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## Some concepts of hydrodynamics and ocean engineering

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## Chapter 3

# Some Concepts of Hydrodynamics and Ocean Engineering

### 3.1. The marine environment

#### 3.1.1. *Ocean waves*

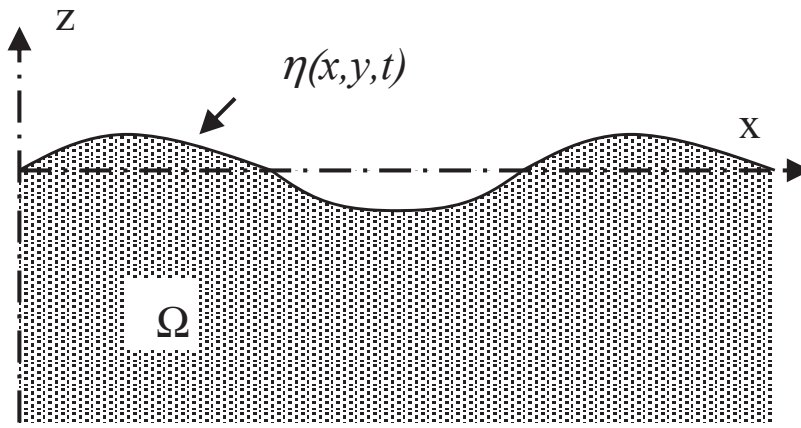
Ocean waves are generated by the effect of the wind on the surface of the ocean. The stronger, longer and further the wind blows, the higher the waves are. One of the particular characteristics of an ocean wave is that it propagates with no loss of energy. Therefore, it can travel long distances before dissipating on the shores.

In order to represent the flow associated with the propagation of ocean waves, we shall be using the framework of an ideal fluid (ignoring the effect of viscosity), and we consider the flow to be incompressible and irrotational. We can then write that the velocity of the fluid  $V$  derives from a potential  $\Phi$ .

$$\vec{V} = \text{grad} \ \phi$$

By combining this equation with the hypothesis of incompressibility, we can show that potential is governed, across the whole of the fluid domain, by Laplace's equation:

$$\Delta \phi (M, t) = 0 \quad \forall M \in \Omega$$



**Figure 3.1.** Definition of the fluid domain

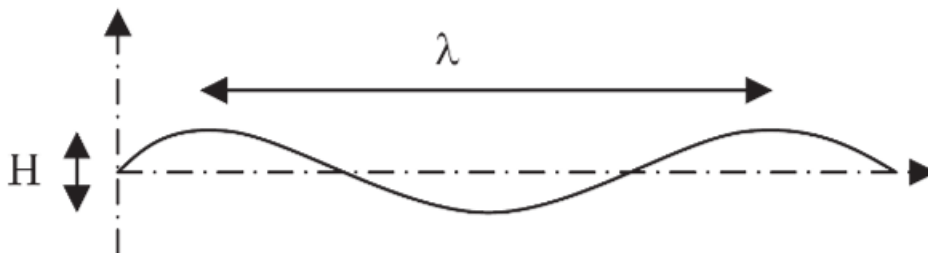
In order to solve the problem, it is also useful to write conditions at the limits of the fluid domain. The most interesting are those which are written at the free surface, the position of which is defined by:

$$z = \eta(x, y, t)$$

These conditions at the limits are:

$$\begin{cases} \frac{\partial \phi}{\partial z} = \frac{\partial \eta}{\partial t} + \frac{\partial \phi}{\partial x} \frac{\partial \eta}{\partial x} + \frac{\partial \phi}{\partial y} \frac{\partial \eta}{\partial y} \\ \eta = -\frac{1}{g} \left( \frac{\partial \phi}{\partial t} + \frac{1}{2} \left| \vec{\text{grad}} \phi \right|^2 \right) \end{cases} \quad z = \eta(x, y, t)$$

The first is the kinematic condition of free surface, which expresses the fact that the free surface is a physical barrier; the second is the dynamic condition of free surface, which expresses the continuity of pressure on either side of the interface (the effects of surface tension being negligible on the scale of ocean waves). In this latter equation,  $g$  is gravity and  $\rho$  is the density of the water.

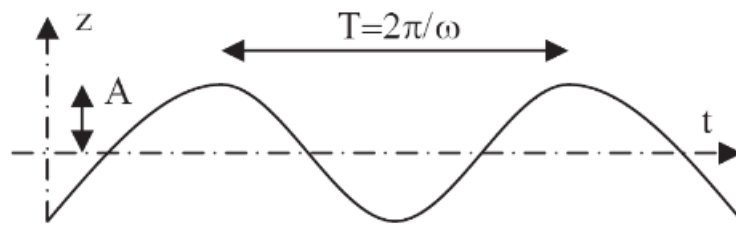


**Figure 3.2.** Definition of wavelength and wave height (trough to crest)

As we can see, the two conditions on the free surface are nonlinear, and it is therefore difficult to go much further analytically using these formulations. However, given that the wave height  $H$  is generally small in relation to the wavelength  $\lambda$ , we can generate a series of disturbances  $\varepsilon = H/\lambda$  of amounts linked to the flow:

$$\begin{cases} \eta = \varepsilon\eta_1 + \varepsilon^2\eta_2 + \dots + \varepsilon^{n-1}\eta_{n-1} + O(\varepsilon^n) \\ \phi = \varepsilon\phi_1 + \varepsilon^2\phi_2 + \dots + \varepsilon^{n-1}\phi_{n-1} + O(\varepsilon^n) \end{cases}$$

This development is called the Stokes development. We call the wave associated with the order of truncation  $n$  Stokes Wave of order  $n$ . If we ignore the effects of order greater than 1, the conditions at the limits are linearized, which allows an analytical solution to the problem to be found using the variable separation method.



**Figure 3.3.** Definition of the (temporal) period and amplitude of a regular wave

Let us consider the particular case of a regular wave (progressive plane monochromatic wave) of pulsation  $\omega$ , amplitude  $A$  (half the trough to crest height  $H$ ) propagating in the direction of the positive  $x$ 's in an environment of infinite depth (1<sup>st</sup> order Stokes wave, also called Airy wave). We can show that its potential is written:

$$\phi(x, y, z, t) = \text{Re}\left(A \frac{ig}{\omega} e^{k(z-ix)} e^{i\omega t}\right)$$

where:

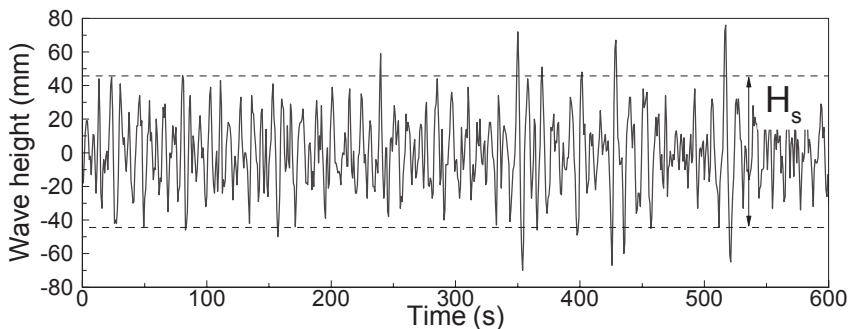
- $g$  is the acceleration due to gravity
- $k$  is the wave number, defined by  $k = 2\pi/\lambda$ , where  $\lambda$  is the wavelength of the wave (typically 100 m).

