Roll-yaw coupling effects on parametric resonance for a ship in regular waves

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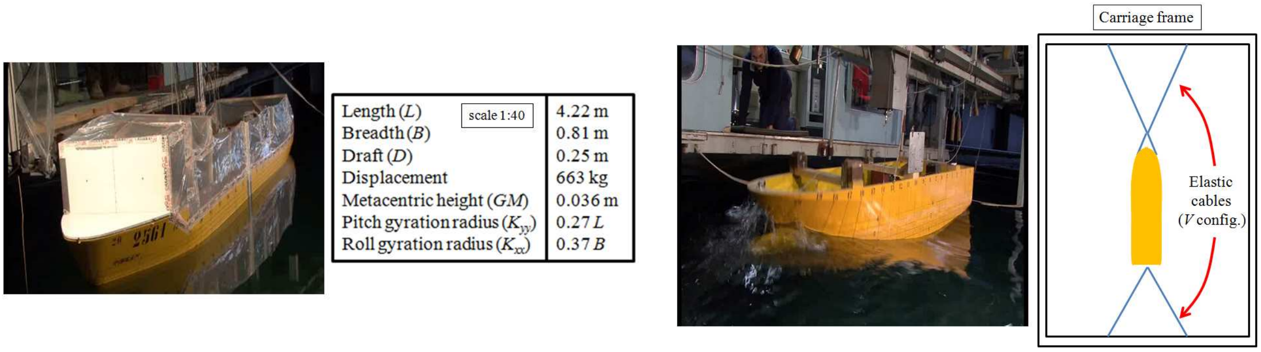
This work represents a further step of the physical study documented by Greco and Lugni (2012b) and Greco *et al.* (2014). Three-dimensional experiments have been performed on a FPSO model in regular waves to investigate the occurrence of parametric roll, the occurrence and features of water on deck and bottom slamming and the sensitivity of the mid-ship bending moment experienced by the vessel to the different operational conditions examined. The model tests provide also a certified database for the validation of the simplified Domain-Decomposition (DD) solver developed for the prediction of the ships behavior, in regular and long-crested irregular waves and with and without forward speed, documented in detail by Greco and Lugni (2012a). The DD couples a weak-scatterer potential-flow solver for the seakeeping problem with a shallow-water approximation for the water flow on the deck, when water shipping occurs, and with a Wagner-type impact solution, in case of bottom impact. The latter needs a proper criterion, this compound method combines the Ochi's criterion based on the impact velocity with a pressure criterion proposed by Greco and Lugni (2012a) and validated in many incident-wave cases by Greco *et al.* (2012).

In the previous steps, head-sea conditions, i.e. $\beta = 180^\circ$, were investigated. Here the cases with $\beta = 175^\circ$ are considered with focus on parametric roll. The comparison between experimental and numerical wave-body interactions, and a subsequent in-depth analysis of the model tests, highlighted some important insights of parametric roll in connection with roll coupling with yaw. These aspects are examined in the following after a brief description of the model tests for the conditions and variables of interest.

Experiments A FPSO model (scale factor 1:40) without bilge keels and any appendages, was tested in regular waves at the Basin No. 2 (length x width x depth $= 220$ x 9 x 3.6 m) of CNR-INSEAN. The model and its main information are given in the table in the left panel of figure 1. The FPSO was fixed to the carriage through a gimble and was left free to oscillate around the center of mass in heave, pitch and roll, while the remaining degrees of freedom were restrained, with a heading angle $\beta = 175^\circ$. The rigid motions of the hull were measured through an inertial platform and an optical system to double check the experimental conditions and ensure model-test reliability. 3D video recordings of the experiments were done using two low-speed cameras (with 25 fps); they provide an enlarged view of the bow and an overall view of the vessel. Undisturbed incident-wave conditions were measured using two wave probes well upstream of the ship. Preliminary free-decay tests in roll were performed in calm water identifying a natural frequency $\omega_{4n0} \simeq 1.76$ rad/s and a linear roll damping-to-critical damping ratio of $B_{44,1}/B_{44,cr} \simeq 0.0262 B_{44,cr}$ assuming a 1-dof roll motion equation. This viscous damping effect was accounted for in the numerical simulations.



scale 1:40	
Length (L)	4.22 m
Breadth (B)	0.81 m
Draft (D)	0.25 m
Displacement	663 kg
Metacentric height (GM)	0.036 m
Pitch gyration radius (K_{yy})	0.27 L
Roll gyration radius (K_{xx})	0.37 B

Figure 1: Experimental set-ups. Left: FPSO model (left part) and its main information (right part). Right: fishing vessel (left part) and top sketch of the cables (right part).

