BREAKING BOW AND STERN WAVES: NUMERICAL SIMULATIONS

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Ship-generated waves have always fascinated scientists, and played a key role in surface-ship hydrodynamics for contributing to hull resistance, generating sounds and radiating very long narrow wakes remotely visible. Some of these phenomena originate abeam the ship through extensive breaking of diverging bow and stern waves, forming a wake.

In this paper we summarize and extend our recent research activity aimed to understand the complex fluid dynamics involved in bow- and stern-wave radiation, including wave breaking. The analysis is limited to practical slender ships, with a sharp stem, for which basic insight can be achieved by an approximate quasi three-dimensional model based on the idea that longitudinal gradients of relevant flow quantities are small compared with vertical and transverse gradients. A historical recollection of slender-body theory for ship hydrodynamics is given by Maruo (1989), Tulin and Wu (1996), Fontaine and Tulin (2001).

In this framework, two methods have been developed at the OEL. One based on a potential flow model, where the velocity field is given through the Laplace equation solved by a Boundary Element Method (BEM), and the evolution in time is obtained by integration of free-surface boundary conditions. Specific details of the latest code are documented in Landrini and Colagrossi (2001 a). The method has the advantage of high resolution, sufficient to capture breaking, and to trace jet overturning up to the impact against the underlying free surface.

Post-breaking evolution is studied by a gridless method, called SPH and developed by Monaghan and co-authors (see *e.g.* Monaghan (1988)), which we applied to breaking waves since the previous Workshop. In this case, Euler equations for a weakly compressible fluid have been considered. Further developments led to a code named *SPlasH*, applied to a variety of free-surface problems, and presented in Tulin and Landrini (2000), Colagrossi *et al.* (2000). A detailed description of the algorithm is given in Landrini *et al.* (2001 b)

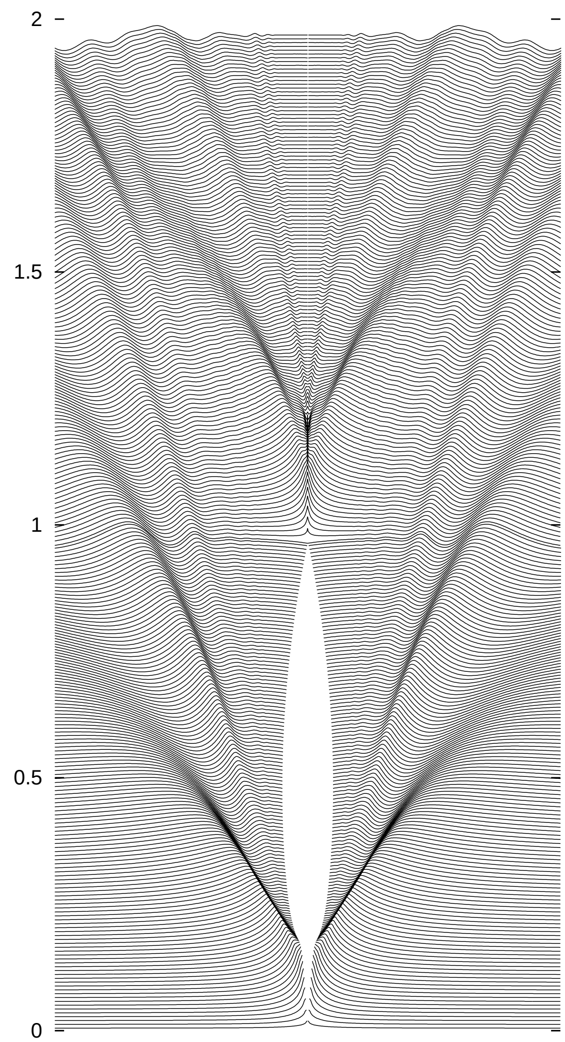

Figure 1. Wave pattern around a Wigley hull ($B/L = 0{\cdot}1$, $D/L = 0.1$, $\mathrm{Fr} = 0{\cdot}1$) by 2D$+t$ (BEM) computations.

The global picture by BEM In the 2D$+t$ method, calculations are carried out in two dimensions, vertical and transverse to the ship, and successively in time. Fig. 1 shows the three-dimensional steady wave pattern around a Wigley hull reconstructed by collecting successive free-surface configurations.

Two key features of the flow are evidenced: first, the system of diverging waves radiated at the bow as a result of the collapse of the "splash", and second the "rooster tail" due to the gravity rebound of the free surface just past the stern which, in turn, is the source of another system of diverging waves.