Note that the free surface conditions imply a relationship between the wave number  $k$  and the pulsation  $\omega$ , called the dispersion relation. In deep water, it is simply written:

$$kg = \omega^2$$

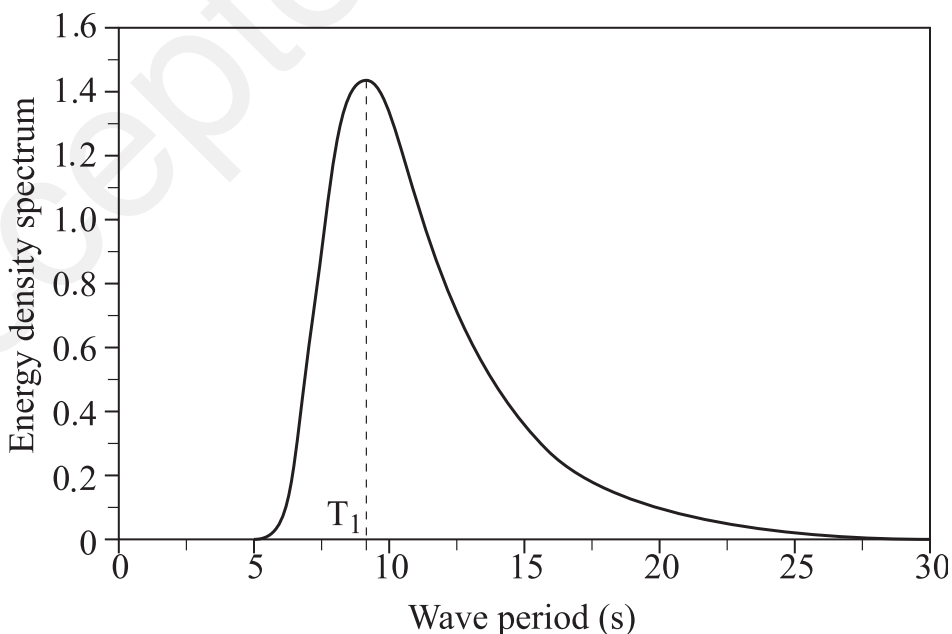
We can therefore see that the wave number (and therefore wave length) depends only on the pulsation of the wave and the acceleration due to gravity. In oceanic engineering, the waves in question have periods of 2-20 s, heights of 0.5-15 m, and wavelengths of 6-600 m.

The Airy wave is a regular (i.e. monochromatic and monodirectional) solution to the problem of the propagation of waves on the surface of the oceans. In practice, ocean waves are irregular; that is, they are multidirectional and multifrequential, and time recordings measured at sea may suggest that they are a perfectly arbitrary phenomenon.



**Figure 3.4.** Time measurements typical of the elevation of the free surface, taken at sea

Fortunately, when dealing with the spectral content of irregular waves, we note that it is relatively steady over periods of about an hour and that, whether for a gentle or a stormy sea, it presents a characteristic shape. This shape can be approximated by a mathematical function, which depends on several statistical parameters, and is called the wave spectrum.



**Figure 3.5.** Example of wave spectrum (Pierson-Moskowitz spectrum)

One of the most widely used mathematical forms is the Pierson-Moskowitz spectrum:

$$S(f) = \frac{5}{16} \frac{H_s^2}{T_1^5 f^5} e^{-\frac{5}{4} \frac{1}{T_1^4 f^4}}$$

It is characterized by only two values, which is advantageous in order to simplify the task of characterizing the sea state:

- the period of the peak of the spectrum  $T_1$ , for which the spectrum is maximum;
- the significant wave height  $H_s$ . This value corresponds to an exact statistical definition, but it is simpler to remember that it also corresponds fairly closely to the height felt by mariners.

The following table gives examples of the typical characteristics of  $H_s$  and  $T_p$  depending on the Beaufort scale.

Beaufort scale	4	5	6	8
$H_s$ (m)	1	2	3	5.5
$T_1$ (s)	6	8	10	14

**Table 3.1.** Typical sea states depending on the Beaufort scale

Finally, let us note that the significant wave height represents an average value of the height of the waves. The height of an individual wave may exceed this value, and it is not uncommon to find waves whose height is more than twice the significant value.

### 3.1.2. Currents and wind

#### 3.1.2.1. Currents

At sea, currents may have different origins. We immediately think of the tide and of the extremely strong currents found around Brittany and the British Isles, for example. However, currents may also be caused by gradients in temperature and/or salinity between masses of water in different parts of the world. The Gulf Stream is an example of this. The currents generated by these gradients may be significant in terms of energy, to the point where devices to harness this energy have been envisaged off the coast of Florida. Finally, let us not forget surface currents generated by the wind: when the wind blows on the surface of the ocean, the

viscous constraints on the interface move the upper layer of the water, and the resulting currents may be up to a meter a second.

Vertically, currents have a complex profile. They vary both in intensity and in direction depending on the height in the water column. They are often modeled using power laws.

### 3.1.2.2. *Wind*

In relation to what it is on land, it is generally accepted that the wind blows stronger and more regularly at sea. In the same way as for the current, it is often modeled using power laws which link the average velocity  $V_{ave}$  of the wind and altitude  $z$ :

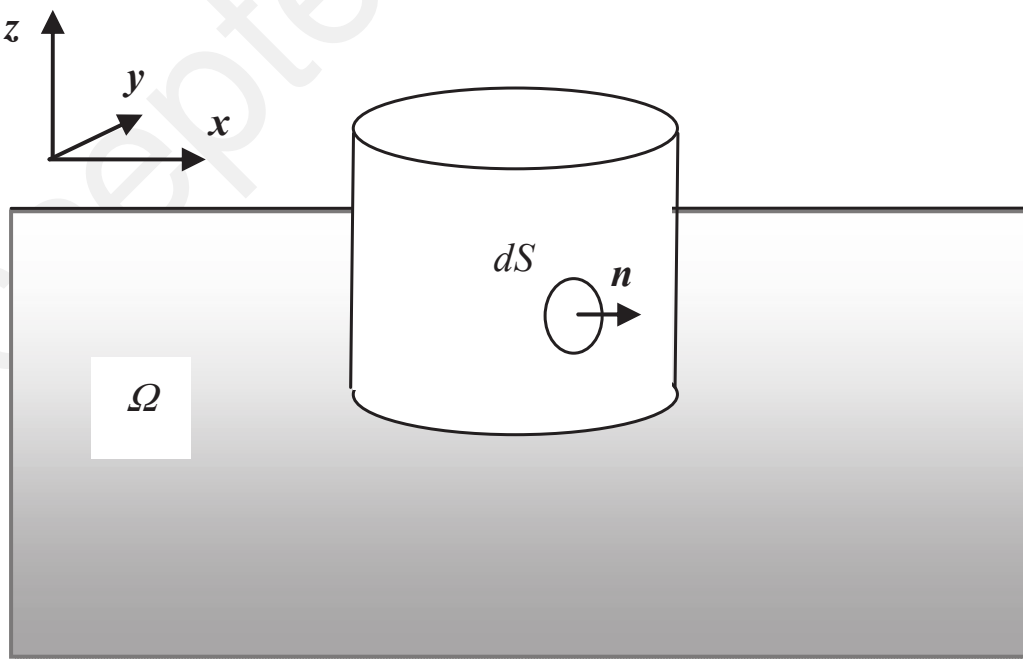
$$V_{ave}(z) = cz^\alpha$$

where  $\alpha$  is the power coefficient, typically between 0.1 and 0.2. The  $c$  coefficient can be calculated if the wind speed at a given altitude, often 10 m, is known.

## 3.2. Loads on marine structures

We now turn our attention to the stresses applied to marine structures, and in particular those generated by waves, current and wind.

The following diagram expresses the problem and the notations used.



**Figure 3.6.** *Diagram of the problem*

The wet surface of the object is notated  $S$ ,  $dS$  is a small part of that surface and  $\mathbf{n}$  is the normal vector of that surface pointing in the direction of the fluid.

The  $z$  axis is taken as vertical and pointing upwards. *A priori*, an object floating on the surface of the ocean has 6 degrees of freedom: 3 translations along the  $x$ ,  $y$  and  $z$  axes and 3 rotations around the  $x$ ,  $y$  and  $z$  axes. Conventionally in ocean engineering, these 3 translations of the structure's center of gravity,  $x_G$ ,  $y_G$ ,  $z_G$  are called surge, sway and heave respectively, and the 3 rotations  $\varphi$ ,  $\theta$  and  $\psi$  – roll, pitch and yaw respectively. The vector of the generalized motions ( $x_G$ ,  $y_G$ ,  $z_G$ ,  $\varphi$ ,  $\theta$ ,  $\psi$ ) is denoted  $X$ .

### 3.2.1. Hydrostatic force

Archimedes' force can be expressed as the following principle:

*Any object, wholly or partly immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object.*

Mathematically, this principle corresponds simply to the integration of the hydrostatic component of field of pressure on the wet surface of the object:

$$\vec{F}_{hydrostatic} = \int_S \rho g z \vec{n} dS$$

For a floating object at rest, Archimedes' force and gravity compensate each other. Assume now that the object is shifted into an unbalanced position. Archimedes' force and gravity are no longer perfectly equal. This difference is called hydrostatic restoring force.

