ABSTRACT

Passenger transport through the upper Adriatic Sea (namely through the Gulfs of Venice and Trieste), especially during the summer season, is increasing more and more. Reciprocal tourist exchanges between the Italian, Slovenian and Croatian coasts, for fast daily excursions or a daily and fast visit to Venice, are very frequent. The most part of boats used for these connections are monohulls (motorboats), some catamarans and, in the past, hydrofoils.

Slovenian and Croatian coasts are characterized by deep waters, whereas near the Italian coasts and especially when approaching Venice, the water depth decreases. Fast boat navigation in shallow waters generates physical phenomena which increase the wave pattern generation and propagation, increase the boat resistance and changes the boat trim and sinkage. These phenomena generate environmental damages and therefore it is necessary to reduce the boat speed.

The study of fast boat hulls demonstrates that the use of multi hulls reduces the wave pattern generation, both in deep and shallow water, but this reduction depends in most part on the hulls disposition and the boat speed. The use of hydrofoils, which generate a lift force on the hulls, reduces the wave pattern generation and, in some cases, prevents wake wash phenomena.

1 INTRODUCTION

The summer seasons have shown in recent years a good presence of foreign guests at the resort beaches of the Adriatic Sea in Italy, Slovenia and Croatia. Political uncertainties that occur in the Mediterranean countries, especially in North Africa and in the Middle East, induce to believe that this trend will stabilize and strengthen in the coming years. It also promises a good influx of tourists from the cruise ships that dock in the ports of Trieste and Koper; but do not entertain for a period exceeding 24 hours. Both these group of tourists often require organized excursions to locations inland and short cruises to the coastal towns, places of historical or natural importance; among them certainly stands the town of Venice.

Shipping links, aimed mostly for tourists, have been activated by the town of Trieste for years, with links along the Istrian coasts, to the towns of Pula, the island of Brioni, the towns of Rovinj, Portorož, Piran, etc..and in the past were made with the motorboat “Marconi”, recently replaced with a less prestigious drive. During the summer season in all the major centres of the coastal regions of Friuli-Venezia Giulia (Grado, Lignano, Bibione) and Veneto (Caorle, Jesolo, etc..), daily cruises are active to the city of Venice and to the Istrian coastal towns The well known catamaran “Prince of Venice”, of the Company Kompas, runs summer cruises from the Istrian towns on the Slovenian and Croatian coasts to Venice. In the past years regular summer services were made by using the Russian airfoils to connect Trieste and the Istrian coasts.

Maritime links between the Italian coasts and the Slovenian and Croatian are held over distances that vary between 15 and 50 miles (for example between Grado and Portorož and Portorož and Venice). If the paths are made in the Gulf of Trieste, the maximum water depth is about 25 m. If the connection involves the city of Venice, the maximum height of the
bottom can reach 25 m – 30 m. The deepest waters are found along the coasts of Slovenia and Croatia where, already a few miles from the coast the height of the sea reaches 25 m to 30 m and more. Along the Italian coasts the sea depth is more limited and reaches 6 m to 10 m at 5 – 10 miles offshore. The presence of shallow water will greatly influence the hydrodynamic behaviour of fast hulls, whose wave generation and the propulsive power require to reduce the speed.

The tourist service organized for visiting a coastal city is carried out within 24 hours, with departures from 8 to 9 a.m. and return within 20 hours, in time for dinner. During this time the visitor is transported into the resort area to visit places of interest, to go shopping, to refresh and then to return to the origin place. The shorter is the time required for the transfer, the longer is the length of stay.

The journey is also influenced by weather and vessel safety conditions. To these constraints, which are essential for navigation, must be added others that relate to the environment and its preservation. These cover not only emissions and discharges into the sea, but also the generation of anomalous waves by the ship, which proceeds at high speed in shallow water. These waves are spread and discharged into the environment and along the coasts and damage the environment itself. This phenomenon, called “Wake Wash”, is very well known and is particularly acute along the coasts of Veneto region and in the lagoon of Venice, for its harmful effects [7].