A thorough analysis of the genesis of diverging bow waves is given by Tulin and Wu (1996). The collapse of

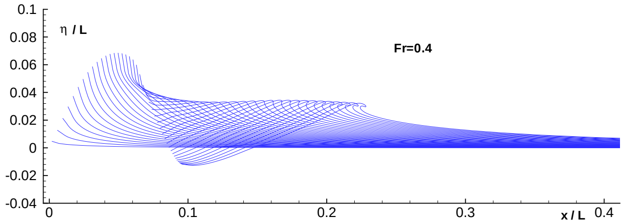

Figure 2. Evolution of the splash at the bow of a Wigley hull $(B/L = 0{\cdot}2,\ D/L = 0{\cdot}1,\ \mathrm{Fr}= U/\sqrt{gL} = 0{\cdot}4)$ by 2D+t (BEM) computations.

splash at the bow is detailed through Fig. 2: the free-surface flow is not much decelerated before the stem, but upon reaching it, is deviated sharply upwards, rises on and eventually levels off and falls down. An entire thin sheet is formed in this process and appears as a splash on either side of the hull. The relaxation of these splashes is the prime source of diverging waves. In the present case, radiated waves are large enough to break, following the typical evolution: crest-rising, front-steepening and jet formation.

Diverging breaking waves can be radiated also by transom sterns. This is shown in the case of a Wigley hull, suitably tapered to have a deep transom stern (*cf.* top-plot in Fig. 3). The computation is performed as in previous cases up to the last section. We then assume that the transom is dry and the potential is continuous across it, this provides the initial conditions for the following free-surface evolution. The resulting wave pattern for $\mathrm{Fr}=U/\sqrt{gL} = 0{\cdot}3$ is shown in the center-plot. Beside the already mentioned bow wave system, here we observe a sharp rooster tail, surrounded by steep breaking diverging waves. The analysis of the flow field shows that the rooster tail is caused by i) the inward motion of the fluid in proximity of the ship associated with the contraction of the hull cross section and eventually colliding after the end of the ship, and ii) the gravity rebound of the free surface. Both features are also detected in the case of Fig. 1, but for a dry transom stern the cavity left in the free surface gives rise to a stronger rebound. The growth of stern waves is better shown in the perspective view in the bottom plot. At first, the free surface move inwards and upwards, creating a sort of triangular hump. Later, the main bulk of fluid starts to collapse down, leaving a thinner and thinner jet, and a couple of steep waves propagating outwards emerge, breaking soon after.

Post-breaking analysis through *SPlasH* In practical cases ship-generated waves break, and further analysis by BEM would require special treatment of the free surface, often unphysical or not practical. The reasons for ship waves to break can be found in ship geometry (bow-flare, transom stern), higher speed of advance, interaction with ambient waves.

The gridless code *SPlasH* has been developed to handle these breaking cases. The evolution of a breaking bore, shown in Fig. 4, gives an idea of the capabilities of the method. The flow is generated by a piston moving horizontally with constant speed. After a while an energetic jet appears, impacting with the underlying free surface and

