WAKE WASH OF HIGH-SPEED CRAFT IN COASTAL AREAS

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Abstract

In recent years fast ferries have been introduced on many ferry routes throughout the world. Particularly when operating in shallow waters and near the coast, the waves generated by these ferries give rise to conflicts with recreational use of beaches and coastal waters. Also the potential coastal erosion caused by a changed wave impact has been a matter of concern. The paper presents the results of studies carried out with the objective of providing an unbiased description of these wave phenomena, which has served as basis for a new legislation for regulation of fast ferry operation. The coastal erosion potential was studied and sediment transport simulations showed that the long-periodic ship-generated waves give rise to beach accretion and steepening of the cross-shore profile.

Introduction

It is known that the waves generated by high-speed craft (HSC) in shallow water are substantially different from the waves generated by conventional ships as a consequence of the higher speed and the size of these modern vessels. This results in different wave impact – also denoted wake wash – in coastal areas. It has been observed that HSC operating in the transcritical and supercritical speed range generate diverging waves in groups of both long-periodic and short-periodic waves. This paper primarily describes the long-periodic wave behaviour. Even though these waves are transient, they are similar to swell and thus may cause changes to beaches in areas not usually exposed to swell or severe local seas. Also the safety of nearshore recreational boaters may be reduced and

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the long waves may increase the risk for people bathing and fishing as the long-periodic waves reach the shore without warning.

Several HSC in the form of catamaran and monohull fast ferries have been introduced on ferry routes in Denmark. Due to the shallow waters conditions in Danish waters the wave effects along the coast were immediately recognized and received much attention. Similar experience has been found in a number of other countries, eg UK, Ireland, USA and New Zealand.

The paper present results and analysis of recent full-scale wake wash measurements from a few of these Danish ferry routes. The measurements have been supplemented by wave propagation modelling in order to develop methods to predict the areas of particular concern. These prediction methods are required in connection with planning of new ferry routes or alteration of present routes to obey new Danish regulation concerning fast ferry operation.

The results of the wake wash studies were included in a report by the Danish Maritime Authority (1997) together with other studies on the effect on the external environment, including noise, emissions, impact on birds and marine life and marine safety.

Wave Generation by High-Speed Craft

When a ship moves through the water, it makes waves and suffers wave resistance. Typically, an advancing ship generates a set of waves at both its bow and stern as a consequence of pressure gradients along the hull. For a ship moving steadily in water of uniform finite depth, the nature of the wash which it creates will closely depend upon two non-dimensionless parameters; the length-based Froude number, $F_{nl}= V_s/\sqrt{gL_w}$, and the depth-based Froude number, $F_{nh}= V_s/\sqrt{gh}$. Here, V_s is the ship speed, g is the acceleration due to gravity, L_w is a characteristic length of the ship and h denotes the water depth.

In the subcritical speed range (ie $F_{nh} < 0.6$-0.7), the wave system consists of diverging and transverse waves in a restricted wedge-shaped Kelvin wake, where the cusp angle is about $\pm 19.5°$ and almost independent of the ship speed, see eg Kostyukov (1959) and Newman (1977). In this speed range, the wave period of the diverging waves is proportional to the ship speed ($T \approx 0.27 V_s$, V_s in knots). For depth-Froude numbers beyond 1 (supercritical speed range), the transverse waves disappear and the wave system is characterised by a Havelock-like wave pattern taken a convex form as illustrated in the aerial photograph shown in Figure 1. This is typically the case for HSC operating in coastal water. The divergent waves are now contained within an angle that depends on the speed of the ship. In the transcritical speed range ($F_{nh} \sim 0.9$-1.1), transverse and divergent waves merge together into wave fronts nearly straight and perpendicular to the ship's course. High-amplitude waves are typically generated for speeds in this speed range. If also $F_{nl} \sim 0.5$, ie in the vicinity of the primary hump, where maximum wave resistance occurs, particularly high waves can be generated.

Figure 1. Aerial photograph of wave pattern generated at supercritical speed. The vessel speed is V_s= 35 knots and the water depth is h= 13-14 m. The Froude numbers are F_{nh} ~ 1.5 and F_{nl} ~ 0.7. The overall length of the catamaran is approximately 78 m.

