Seakeeping Computations for Fast and Unconventional Ships

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Abstract

Seakeeping is more important for fast ships than for conventional ships. Classical strip methods should not be applied for fast ships. Instead special high-speed strip methods and three-dimensional methods offer today suitable tools for analysis of seakeeping problems for fast ships. For slamming, three-dimensional RANSE solvers offer considerable progress and first 3-d applications appear to yield realistic results.

1. Introduction

Seakeeping of ships is investigated with respect to the following issues:

- Maximum speed in a seaway: "Involuntary"' speed reduction due to added resistance in waves and "voluntary" speed reduction to avoid excessive motions, loads etc.
- Route optimisation (routing) to minimise e.g. transport time, fuel consumption, or total cost.
- Structural design of the ship with respect to loads in seaways
- Habitation comfort and safety of people on board: motion sickness, danger of accidental falls, man over board
- Ship safety: capsizing, large roll motions and accelerations, slamming, wave impact on superstructures or deck cargo, propeller racing resulting in excessive rpm for the engine
- Operational limits for ships (e.g. for offshore supply vessels or helicopters landing on ships)

Computational tools to predict ship seakeeping include:

- Computations in the frequency domain: Determination of the ship reactions to harmonic waves of different wave lengths and wave directions
- Computations in the time domain (simulation in time): Computation of the forces on the ship for given motions at one point in time; based on that information the computation of the motions at a following point in time etc.

For many seakeeping issues, seakeeping is determined as follows:

1. Representation of the natural seaway as superposition of many regular (harmonic) waves. (Fourier decomposition)
2. Computation (or sometimes measurement in model tests) of the ship reactions of interest in these harmonic waves
3. Addition of the reactions in all these harmonic waves to a total reaction (superposition)

This procedure assumes (respectively requires) that the reaction of one wave on the ship is not changed by the simultaneous occurrence of another wave. This assumption is valid for small wave heights for almost all ship reactions with the exception of the added resistance. However, the procedure is often applied also for seaways with large waves. In these cases it can only give rough estimates requiring proper corrections. One consequence of the assumed independence of the individual wave reactions is that all reactions of the ship are proportional to wave height. This is called linearisation with respect to wave height.

The computations become considerably more expensive if this simplification is not made. Non-linear computations are usually necessary for the treatment of extreme motions (e.g. for capsizing investigations); here simulation in the time domain is the proper tool. However, for the determination of maximum loads it often suffices to apply corrections to initially linearly computed loads. The time-averaged added resistance is in good approximation proportional to the square of the wave height. Here the effect of harmonic waves of different lengths and direction can be superimposed as for the linear ship reactions.

To determine global properties (e.g. ship motions and accelerations) with sufficient accuracy, simpler methods suffice than for the determination of local properties (pressures, relative motions between water and ship).

Bertram (2000) gives a practical overview of various computational methods for ship seakeeping pointing out the strong points and weaknesses of each approach. This is recommended for readers for further studies.

2. Numerical prediction of ship seakeeping

If the effect of the wave amplitude on the ship seakeeping is significantly non-linear, there is little sense in investigating the ship in elementary waves, since these waves do not appear in nature and the non-linear reaction of the ship in natural seaways cannot be deduced from the reaction in elementary waves. In these non-linear cases, simulation in the time domain is the appropriate tool for numerical predictions.

However, if the non-linearity is weak or moderate the seakeeping properties of a ship in natural seaways can be approximated by superposition of the reactions in elementary waves of different frequency and direction. In these cases, the accuracy can be enhanced by introducing some relatively simple corrections of the purely linear computations to account for e.g. force contributions depending quadratically on the water velocity or considering the time-dependent change of position and wetted surface of the ship. Even if iterative corrections are applied the basic computations of the ship seakeeping is still based on its reaction in elementary waves, expressed by complex amplitudes of the ship reactions. The time dependency is then always assumed to be harmonic, i.e. sinusoidal.

The Navier-Stokes equation (conservation of momentum) and the continuity equation (conservation of mass) suffice in principle to describe all phenomena of ship seakeeping flows. However, we neither can nor want to resolve all little turbulent fluctuations in the ship's boundary layer and wake. Therefore we average over time intervals which are long compared to the turbulent fluctuations and short compared to the wave periods. This yields the Reynolds-averaged Navier-Stokes equations (RANSE). By the early 2000's RANSE computations for ship seakeeping appeared at the threshold of practical applicability for short-term, highly non-linear flow simulations. If viscosity is neglected the RANSE turn into the Euler equations. Euler solvers do not have to resolve the boundary layers and allow thus coarser grids and considerably shorter computational times. Nevertheless, Euler solvers are rarely used for ship seakeeping, as it is often simpler to employ a commercial RANSE solver in laminar flow mode or with the simplest turbulence model offered.

In practice, almost exclusively potential flow solvers are used in seakeeping predictions. The most frequent application is the computation of the linear seakeeping properties of a ship in elementary waves. Potential flow assumes in addition to the assumption for Euler solvers that the flow is irrotational. This is no major loss in the physical model, because rotation is created by the water adhering to the hull and this information is already lost in the Euler flow model. Relevant for practical applications is that potential flow solvers are much faster than Euler and RANSE solvers, because potential flows have to solve only one linear differential equation instead of 4 non-linear coupled differential equations. Also potential flow solvers are usually based on boundary element methods and need only to discretise the boundaries of the domain, not the whole fluid space. This reduces the effort in grid generation (the main cost item in most analyses) considerably. On the other hand, potential flow methods require a simple, continuous free surface. Flows involving breaking waves and splashes can hardly be analysed properly by potential flow methods.

In reality, viscosity is significant in seakeeping, especially if the boundary layer separates periodically from the hull. This is definitely the case for roll and yaw motions. In practice, empirical corrections are introduced. Also, for flow separation at sharp edges in the aftbody (e.g. vertical sterns, rudder, or transoms) a Kutta condition is usually employed to enforce a smooth detachment of the flow from the relevant edge.

