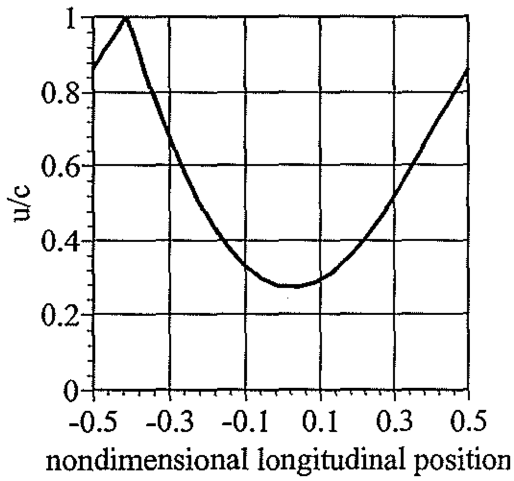

Fig. 6 Periodic attractor in surge ($Fn=0.3247$ and $\chi_c=10$ degrees)

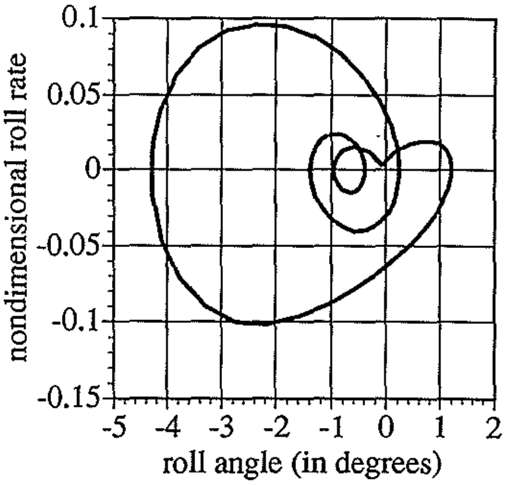

Fig. 8 Periodic attractor in roll ($Fn=0.3247$ and $\chi_c=10$ degrees)

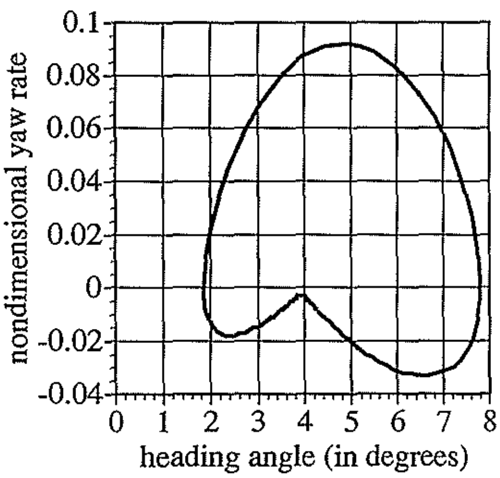

Fig. 7 Periodic attractor in yaw ($Fn=0.3247$ and $\chi_c=10$ degrees)

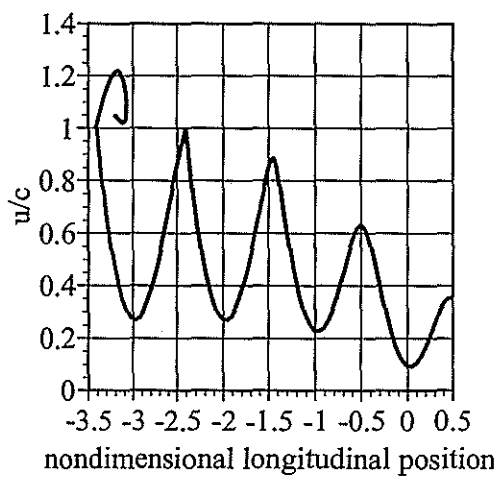

Fig. 9 Transient behaviour in surge ($Fn=0.3248$ and $\chi_c=10$ degrees)

The transient behaviour leading to capsizing for the new nominal Froude number 0.3248 is shown in Figs. 9-11. At the final stage, the ship centre situates on downslope and the ship violently turns to starboard despite of the maximum opposite rudder action. And then she capsized to port side. This is capsizing due to broaching. Here capsizing has a role as a kind of attractor.