For small displacements, we can show that the resulting generalized force can be written as a linear spring (possibly the result of a linearization), whose  $K_H$  coefficient is the matrix of hydrostatic stiffness.

$$F_{hydrostatic} = -K_H X$$

Most coefficients of this matrix are null. Indeed, Archimedes' force is not changed by horizontal motions (surge and sway) or the yaw motion.

Note also that the sign of the coefficients  $K_{H44}$  and  $K_{H55}$  provides information as to the stability of the structure. A negative sign indicates that disturbances will be magnified, and therefore characterizes instability. In other words, it will capsize.



### 3.2.2. Excitation forces on waves

#### 3.2.2.1. Froude-Krylov forces

Now let us consider the case of a regular waves being propagated on the surface of the fluid domain in the absence of any structure and in the direction of the positive  $x$ 's:

$$\eta(x, t) = A \cos(kx - \omega t)$$

This disturbance of the free surface is felt in the fluid domain via a term of unsteady pressure, which is written:

$$p(x, y, z, t) = -\rho g A e^{kz} \cos(kx - \omega t)$$

In this latter expression, we note the presence of a term in  $e^{kz}$ . The effect of the wave, then, is felt only around the surface. Once the object is immersed to a depth greater than half the wavelength, the effect of fluctuations in pressure due to the presence of waves is negligible.

This unsteady term is qualified as hydrodynamic, as opposed to the hydrostatic component of the forces of pressure.

Now let us place an object in the fluid domain, and let us for the moment ignore its interactions with the waves, so that the flow is not disturbed by the presence of the object. The force corresponding to the integration of dynamic pressure on the surface of the object is called the Froude-Krylov force:

$$\vec{F}_{\text{Froude-Krylov}} = \int_S p \vec{n} dS$$

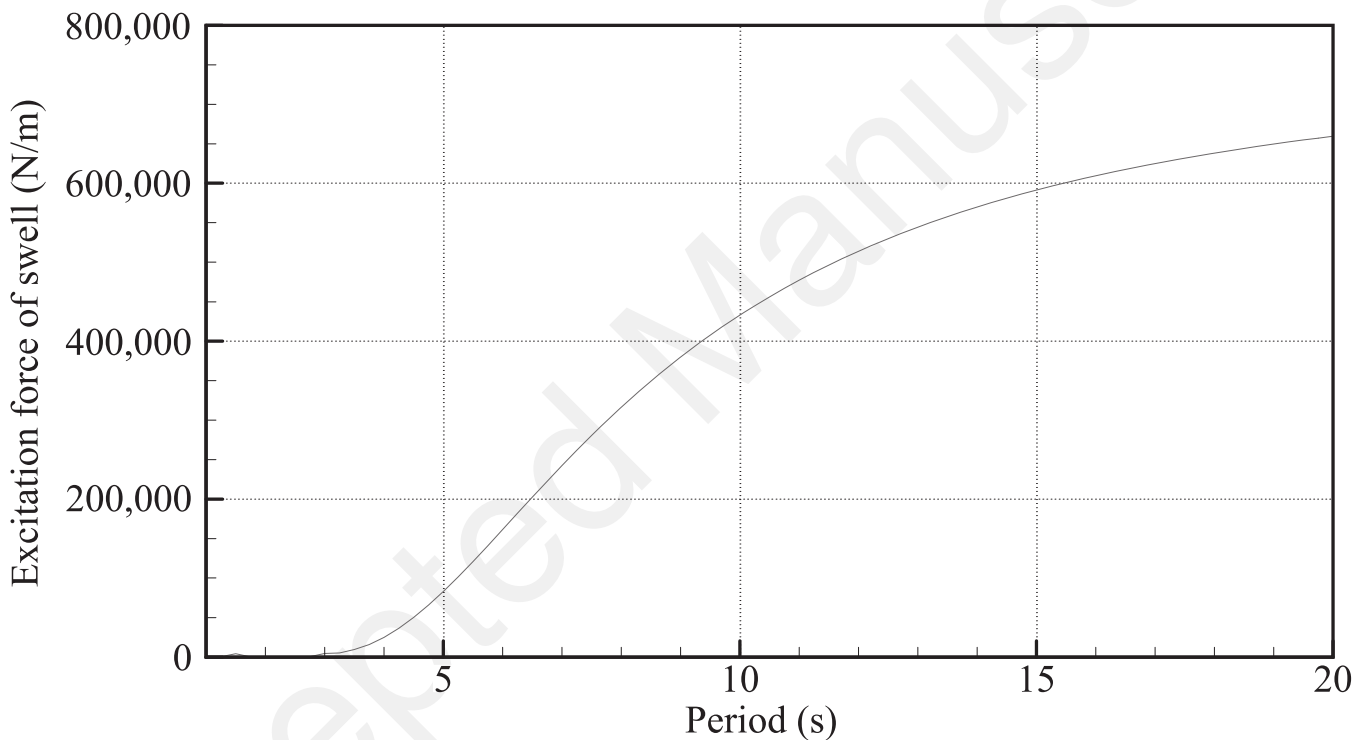
*A priori*, the disturbance caused by the object is not insignificant, and this force is therefore not a good approximation of hydrodynamic forces.

#### 3.2.2.2. Diffraction forces

Now let us consider the case of a fixed object in the waves. Its interaction with the incident wave field (field of undisturbed wave which would exist in the absence of the object) creates an additional wave field called the diffracted wave field.

Also associated with this diffracted wave field is a field of hydrodynamic pressure in the fluid domain. The integral of this field of pressure on the wet surface is called diffraction force. When the characteristic size of the object is equal to or greater than the wavelength of the waves, the order of magnitude of these diffraction forces is similar to that of the Froude-Krylov forces. On the other hand, when the object is extremely small in comparison to the wavelength of the waves, the diffracted wave field it generates will likewise be extremely small, and the diffraction force could be ignored.

The sum of the Froude-Krylov forces and the diffraction forces is the wave excitation force of the structure due to the action of the incident wave. Figure 4.7 shows the module of these excitation forces with heave for a regular wave of 1 m amplitude depending on the period of the waves. The object in question is a vertical cylinder 10 m in diameter and with a 10 m vertical draft.



**Figure 3.7.** Wave excitation force per meter of waves in heave depending on the period for a cylinder 10 m in diameter, and with a 10 m vertical draft

### 3.2.3. Radiation forces

Let us now consider the case of a structure placed anywhere in the fluid domain, initially at rest. Now let us set it in an oscillating motion: we see a field of waves develop around the structure, which propagate away from the object. This is the field of waves radiated by the structure. The associated field of pressure and the corresponding force are, respectively, called radiation pressure and radiation forces.

Of the first order and for a harmonic movement of pulsation  $\omega$ , we can show that this radiation force can be written as the sum of a term proportional to the object's velocity and a term proportional to its acceleration:

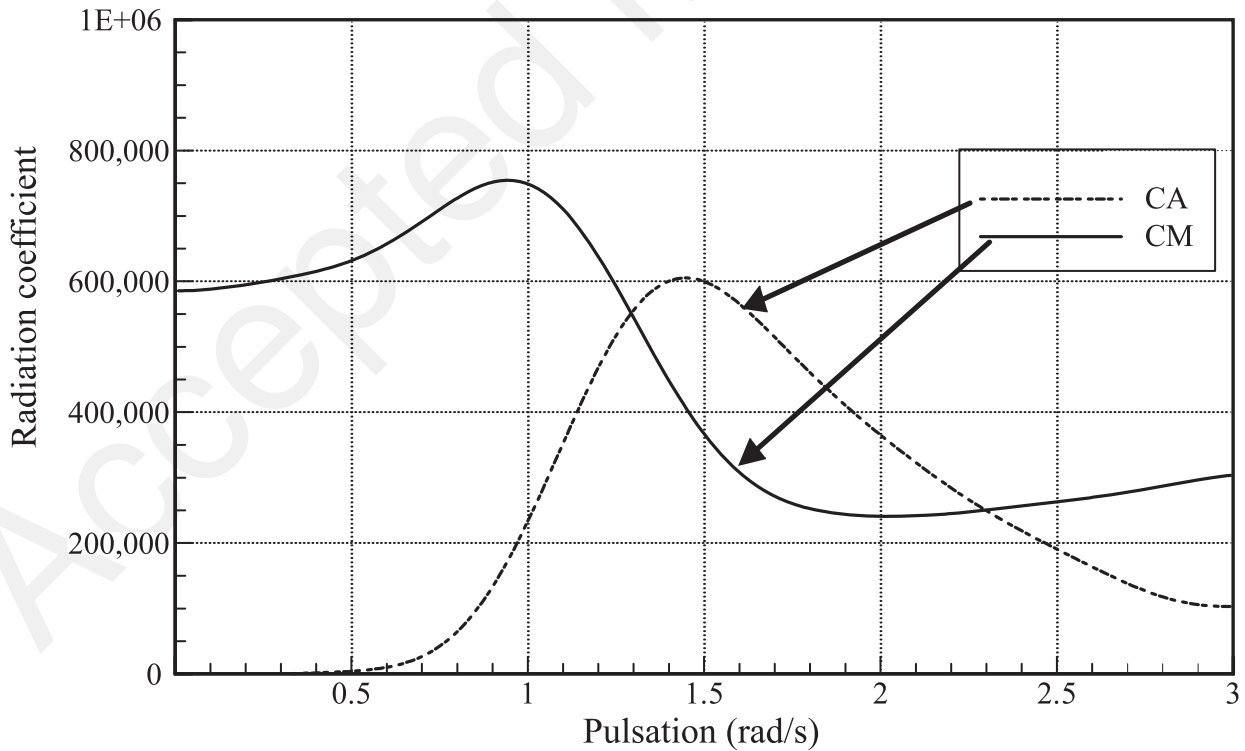
$$\vec{F}_{radiation} = -CM(\omega)\ddot{X} - CA(\omega)\dot{X}$$

The coefficient of the acceleration term is called added mass. It can be interpreted as the mass of water entrained by the object in its motion. The coefficient of the velocity term is the radiation damping coefficient. It represents the conversion of kinetic energy from the object into the energy corresponding to the wave field radiated. These two coefficients depend on the frequency.

In the temporal domain, of the first order, radiation force is written:

$$\vec{F}_{radiation} = -\mu_{\infty}\ddot{X} - \int_0^t K(t-\tau)\dot{X}(\tau)d\tau$$

Again, there is a term of added mass. However, the velocity term now appears as a product of convolution of the history of the object's velocity with a memory function, which takes the effect of the propagation of the waves along the length of the object into account.



**Figure 3.8.** Radiation coefficients for a heaving motion of a vertical cylinder 10 m in diameter and with a 10 m vertical draft

Memory function and the water added mass coefficient in the temporal domain are linked to the radiation coefficients in the frequential domain by the following formulae:

$$\mu_{\infty} = CM(\omega) + \frac{1}{\omega} \int_0^{\infty} K(\tau) \sin(\omega\tau) d\tau$$

$$K(t) = \frac{2}{\pi} \int_0^{\infty} CA(\omega) \cos(\omega t) d\omega$$

### 3.2.4. *Drift forces in waves*

Excitation and diffraction forces are first-order forces. Other effects appear in the second order. In particular, it can be shown that for any object in waves, moving or otherwise, there exists a constant force. This force is called drift force.

Although it is secondary in comparison to the effects of excitation and radiation, it is crucial to take this force into account when designing the moorings of a marine structure.

### 3.2.5. *Viscous drag forces*

#### 3.2.5.1. *Friction forces*

Because of viscosity, the velocity of fluid on the surface of the object is null (adherence condition). At a certain distance from the object, the velocity of the fluid is about the velocity typical of the flow. Between these two points there is an area of fluid transition called the boundary layer. In marine applications, its thickness is very slight.

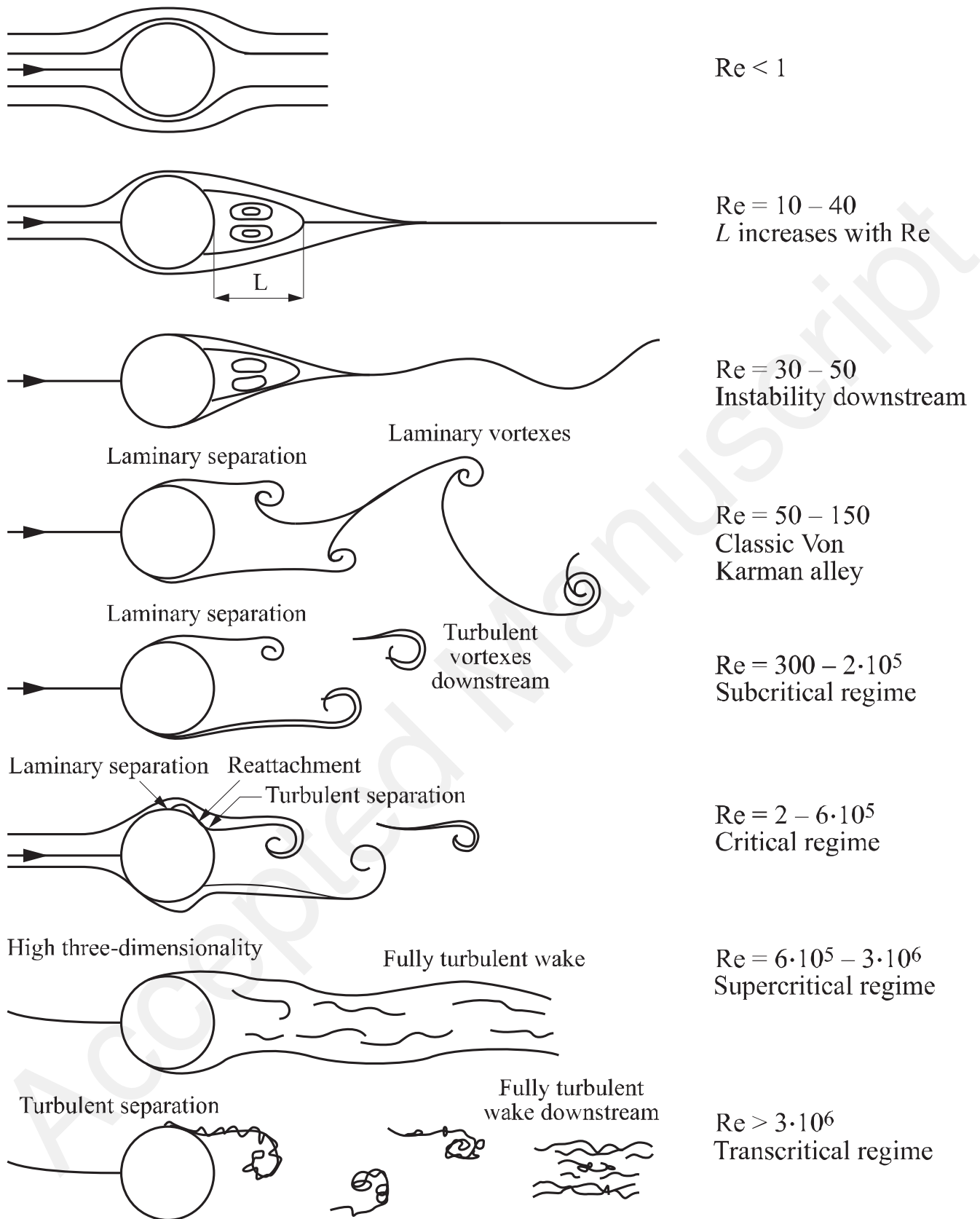
In the boundary layer, viscous effects are great, and flow is largely sheared. This shearing is due to a viscous constraint. The integration of this viscous constraint on the surface of the object is the force of friction, which tends to oppose the object's movement.

This friction force may be significant, and even great in the case of boats with forward velocity on calm water, or for estimating the force on the blades of a water turbine. In the case of non-high-speed structures, it is generally negligible in comparison to the wave forces (excitation and radiation).

#### 3.2.5.2. *Viscous shearing forces*

When the structure is placed in a strong current, or when the movement of the fluid is great in comparison to its dimensions, the flow often separates: the boundary

layer peels off and vortices are generated in the flow. This phenomenon is illustrated in Figure 3.9, taken from [MOL 02].