Physical investigations Table 1 gives the incident wave conditions examined in terms of the nominal wavelength-to-ship length ratio λ/L (and the corresponding calm-water roll natural frequency-to-excitation frequency ratio ω_{4n0}/ω) and of the incident-wave steepness kA. The actual generated waves were slightly different and those were reproduced numerically for comparison, but here for convenience the nominal values are reported. For each condition the occurrence of parametric roll (PR) and water on deck (WOD) phenomena is provided in terms of boolean values both for the model tests and the DD simulations. In the table, 'X' indicates cases not studied experimentally because too dangerous and so neither reproduced numerically. Concerning the water on deck, 'NI' for the experiments means that the water shipping was observed but not periodically, *i.e.* at every incident-wave period T, and was small; for the numerics it means that it was small, corresponding to an averaged water level of 0.7 mm on the deck at model scale. From the comparison, the numerics slightly overestimates the occurrence of WOD for sufficiently small kA while both results record WOD for $kA >= 0.2$. It is interesting to note that both experiments and numerics document a water shipping induced by parametric roll at $\omega_{4n0}/\omega = 0.402$ and $kA = 0.2$, i.e. the WOD occurs once sufficiently large roll oscillations at the roll natural frequency characterize the motion of the vessel. Concerning the parametric roll, for the three smallest kA, the results are globally consistent and indicate occurrence only at $\omega_{4n0}/\omega = 0.464$ for sufficiently small steepness. At this frequency ratio, nonlinear effects tend to avoid the parametric resonance while they cause PR for smaller ω_{4n0}/ω as kA increases. Only the experiments show a resonance also at the largest frequency ratio, $\omega_{4n0}/\omega = 0.568$, for $kA = 0.2$. At the largest steepness, the two results are consistent only for $\omega_{4n0}/\omega <= 0.464$. For larger values the numerics does not predict any parametric roll while numerics and experiments have a different behavior starting from the case with $\omega_{4n0}/\omega = 0.519$ indicated with 'NO/YES' in the table. This incident-wave condition was repeated twice experimentally (runs 44 and 46). Consistently with the numerics, run 44 was not associated with PR and produced large amount of WOD (see left plot of figure 2). Important amount of liquid entered the vehicle and produced a change in the hydrostatic properties of the vessel,

Table 1: Occurrence of parametric-roll resonance (PR, left) and water on deck (WOD, right) for the cases studied experimentally and reproduced numerically.

$\lambda/L \rightarrow$	0.75	1.00	1.25	1.50	2.00	0.75	1.00	1.25	1.50	2.00
$\omega_{4n0}/\omega \rightarrow$	0.402	0.464	0.519	0.568	0.656	0.402	0.464	0.519	0.568	0.656
Method kA	PR					WOD				
Exper. 0.10	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO
Num 0.10	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO
Exper. 0.15	NO	YES	NO	NO	NO	NO	NI	NI	NI	NO
Num 0.15	NO	YES	NO	NO	NO	NO	YES	YES	NI	NO
Exper. 0.20	YES	YES	NO	YES	X	due to PR	YES	YES	YES	X
Num 0.20	YES	YES	NO	NO	X	due to PR	YES	YES	YES	X
Exper. 0.25	YES	NO	NO/YES	YES	X	YES	YES	YES	YES	X
Num 0.25	YES	NO	NO	NO	X	YES	YES	YES	YES	X