Even though a considerable amount of theoretical and experimental research effort has been devoted to HSC operating within the transcritical and supercritical speed range, particularly in shallow water channels (eg Johnson, 1958), yet no simple methods exist for ship wave prediction similar to Sorensen and Weggel (1986), see also Weggel and Sorensen (1984). These are only applicable for subcritical ship speeds.

Full-scale Measurements

A number of comprehensive full-scale measurement programmes have recently been carried out at various locations in Denmark and abroad (eg Kalundborg Fjord, Lindholm Dyb, Tunø Harbour and Odden Ferry Terminal, Denmark, and in Derwent River and Norfolk Bay, Tasmania). One of the objectives was to evaluate the consequences of wake wash from high-speed ferries as well as for route planning in order to reduce environmental impacts. The measurement programmes covered various navigation conditions for the involved catamarans, which have a service speed of 35-45 knots. Also wake wash caused by conventional ferries having a service speed of about 17 knots was measured. The ship-generated waves were measured at various water depths (2 m to 25 m) and at various distances to the navigation track. A few results of the comprehensive measurement campaigns carried out in Kalundborg Fjord are presented and discussed in Kofoed-Hansen and Mikkelsen (1997), see also Kofoed-Hansen and Kirkegaard (1996) and Kirkegaard et al (1998).

Wave generation

The measurements show that a catamaran advancing with a supercritical speed generally generates a wave system characterised by groups of both short-periodic and long-periodic waves as illustrated in the time series of surface elevation shown in Figure 2a (F_{nh} ~ 1.39, F_{nl} ~ 0.74). It is seen that the long waves have periods in the range of 7-9 s and the short waves 2-4 s. Figure 2b shows that in the subcritical speed range (F_{nh} ~ 0.66, F_{nl} ~ 0.34), the wave period is approximately 5 s, which is in reasonable agreement with Kelvin's classical theory. For a ship speed near the critical speed (F_{nh} ~ 0.93, F_{nl} ~ 0.47), the generated long-periodic waves are high as expected. From Figure 2c, it is seen that the maximum wave height is approximately H_{max} ~ 1.3 m.

In Figure 3, the relationship between the measured maximum wave height of the long-periodic wave component (T> 5s) and the depth-Froude number is depicted. A realistic trend line is also indicated. All measured data have been adjusted so they correspond to a distance of approximately 700 m (~ 10 ship-lengths) from the navigation track using the trend line shown in Figure 4. Although the scatter of the data is relatively high, it is seen that the highest waves appear in the transcritical speed range. The critical Froude number is slightly smaller than the theoretical value of one, which is in agreement with experience from model tests and CFD calculations. For supercritical speeds, it is also seen that the wave height is less than in deep water (ie subcritical speed). The reason for this is a lower pressure due to an increased particle velocity between the ship hull and the seabed.

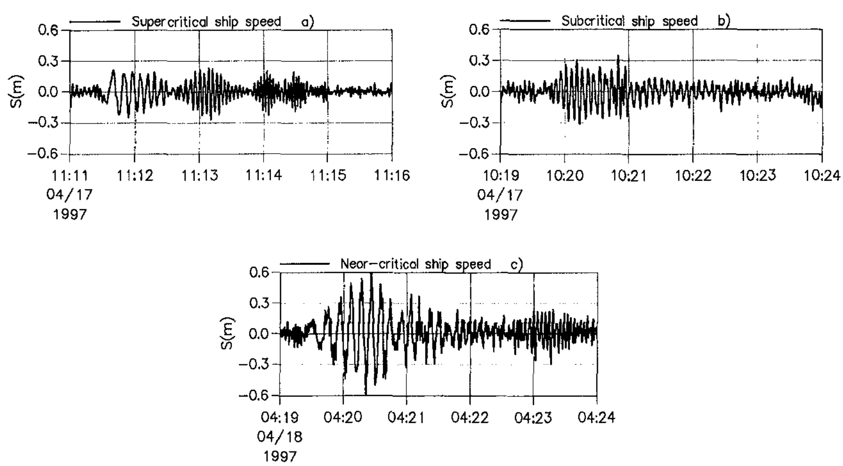


Figure 2. Time series of measured surface elevation generated by a HSC catamaran at Lindholm Dyb, Denmark. a) supercritical speed ($V_s \approx$ 36 knots, $h \approx$ 18 m, $F_{nh} \approx$ 1.39, $F_{nl} \approx$ 0.74), b) subcritical speed ($V_s \approx$ 17 knots, $h \approx$ 18 m, $F_{nh} \approx$ 0.66, $F_{nl} \approx$ 0.34), c) near-critical speed ($V_s \approx$ 24 knots, $h \approx$ 18 m, $F_{nh} \approx$ 0.93, $F_{nl} \approx$ 0.47). The distance between the measurement buoy and the navigation track was approximately 300-400 m.