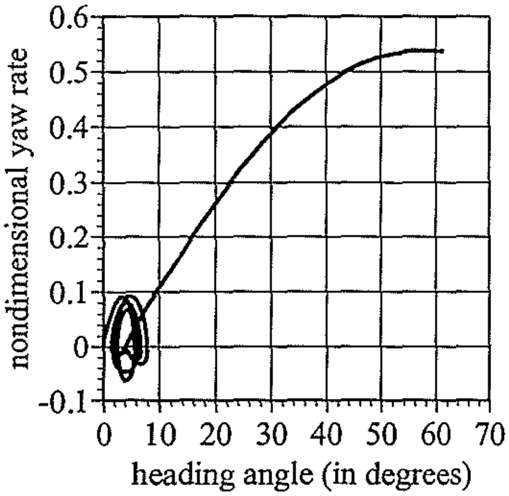

Fig. 10 Transient behaviour in yaw ($Fn=0.3248$ and $\chi_c=10$ degrees)

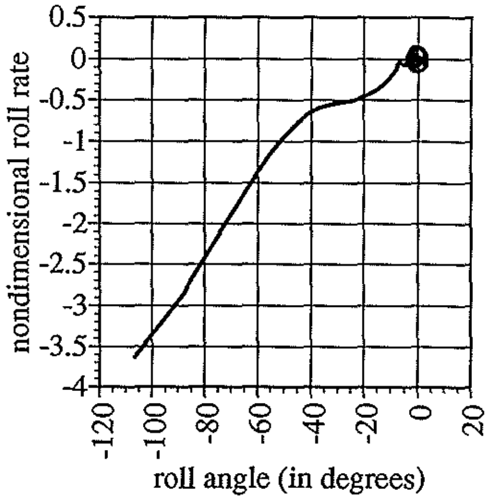

Fig. 11 Transient behaviour in roll ($Fn=0.3248$ and $\chi_c=10$ degrees)

Nonlinear Dynamics

It is desirable to apply nonlinear dynamics for more rigorously identifying the initial-condition dependence for capsizing. Besides capsizing in beam seas, the author [14-15] and Spyrou [11, 16] have applied nonlinear dynamics to broaching and capsizing in quartering seas since 1992. As steady states, the surf-riding equilibria and periodic motions were identified and their local stability were discussed with a mathematical model. If a stable periodic motion cannot exist and a stable equilibrium can exist, stable surf-riding can occur. If the equilibrium becomes unstable, the ship can suffer broaching. Since surf-riding, broaching and capsizing are transitions between different steady states, the analysis focused on steady states may explain the occurrence of these phenomena to some extent. However, to more precisely identify the critical conditions for these phenomena, it is necessary to investigate transient states. In other words, the invariant manifold analysis is essential.

For uncoupled surf-riding, the global structure of initial-condition dependence has been identified by an invariant manifold analysis of a unstable surf-riding equilibrium. [17] For surf-riding in quartering seas, which is coupled with lateral motions, it is shown that an unstable invariant manifold of a surf-riding equilibrium point with the maximum opposite rudder angle corresponds to a typical behaviour of broaching. [14] In this investigation, an invariant manifold analysis of a surf-riding equilibrium point with a proportional auto pilot, whose gain $K_P=1.0$, is carried out and compared with the numerical experiments based on "sudden change concept".

Since the mathematical model used here [10,15] has four degrees of freedom, the state vector is eight dimensional. The eigenvalues of surf-riding equilibrium point near wave crest for $Fn=0.3248$ and $\chi_c=10$ degrees are shown in Fig. 12. Since one eigenvalue has a positive real part and seven eigenvalues have negative real parts, this equilibrium point is a saddle of index one in eight dimensional phase space. An invariant manifold, or an outset, is obtained by numerically integrating the state equation from the equilibrium point with a small perturbation for the positive or negative direction of eigenvector of the eigenvalue having a positive real part. Since the index of the saddle is one, the manifold, or hyper surface, is one dimensional, namely, a trajectory. All points on this manifold situate on this manifold for $-\infty<t<\infty$. This is the reason why this manifold is invariant.