**Figure 3.9.** Flow around a cylinder as a function of the Reynold's number. The Reynold's number is defined by  $Re = VD/v$ , where  $V$  and  $D$  are the typical velocities of the flow, and  $v$  is the dynamic viscosity of the fluid. The Reynold's number is interpreted as the ratio of inertia forces to viscous forces. The figure is taken from [MOL 02]

This creation of vortexes in the flow corresponds to a certain dissipation in energy which is often modeled by means of a quadratic damping force:

$$\vec{F}_{drag} = -\rho C_D A |\vec{V}| \vec{V}$$

where  $V$  is the relative velocity of the object in relation to the flow,  $A$  is the characteristic surface of the object on a plane perpendicular to  $V$ , and  $C_D$  is the drag coefficient. The effect of friction is taken into account in the  $C_D$  coefficient.

In general, one takes account of the forces due to wind on the structure, with the same formalism. For structures with a great deal of dunnage, such as oil rigs or of course offshore floating wind turbines, this term may be significant.

### 3.3. Numerical and experimental tools for analysis

Evaluating the ensemble of these loads, separately or globally, is a complex matter. It is generally not possible to resolve them analytically, other than in very simple cases and with a great many hypotheses. Historically, the only chance of getting answers was to experiment on reduced-scale models in a testing basin. There are many different types of basin: wave basins, towing tanks, circulation channels, etc., depending on the effects we wish to investigate.

As computing power has grown over the past twenty years, numerical simulation tools have appeared in the field of hydrodynamics – virtual representations of physical basins. A great many numerical tools currently exist, differentiated by the hypotheses on which they are based, the precision of their results and the speed of their execution.

In the next part of this chapter, we look first at the different numerical methods normally used to examine the problem of fluid-structure interaction, and then at the experimental methods used chiefly to validate the predictions of these numerical models.

#### 3.3.1. Numerical methods

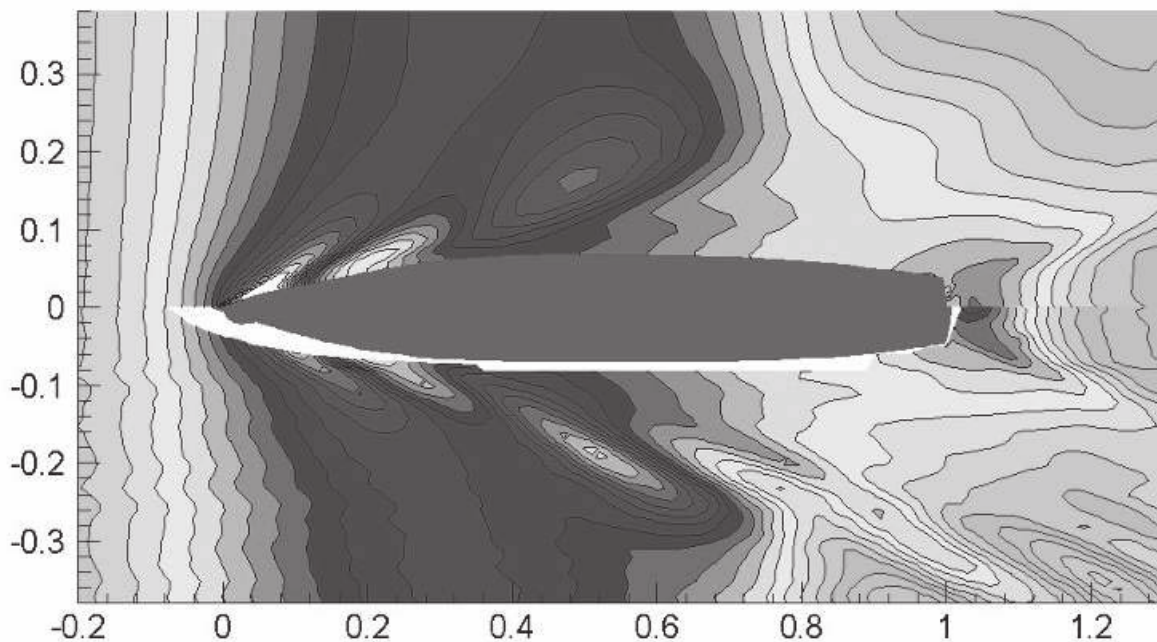
With no particular approximation, in order to numerically simulate a marine structure's interaction with its environment, one must directly solve the Navier Stokes equations (DNS – direct numerical simulation). This approach constitutes one type of numerical method, for which pertinent applications exist. However, in ocean engineering, the size and density of the meshes required would lead to prohibitive calculation times, and that is why this approach is never used. The



methods used in practice are all based on simplifying hypotheses, which are often perfectly justified. Essentially, these hypotheses consist of modeling the effects of turbulence, or ignoring it.

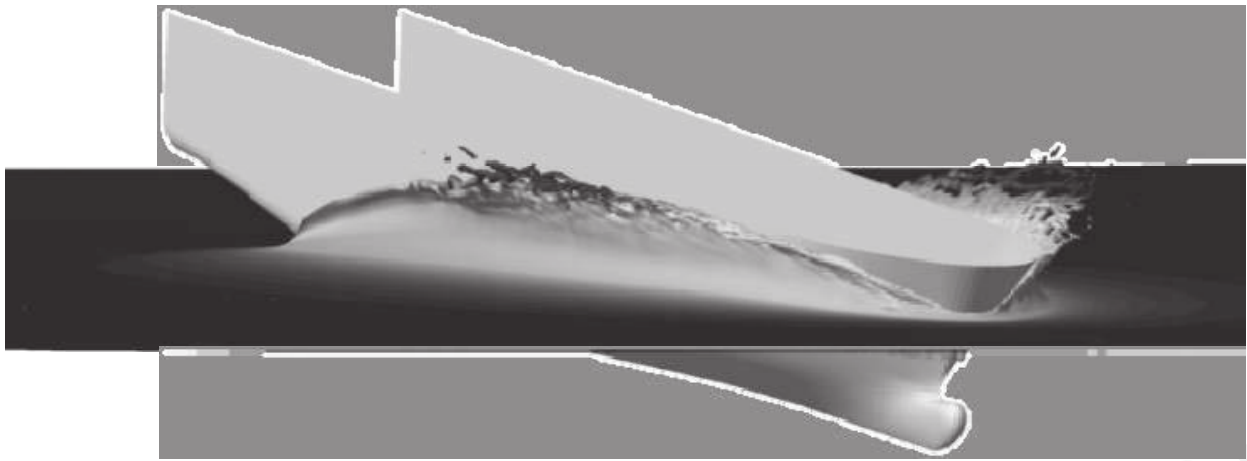
A first level of simplification consists of modeling small-scale turbulence in the flow, while larger structures remain simulated. Simulations and methods based on this principle are called LES (large eddy simulations). The results obtained are precise, but the calculation times are, again, far too great for most practical applications in ocean engineering.

A second level of simplification consists of solving the Reynold's averaged Navier Stokes equations (RANSE). In this approach, fluctuations in velocity due to turbulence are represented by a model, whose parameters are also dealt with in the simulation. These methods are, in general, fairly accurate, but the calculation times are still high. However, they are justified in a great many applications, and that is why these methods are being used with increasing frequency.



**Figure 3.10.** Comparison of the elevation of free surface around a boat with forward velocity. The upper half of the figure was obtained by a numerical calculation using the ICARE solver (RANSE above) and the lower half corresponds to experimental measurements

The methods mentioned above rely on a numerical mesh of the fluid space. Creating this mesh, adapting it to the initial problem and to the flow, as it develops, represents a very real difficulty which is all too often underestimated. Over the past few years, mesh free methods have appeared, such as the SPH (Smooth Particle Hydrodynamics) method. These meant the applicability of numerical methods could be extended to problems which had persisted up until then, in particular rapid dynamic flows (impacts).