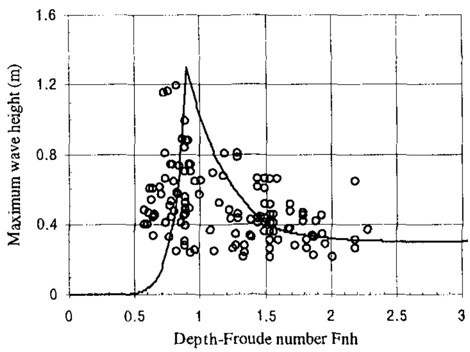


Figure 3. Maximum wave height of the long-periodic waves versus the depth-Froude number. The measured data (ooo) have been corrected to be valid in a distance of 700 m (~ 10 ship lengths) from the ship track. (—) indicates a trend line.

The influence of the distance from the navigation route on the maximum zero-crossing wave height, ie the wave decay due to diffraction, is illustrated in Figure 4. The figure shows the maximum wave height versus the perpendicular distance between the ship track and the Waverider buoy. The data are not affected by shoaling and refraction effects as the water depth is in the range of 10-30 m. It is seen that the wave decay is exponential, which is in agreement with Crapper (1984), page 125.

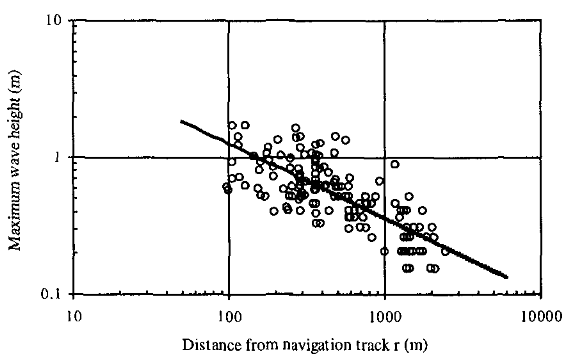


Figure 4. Maximum wave height of the long-periodic waves versus the distance from the ship track. The measured data (ooo) have been based on various field campaigns involving catamarans only. The trend line (—) is given by $H_{max}= 16r^{-0.55}$, where r (in meters) denotes the distance from the track.

Usually ship-generated waves are assumed to be caused by the ship hull alone, and the wave formation from the propulsion system is neglected. Based on a number of recent model tests, however, Taatø et al (1998) concluded that the propulsion system on large HSC (water jets) may cause increased wave heights of 20-40 per cent compared to the bare hull.

Wave propagation and transformation

The wave height, and to some extent, the wave period change during the wave propagation due to diffraction of the short-crested waves as well as to nonlinear wave interactions and wave breaking. When the long-periodic transient waves reach shallow water, the nonlinear shoaling results in rapid growth of the waves which ultimately break, typically as plunging breaker, and may cause transient run-up on the beach.

The photographs shown in Figures 5 and 6 illustrate an example of an HSC-generated wave pattern under propagation towards the coast.

Figure 5. Photograph of wave pattern generated by a mono-hull fast ferry at Hundested, Denmark.

Figure 6. Photograph of a plunging breaker east to Gedser Harbour, Denmark. A monohull fast ferry generated the wash.

Figure 7 shows two time series of wake wash measured at 2-3 m water depth. The wave train shown on the left panel was caused by a passing HSC with its service speed, and the right panel shows the wake wash caused by the same HSC operated in the transcritical speed range. It clearly illustrates that very large transient waves may occur in shallow water without any warning and cause transient currents and run-up. The consequence of this type of wave impact is discussed in the next section.