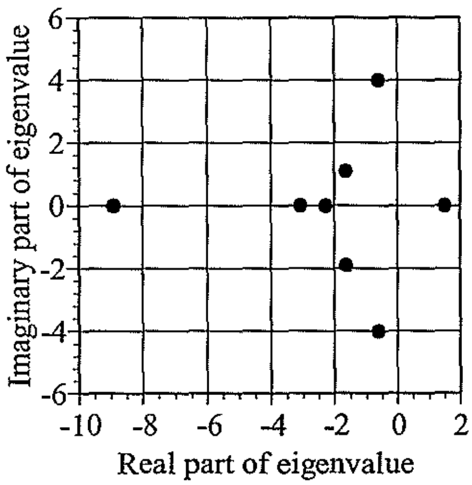

Fig. 12 Eigenvalues of a surf-riding equilibrium point near wave crest (Fn=0.3248 and χ_c=10 degrees)

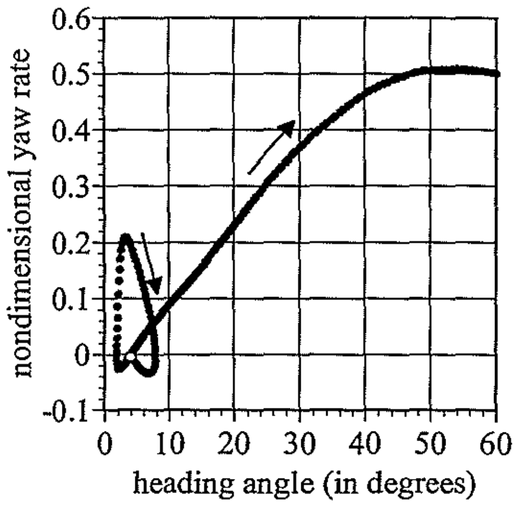

Fig. 14 Unstable invariant manifolds of a surf-riding equilibrium point (Fn=0.3248 and χ_c=10 degrees)

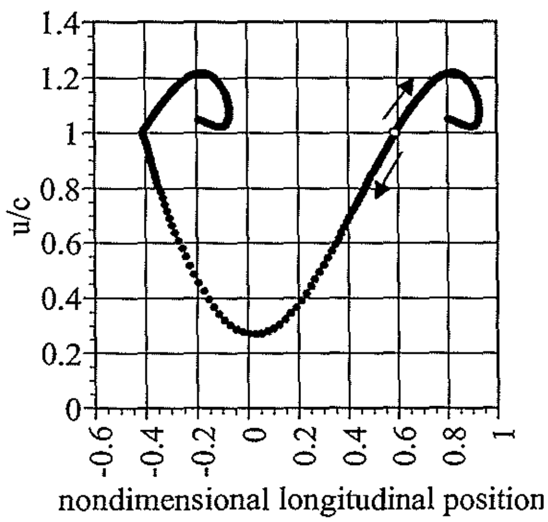

Fig. 13 Unstable invariant manifolds of a surf-riding equilibrium point (Fn=0.3248 and χ_c=10 degrees)

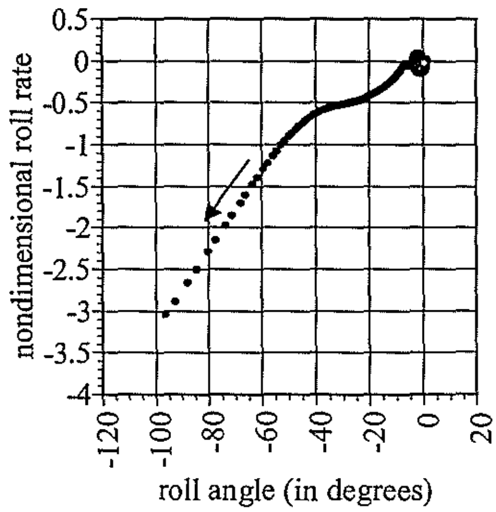

Fig. 15 Unstable invariant manifolds of a surf-riding equilibrium point (Fn=0.3248 and χ_c=10 degrees)

Figs. 13-15 show the unstable invariant manifolds of surf-riding equilibrium point near wave crest for Fn=0.3248 and χ_c=10 degrees. The trajectory towards downslope shows that the heading angle rapidly increases to starboard despite of the maximum opposite rudder angle and then the ship capsizes to the port side. During these behaviour the ship centre remains on wave downslope and at the final stage the ship centre situates on downslope near wave trough. This is a typical example of capsizing due to broaching. The trajectory towards upslope approaches a saddle next to the original saddle and then realises capsizing due to broaching. The unstable invariant manifolds towards both directions tend to capsizing due to broaching.

