# Pure loss of stability in stern quartering waves: revisited with numerical simulations reproducing accidents

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**ABSTRACT**

For identifying the accident case suitable for validation of direct stability assessment for pure loss of stability failure modes, three accidents known as those due to pure loss of stability in stern quartering waves were examined with comparative numerical simulations using a surge-sway-yaw-roll coupled model. They include the large heel accidents of a RoPax ship in 2009, capsizing of an ocean research vessel in 1986 and a torpedo boat in 1934. As a result, we confirmed that major cause of these three accidents was not roll restoring variation due to waves but rather the coupling effect of sway-yaw motion to roll.

**Keywords:** *IMO second generation intact stability criteria, RoPax ship, ocean research vessel, torpedo boat, dynamic loss of stability.*

## 1. INTRODUCTION

The International Maritime Organization (IMO) agreed to develop the second generation intact stability criteria those dealing with the five failure modes by using physics-based approaches. Their standards are to be preferably based on known accidents. For example, the known accidents for parametric rolling and pure loss of stability are the cargo loss accident of the C11 class post-Panamax containership in the North Pacific and the fatal accident of the containership "Chicago Express" off Hong Kong, respectively. In case of the pure loss of stability, accidents of large heel of the RoPax ships in Japan (Japan Transport Safety Board, 2011) and New Zealand (New Zealand Transport Accident Investigation Commission, 2007) are mentioned. Other than these RoPax ships, capsize of an ocean research vessel (Umeda et al., 2017) and a torpedo boat in Japan (Maki et al., 2018) are often mentioned as candidates of accidents of pure loss of stability in stern quartering waves. In this paper, the authors attempt to reexamine whether these can be regarded as pure loss of stability or not.

Pure loss of stability in astern waves is defined by Oakley et al. (1974) as follows: a ship encounters one or more very steep high waves, with little or no preliminary rolling motion, simply loses all stability when a crest moves into the amidships position and "flops" over. They observed capsizing due to this phenomenon in free-running model experiments in San Francisco Bay. Kan et al. (1990 and 1994), de Kat and Thomas (1998) and others also realised capsizing due to this phenomenon by free-running model experiments in seakeeping and manoeuvring basins. Here key factors could be the magnitude and duration of roll restoring moment reduction due to the relative longitudinal wave profile. The magnitude depends on the wave height, wavelength and heading angle and the duration does on the relative forward speed of a wave crest to the ship. Thus, a surge-roll coupled simulation model was initially used for estimating the failure probability for pure loss of stability (e.g. Umeda & Yamakoshi, 1994). Such model was well validated with a towing model experiment of the ONR tumblehome topside vessel in regular following waves with the bias of roll angle of 4 degrees (Hashimoto, 2009). The danger increases with the increasing forward speed because the duration of restoring reduction is longer.

It failed, however, to explain the free-running model experiment of a containership in regular and irregular stern quartering waves. While the danger in the experiment increases with the increasing the forward speed, the danger in the numerical simulation does not. Thus, a surge-sway-yaw-roll model was applied and then succeed to explain its qualitative tendency observed in the experiment. This was thought to be because, once large heel occurs due to restoring reduction, the underwater hull becomes unsymmetrical so that hydrodynamic sway force and yaw moment act on the ship. As a result, the lateral motion shall be induced so that the additional heel moment due to the lateral motion, which can be regarded as a centrifugal force effect and are proportional to the square of the ship forward speed. Since this additional effect seems to be essential to explain the speed dependence for danger of pure loss of stability in stern quartering waves (Kubo et al., 2012). Based on this understanding, the IMO (2019) agreed to take account of the moment due to centrifugal force as a function of the forward speed, in the level 2 vulnerability criteria for pure loss of stability.

Then the standard of the level 2 vulnerability criteria for pure loss of stability was determined with the large heel accident of the Ropax ship in stern quartering waves (Umeda et al. , 2013). Since similar large heel incidents often reported for large RoPax ships in stern quartering waves (Japan, 2015), the danger modelled in the IMO level 2 vulnerability criteria for pure loss of stability surely exists. Indeed, seven cases of large heel angles in following and stern quartering waves were reported during the five years. The reported roll angles were 25 degrees or over, which happened for more than 7,000 gross tonnage ship in the North Pacific with the Froude number close to 0.3. As a result, some on board vehicles and containers were transversely moved. Therefore, the criteria could be effective for avoiding such danger.