2 DEFINITIONS AND WAVE GENERATION

The term “High Speed Vessel” or “High Speed Craft (HSC)” includes a vessel capable of a maximum speed equal or exceeding 3.7 \( V^{0.1667} \) (m/s), where \( V \) (m\(^3\)) is the volume displacement of the vessel at the design waterline. The main features of a HSC must be defined according to the IMO – HSC Code. As regards the environmental impact, a series of investigations have been made to define and establish standards for a safe environmental impact associated to HSC wake in confined waters and are shown in many reports. The principles which define these standards associate the craft speed with the maximum allowed wave height or with the maximum allowed wave energy and the risk assessments; other measures include the inland installation to face up the wake wash effects [1].

The continuation of the treatment requires the establishment of general principles that govern the generation of hull waves in deep or shallow water.

The basic principles date back to Lord Kelvin (1887), who described the wave generated by a moving pressure source (figure 1). As well known, it consists of two wave systems that overlap and are formed by transverse and diverging components and are confined within an apex angle \( \alpha \) of 19.47°. The diverging components propagate at an angle \( \theta \) which ranges between 35° and 90° and are dangerous to the environment; they are also called “propagating or spreading waves”. The transverse components are generated between an angle of 0° to 35°, have a limited propagation in the environment and damp locally; are also called “oscillating waves” and are important because require a lot of energy for their generation. The speed of transverse generated waves, along the track of the vessel, equals the vessel speed. The wave generated length depends from the vessel speed \( V \); for this reason a relation between the wave generated length and the vessel length exists, it depends on the vessel speed \( V \) (m/s) and can be defined through the Froude Length Number \( F_{NL} = V / \sqrt{gL} \), where \( g \) (m/s\(^2\)) is the acceleration of gravity and \( L \) (m) is the vessel length. When \( F_{NL} = 0.4 \) (\( \approx \sqrt{(2 \pi)} \)) in deep water, the wavelength of the transverse wave equals the vessel length. The Kelvin model represents a wave generated by source of pressure, but a vessel wave pattern is generated by a distribution of pressure sources; the stern wave pattern is particularly important, because it creates the wake wash, which propagates in the environment.
Figure 1: Steady state Kelvin wave pattern

Going from deep water to shallow depths, defined by d (m), is more correct to refer to Froude Number $F_{Nd} = V/\sqrt{gd}$ calculated on the depth. It has been shown that the classical wave formation of Kelvin is theoretically accepted up to $F_{Nd} = 0.57$. By increasing $F_{Nd}$, the transverse wave pattern tends to lengthen and the original system changes. The value of $F_{Nd}$ to which significant changes are detected in the wave system corresponds to $F_{Nd} > 0.85$. If the value of $F_{Nd}$ approaches to the unit value, the apex angle $\alpha$ is close to 90° (figure 2) and the wave propagation angle $\theta$ approaches to 0°.

Figure 2: Wave pattern in critical regime

The navigation regime can be characterized by the values of $F_{Nd}$. If $F_{Nd} < 1.0$ the regime will be called subcritical and critical if $F_{Nd} = 1.0$. By increasing the vessel speed at $d = \text{constant}$, the navigation switches from critical to supercritical condition (figure 3); in these conditions the transverse components disappear and remain the diverging components only, i.e. the components of translation. In the supercritical regime the angle of propagation of the first wave generated is given by $\cos \theta = 1/F_{Nd}$. It follows that, by reducing the seabed or increasing the speed, the waves bend towards the advancing direction of the vessel and their direction of propagation tends to be perpendicular to travel itself. For example at $F_{Nd} = 1.5$ the $\theta$ value is 48°, whereas at $F_{Nd} = 2.0$ the angle $\theta = 60°$. It should be noted that $F_{Nd}$ depends both on $V$ and $d$; then the phenomena referred to depend on both parameters.
2.1 Wake wash and wake characteristics

The phenomena of propagation towards the coast of wide and large waves produced by fast boats and the subsequent coast wash is known as the “wake wash”; the waves are generated mainly from the aft parts of the boats.

From research carried out [2] [7] we deduce that there is a direct correlation between the waves of the wake, the residuary resistance of the hull and the wave hull resistance. The residual resistance of a hull is easily measured on physical models and is a hull resistance component which can be evaluated during the design stage of a hull. The wave resistance is caused by the hull wave generation, which damps locally or spreads in the environment, and is the main component of the residuary resistance. The wave resistance is more difficult to measure, because it requires specific instrumentation during the traditional towing tests, but it can be measured also at full scale. Nowadays it can be obtained with good precision also adopting numerical computation programs. The wave resistance can be expressed through the wave resistance coefficient $C_W$ which, in turn, can be decomposed into a residuary ($C_R$) and a form component ($K C_{F0}$, $K$ : Form factor) ($C_W = C_R - K C_{F0}$), or into a potential ($C_{WP}$) and breaking ($C_{WB}$) component ($C_W = C_{WP} + C_{WB}$). The potential component can be calculated with potential programs, but the second component is not easy to obtain and requires the use of numerical computation programs.