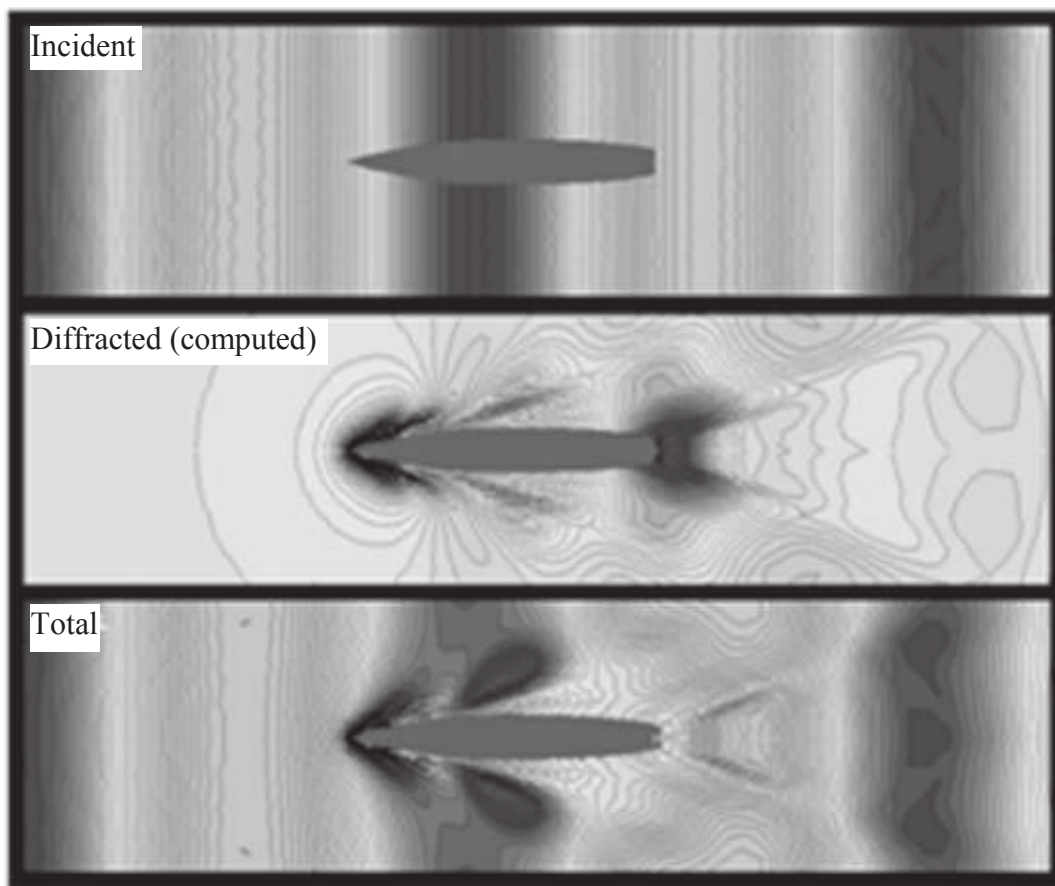
**Figure 3.11.** *Impact between a boat and the free surface, simulated using the solver SPHFlow (SPH). With the kind permission of Hydrocean (for a color version of this figure please see [www.iste.co.uk/multon/marine.zip/](http://www.iste.co.uk/multon/marine.zip/))*

Note, however, that all the aforementioned methods run into difficulties when analyzing problems to do with ocean waves, because the numerical schemes on which they are based introduce dissipation into the flow. When you attempt to propagate waves with these methods, you get a non-physical damping of the amplitude of the waves. One way to get around this problem is to use a SWENSE-based (spectral wave explicit Navier Stokes equations) approach. The approach consists of breaking down the variables of the problem (pressure, velocity) into two terms: one to represent the field of undisturbed incident waves, and the other to represent the disturbance. The field of incident waves can then be modeled precisely using adapted methods, such as HOS (High Order Spectral) modeling, and the task of the numerical solver is then to simulate the complementary part of the flow. The total flow is finally obtained by superimposing one on the other.

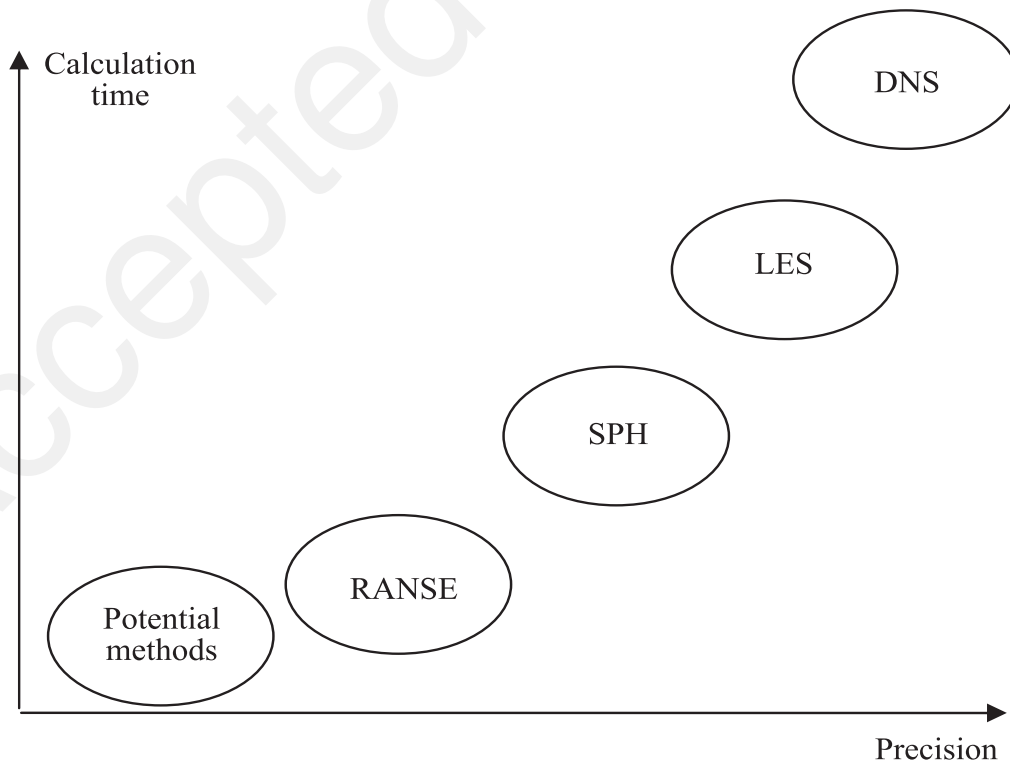
The final level of simplification consists of ignoring the effects of viscosity. We then find ourselves in the framework of the theory of potential flows. Often, the problem is further simplified by assuming that the disturbances are minor, which allows it to be linearized. Numerical tools created based on these hypotheses perform very well from the point of view of calculation time, but at the cost of lesser precision than the previous methods. The coefficients given in Figures 3.6 and 3.7 were calculated with a method of this type (Aquaplus). Note also that these tools do not allow for the effects of forces due to drag. In practice these are added to the empirical coefficients, using additional terms.

All these methods present advantages and disadvantages, and different compromises between precision and the effort needed to perform the calculations. Figure 3.15 shows the qualitative distribution of these methods. They are thus mutually complementary. In practice, we may end up implementing them one after another on the same project, as the sizing becomes clearer.