As the next stage, it is necessary to validate a time-domain numerical simulation code to be used for the direct stability assessment with model experiments preferably relevant to actual accidents due to pure loss of stability. Therefore, the authors attempt to compare the numerical simulations using a surge-sway-roll-yaw model (Kubo et al., 2012) and the free-running model experiments for the accidents of the Ropax ship, the ocean research vessel and the torpedo boat mentioned above. These three accidents occurred when they ran in stern quartering waves with higher speed. For identifying the reason of the accidents, the numerical simulation was executed without and with key elements in the simulation model.

## 2. NUMERICAL MODEL

The accidents often occurred when ships ran in stern quartering waves. Under such situation the encounter wave frequency is low so that the heave and pitch, of which the natural frequencies are much higher, can be regarded to just trace their static equilibria and the hydrodynamic lift forces are more important than high-frequency wave making forces. Therefore, a coupled surge-sway-roll-yaw model based on manoeuvring model with heave and pitch motions as constraints is suitable for simulating such accidents. Here the wave forces should be estimated with a slender body theory based on the low encounter frequency assumption and the auto pilot should be included for keeping the commanded. In this paper, as one of such models, the model proposed by Kubo et al. (2012) is used. This model was based on the model used by Umeda (1999) for broaching prediction but the roll restoring moment, which is essential to pure loss of stability, is estimated using with Grim's effective wave concept (Grim, 1961) and the manoeuvring coefficients in calm water were determined by captive model experiments using the circular motion technique. The wave effects on the manoeuvring forces are ignored as higher order terms under the assumption of small wave steepness and the linear relationships between the forces and waves. Nonlinearity essential here is the position dependence of wave forces, in other words, the wave forces proportional to the sinusoidal function depending on the horizontal ship motions. This is indispensable for surf-riding at the wave downslope and riding on a crest.

## 3. ROPAX SHIP ACCIDENT CASE

The accident of large heel of the RoPax ship in Japan (Japan Transport Safety Board, 2011) occurred when the ship ran with the Froude number of 0.275, the significant wave height of 4.59 m, the wave period of 10.0 s and the heading angle of 35 degrees from the wave direction. The waves came from the port side. The ship is equipped with two propellers, one rudder and a pair of the fin stabilizer but at the accident the fin stabilizer was utilized.

The accident report says that the ship suffered the heel angle of 25 degrees because of roll restoring moment due to the decrease of water plane area as a result of a wave. Then the cargo shift occurred so that the heel angle increased up to 40 degrees by the action of the following waves and turning motion due to the heel. This means that pure loss of stability is mentioned as one of primary reason of the initial large heel of 25 degrees. The principal particulars are shown in Table 1.

For this accident condition, the numerical simulation is executed with and without the roll restoring variation due to waves. The wave spectrum here is assumed to be unidirectional ITTC spectrum and the autopilot is simulated with the rudder gain of 1.0. Although the hull manoeuvring coefficients including propulsion ones are determined by the captive model experiment at the seakeeping and manoeuvring basin of National Research Institute of Fisheries Engineering, some of the rudder parameters are estimated from the experimental data of a similar ship (Kondo et al., 2015). These details will be published later. For this accident condition, Ueno et al. (2012) executed a free-running model experiment in short-crested irregular waves at the seakeeping and manoeuvring basin of National Maritime Research Institute, and reported that the maximum roll was about 30 degrees before the cargo shift so that they succeeded to realise roughly similar heel angle occurred at the accident. In their experiment, the fin stabilizer was not actively used.

**Table 1: Principal particulars of the Ropax ship.**

| Items | Values |
|---|---|
| Length | 150.0 [m] |
| Breadth | 22.80 [m] |
| Draft | 6.26 [m] |
| Trim | 1.68 [m] |
| Metacentric height | 1.80 [m] |
| Natural roll period | 17.1 [s] |

An example of the numerical simulation results using the fore-mentioned model with the roll restoring variation due to waves is shown in Figure 1. The wave elevation at the midship and the roll angle are shown as time series: the negative wave elevation indicates the wave elevation from the calm-water surface and the positive roll angle does the roll towards starboard. The roll period is generally the same as the wave encounter period so that the obtained roll motion is harmonic. When the ship meets a wave crest or shortly before a wave crest, the ship significantly rolls towards starboard side. This seems to be a typical pure loss of stability but significant rolls towards port side also happens. If the phenomenon is harmonic, the significant rolls also for port side is natural and the restoring variation could be a major source of large roll.