When the diverging components leave behind the hulls for the coast, they interfere each other and suffer the effects of shallow water; these phenomena change their amplitudes and phases. In figure 4 is shown a typical record of wash waves, generated by a HSC near the coast, in supercritical conditions, and responsible for the phenomena of wake washing.

Figure 4: Typical wave record of a large HSC at supercritical speed [3]
This record of the waves generated is divided into n. 3 zones, characterized by a different wave period. The condition I of the area is the “wake washing” with waves of long period (T = 8 ÷ 11 sec.) in supercritical sailing conditions; these waves damp very slowly, carrying on shore most of the energy required for their generation. In zone II the waves are characterized by a shorter wave period (T = 4 ÷ 5.5 sec.), measured on fast displacement hulls (or semi-displacement hulls), having appreciable displacement and length, which navigate at subcritical speed (F_{Nd} < 0.9). Their amplitudes are significantly lower than those found in zone I.

In zone III are represented instead the wave formations typical of fast hulls (presumably having lines with large aft transom), characterized by low periods (T ≈ 3 seconds) and steep slopes, which can damage the coastal constructions. Survey similar to those reported in [3] has been performed also in Denmark, in the harbour of New York, in Australia and other countries [4]. The Kelvin model also provides information on the propagation of the generated waves; the water depth plays a significant role in this case.

In deep water wave celerity C is a function of wavelength λ, C = (gλ/2π)_{1/2}, whereas in shallow water the water depth reduces the wave celerity ( C = ((gλ/2π) tgh(2πd/λ))_{1/2}). If depth d>λ/2, a deep water condition can be assumed; but if d<1/20 λ shallow water condition is assumed.

Several methods to represent the wave propagation, limited or unlimited in depth, and taking in account the hull speed and the water depth are used.

2.2 Propagation and transformation of wake wash

Wash waves, once generated, propagate into the surrounding environment with amplitude and direction depending, especially in supercritical conditions, only from F_{Nd}. This property was taken over by T. Havelock in 1908 [5] and can be represented in figure 5.

![Figure 5: Wave propagation angle at sub-critical and super-critical conditions](image)

Besides the main wave, also different components are generated, that form specific, but smaller, angles of propagation with the main component, as shown by T. Whit-taker [3]. In supercritical conditions due to high values of F_{Nd}, the wave components are almost parallel each other; this parallelism is partly lost at the lower values of F_{Nd}. The difference decreases with the normal distance from the route line; the magnitude of this reduction depends on the water depth. In deeper water the wave pattern changes are less pronounced than those that have the same normal distance in shallow water.

The divergent components of higher order have a smaller divergence angle at the same distance from the route, when compared with the main component. The waves generated at a
considerable distance from the stern, tend to arrange themselves parallel to each other, and this applies especially to the humps line. Small changes in the direction of wave propagation leads to an apparent lengthening of the wave pattern. There is therefore a slight increase of the distance between the humps in the wave pattern. Wave formations have been measured with periods longer than 40 seconds at a distance of 2.7 km from the ship [3].

Another noted factor is that the period of waves in the ship wake is no longer dependent on the geometry of the hull, but on the hull speed, on the water depth and on the distance from the generation point. Quite the contrary, the wake wash generated by different hulls have different heights; shorter hulls generate smaller waves, less than those generated by longer hulls, under the same navigation conditions.

The wave generation results also in the transfer to the sea of the energy required for their creation. This energy can be represented by the amplitude spectra, that is through the diagrams that represent the energy distribution of the generated waves, on the basis of their propagation angle $\theta$. The spectrum can be represented through the variation of the coefficient $C_W$, the wave resistance coefficient, as a function of $\theta$. By this way the wave energy dissipation is represented when $\theta$ varies from $0^\circ$ to $39.7^\circ$ for the transverse wave components and when $\theta$ varies between $39.7^\circ$ to $90^\circ$ for the divergent components. During the navigation in shallow water at supercritical speeds the wave energy is concentrated mainly in the second angular range.