The most important linear methods can be classified as follows:

- Strip method
  Strip methods reduce the 3-d problem to a set of 2-d, independent boundary value problems. This requires also a simplification of the actual free-surface condition. Most of today's strip methods are variations of the strip method proposed by Salvesen, Tuck and Faltinsen (STF methods) in 1970. The 2-d problem for each strip can be solved analytically (Lewis sections) or by panel methods, *Bertram (2000).* Strip methods are - despite inherent theoretical shortcomings - fast, cheap and for most problems and moderate speeds ($F_n<0.6$) sufficiently accurate.

- Unified theory
  Newman and Sclavounos developed at the MIT the 'unified theory' for slender bodies. The theory uses the slenderness of the ship hull to justify a 2-d approach in the near field which is coupled to a 3-d flow in the far field. The far-field flow is generated by distributing singularities along the centreline of the ship. This approach is theoretically applicable to all frequencies, hence 'unified'. Despite its better theoretical foundation, unified theories failed to give significantly and consistently better results than strip theories for real ship geometries. The method therefore failed to be accepted by practice.

- 'High-speed strip theory' (HSST)
  Several authors have contributed to the high-speed strip theory after the starting work of Chapman in 1975, see *Kashiwagi's (1997)* review. HSST computes usually the ship motions in an elementary wave using linear potential theory. The method is often called 2½-d, since it considers the effect of upstream sections on the flow at a point x, but not the effect of downstream sections. Starting at the bow, the flow problem is solved for individual strips (sections) x=constant. The boundary conditions at the free surface and the hull (strip contour) are used to determine the wave elevation and the velocity potential at the free surface and the hull. Derivatives in longitudinal direction are computed as numerical differences to the upstream strip which has been computed in the previous step. The computation marches downstream from strip to strip and ends at the stern resp. transom. HSST is the appropriate tool for fast ships with Froude numbers $F_n>0.4$. For lower Froude numbers, it is inappropriate.

- Green function method (GFM)
  GFM distribute panels on the average wetted surface. The velocity potential of each panel (Green function) fulfils automatically the Laplace equation, the radiation condition (waves propagate in the right direction) and a simplified of the free-surface condition. The unknown (either source strength or potential) is determined for each element by solving a linear system of equations such that for each panel at one point the no-penetration condition on the hull (zero normal velocity) is fulfilled. The various methods differ primarily in the way the Green function is computed. This involves the numerical evaluation of complicated integrals with highly oscillating integrands. While GFM dominate for zero-speed flows, they are increasingly less suited for higher speeds.

- Rankine singularity method (RSM)
  RSM allow in principle to capture the interaction between steady flow and waves completely. They allow also more complicated boundary conditions on the free surface and the hull. In summary, they offer the option for the best approximation of the seakeeping problem within potential theory. This comes at a price. Both ship hull and the free surface in the near field around the ship have to be discretized by panels. Capturing all waves while avoiding unphysical reflections of the waves at the outer (artificial) boundary of the computational domain poses the main problem for RSM. This problem is relatively easily solved in time domain simulations. RSM are drifting from research to practical applications.

3. Special considerations for fast ships

Seakeeping computations are a particular topic for fast and unconventional ships. Seakeeping plays a special role here, as fast ships often are passenger ferries, which need good seakeeping characteristics to attract passengers. This is the reason why e.g. planing boats with their bad seakeeping are hardly ever used for commercial passenger transport. For fast cargo ships, the reduced speed in seaways can considerably influence transport efficiency. A hull form, which is superior in calm water, may well become inferior already in moderate seaways, *Long and Slogett (1985), Bertram and Schmidt (1996),* Table I. Warships also often require good seakeeping to supply stable platforms for weapon systems, helicopters, or planes.

Table I: Speed loss in seaways for various ship types, *Bertram and Schmidt (1996)*

	Ship type	Speed loss in H_s=1m	Speed loss in H_s=2m	Speed loss in H_s=3m
Corsair 600	SES	7%	13%	22%
SSW 320A	SWATH	0%	1%	2%
Aquastrada	monohull	4%	10%	15%

Unfortunately, computational methods for conventional ships usually are not at all or only with special modifications suitable for fast and unconventional ships. The 'High-speed strip theory' has been successfully applied in various forms to both fast monohulls and multi-hulls. Japanese benchmark studies showed that for a fast monohull with transom stern the HSST faired much better than both conventional strip methods and three-dimensional GFM and RSM, *Takaki and Iwashita (1994). Bertram and Iwashita (1996)*, Appendix I. However, some of the conventional strip methods and the three-dimensional methods did not use any special treatment of the large transom stern of the test case. This impairs the validity of the conclusions. Researchers at the MIT have shown that at least for time-domain RSM the treatment of transom sterns is possible and yields good results also for fast ships, albeit at a much higher computational effort than the HSST. In most cases, HSST should yield the best cost-benefit ratio for fast ships.

It is claimed often in the literature that conventional strip methods are only suitable for low ship speeds. However, benchmark tests show that strip methods can yield good predictions of motion RAOs up to Froude numbers $F_n \approx 0.6$, provided that proper care is taken and the dynamic trim and sinkage and the steady wave profile at the hull is included to define the average submergence of the strips. The prediction of dynamic trim and sinkage is relatively easy for fast displacement ships, but difficult for planing boats. Neglecting these effects, i.e. computing for the calm water wetted surface, may be a significant reason why often in the literature a lower Froude number limit of $F_n \approx 0.4$ is cited.

For catamarans, the interaction between the hulls plays an important role especially for low speeds. For design speed, the interaction is usually negligible in head seas. Three-dimensional methods (RSM, GFM) capture automatically the interaction as both hulls are simultaneously modelled. The very slender form of the demihulls introduces smaller errors for GFM catamaran computations than for monohulls. Both RSM and GFM applications to catamarans can be found in the literature, usually for simplified research geometries. Strip methods require special modifications to capture at least in good approximation the hull interaction, namely multiple reflection of radiation and diffraction waves. Simply using the hydrodynamic coefficients for the two-dimensional flow between the two cross sections leads to strong overestimation of the interaction for V>0.