For directly investigating this hypothesis, the numerical simulation without the restoring variation is also executed and its result is shown in Figure 2. The maximum roll angle here, as well as the qualitative nature of the relationship between the roll and waves, is the almost the same as the simulation with the restoring variation. This suggests that the roll restoring variation is not a major cause of the significant roll.

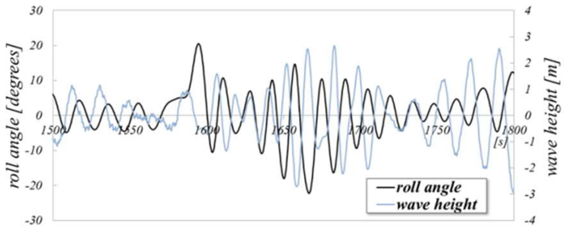


**Figure 1: Numerical simulation of the RoPax ship with the roll restoring variation.**

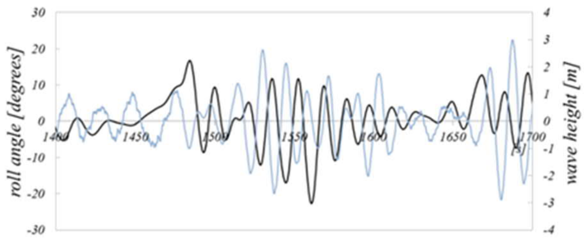


**Figure 2: Numerical simulation of the RoPax ship without the roll restoring variation.**

The simulated results also indicate that the wave encounter period is about 17.5 s, which is close to the natural roll period of 17.1 s. Thus we may suppose that the significant roll could be a simply harmonic resonance of uncoupled roll motion in stern quartering waves. If so, the major course could be a wave exciting roll moment. For examining this hypothesis, the numerical simulations with and without the effects of sway and yaw to roll are executed and their results are shown in Figures 3-4. Here the yaw rate and the roll angle are shown as time series: the positive yaw rate indicates the increase of yaw angle towards a starboard turn. It is clearly seen in Figure 4 that large yaw rate towards port results in a large starboard heel and the large yaw rate towards starboard does in a large port heel. This is well known tendency as a result of yaw-roll coupling. On the other hand, if we ignore such coupling effect, no significant roll as well as no significant yaw rate cannot be found. Therefore, we should conclude that the significant roll that the Ropax ship experienced is a harmonic resonance due to coupling from the yaw motion. More systematic numerical investigation including the ensemble average of the maximum roll and the effect of fin stabilizer was published in Osugi et al. (2019). The yaw-roll coupling mentioned here seems to be identical to "dynamic loss of stability due to surge-roll-yaw coupling" identified by de Kat and Thomas (1998) in their experiment of a frigate model with the artificially lowered GM in stern quartering waves, in which the model typically capsized at a wave crest. They also noted that this phenomenon is different from "quasi-static loss of transverse stability in wave crest" that they also found. Since both phenomena occurred at a wave crest, they are not easily distinguished. Indeed, Kan et al. (1990) regarded rather dynamic phenomenon observed in their experiment of a containership model at a wave crest as "pure loss of stability". Further discussion is needed.

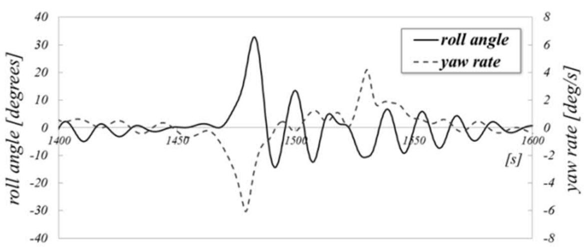


**Figure 3: Numerical simulation of the RoPax ship with the roll restoring variation and the coupling effect from sway and yaw to roll.**