**Figure 3.12.** Flow around a boat in waves, calculated by the SWENSE method of domain decomposition. Top: elevation of free surface associated with the undisturbed wave field; middle: elevation of free surface associated with the diffracted field, calculated by the numerical solver; bottom: the total

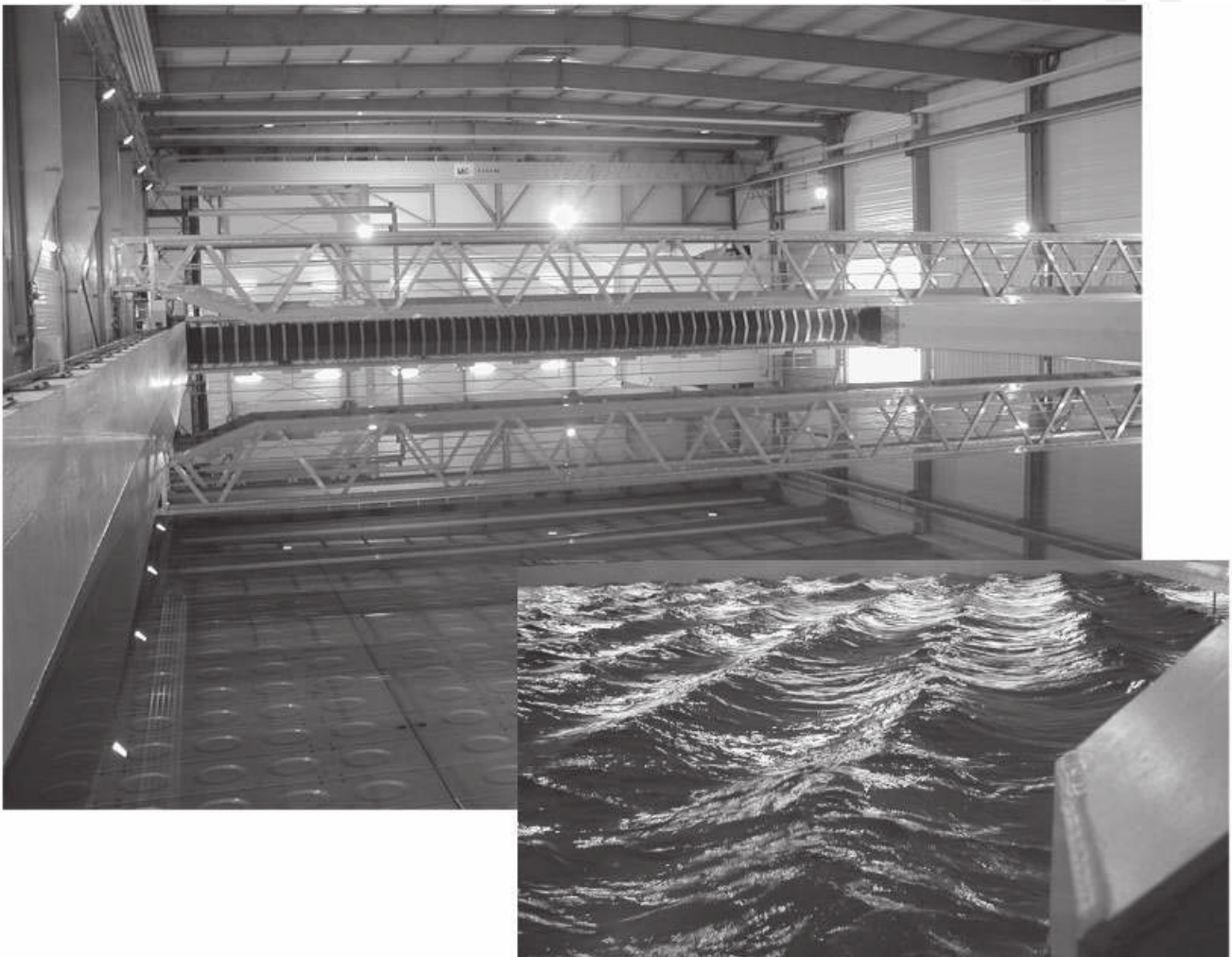


**Figure 3.13.** Qualitative distribution of the compromises between precision and calculation time inherent in the numerical methods

### 3.3.2. Experimental methods

#### 3.3.2.1. Tank testing

The main objective of carrying out tests in basins is to study the behavior of the structure and assess its performance, using a reduced-scale model placed in simulated, controlled environmental conditions. Therefore, it is a question of replicating the device as accurately and realistically as possible, measuring the physical values in order to describe the system and then comparing these data to the results of numerical studies. In this context, depending on the type of tests envisaged, the most apt testing basin may be a so-called ocean engineering basin, a towing tank, a cavitation tunnel, etc.



**Figure 3.14.** *Ocean engineering basin at École Centrale De Nantes*

An ocean engineering basin is a tank usually containing fresh water, with a wave generating device at one end. The waves may propagate in one direction only (along the axis of the basin) or in many directions (multidirectional waves). They are absorbed at the end of the basin, generally by a system which acts like a beach on which the waves break. Some basins may be in seawater, others may have devices

to generate wind over the free surface, or currents moving all or some of the water column. We can cite, for example, the ocean engineering basin in the École Centrale de Nantes, which is the largest in France. 50 m long by 30 m wide, with a constant depth of 5 m, this freshwater basin has 48 flaps, allowing it to generate multidirectional waves of more than 1 m from trough to crest. For a typical 1/20 scale model, this corresponds to real waves of over 20 m in height. Finally, note that ocean engineering basins are the favored equipment for testing wave energy converters.

A towing tank is also a tank containing fresh water, but this time with a carriage to tow a model. These tanks are therefore characteristically much longer than the others, in the direction of towing. Sometimes, these tanks are equipped with a wave generator, in order to study the behavior of a boat with forward velocity on waves. In France, the largest towing tank is the B600 of the *Bassin d'Essai des Carènes* of the DGA (French armory department) in Val de Reuil. This facility is 600 m long, 10 m wide and 10 m deep. It is equipped with a wave generator. In École Centrale de Nantes, the towing tank is 130 m long, 5 m wide and 3 m deep. The maximum speed of the towing platform is 8.5 m per second. On the typical scales of the models, this corresponds to several dozen knots in the real world.



**Figure 3.15.** *Towing tank in École Centrale de Nantes*



The choice of the scale of reduction is a first critical stage in preparing experiments, as it must be compatible with the dimensions and technical capacities of the basin, and the mechanical characteristics of the reduced model.

In order to model these characteristics physically and pertinently, it is more often than not a question of respecting the proportionality of the exterior forces applied to the system being studied, and the forces of gravity: the value of this ratio must remain identical whatever the scale in question. This approach corresponds to respecting Froude similarity: Froude's number,  $Fr = V^2/gD$ , must be the same for the model and in the real world, where  $V$  and  $D$  are the characteristic velocity and dimensions of the problem.

Let  $\lambda$  be the factor of geometric reduction. Respecting this similarity involves the time and velocity of the model being reduced by a factor of the square root of  $\lambda$  and the forces by a factor of  $\lambda^3$  in relation to the prototype. For example: a real machine (called a prototype) which is studied on a 1:25 scale sees its dimensions divided by 25, its velocity by 5 and its forces divided by  $25^3 = 15,625$ . In the case of a wave energy converter, we are also interested in the energy absorbed. This varies with the 3.5 power of the scale factor: if the power of the prototype is 500 kW in the real world, the power of the model on the 1:25 scale is only 6.4 W!

For the prototype or for the model, the characteristics of the water are practically identical: the result is a distortion of another similarity, called the Reynold's similarity, which characterizes the effects of the viscosity of the water on flows around the system being studied. As the Reynold's number cannot be respected for both the prototype and the model, it then becomes a question of ensuring that the pattern of flow does however remain identical. This usually involves ensuring that the flows remain turbulent locally, near to the model. This approach often leads to the addition of a slight roughness on parts of the model (sandpaper stuck on the sides, etc.) to generate turbulence on the walls.

The choice of the scale of reduction must also take account of the constraints caused by the testing basin itself: the characteristics of the generated waves, the size and cost of making the model, etc. In the case of a wave energy system, for example, it is common to dissociate its behavior in a normal operational situation, i.e. in a production situation for the usual environmental conditions (direction, height and period of waves, speed and direction of the wind, of the current, etc.), from its behavior in extreme situations close to its ultimate limit. We then speak of survivability testing. Thus it is sometimes necessary to build two models on different scales in order to study the two cases. The dimensions of the "production" setup are then chosen as the greatest possible in order to limit the effects of scale which might skew the extrapolation of data from the model to the prototype. These effects of scale can be observed in complex situations during which the physical

phenomena are not correctly modeled, either because they are not known initially or because of the difference in the environments in question (open sea and “infinite” space for the prototype, walls and “finite” space for the model).

Tank testing, therefore, involves making a model on which numerous types of measurements can be carried out. Let us first cite those linked to the model’s environment: measurements of the elevation of free surface which, once analyzed, reveal the statistical and spectral characteristics of the waves (heights, periods, direction); measurements of the wind (module of velocity, direction), of the currents, etc.