Seakeeping computations for air cushioned vehicles and surface effect ships are particularly difficult due to additional problems:

- The flexible skirts deform under the changing air cushion pressure and the contact with the free surface. Thus the effective cushion area and its centre of gravity changes.
- The flow and the pressure in the cushion contain unsteady parts which depend strongly on the average gap between free surface and skirts. Especially the narrow gaps between skirts and free surface result in a strongly nonlinear behaviour that so far excludes accurate predictions.
- The dynamics of fans (and their motors) influences the ship motions.

4. Rankine Singularity Method in Time Domain

Bertram and Landrini (2002) present a three-dimensional Rankine singularity method for ship seakeeping. applicable for a wide speed range and also low frequencies of encounter. The inviscid boundary element method solves the linearized ship seakeeping problem in time domain. A transient-test technique simulates interaction with a whole wave packet at one time increasing the efficiency of the method. The problem is solved in two steps. At a given instant of time, the potential on the free surface and the normal gradient on the body boundary are known and the resulting mixed Neumann-Dirichlet boundary value problem for the Laplace equation is solved by a standard panel method. Once the velocity potential is computed on the boundary domain, the free surface equations, as well as the equations of the body motion, are stepped forward by a fourth-order Runge-Kutta scheme.

Outgoing waves are damped out by dissipative terms inserted in the kinematic free surface boundary condition. The damping is applied only in a damping zone surrounding the inner physical free surface. A smooth increase from zero up to an empirically determined maximum value is used. Fig.1 show a typical computational domain. An apparent feature of the adopted discretization is the use of a unstructured grid for the free surface. This is a key point to easily deal with multi-hulls and transom stern and also to allow an easy local mesh refinement. A transom stern is handled using a fictitious extension to smoothly reconcile the hull with the surface level, Fig.2. This fictitious extension is used only to ensure tangential flow, but not considered in the pressure integration for the forces acting on the ship.

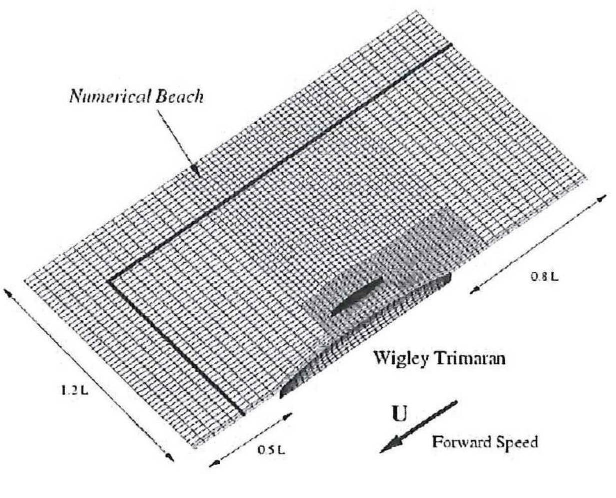

Fig.1: Discretized domain for trimaran; damping zone bounded by thick line

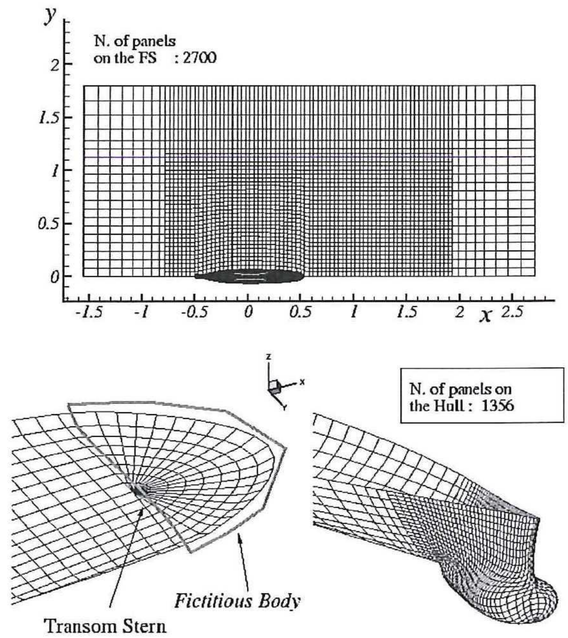

Fig.2: DDG 51 grid details

Three-dimensional methods to analyze seakeeping make particular sense for multi-hull where the hull interaction can introduce considerable 3-d effects. We investigated therefore also a generic trimaran composed of simple parabolic Wigley hull shapes, *Colagrossi et al. (2002).* The unstructured free-surface grid allows a good resolution of the area between the hulls and allows easy grid generation. The results of our 3-d method were compared with a special multi-hull strip method of *Söding (1999)* and model tests performed at INSEAN. As expected qualitatively, the strip method approximation is progressively less accurate as speed decreases, Fig.3. For Froude number F_n = 0.2, our three-dimensional model agrees well with experiments over the whole region of wave lengths. Söding's strip method recovers the location of the RAO peaks near $\lambda/L \approx 0.85$ and 1.2 but not the magnitude. As the velocity increases, experiments show an increase of the first peak and a decrease of the second peak.

Our model over-predicts the second peak, mostly for pitch, but is closer to experiments than the strip method.