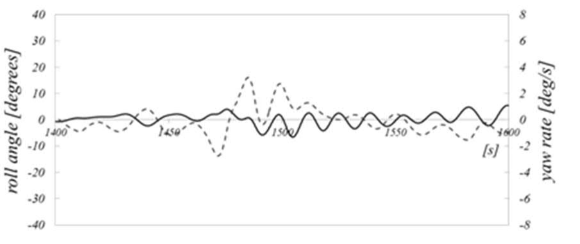


**Figure 4: Numerical simulation of the RoPax ship without the roll restoring variation and the coupling effect from sway and yaw to roll.**

## 4. OCEAN RESEARCH VESSEL ACCIDENT CASE

The accident of an ocean research vessel in stern quartering waves was examined by the maritime court (the Japan Association of Marine Safety, 1990), which suggests that this accident was triggered with loss of roll restoring moment in stern quartering waves. In June 1986, the ocean research vessel sank off Fukushima in Japan on its maiden voyage without any emergency call. The maritime court concluded that the height of centre of gravity was increased due to several changes of design during construction and then during her maiden voyage the ship heeled significantly when she ran in severe stern quartering waves. The principal particulars of the ship and the estimated condition at the accident are shown in Table 2 (Umeda, Osugi et al., 2017).

**Table 2: Principal particulars of the ocean research vessel and its accident condition.**

| Items | Values |
|---|---|
| Length | 22.00 [m] |
| Breadth | 5.00 [m] |
| Depth | 2.20 [m] |
| Mean draft | 1.75 [m] |
| Metacentric height | 0.41 [m] |
| Natural roll period | 7.11 [s] |
| Ship speed | 10 [kts] |
| Wave height | 3.0 [m] |
| Wave period | 5~6 [s] |
| Encounter angle from wave direction | -45 [degrees] |

For investigating the reason why large roll occurs, comparative simulations were executed. Firstly, the time series of numerical simulation with and without the roll restoring variation for a typical case are shown in Figures 5 and 6, respectively. Here the wave elevation indicates its value at the midship and its minima correspond to a wave crest. The positive roll angle means the starboard downwards, the positive yaw angle does the starboard turn and the positive rudder angle normally induces the starboard turn. As shown in Figure 5, a large roll angle of about 35 degrees towards port side occurs shortly after the wave crest amidship. This seems to be relevant to a pure loss of stability. However, it is noteworthy here that at the moment the yaw rate towards starboard side becomes very large. It could induce large centrifugal force due to this large yaw rate, which could result in large heel towards the port side. Indeed, the numerical simulation without the restoring variation, as shown in Figure 6, shows that slightly smaller but still more than 20 degrees roll occurs at the relevant moment. Therefore, we should conclude the roll restoring variation is not the only reason of large roll.