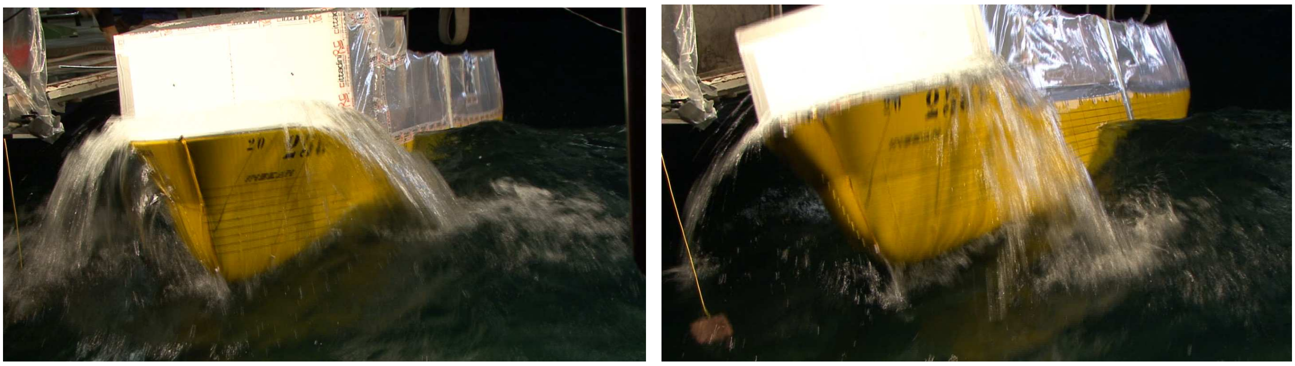


Figure 2: Nominal incident waves with $\omega_{4n0}/\omega = 0.519$ and $kA = 0.25$: Run 44 (left) and run 46 (right) at the time instant with wave crest at mid-ship.

confirmed by the behavior of the recorded ship motions (not reported here). As a result, the vessel was suitably dry and made waterproof and the test was repeated as run 46. In this case PR occurred, as well as important WOD (see right plot of figure 2). The different observed behavior required a more in-depth analysis of the experiments. The comparison of the rigid motions for the two runs showed very similar heave and pitch amplitudes but a non negligible yaw motion for case 46. This is confirmed by the 3D video and is reasonably due to some slack of the shaft blocking the yaw.

This discovered experimental problem highlighted an important effect of the coupling between roll (ξ_4) and yaw (ξ_6) on the parametric-roll occurrence and features. One can identify four stages in the ξ_4 and ξ_6 time evolutions for run 46 shown in figure 3 (left column) together with the corresponding Poincaré maps (right column). At the beginning (first