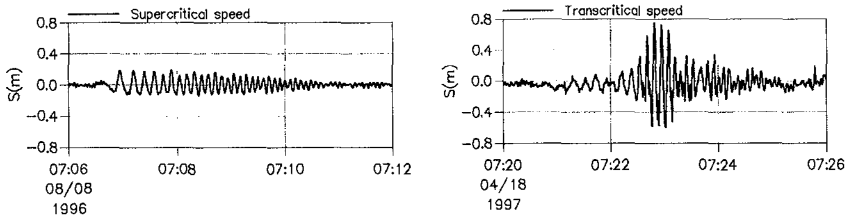


Figure 7. Time series of measured surface elevation in shallow water. Left panel shows the wake wash caused by an HSC operating in the supercritical speed range and the right panel for a transcritical speed. The water depth and distance to the navigation track are 2.4 m and 1500 m (left panel) and 3.2 m and 1100 m (right panel).

Sediment Transport and Coastal Impact

As the waves approach the coastline, changes in wave shape, size and direction occur due to transformation mechanisms such as refraction, shoaling and breaking. Mass transport in the direction of wave propagation occurs due to the wave orbital motion and the surface rollers in the breaker zone. If the bed shear forces generated by the wave orbital motion exceed a critical value, transport of bed sediments is initiated.

Long-shore sediment transport

Oblique incident natural waves give rise to littoral currents in the surf zone driven by the radiation stress gradient. For ship-generated waves, the long-shore current is not established due to the short duration of the wave event. The usual large run-up of the ship waves, however, may give rise to a long-shore sediment transport in the swash zone due to the zigzag motion of the water and sediment particles. Under natural conditions, the bulk of the littoral transport occurs in the surf zone. The long-shore component of the sediment transport in the swash zone is small compared to the transport in the surf zone Elfrink (1997).

Cross–shore sediment transport

In natural waves the mass transport perpendicular to the coast is balanced by means of a return current driven by the sloping water surface, the wave set-up. The vertical distribution of the shear stress under breaking and non-breaking waves was analysed by Deigaard and Fredsøe (1989) and Deigaard (1993).

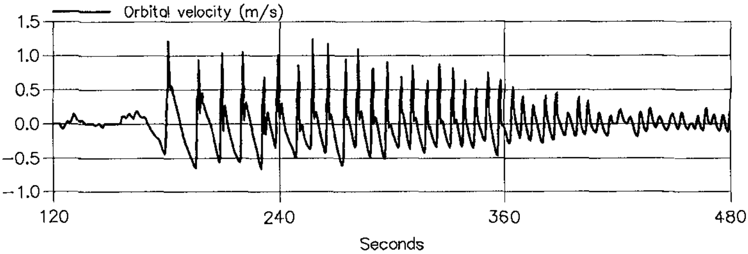
In ship-generated waves the balance between onshore directed flow due to the mass transport and offshore directed flow due the sloping water surface is not established due to the relative short duration of the wave event. The mass transport occurs during the passing of breaking waves, the return flow occurs later. The response time depends on the distance from the shoreline. The result is that onshore velocities occur over the entire water column during the wave event. Offshore-directed velocities, to balance the net drift occur later after the passage of the wave train. During the passage of the wave train, the level of turbulence and the suspended sediment concentrations are higher than during the return flow period. Therefore a net onshore transport of sediment occurs.

In order to illustrate the sediment transport mechanisms, a number of simulations were performed with the model presented in Elfrink et al (1996). The model was specially customised in order to account for the non-equilibrium conditions with regard to the turbulence levels, the mean flow, and the suspended sediment concentrations. The time series of water surface elevation shown in Figure 7 (left panel) was used as boundary conditions. The wave transformation on a beach slope of 1:50 was simulated with a wave model based on the Boussinesq type equations presented in Madsen et al (1997). Figure 8 shows the simulated wave orbital velocity (upper panel) at a water depth of 0.65 m. At this water depth the waves are fully breaking. The calculated instantaneous sediment flux is also shown in Figure 8 (lower panel). It is noticed that the highest sediment fluxes occur under the wave crests and that the resulting sediment transport is directed onshore (positive values).

Coastal Impact

The run-up height is higher for the long-periodic ship-generated waves than for natural wind waves with the same height. Thus, the swash zone of the beach will become wider and higher due to the ship waves caused by HSC.