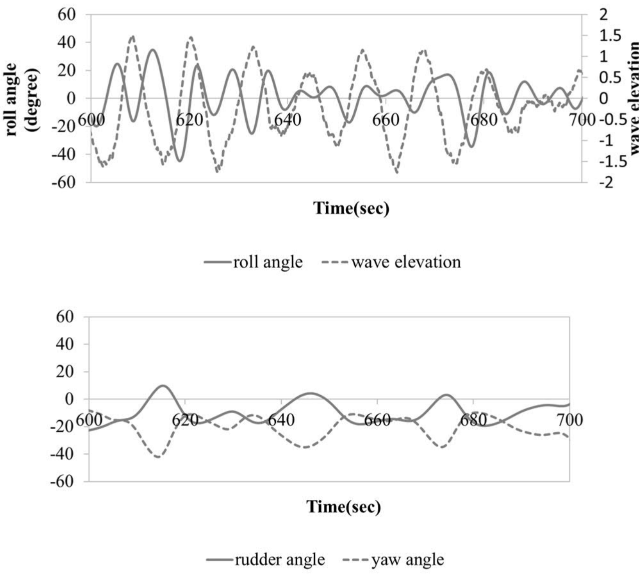


**Figure 5: Numerical simulation of the ocean research vessel with the restoring variation.**

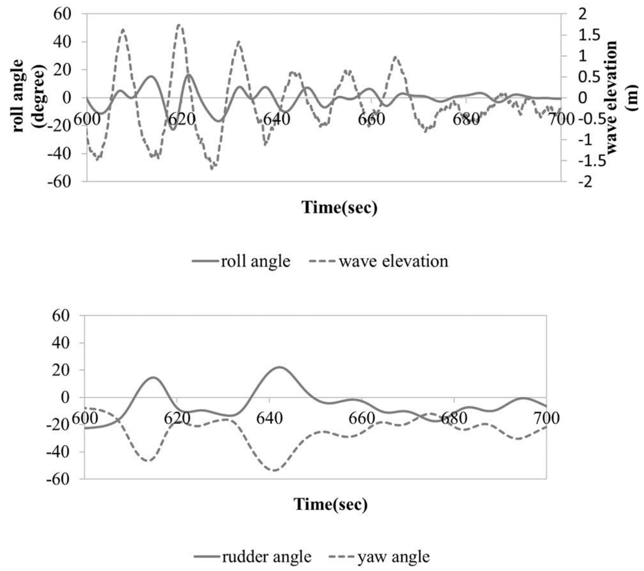


**Figure 6: Numerical simulation of the ocean research vessel without the restoring variation.**

For more directly confirming the reason of large heel, the numerical simulation without roll damping components due to sway velocity and yaw angular velocity was executed as shown in Figure 7. This indicates that the roll angle is also reduced from about 35 degrees to about 20 degrees. Thus, we can conclude that the coupling between sway/yaw and roll is also a major reason of the large heel at the wave crest amidship. Therefore, we can presume that both roll restoring variation and the roll-sway/yaw coupling are important for large heels in stern quartering waves.

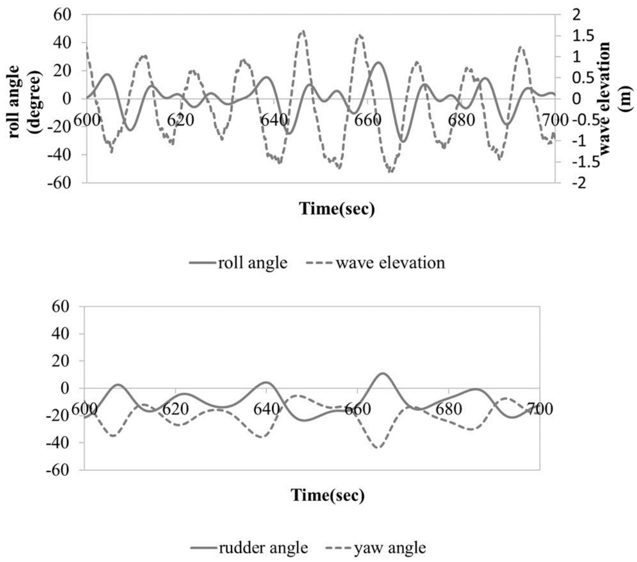


**Figure 7: Numerical simulation of the ocean research vessel without the roll damping components due to sway velocity and yaw angular velocity.**

## 5. TORPEDO BOAT ACCIDENT CASE

On March 12, 1934, a torpedo boat conducted a military training outside Sasebo port. Returning to the port after the training, she made a sharp turn to starboard and capsized to the port side in heavy wind and waves. After the accident, IJN (Imperial Japanese Navy) intensively investigated the reason of the accident. Its accident report in1934 concluded the accident was caused by high KG values due to her excessive armament, insufficient GZ and significant decrease of her restoring variation due to bulge-exposure. After the WWII, Matsumoto (1954) released the IJN report to public domain.

In 1978, Takaishi introduced this Matsumoto's article and emphasized the effect of GM decrease in waves. After Takaishi's introduction, Japanese research community of naval architecture believed that the major cause of her accident was restoring decrease in waves, which is known as pure loss of stability in following waves. Therefore, in this research, we attempted to verify the above hypothesis on her accident by conducting captive model experiments and numerical simulations.

The torpedo boat had bulges for compensating high KG due to heavy armament so that the ship was regarded as having sufficient GM. The principal particulars are shown in Table 3. The estimated condition at the capsize accident is shown in Table 4.