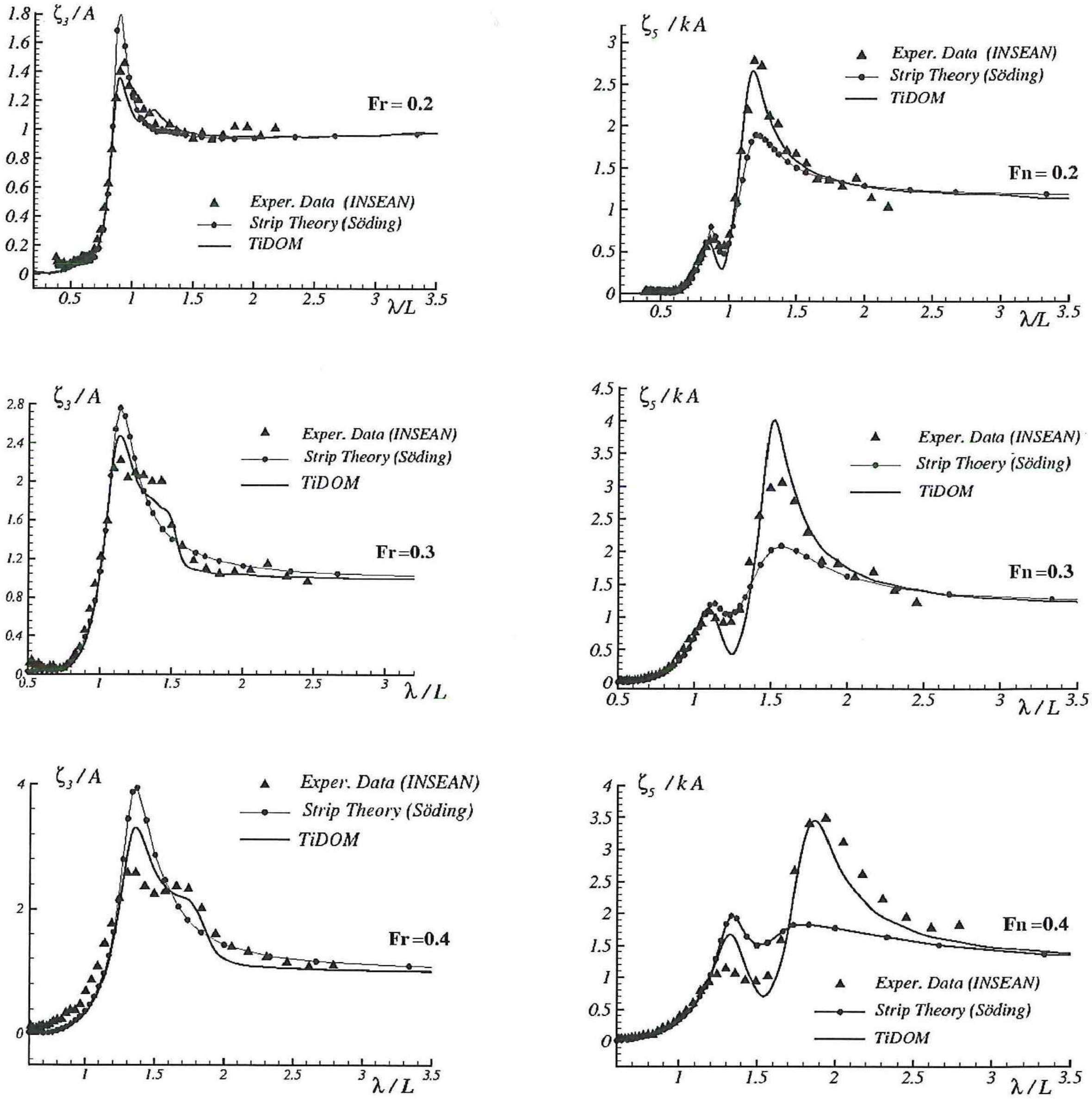

Fig.3: Wigley Trimaran: RAOs for heave (ζ_3) and pitch (ζ_5)

Another application was for the combatant DDG 51 is a representative of a standard frigate. Reasonable agreement with experiments conducted at INSEAN is obtained, Fig.4, *Colagrossi et al. (2001)*. The experiments used alternatively a JONSWAP spectrum and transient test technique.

The method is at present well validated for heave and pitch. The transient test approach combined with the capability for unstructured grids (grid refinement only where it is needed) approach allows relatively good efficiency for the results obtained. Typically, RAOs of a ship with complex geometry can be obtained by overnight computations on a PC (Pentium III 600 MHz). Future development will focus first on an extension to all 6 degrees of freedom. Better models for the base flow, extension to include added resistance and techniques to model transom sterns are among the topics that require further studies. But the method may well become an intermediate seakeeping analysis tool surpassing strip methods in accuracy and being considerably faster than volume methods. The method is not applicable to planing hulls.