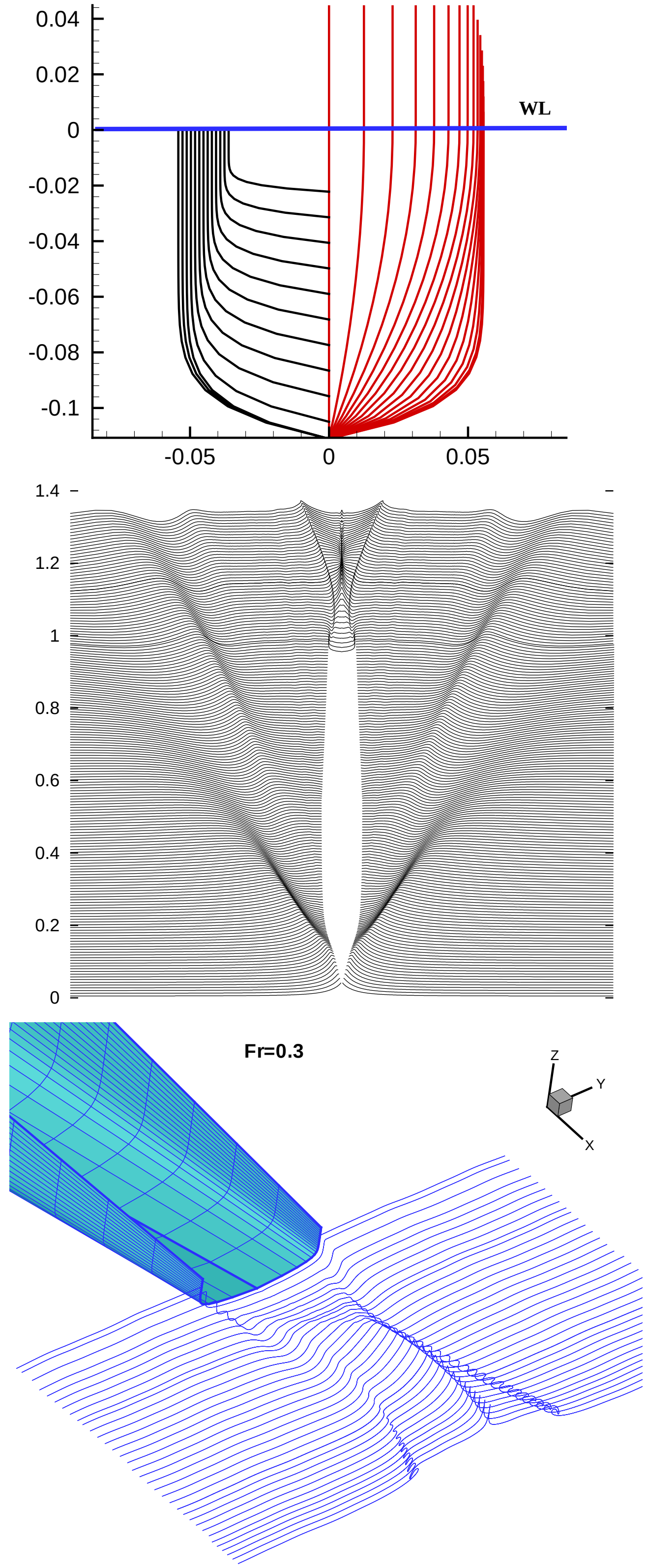

Figure 3. Wave pattern around a modified Wigley hull with a transom stern by 2D+t (BEM) computations. Top: ship cross sections; center: wave pattern; bottom: detail of rooster tail and breaking waves past the stern.

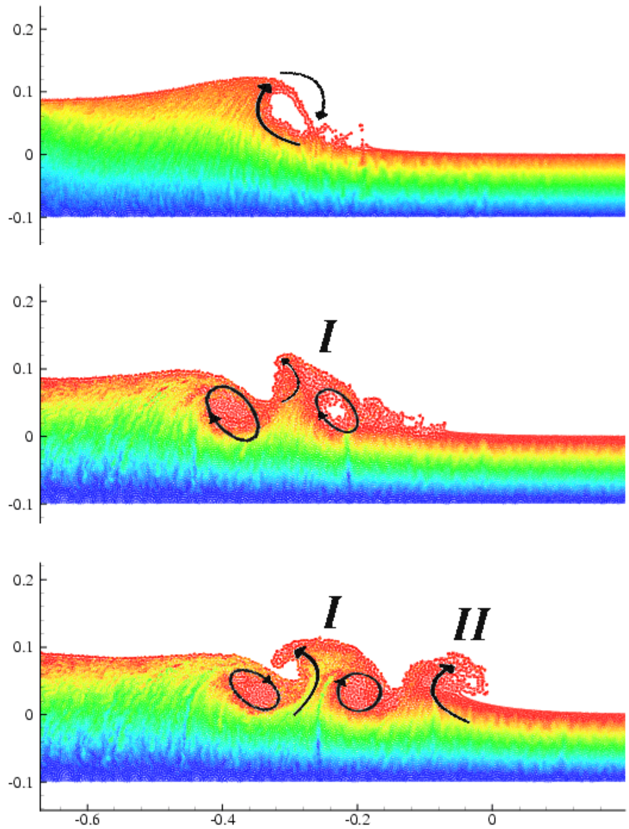

Figure 4. Breaking bore and splash-up cycles forced by a piston moving from left to right in finite depth water. Computations by SPH method.

creating a cavity and therefore circulation (here clockwise). The strong splash-up *I* appears, center-plot, evolving into a counter-rotating vortical structure and another forward splash up *II*, bottom-plot. The strength of the plunging jet is crucial in determining that of the following splash-up and the entire resulting process, which for the breaking bore here considered is characterized by several splash-up cycles, Tulin and Landrini (2000).