In the figures 6A and 6B two typical representations of the wave energy loss of a fast hull, measured in sub-critical and in super-critical range are shown. The area underneath these curves is proportional to the wave pattern resistance. These measurements can be made experimentally in towing tanks, with the techniques of wave cuts (transversal or longitudinal) or can be obtained with specific numerical programs.

The waves produced by the diverging wave components spread fast to the shore. Along the way they propagate and disperse some of their energy, attenuate in amplitude and change their step.

T. Havelock (1908) [5] found that the attenuation of the amplitude is proportional to $y^n$, where $y$ is the distance from the vessel and $n$ is a coefficient equal to (-1/3). Coefficients of different value, ranging between -0.2 and -0.55 have been proposed by other authors, depending on whether the decay is measured far or close to the hull; the indices are higher in absolute value in relief near the hull. It is also important to assess the sea state conditions where the wave propagation takes place; the attenuation in waves can be higher.

When the waves arrive close to the coast or in shallow water areas, there are a number of processes that affect the wave configuration and energy; the most important are the refraction, the diffraction, the shoaling, the wave breaking, the reflection, etc..
2.3 Design criteria to reduce the wake wash and the coastal damages.

After having defined the principles that define the generation and propagation of the wake wash, it is important to find ways to reduce or eliminate the potential environmental damage. Three criteria can be used:

A) Prevent or reduce the wave pattern generation in the wake of the hull;
B) Prevent or reduce the wave propagation towards the coast;
C) Prevent or reduce the damages caused to the bank.

The third criterion concerns mainly the coastal and hydraulic engineers and is achieved by providing adequate protections to the coast.

The first criterion is the most effective and can be implemented either by legislative acts or regulations or by establishing new methods to design the vessels which have to operate along the coastal routes. These measures require:

a) The speed reduction of HSC (High Speed Craft) when approaching the coast;
b) The run on specific routes at a defined speed near the coasts or along canals.

For example some Coast Guard Authorities of the Tyrrhenian harbours established the reduction of the fast ferries speed when these ships approach the coast, by defining the maximum allowed speed and the distance from the coast at which apply these rules.

To be considered dangerous a wake wash, it is first necessary to define the criteria of dangerousness. The criteria that are used most frequently are:

1) The maximum wave height;
2) The highest wave energy.

The application of the first criterion requires the definition, for a specific hull navigating at a fixed speed, of the true heights of the generated waves at specific distances from the hull itself. These heights can be measured at full scale or on models or can be calculated by using numerical programs. In figure 7A is sketched a typical representation of a measured wave generated by a boat.

T. Havelock [5] expressed the maximum wave height in the form: \( H_m = \gamma \gamma^{1/3} \).

This can be used to derive the wave height at the point of impact. The \( \gamma \) value can be derived either from statistical data obtained on similar hulls, or from experimental data obtained by measuring the wave heights at different distances from the hull itself in navigation, or by measuring the wave heights on a model on a wide experimental basin. From these results a curve can be obtained as an envelope of the experimental data, representing the evolution of wave heights at different distances from the hull (figure 7B). The value obtained for \( H_m \), on a specific location along the coast, must be less than the maximum allowed in the environment affected by the wake wash.
Examining the Northern Adriatic, the area most certainly affected by these issues is the town of Venice. In this city were made in the past many studies and research to reduce the degradation generated by the waves and, to this end, it was determined that the maximum wave height that could be generated in the Great Canal was 100 mm.

Similar criteria were adopted in England, for navigation on Thames, in Denmark and other countries.

The second criterion (2) imposes a limit to the energy spread from waves. Starting from the definition of a wave energy, given by: 
\[
E = \rho g^2 H_m^2 T_m^2 / 16\pi
\]
(\(T_m\): Wave period; \(H_m\): Wave height; \(\rho\): Water density; \(g\): Acceleration of gravity), it is noted that E depends on the square of the period and height of the detected wave. This second criterion was used to define the maximum energy rate on the rivers of Australia and along the routes from Tasmania and Australia [4].

A principle to reduce the generated wake wash is certainly that to design a hull to be used on a fixed route at specific speeds. Then the most appropriate hull lines will be designed, to reduce the generated wave. This criterion is that used on mono-hulls, but frequently non specifically designed commercial boats are used, especially on routes of major touristic attraction. The performance of these hulls will not be optimal for the purpose of protecting the environment, even if their general performance is good.