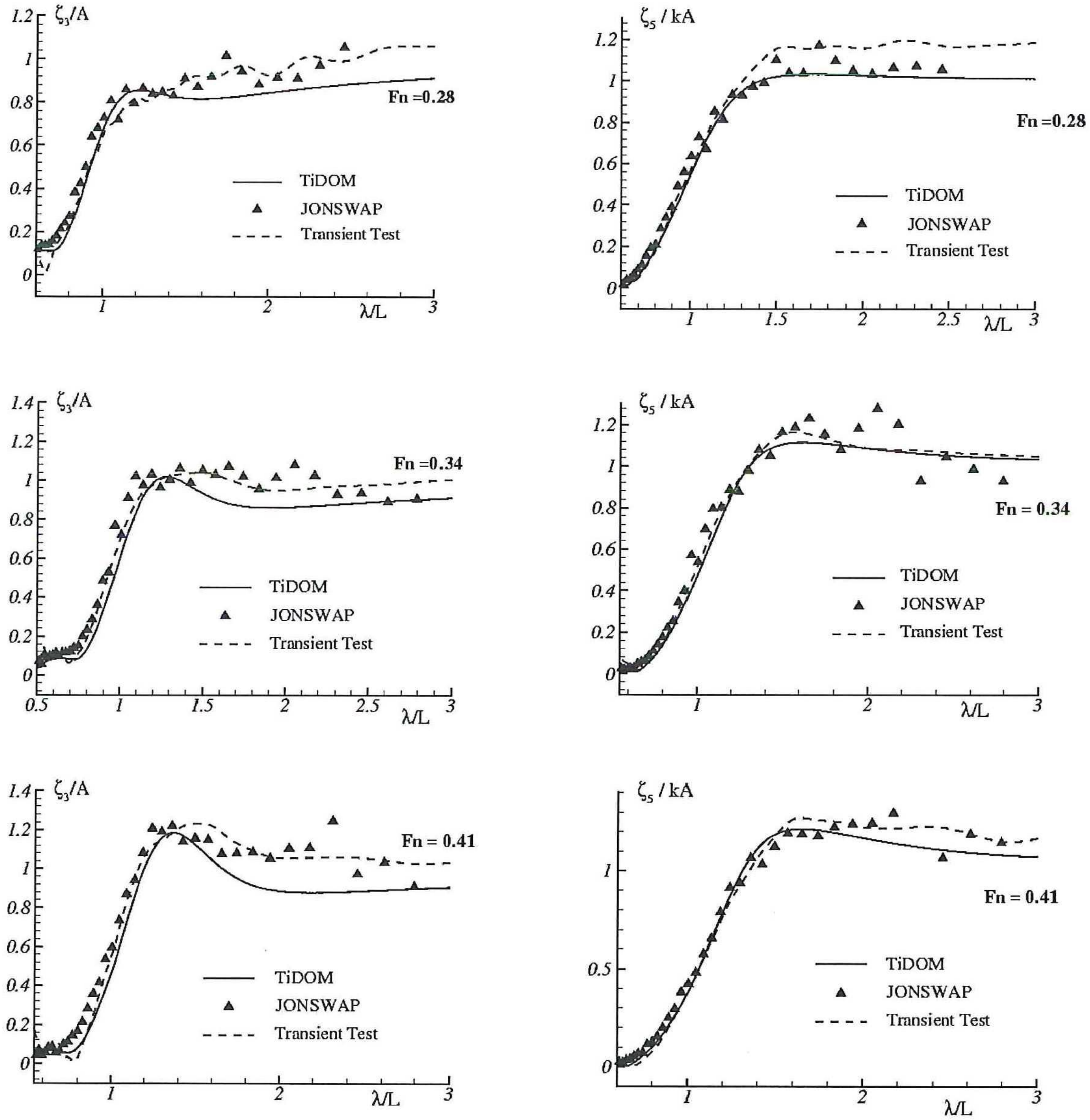

Fig.4: Numerical and experimental RAOs for DDG 51: heave (ζ_3) and pitch (ζ_5)

5. Slamming

In rough seas with large relative ship motion, slamming may occur with large water impact loads. Usually, slamming loads are much larger than other wave loads. Sometimes ships suffer local damage from the impact load or large-scale buckling on the deck. For high-speed ships, even if each impact load is small, frequent impact loads accelerate fatigue failures of hulls. Thus, slamming loads may threaten the safety of ships. The expansion of ship size and new concepts in fast ships have decreased relative rigidity causing in some cases serious wrecks.

Slamming has challenged many researchers since von Karman's work in 1929. Today, mechanisms of wave impacts are correctly understood for the 2-d case, and accurate impact load estimation is possible for the deterministic case. The long-term prediction of wave impact loads can be also given in the framework of linear stochastic theories. However, our knowledge on wave impact is still far from sufficient.

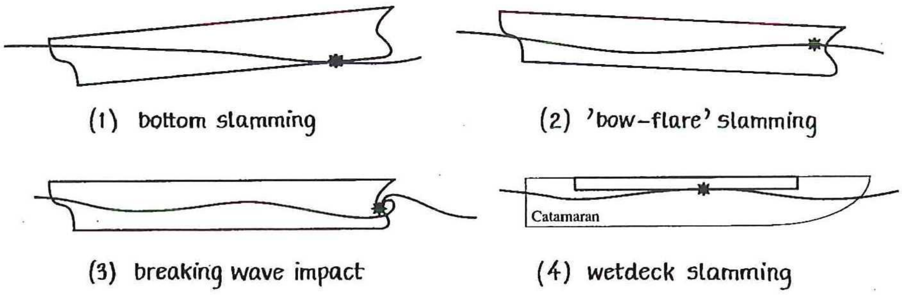

Fig.5: Slamming forms, *Bertram (2000)*

The wave impact caused by slamming can be roughly classified into four types, Fig.5:

1. Bottom slamming occurs when emerged bottoms re-enter the water surface.
2. Bow-flare slamming occurs for high relative speed of bow-flare to the water surface.
3. Breaking wave impacts are generated by the superposition of incident wave and bow wave hitting the bow of a blunt ship even for small ship motion.
4. Wet-deck slamming occurs when the relative heaving amplitude is larger than the height of a catamaran's wet-deck.

Both bottom and bow-flare slamming occur typically in head seas with large pitching and heaving motions. All four water impacts are 3-d phenomena, but have been treated as 2-d for simplicity. E.g., types (1) and (2) were idealised as 2-d wedge entry to the calm water surface. Type (3) was also studied as 2-d phenomenon similar to wave impact on breakwaters.

A fully satisfactory theoretical treatment of slamming has been prevented so far by the complexity of the problem:

- Slamming is a strongly non-linear phenomenon which is very sensitive to relative motion and contact angle between body and free surface.
- Predictions in natural seaways are inherently stochastic; slamming is a random process in reality.
- Since the duration of wave impact loads is very short, hydro-elastic effects are large.
- Air trapping may lead to compressible, partially supersonic flows where the flow in the water interacts with the flow in the air.

Most theories and numerical applications are for 2-d rigid bodies (infinite cylinders or bodies of rotational symmetry), but slamming in reality is a strongly 3-d phenomenon. *Bertram (2000)* reviews briefly the most relevant theories. All classical theories approximate the fluid as inviscid, irrotational, incompressible, free of surface tension. In addition, it is assumed that gravity effects are negligible. This allows a (predominantly) analytical treatment of the problem in the framework of potential theory.