The simulations showed an increasing onshore sediment transport rate towards the shore. This gives rise to a tendency of steepening of the cross-shore beach profile and sediment accumulation in the run-up zone. If the total amount of wave energy originating from the ship-generated waves is of the same order of magnitude as the energy from natural waves, this can lead to permanent changes in the cross-shore profile. The profile-steepening is counteracted by the natural waves. If the wave conditions are dominated by natural waves, the impact of the ship-generated waves on the cross-shore profile is negligible.



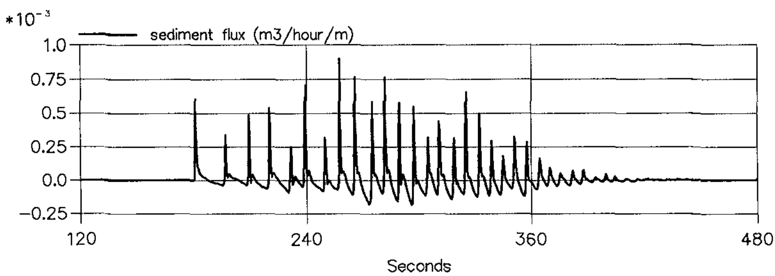


Figure 8. Time series of simulated wave orbital velocity (upper panel) and sediment flux (lower panel) caused by waves generated by a HSC. The water depth is 0.65 m.

Criteria of Acceptable Wake Wash

To ensure safe navigation of small craft in shallow water and leisure activity the Danish Maritime Authority has per May 1997 issued a governmental order that requires the HSC owner/operator to document that the ship-generated waves do not exceed a prescribed criterion along the entire route. The wake wash criterion is presently formulated as

$$H_h \leq 0.5\sqrt{\frac{4.5}{T_h}} \tag{1}$$

where H_h is the maximum wave height (in meters) of the long-periodic waves having a mean wave period of T_h (in seconds). The criterion is applicable at a still water depth of 3 m. Assuming that the mean wave period of the long-periodic waves is approximately 9 s at 3 m of water depth, the criterion gives H_h= 0.35 m. The background for this criterion is briefly described below, see also Kofoed-Hansen and Kirkegaard (1996).

Despite the fact that wash generated by HSC is substantially different from wash caused by conventional ships and ferries, the choice of criterion of acceptability must reflect a connection between these two types of wash, where the latter is generally accepted by the public. Characteristic measures such as wave energy, maximum wave height prior to breaking and wave run-up on the coast have been used tentatively in the formulation of a criterion. A criterion based on the maximum wave height immediately before breaking was originally suggested as the most reasonable choice because it is directly connected to public's experience at sea.

Based on analysis of experimental data, the original criterion was formulated as

$$H_{HSC} \leq \beta_b^{3/2} \sqrt{\frac{T_c}{T_{HSC}}} H_c \qquad (2)$$

which is applicable at about 3 m of water depth and for wave periods longer than 4-5 s. H indicates a maximum wave height at 3 m of water depth and T the related wave period. Index HSC refers to a High-Speed Craft, whereas index c refers to a conventional ferry. The decision parameter, β_b, is indicated in the equation $H_{b,HSC}= \beta_b H_{b,c}$, where H_b is the wave height immediately before breaking. The criterion in Eq. (1) appears immediately by setting $\beta_b = 1$, $H_c= 0.5$ m and $T_c= 4.5$ s, which may be taken as very rough estimate of wash caused by a conventional ferry (in Kalundborg Fjord, Denmark) at a distance of 1-2 km from the track. It should be mentioned that the criterion does not state how the wake wash will break on the coast. Even though the wave height is less than the above-mentioned limit at 3 m of water depth, the wave height can be considerably higher in water depths less than 3 m due to the shoaling.

Legislation, Regulation and Approval

The conflicts between the ferries on the one side and environmental and recreational interests on the other have prompted the Danish authorities to impose certain restrictions on the operation of HSC. With this objective the Environmental, Coastal and Maritime Authorities introduced new legislation in 1997. The legislation relates to environmental protection of the marine environment, coastal protection and safe navigation and take into account waves but also noise, emissions and disturbance of marine life.