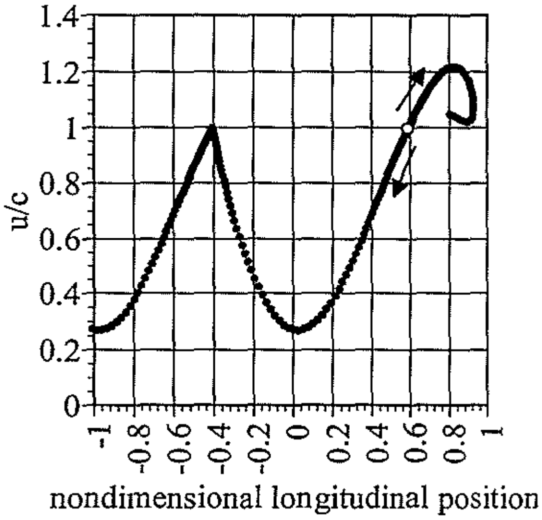

Fig. 16 Unstable invariant manifolds of a surf-riding equilibrium point (Fn=0.3247 and χ_c=10 degrees)

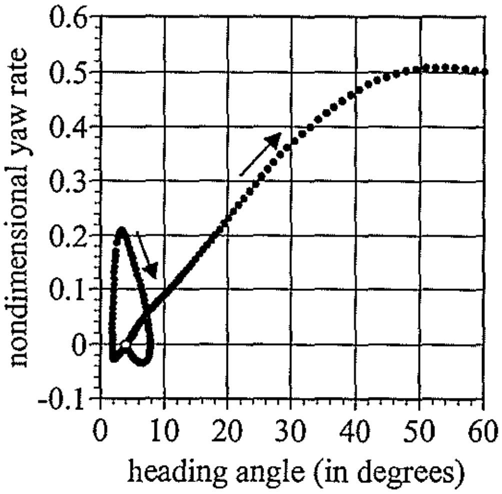

Fig. 17 Unstable invariant manifolds of a surf-riding equilibrium point (Fn=0.3247 and χ_c=10 degrees)

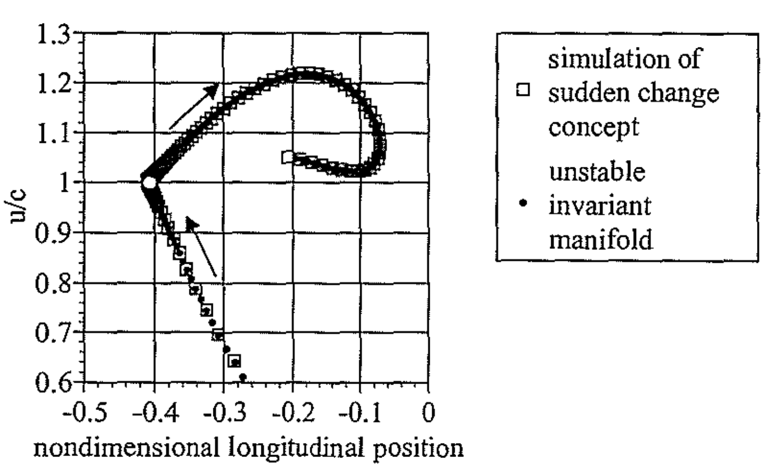

Fig. 18 Comparison between the numerical experiment based on sudden change concept and the unstable invariant manifold (Fn=0.3248 and χ_c=10 degrees)

Figs. 16-17 show the unstable invariant manifolds for Fn=0.3247. Here the trajectory towards downslope tends to capsizing due to broaching like the previous example. However, the trajectory towards upslope approaches the saddle next to the original one and then tends to a periodic attractor. Thus we can presume that between Fn=0.3247 and Fn=0.3248 there is a nominal Froude number whose unstable invariant manifold of a saddle tends to a different saddle. This is the "heteroclinic connection". Thus, if the ship situates below this heteroclinic trajectory, capsizing due to broaching is not likely to occur. That is to say, the nominal Froude number for the heteroclinic bifurcation is the critical condition for capsizing due to broaching. In the numerical experiment described before, the initial value was a periodic orbit for Fn=0.1 and χ_c=0 degrees and the critical condition for capsizing exists in 0.3247<Fn<0.3248. Thus, the results of this numerical experiment completely agree with the conclusion from the present invariant manifold analysis. Moreover, Fig. 18 shows that the invariant manifold towards upslope well corresponds to the trajectory obtained by the numerical experiment based on the "sudden change concept". The further investigation in this direction is now under way. As you see, the nonlinear dynamics has a possibility to be substituted for a numerical experiment.

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