- Von Karman theory (1929) (momentum impact model)
  Von Karman was the first to study theoretically water impact (slamming). He idealised the impact as 2-d wedge entry problem on the calm water surface to estimate the water impact load on a seaplane during landing, assuming small deadrise angles β.

- Wagner theory (1932)
  Wagner derived a more realistic water impact theory. Wagner's theory can be applied to arbitrary shaped bodies as long as the deadrise angle is small, but larger than 3° (to avoid air entrapment). Wagner's theory is simple and useful, even if the linearisation is sometimes criticised for its inconsistency. Many experimental studies have checked the accuracy of Wagner's theory. Measured peak impact pressures are typically a little lower than estimated. This suggested that Wagner's theory gives conservative estimates for practical use. However, a correction is needed on the peak pressure measured by pressure gauges with finite gauge area. Special numerical FEM analyses of the local pressure in a pressure gauge can be used to correct measured data. The corrected peak pressures agree then well with estimated values by Wag-

ner's theory. Today, Wagner's theory is believed to give accurate peak impact pressure (for 2-d bodies).

- Bagnold's theory (1930s)

  The body is preceded by an air cushion that displaces water already before the actual body entry. The density of air plays a large role if air trapping occurs. Bagnold performed pioneering work in the development of theories that consider this effect. Bagnold's impact model is simply constructed from added mass, rigid wall, and non-linear air cushion between them. This model allows already qualitative predictions of the relation between impact velocity, air cushion thickness, and peak impact pressure. Further research has resulted in more sophisticated models in the 1960s and 1970s. Dedicated experiments with high-speed cameras have shown that the mechanism of wave impact with air trapping is in reality much more complicated. Viscosity of air, the effect of air leakage during compression, shock waves inside the air flow, and the complicated deformation of the free surface may all play an important role. Computational fluid dynamics may be the key to significant success here, but has not yet progressed sufficiently yet as discussed below.

- Korobkin (1996) - Effect of water compressibility

  When a blunt body drops on calm water or a flat bottom drops on a smooth wave crest, usually no air trapping occurs. Nevertheless, one cannot simply use Wagner's theory, because at the top of such a blunt body or wave crest the relative angle between body and free surface becomes zero. Then both Wagner's and Watanabe's theories give infinite impact pressure. In reality, compressibility of liquid is important for a very short time at the initial stage of impact, when the expansion velocity of the wet surface exceeds the speed of sound for water producing a finite impact pressure. *Korobkin (1996)* developed two-dimensional theories which consider compressibility and free-surface deformation.

All of the above slamming theories are two-dimensional. In reality slamming for ships is a strongly three-dimensional phenomenon due to e.g. pitch motion and cross sections in the foreship changing rapidly in longitudinal direction. For practical purposes, one tries to obtain quasi 3-d solutions based on strip methods or high-speed strip methods. The 3-d treatment of slamming phenomena is subject to active research. It is reasonable to test and develop numerical methods first for 2-d slamming, before one progresses to computationally more challenging 3-d simulations.

It is important to evaluate not only peak impact pressures but also structural responses to the impact, to consider the impact pressure in the design of marine structures. Whipping (large-scale, weakly dampened oscillations of the longitudinal bending moment) is a typical elastic response to impact. Research is active to develop numerical methods to analyse both fluid and structure simultaneously. These will improve considerably our capability to analyse hydro-elastic slamming problems within the next decade.

For most practical impact problems, the body shape is complex, the effect of gravity is considerable, or the body is elastic. In such cases, analytical solutions are very difficult or even impossible. This leaves CFD as a tool. Due to the required computer resources, CFD applications to slamming appeared only since the 1980's. While the results of boundary element methods for water entry problems agree well with analytical results, it is doubtful whether they are really suited for this problem. Real progress is more likely to be achieved with field methods. Various researchers have approached slamming problems, usually employing surface-capturing methods, e.g. marker-and-cell methods or level-set techniques, e.g. *Arai et al. (1994, 1995a,b), Schumann (1998), Muzaferija and Peric (1998), Muzaferija et al. (1998), Sames et al. (1998).*

Due to the large required computer resources, few really three-dimensional applications to ships have been presented. *Caponnetto (2002)* presented the first convincing 3-d time simulations for planing hulls in waves, see also *Bertram et al. (2003).*

6. Three-dimensional RANSE simulation of planing hulls in waves

The design of a hard chine vessel requires, more than for other kind of boats and ships, a trade-off between calm-water resistance and sea-keeping qualities. Following Savitsky theory, the prismatic hull of minimal resistance (above a certain speed) is a flat hull. Even if we more complex consider hull shapes, the deadrise angle remains a fundamental parameter for calm-water resistance and this angle should be minimized. Keeping all the rest fixed, a flat hull generates more lift, allows a lower trim angle (lower wave drag) and smaller wetted surface (lower friction drag). In waves, a flat hull is one of the worst shape we can image. Large impact pressures are suddenly generated as the waves hit the bottom; this creates structural problems as well as vertical accelerations that can be hardly sustained by the crew. In practice, a deadrise angle is always necessary but the amount of V-shape depends on speed, boat dimensions and expected wave amplitude. Modern boats are seldom prismatic, and have a deadrise angle that varies along the boat length. Depending on the applications, this angle may vary from 10°/20° at the transom to 20°/50° near the bow, where impact pressures are expected to be higher. These "warped" hulls pose new problems to the naval architects. First, Savitsky theory cannot be used to calculate calm-water trim and resistance of warped hulls. Second, there is a lack of data to predict sea-keeping qualities of warped hulls.