Research and progress in the shipbuilding industry have shown that, in the field of high speeds, good performance can be obtained from the multi-hulls. In fact the waves are generated by the pressure fields that are created in the water surrounding the hull with the ship running. The greater the volume of the hull advancing at higher speed, the greater the wave pattern generated. Dividing the original volume of the hull in two or more smaller hulls, the pressure field generated by each hull and the consequent wave pattern is reduced. In the multi-hulls and especially in the catamarans, there are effects of mutual interference between the pressure fields, and hence the consequent wave train can be larger. Generally at very low speeds or at very high speeds the interference phenomena are positive, i.e. the wave generated by the multi-hull is lower than the sum of the components created by the single hulls. Also the hull lines of the catamarans are very sensitive to the effects of the waves generated; using hull lines that require the swelling of the hull lines of the internal channel, increases the resistance of the catamaran, but the propagation of waves in the external environmental is extremely contained. The opposite happens if the mono-hull lines are more “swollen” to the outside. It follows that the hull lines of a catamaran can be designed with environmental goal, requiring more power for its propulsion, or by reducing its resistance, but generating more waves into the environment.

A particular class of hulls designed for high speed and low environmental impact are those of the hydrofoils. In fact, at high speed, profiles rise the hull out of the water, avoiding the generation of waves. The waves generated by the deep profiles and supports are well below those of the central hull when navigating in displacement conditions. These HSC are more expensive, do not have high seakeeping qualities at high speeds and for this reason their use is very limited.

2.4 The impact of the international regulation

The international regulation governing the construction and behaviour of fast hulls is defined by the IMO 2000 HSC Code and its amendments. The sub-Committee on Ship Design and Equipment, in the 51-th session of 2007 [6] outlined the guidelines for uniform operational limitations of High Speed Craft. In particular in Appendix C are highlighted the Risk Assessment in relation to wake wash waves and proposed criteria to make it suitable for a ship to operate in restricted area and shallow water, without environmental damage.
Particularly in these documents will be required the identification of risk which will define the ship’s route, in order to avoid the impact to possible sensitive areas (beaches, marinas, etc.). This problem can be easily defined through the identification of the operational area (figure 8), based on the regimes of wake wash (near sub-critical or super-critical) that are believed to be found along the route.

![Figure 8: Operational zones for the route, defined on the wash regime.](image)

### 3 A LOCAL APPLICATION

One of the craft that are carrying the tourists between the coasts of Slovenia and Croatia and the city of Venice is the catamaran “Prince of Venice”, of the Co. Kompas. (figure 9). The catamaran has a length of 40 m, a breadth of 16m, a G.T. of 146 t and is capable of a travelling speed of 22.2 kn, while maintaining an average speed of 20.9 kn. It performs tourist service between the ports of Poreč, Umag, Rovinj and Pula; the route is normally covered in 2 h 30 min.

Considering a typical route from Umag to Venice, the distance covered up to Punta Sabbioni, at the entrance of the lagoon of Venice, is approximately 45.5 nm., whereas to arrive from Punta Sabbioni to the terminal of San Basilio the distance is 4.5 nm and the boat must limit its speed to 20 km/h or less, when crossing the Giudecca canal.

![Figure 9: Catamaran Prince of Venice](image)

Looking at the bathymetric maps, it is shown that the average water height can be estimated in 23 m, falls to 4 ÷ 6 m. The critical speeds related to depths of 23 m and 18 m are
respectively 29.2 kn and 25.83 kn, values above the maximum speed of “Prince of Venice”; then its sailing conditions are always sub-critical.

From this survey it can be deduced that environmental damages in the North Adriatic sea can be caused at speeds exceeding 30 knots, a value that could be an upper bound for the navigation for the purposes of the environmental safety.

5 CONCLUSIONS

In this problems that occur when navigating with fast craft on narrow and shallow water have been outlined. These problems could also affect the Northern Adriatic Sea whenever new HSC lines, with speeds exceeding 30 knots would be allowed. To these effects the Italian coasts, characterized by lower depths, are most exposed. However, the entry into force of the new IMO regulations relative to HSC should be a safeguard to protect the environment through the establishment of shipping routes, characterized by speed affected by the shallow water.

REFERENCES