We have discovered similar features in breaking ship waves by analyzing pictures of model testing (pictures taken by Penna and Guerra at the INSEAN model basin). In particular, Fig. 5 shows the bow wave generated by a frigate (DDG51-type of the US Navy) with a strong flare. For Fr$=0{\cdot}41$, the splash readily evolves into a plunging jet, creating the splash-up shown in the enlarged detail which reveals also the surface scar associated with the backward facing jet to be compared with the bottom-plot in Fig. 4.

We applied *SPlasH* in a 2D+t fashion to study the post-breaking behavior of ship waves. We first discuss the case of a Wigley hull. The initial evolution has been already shown in Fig. 2 and, in this case, the computations are initialized by those BEM results. This procedure simplified the modeling, increased the efficiency and allowed an optimal resolution of the computation, with a high number of particles clustered into the jet. The three-dimensional wave pattern is reconstructed in Fig. 6, where only the upper layer of particles is represented. Only the portion around the breaking is

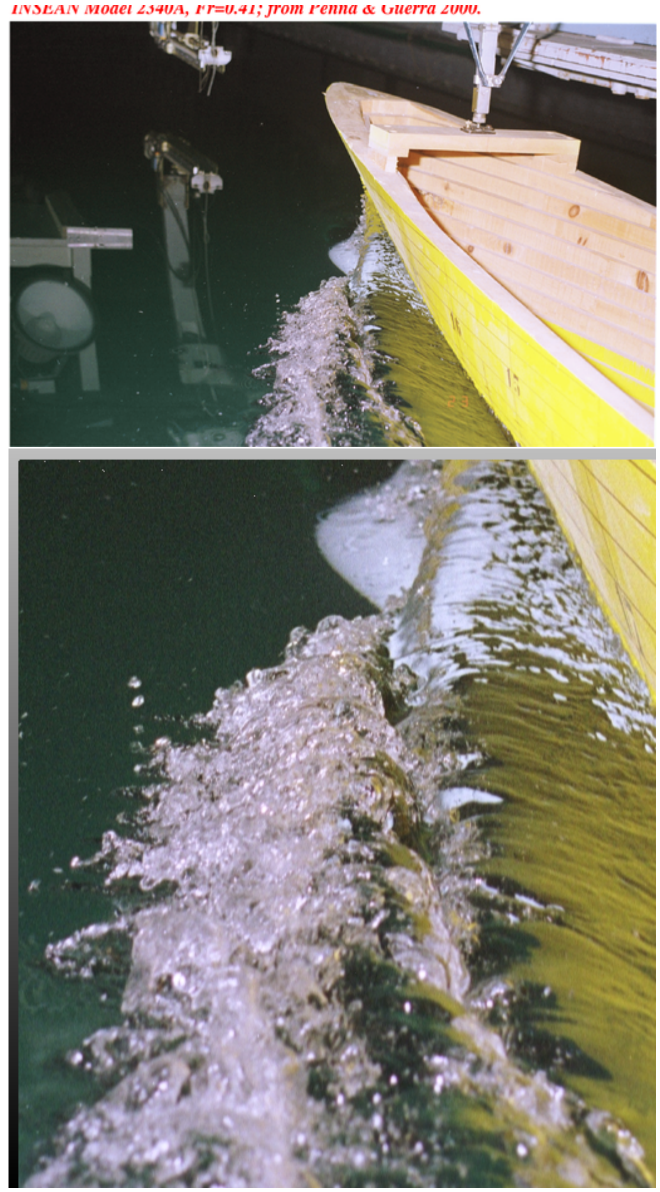

Figure 5. Breaking bow waves in model testing. INSEAN Model 2412 of the US Navy DDG51 (Fr$=0{\cdot}41$).

shown, with the ship center plane located at $y = 0$, and the mid-ship cross section at $x = 0$. The impacting jet generates a splash-up, evolving into i) a vortical structure left behind the crest, and ii) remaining particles riding on the crest emerging after the breaking which resemble the steady eddy used by Cointe and Tulin (1994) to model two-dimensional steady spilling breakers. This flow pattern is better visible in the two-dimensional bottom plot, and is remarkably similar to pictures of (two-dimensional) breaking waves shown in Melville (1996).

On this ground, in breaking ship-wave patterns, we can distinguish a TYPE I breaking, resulting from less energetic breaking waves, and resembling the steady spilling breaking observed *e.g.* past hydrofoils at small incidence, and a TYPE II breaking, with strong (possibly multiple) splash-up, causing larger air entrapment and vortex generation.