Comet has been used both for both steady (calm-water), *Caponnetto (2000,2001)*, and unsteady (sea-keeping) computations, *Caponnetto (2002), Caponnetto and Söding (2003).* The high-resolution interface capturing approach of the code allows to compute spray, breaking and overturning waves, detachment and reattachment of the flow along the chine, the side hull and the transom, and ventilation of the hull. For conventional hard chine hull forms, block-structured hexahedral meshes yield the most accurate results and are easy to generate. Hull, deck and transom are discretized with special care for the proper definition of the chine and the spray rails. Flaps, tunnels and skegs can be also modelled. The time required to build all the files needed to feed the solver is very short; about 10 seconds for a typical mesh having 200,000 cells.

In a sea-keeping simulation, the hull changes its relative position in the calculation domain at each new time step. So far, we included only heave and trim as degrees of freedom. At each time step updated values for the trim and sink are supplied to the mesh program to built the new mesh. The cell vertices along the external boundary of the computational domain remain fixed, while those over the hull are moved rigidly by the right amount. All the vertices in between will be consistently moved by a fraction of the hull movements, keeping the same topology. Cells and vertices numeration remains the same. Thus the solver can restart without the additional efforts needed to interpolate the old variables (pressure, velocity…) to the new cells. At the end of each time step, the pressure over the hull is integrated to the vertical force and moment. Vertical and angular accelerations are then used to compute the new trim and sinkage. A problem arose from numerical fluctuation of the calculated pressure distribution and forces between an iteration and the next one. Due to these small oscillations, a boat left free to heave and trim would oscillate continuously around the mean position even for steady flow. This numerical instability is removed by smoothing the vertical force (and moment) over several previous time steps.

At the inlet, sinusoidal waves of height h are generated by prescribing horizontal and horizontal velocities of an Airy wave and the corresponding pressures. For a smooth launch of the computation, the wave height at the inlet is let to grow linearly from zero to h in one encounter period. The simulation is carried on until about 10 waves are encountered, but usually the phenomenon becomes periodic at the third or fourth encountered wave.

Due to lack of detailed experimental data, validation and verification of the code for planing hulls had to be limited so far to check the robustness of the method and to perform convergence and mesh sensitivity tests for many planing hulls. The accelerations computed are realistic. The code is very robust, since typically 5000 time steps are completed without crashes in the 90% of the cases. As far as accelerations are concerned, the results are converged with about 100.000 cells (for one half of the physical domain considering the lateral symmetry of the problem). The time history of the drag integrated over time gives the "average" increase of drag, allowing an estimation of the speed reduction in waves. Changes of hull geometry give qualitatively the expected results, and this is important in the perspective to rank different boats at the design stage.

Very extreme situations have be encountered in our simulations, Figs.6 and 7. Sometimes the entire hull comes out of the water and then slams into the new incoming wave, rising the water above the deck. In these cases, pressure impacts are too large to neglect hydro-elastic interaction. Also surge motion should be considered in future simulations.

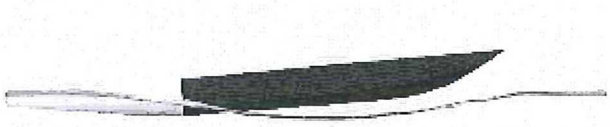

Fig.6: 24 m boat at 45 knots coming near completely out of the water in regular waves with λ=30 m and h=2 m.

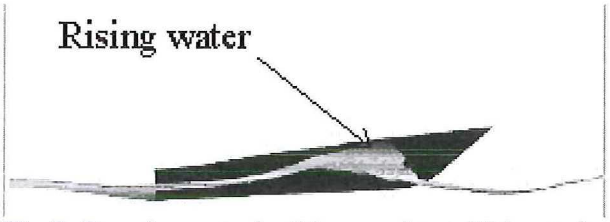

Fig.7: Bow impact of a 35 m yacht at 30 knots in similar wave conditions

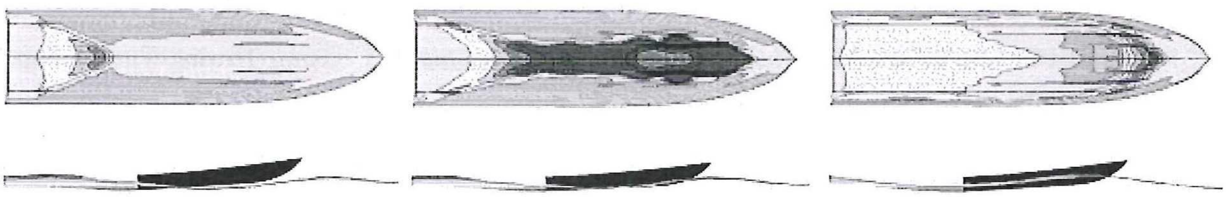

Fig.8: Three time instants in simulation of planing hull in waves

Fig.8 shows the calculated pressure distribution, and the corresponding trim of the hull, at three different instants of the simulation. In the first frame, the boat is nearly out of the water and there is only a small V-shaped high pressure region ahead of the transom. After that the hull, falling down, hits the water all along the keel, and the impact pressure is maximum. The water is partly deflected by the spray rails. Finally the bow enters the incoming crest. These data could be very useful for structural calculations. The results obtained so far are still to be validated, but the code has been proven to be robust and supplies qualitatively satisfactory results.

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Appendix I: Japanese validation study

Ship motion experiments were performed in a towing tank for a model of a typical Japanese hard-chine fishing boat, Tables II and III. Table IV gives sinkage and trim (positive for bow immersion) for conventional resistance test ("still water") and for the ship in waves (time-averaged value). The model's eigenperiods of heave and pitch were both 0.9s. The experiments determined heave and pitch motions and surge force in regular head waves for F_n=0.4, 0.6, and 0.8. Wave lengths were varied from $\lambda/L=1$ ($L=L_{pp}$) to 4. The towing point was at the longitudinal position of the centre of buoyancy, 17.8cm (=9.7% L) above the base line. For high speeds, considerable spray formed in the forepart of the model. Standard wave height was H=4.5cm. Experiments with 9cm wave height determined the degree of non-linearity in some cases. None of the motions were affected by non-linearity. Only heave acceleration showed a weak nonlinear influence for F_n =0.8.