It is now required that a shipping company shall obtain approval from the authorities before it establishes a high-speed ferry route operating on a Danish port or puts a new high-speed ferry into service on an existing route. With respect to wave impact, the shipping company shall document that the ferry on the proposed route does not exceed the wave height criterion described above.

Prediction of wake wash in coastal areas

A numerical model capable of calculating ship-generated waves, wave propagation and wave transformation in non-homogeneous media is the ultimate tool when new regulations and approval procedures are introduced for HSC. Today's CFD methods are used to compute the wave field around ships advancing in deep or shallow water, but the wave propagation and transformation towards a coastline are seldom not considered, see Larsson (1997). Time-domain models based on depth-integrated Boussinesq type equations, eg Madsen and Sørensen (1990), can be justified for practical purposes in shallow water. As for conventional CFD models, the computational effort may be huge for large domain areas why approximate and efficient methods are needed in practice.

Based on the knowledge of the waves generated along the route, the ship-generated wave climate in larger coastal and shallow water regions can be assessed using a phase-averaged model describing the most important physical processes (including wave decay) the waves are undergoing during their propagation and transformation. An example of a model output is illustrated in Figure 9 showing the computed maximum wave height and the wave directions. The HSC is navigating along the edge of the model in direction of the arrow. The figure shows distinctive focusing of wave energy in a number of areas, which is in agreement with field observations on the site. Even though such types of models neglect the transient effect of the wash, they are extremely helpful in eg route planning of new and existing HSC routes.

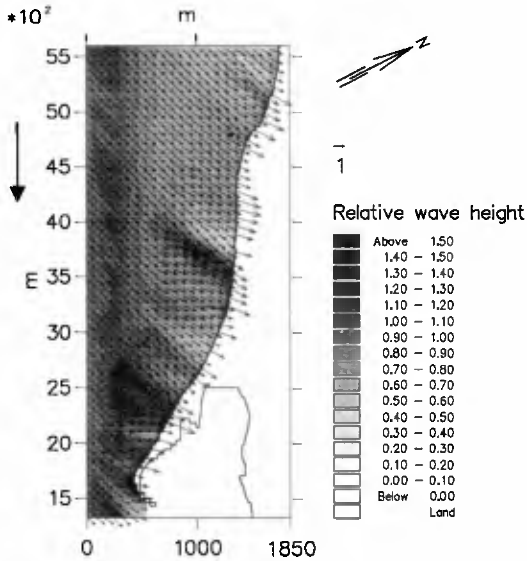


Figure 9. Wave propagation and transformation in Kalundborg Fjord, Denmark. The contour values show the relative wave height defined as the local wave height divided by the wave height at the boundary (the navigation route). The direction of the arrows indicates the wave propagation direction.

Conclusions

Wake wash generated by HSC is markedly different from waves from conventional ships. Wave measuring programs have demonstrated that HSC generates diverging wave patterns consisting of groups of long-period waves and short-periodic waves. The long waves from large car-carrying fast ferries are typically of more than 9 s wave period. These waves have a relatively larger wave height growth during shoaling and wave refraction caused by sea floor irregularities appears in deeper water. The result is that the waves when reaching the shore may cause higher breaking waves and larger run-up than traditional ship waves and the breakers are more often plunging. The waves will arrive faster than ordinary Kelvin waves and particularly during calm whether conditions, people on the beach will not be prepared for a breaking wave appearing without any warning. This is a main reason for the public concern over wake wash from HSC.

The full-scale measurements have also confirmed the significance of the vessel speed versus water depth, expressed in the depth-based Froude number. When operating at near the critical Froude number (~ 1.0), the wave generation is maximum. HSC will operate at critical speed during acceleration and deceleration and due to depth variations several times during transit. It is important that passage of critical speed is carefully planned in order not to coincide with sensitive coastal areas.

Due to the different wave characteristics and the repeated exposure to groups of long waves some variation of coastal characteristics may be experienced near HSC routes. The effect is mainly a steepening of the beach face and grading of sediments. However, the effects of ordinary storm waves will typically dominate the general coastal development.

The inherent conflict between fast ferry operation and recreational use of Danish coastal waters due to wake wash have to be solved by the authorities. New legislation has been made to cope with this issue and today a shipping company has to demonstrate that wake wash does not exceed certain limits along the route and that the environmental impact is limited.

Acknowledgement

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