TYPE II breaking is (usually) generated at the bow of

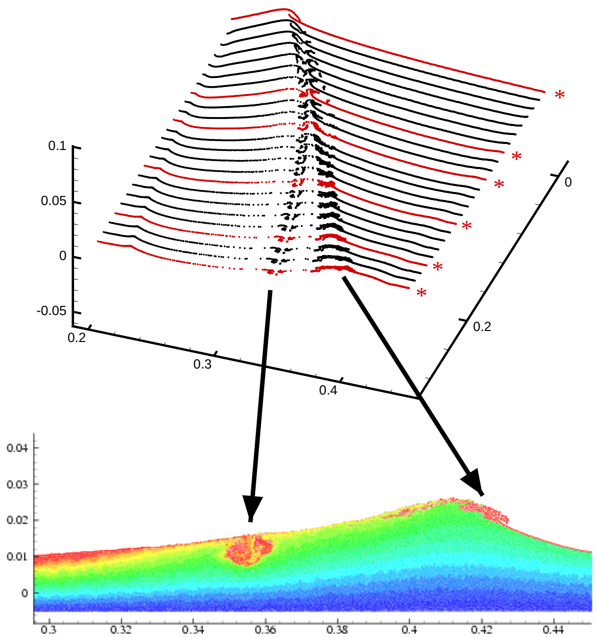

Figure 6. Top: perspective view of 2D+t computation by *SPlasH* of the wave pattern generated by a Wigley hull ($B/L = 0{\cdot}2$, $D/L = 0{\cdot}1$, Fr$= 0{\cdot}46$); bottom: two-dimensional view of late evolution.

ships with pronounced flare, and the numerical simulation by SPH requires the modeling of arbitrary curved boundaries. This extension of *SPlasH* has been recently accomplished by generalizing the concept of ”ghost particles”, and a preliminary result is given in Fig. 7 for a frigate-type ship (used by O’dea and Walden in their analysis of deck wetness). The flare is less pronounced than in Model 2412, and the collapse of the splash, top plot, causes a weaker breaking than that observed in Fig. 5. The resulting three-dimensional wave pattern is reconstructed in the bottom plot.

Results for Model 2412 and for the post-breaking evolution of stern waves will be discussed at the Workshop.

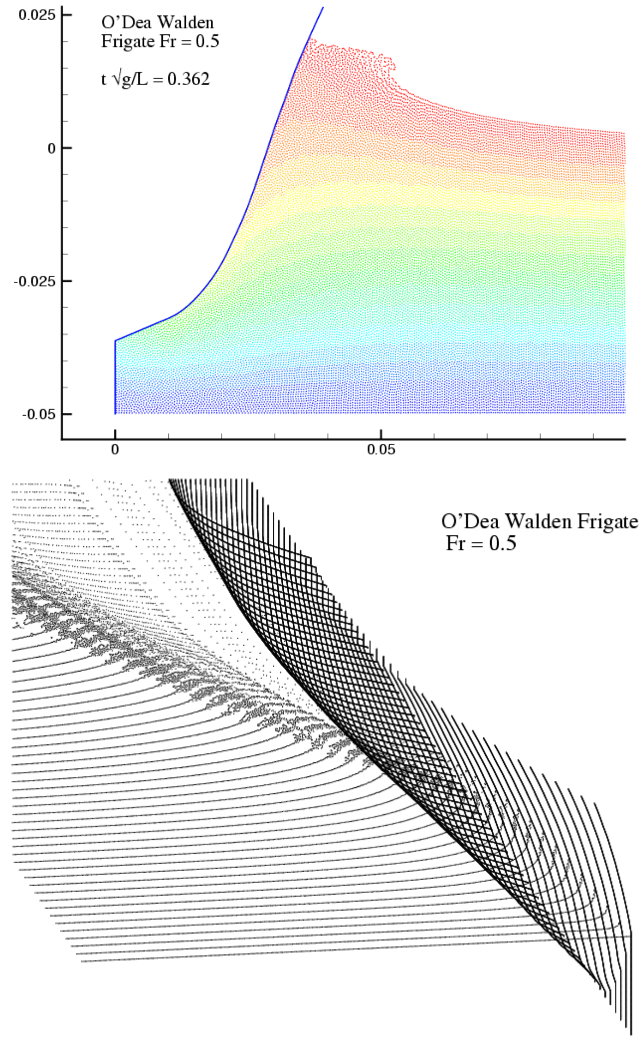

Figure 7. 2D+t computation by *SPlasH* of wave pattern around a frigate. Top: the collapsing splash at the bow; bottom: perspective view of the resulting wave pattern.

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