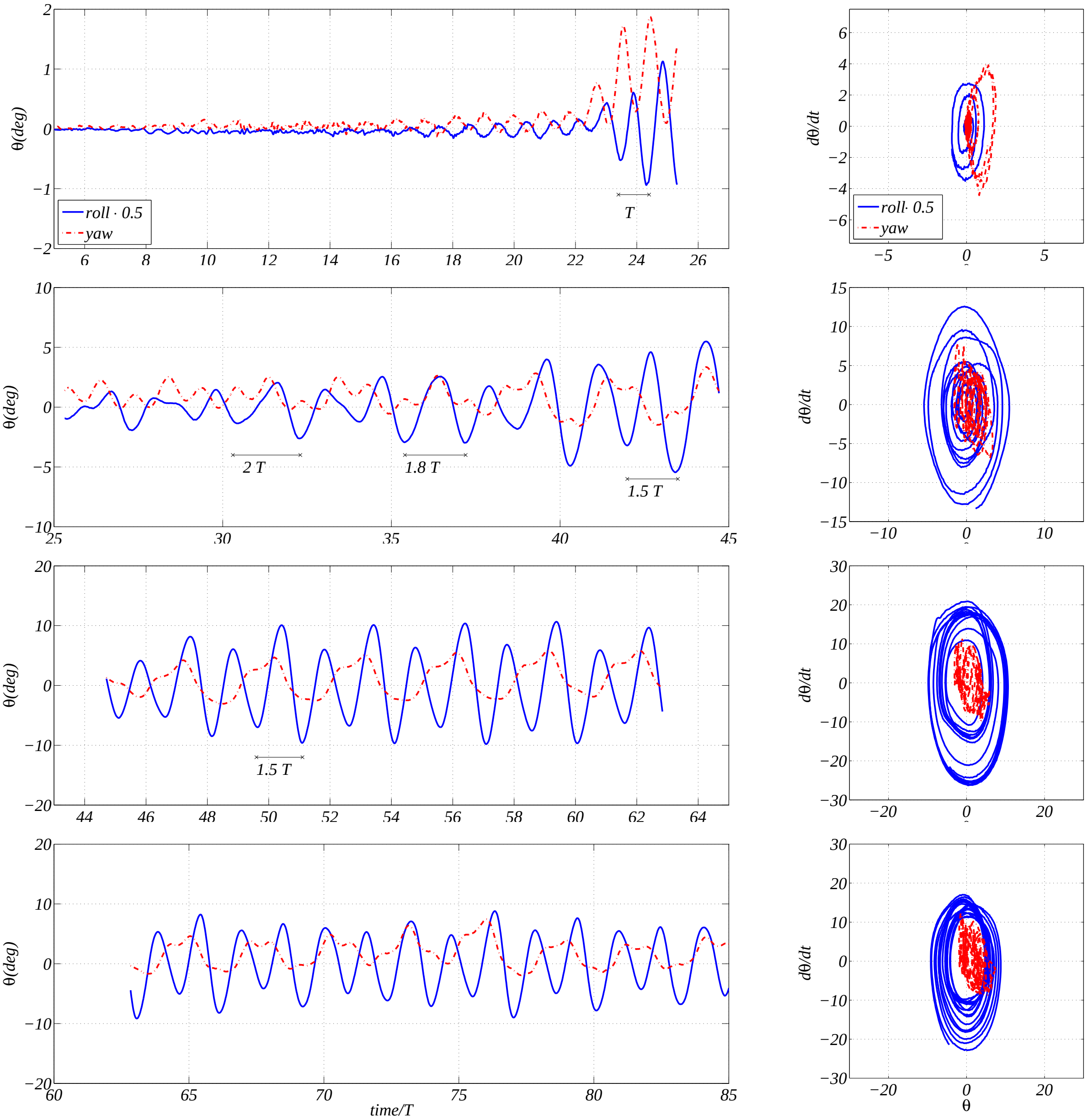


Figure 3: Nominal incident waves with $\omega_{4n0}/\omega = 0.519$ and $kA = 0.25$: Run 46. Four stages (increasing from top to bottom) of the roll and yaw motions and the corresponding Poincaré maps.

row), linear effects dominate and both motions oscillate with the incident-wave period; then (second row) ξ_6 shows a chaotic behavior with a global trend to increase the period of oscillation, its coupling with ξ_4 leads to a reduction in the roll period from $2T$ (first fundamental roll resonance) to $1.5T$; until (third row) the roll period is dominated by $1.5T$ and the yaw becomes a regular motion with dominant period equal to $3T$, i.e. twice the roll period. At this stage ξ_6 modulates ξ_4 inducing essentially two modes well visible in the corresponding roll Poincaré map. Eventually (fourth row) the chaotic regime of the yaw motion comes back again, this is dominated by the nonlinear effects in the roll-yaw coupling.

A similar roll-yaw coupling characterizes also the model behavior in the cases with $\omega_{4n0}/\omega = 0.568$ and $kA = 0.2 - 0.25$, justifying the PR experimentally observed but not numerically predicted (see table 1).

Due to the strong nonlinearities expected in the yaw restoring caused by the slacked shaft, it is not easy to reproduce numerically similar conditions for further investigation. But a numerical study on a fishing vessel, performed by Greco and Lugni (2013) to help the design of CNR-INSEAN experiments, confirms the importance of the yaw-roll coupling and some similar features. Right plot of figure 1 shows the model and the sketch of the planned set-up with a system of four elastic cables, used to limit the horizontal vessel motions. More details about this study can be found in Greco and Lugni (2013), here a relevant result presented at that conference is reported in figure 4. It concerns the roll and yaw motions corresponding to a regular incident head-sea wave with $\omega_{4n0}/\omega = 0.47$ and $kA = 0.25$; no viscous damping effects are