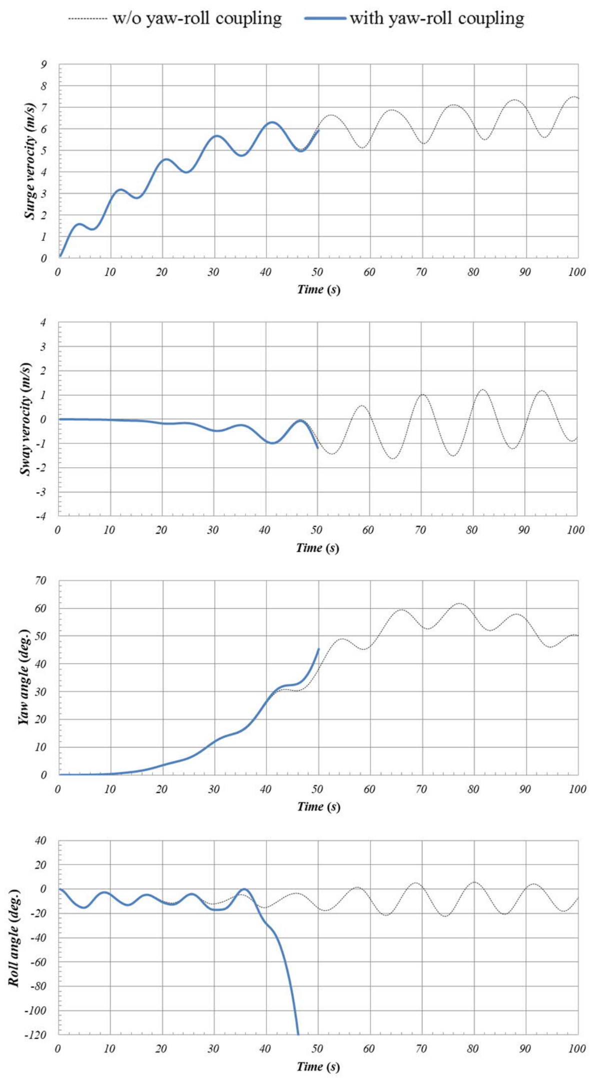


**Figure 8: Numerical simulation of the torpedo boat with and without yaw-roll coupling. Here the wave steepness of 0.06, the wavelength to ship length ratio of 1.0, the Froude number of 0.26 and the heading angle of 50 degrees from the wave direction.**

In order to explain the accident, the 4 DoF (surge-sway-yaw-roll) numerical simulation model mentioned before was utilized with the wave and operational conditions at the accident. A constant heel angle due to wind was also considered. Figure 8 shows the simulated results with and without the yaw-roll coupling.

The simulated result with yaw-roll coupling demonstrates that the ship rapidly turns to starboard side and then capsizes to port side. This is the same as the accident report (Matsumoto, 1954). On the other hand, the ship does not capsize if we ignore yaw-roll coupling in the numerical model. Therefore, we presume that the reason of capsizing could be considered yaw-roll coupling.

**Table 3: Principal particulars of the torpedo boat at the accident.**

| Items | Values |
|---|---|
| Length | 80.12 [m] |
| Breadth | 8.01 [m] |
| Draft | 2.25 [m] |
| Block coefficient | 0.502 |
| Natural roll period | 7.86 [s] |
| Metacentric height | 0.698 [m] |
| Propeller diameter | 1.99 [m] |
| Rudder area | 2.331 [m$^2$] |

**Table 4: Conditions of the accident.**

| Item | Values |
|---|---|
| Froude number | 0.257 |
| Wave height | 3~4 [m] |
| Wind speed | 15~20 [m/s] |
| Encounter angle | 50 [degrees] |

## 6. CONCLUDING REMARKS

For identifying the accident case suitable for validation of direct stability assessment for pure loss of stability failure modes, three accidents known as those due to pure loss of stability in stern quartering waves were examined with numerical simulations together with model experiments. As a result, we confirmed that major cause of these three accidents was not roll restoring variation but rather the coupling effect of sway-yaw motion to roll. Since the current draught level 2 vulnerability criteria for pure loss of stability take account for both roll restoring variation and the coupling effect of sway-yaw motion to roll and are tuned with the Ropax ship accident, the criteria could work for the stability failure examined here. However, it is noteworthy here that the countermeasures for the roll restoring variation, e.g. the avoidance of excessive bow flare and transom stern, are not so effective for the stability failure examined here. The increase of rudder area, improvement of directional stability and appropriate steering could be solutions.

Further discussion on pure loss of stability should be expected. The large roll at a wave crest in stern quartering waves is not necessarily a result of transverse stability loss. The relationship with the quasi-static large roll that observed by de Kat and Thomas (1998) and Hashimoto (2009) at a wave crest still may remain as a discussion item.

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