The other measurements correspond to characterizing the behavior and performance of the system being studied. In particular, we can cite (list not exhaustive):

- the motions of the model (the six degrees of freedom), gleaned using trajectography or using an inertial center unit;
- the global and local loads, measured using dynamometers and pressure sensors;
- the strains in the mooring system if the system is floating;
- the internal strains on the materials, measured using strain gauges;
- the physical characteristics which allow us to approximate the performance of the energy converter (measurement of torque, velocity, deformation, current – electrical or otherwise, depending on the technology used).

The wide variety of machines tested in this way means internationally standardizing the methodologies adopted, approved and followed by the different protagonists (designers, researchers, the managers of testing basin facilities, etc.). A similar approach was initiated nearly a century ago now, in the field of naval hydrodynamics (shipbuilding) and hull testing basins: it is still active today, and improvements are continuously being made, particularly in the framework of the International Towing Tank Conference (ITTC). Since the field of marine energy is just emerging, testing methodologies have not yet been completely validated and approved.

#### 3.3.2.2. *Open sea experimentation sites*

The step-by-step development of new technologies to produce energy using marine resources necessitates an evaluation of the technical feasibility and an estimation of the costs of producing this energy. Programs of testing prototypes in real conditions come before commercialization.

Open-sea experimentation is one stage in the process of verifying the behavior and performance of machines in operational conditions. This stage may involve demonstrating their functionality, and observing the interaction of all the components of the system in the case of a prototype. Means of building, installing and dismantling the systems are also tested at sea.

Testing an energy production system at sea involves having access to an offshore base in order to carry out the tests, and to the infrastructures of the electricity grid. Collecting the measured data and running testing programs involves having access to a base on land from which to control the prototypes being tested.

Tests at sea are done at scales which are representative of the prototypes in relation to the nature of the waves found in real conditions. Typically, prototypes tested at sea are studied at scales between 1:3 and 1:1. These prototypes have the energy conversion system (Power Take Off) on board, as well as a multitude of sensors and measuring instruments which allow the state of the system to be monitored during the tests.

The aim of the tests is to study and validate the following points:

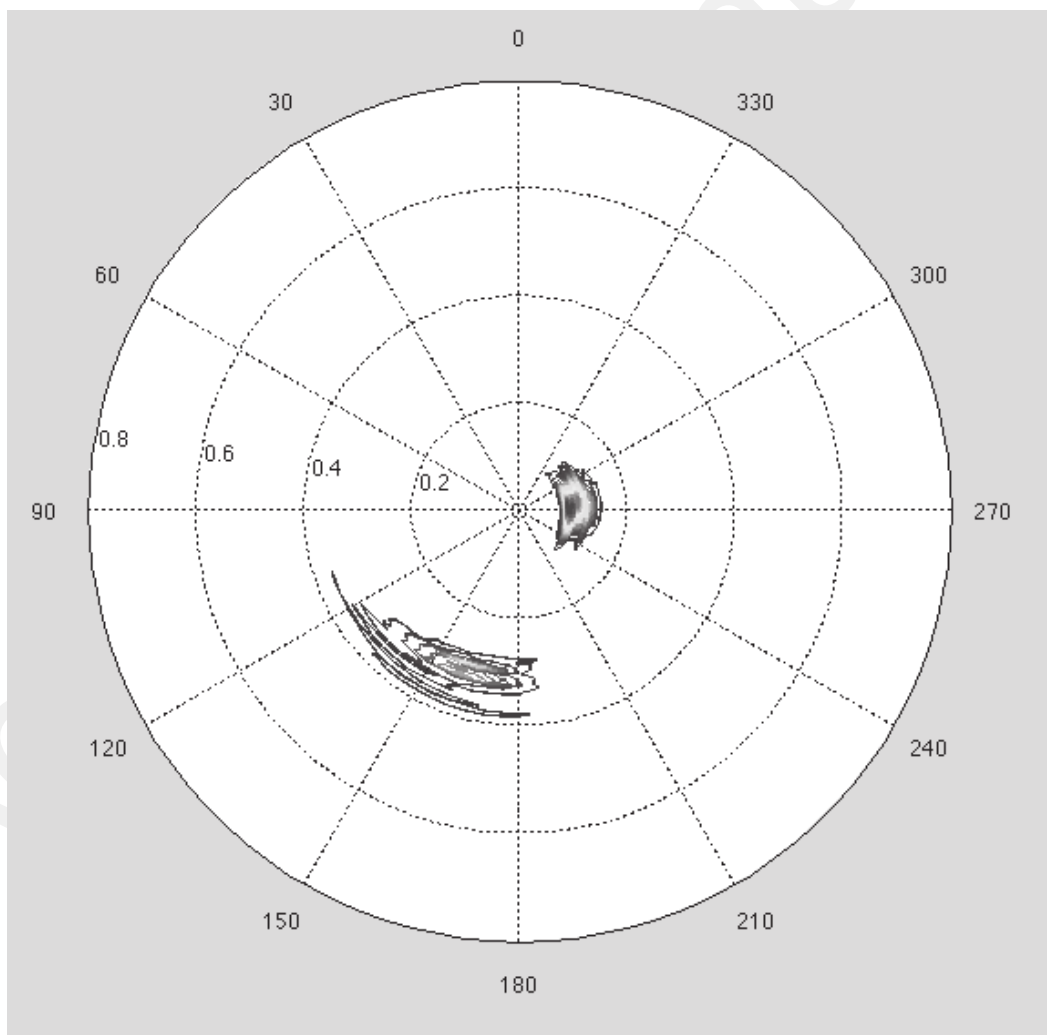
- operating procedures at sea;
- the quality of the electrical current produced;
- integration onto the electrical grid;
- the yields of the energy conversion system;
- the effectiveness of monitoring strategies;
- the sea-keeping ability of the structures.

In the case of wave energy converters, these tests may be carried out on dedicated infrastructures called Full Scale Test Sites. These test sites are infrastructures which give access to the public maritime domain in order to carry out temporary programs to evaluate the prototype at sea. A full scale test site gives access to an area demarcated by signaling buoys, adapted to local marine regulations. The duration of testing campaigns at sea usually ranges from 3 months to 1 year. Such infrastructures either exist or are being developed. One might point, for example, to the European Marine Energy Centre (EMEC) in Scotland, built in 2004; the SEM-REV, a project under construction, run by École Centrale de Nantes, off the coast of Croisic in France, for testing wave energy converters, or the Paimpol-Bréhat site in Brittany for testing water turbines. These test sites are also equipped with electrical infrastructure in order to transfer the energy produced. This means the presence of a static high-voltage cable placed on or embedded in the sea bed, and an electrical delivery station with cells for coupling and protecting the

machines. Depending on the voltages used, the delivery stations may be equipped with step-up transformers which amplify the voltage. The electrical tests correspond to the analyses of the following elements of the system:

- states of charge of the converter depending on the operating conditions;
- electrical stability;
- collection of the levels of energy production and thresholding;
- quality of the current (permanent voltage, flicker, variations under strain, harmonics, reactive power, filtering and default behavior).

These measurements are carried out at the level of the electrical delivery station and within the prototype's energy conversion system itself. The data collected at sea are transmitted back to shore by fiber optic or by high frequency radio. The electrical measurements are carried out in accordance with the International Electrotechnical Commission specifications, using appropriate electrical qualimetry instruments.



**Figure 3.16.** *Environmental measurements, spectrum of directional wave energy in the SEM-REV on 01/06/09 at 09:00 (for a color version of this figure please see [www.iste.co.uk/multon/marine.zip/](http://www.iste.co.uk/multon/marine.zip/))*

Like testing in ocean engineering basins, testing done at sea necessitates the characterization of the environment using measurements of the ocean-meteorological conditions. These measurements at sea are taken using the following instruments:

- a buoy measuring directional waves;
- Doppler effect current meters;
- PUV (pressure and velocity) sensors;
- 3D measurements of wind at sea;
- tide gauges.

Measurements of the system's movements are done using different inertial measurement technologies on board the prototype. Load cells may be used on the mooring lines in order to characterize the straining force and the response of the lines.

### 3.4. Conclusion

In this chapter, we have examined the causes of the loads on structures at sea, and the different effects these loads have on the structures. We then looked at the different approaches which exist in numerical and experimental modeling which allows us to study them.

### 3.5. Bibliography

The above is merely an introduction to the hydrodynamic aspects of converting marine energy. For readers wishing to know more about the subject, we recommend the following works:

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