Forced oscillation and exciting force experiments were performed for F_n =0.4 and F_n=0.6 in a model basin to supply intermediate results necessary to evaluate the accuracy of the calculations methods. However, unlike in the motion experiments, trim and sinkage were suppressed. The amplitude of the forced oscillations was 2cm, the frequency parameter $\omega_e^2 L/g$ ranged from 1 to 25. The exciting force experiments were performed in regular head sea of wave steepness $H/\lambda=1/50$. The wave length was varied from $\lambda/L=0.5$ to 1.5.

Table II: Offset data of fishing boat (full-scale, $L=L_{pp}$=9.90m; A = -0.05543 L, B = -0.06086 L)

X/L	Y	Z	Y	Z	Y	Z	Y	Z	Y	Z	Y	Z	Y	Z
B	0.0	0.34			1.04	0.41	1.04	1.02	1.19	1.10			1.19	1.73
A	0.0	0.32			1.05	0.42	1.05	0.98	1.20	1.04			1.20	1.68
AP	0.0	0.32			1.06	0.42	1.06	0.945	1.20	1.00			1.21	1.625
1	0.0	0.28			1.07	0.39	1.08	0.87	1.23	0.93			1.22	1.56
2	0.08	-0.55	0.08	0.20	1.09	0.325	1.10	0.81	1.23	0.89			1.23	1.50
3	0.15	-0.49	0.15	0.13	1.12	0.26	1.12	0.77	1.25	0.83			1.25	1.43
4	0.22	-0.42	0.22	0.055	1.14	0.21	1.14	0.73	1.28	0.79			1.28	1.41
5	0.22	-0.35	0.22	0.0	1.15	0.16	1.16	0.70	1.29	0.75			1.30	1.39
6	0.22	-0.28	0.22	-0.06	1.12	0.13	1.15	0.70	1.30	0.75			1.32	1.45
7	0.22	-0.21	0.22	-0.08	1.07	0.16	1.12	0.76	1.28	0.80			1.32	1.45
8	0.17	-0.14	0.18	-0.10	0.92	0.26	0.99	0.87	1.12	0.92	1.24	1.44	1.24	1.56
8.5	0.14	-0.10	0.15	-0.08	0.75	0.37	0.84	0.945	0.97	1.00	1.14	1.52	1.14	1.63
9	0.11	-0.07			0.48	0.53	0.66	1.05	0.73	1.12	1.02	1.61	1.03	1.74
9.5	0.03	0.48			0.15	0.703	0.38	1.18	0.44	1.24	0.86	1.71	0.87	1.85
FP	0.0	1.34									0.70	1.81	0.70	1.96

Table III: Principal particulars of model (model scale 1:5.38), k_{yy} with respect to center of gravity

L_{OA}	2.543 m	D	0.158 m	Δ	52.3 kg
L_{pp}	1.840 m	T_{ap}	0.1180 m	LCB	0.1632 m
B	0.428 m	T_{fp}	0.0586 m	k_{yy}/L_{pp}	0.275

Table IV: Trim and sinkage (model scale), values indicated by * are for 9cm instead of 4.5cm wave height

F_n	sinkage [cm]		Trim [deg]	
	still water	averaged in waves	still water	averaged in waves
0.4	1.18	0.60	0.80	0.72
0.6	1.65	1.52 / 1.54*	-1.98	-1.91 / -1.76*
0.8	0.77	0.88 / 1.04*	-1.59	-1.54 / -1.30*

12 strip methods were compared, varying the strip method formulation (New Strip Methods, Salvesen-Tuck-Faltinsen, Ordinary Strip Method), the technique to represent the two-dimensional strip (Lewis form, close fit), the technique to compute the exciting forces (based on ω_0 or ω_e), transom stern treatment, etc. Added mass for heave and pitch were generally under-predicted, while damping for heave and pitch was generally over-predicted, especially for long waves. The coupling terms (A_{35}, A_{53}, B_{35}, and B_{53}) agreed better with experiments than the main terms, especially for methods with transom stern treatment. Surge exciting forces were typically predicted to only half the measured value. However, the surge exciting force is small compared to heave and pitch exciting forces making large relative errors more acceptable. Also, it is difficult to measure surge forces and measured values may therefore also be wrong. Heave and pitch exciting forces agreed well with experiments for F_n=0.4. Only the pitch exciting moment was somewhat under-predicted for $\lambda/L>1$. For F_n=0.6 the heave exciting force disagreed for $\lambda/L<1$ and pitch exciting moment for $\lambda/L>1$. Heave and pitch motions agreed well with experiments for close-fit methods. For F_n =0.6, Lewis form methods sometimes strongly over-predicted heave and pitch. Added mass measurements showed considerable scatter for $\lambda/L<1$ allowing no meaningful comparison in this range. Close-fit methods generally predicted added resistance better than Lewis form methods, but also tended to over-predict for $1<\lambda/L<2.5$. The transom stern treatment (termination of longitudinal integration just before the transom) was found to be important in computing the hydrodynamic coefficients for this ship with its pronounced transom stern and high speed. Computed hydrodynamic coefficients including end terms agreed well with experiments. Subsequently, motions also agreed better especially around $\lambda/L=2$. For $\lambda/L=2$, non-linear time-domain calculations gave virtually the same results as strip methods. So in this case, non-linear effects play no role as the ship is wall-sided over most of its length.

Various authors have contributed to the development of HSST, e.g. *Ohkusu and Faltinsen (1990), Faltinsen and Zhao (1991a,b). Takaki et al. (1995)* give a summary of the involved equations. In the benchmark test for the Japanese fishing vessel at F_n=0.6, HSST performed best. HSST gave better results than GFM and was twice as fast. The study concludes that for practical purposes, HSST seems to be the best choice for linearized seakeeping. Strip methods were valid only to roughly F_n <0.4. For ships with transom sterns, special treatment of the transom stern is required.