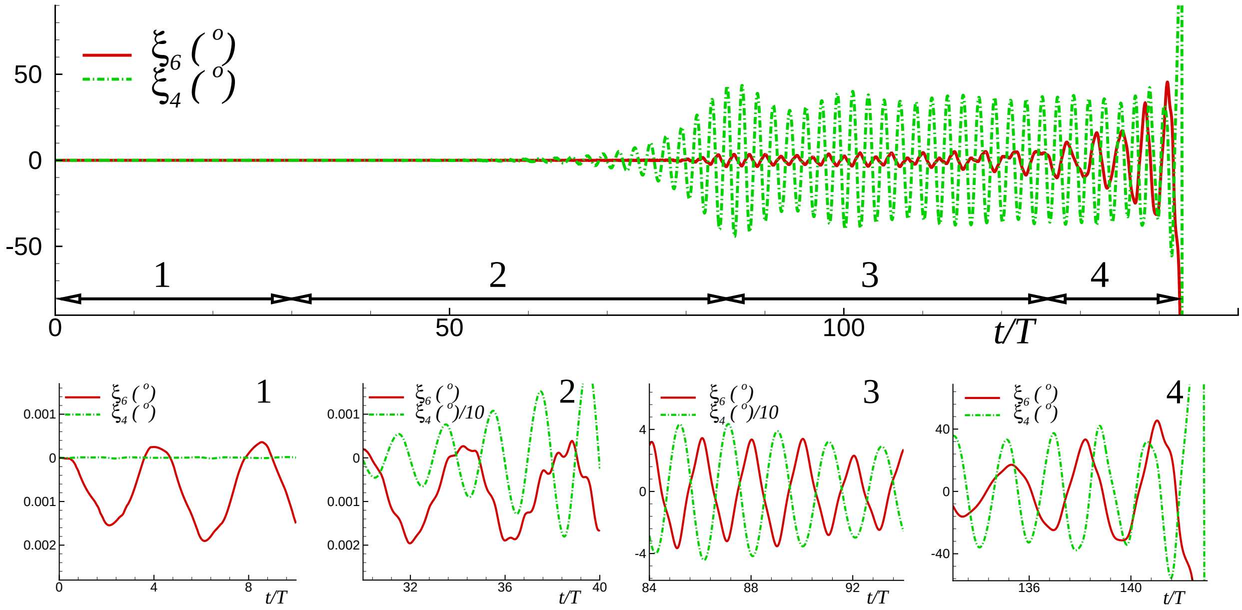


Figure 4: Fishing vessel in regular head-sea wave ($\omega_{4n0}/\omega = 0.47$, $kA = 0.25$). Overall (top) and zoomed views (bottom) of the time histories of the roll and yaw motions.

accounted for in the simulations. From the results, at first (1) the yaw motion oscillates at its natural frequency induced by the linear-restoring from the cables, while the roll is negligible; then (2) PR is excited by the wave-body interaction, ξ_4 oscillates at a period $2T$ and the yaw shows also an additional higher frequency superimposed to the oscillation at a frequency twice the roll. The roll-yaw coupling leads ξ_6 to oscillate with the same frequency as the roll (3), but eventually the yaw goes back to its natural frequency (changed by the coupling with roll) and induces a reduction in the roll oscillation period. This process leads to a progressive increase of the two motion amplitudes until the break-down of the simulation. Compared with the same case but with fixed yaw, the roll-yaw coupling appears to induce more rapidly the parametric resonance.

These studies suggest that the roll-yaw coupling, when yaw amplitude becomes sufficiently large, is dangerous for the parametric roll in head or bow sea and tends to reduce the roll oscillation period with respect to $2T$. This means that the use of a proper control system is crucial not only for directional stability but also for parametric-roll resonance. The results will be further discussed at the Workshop together with other outcomes from the FPSO model tests in terms of mid-ship bending moment. The global comparison between experiments and DD results indicate a possible use of the method not only for $\beta = 180°$ but also with β smaller and close to head-sea conditions. A next step of the numerical development is to extend the method to short-crested waves with main direction at $\beta = 180°$.

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