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# GUIDELINES FOR NONLINEAR WAVE LOAD CALCULATION OF SHIPS BASED ON VISCOUS FLOW

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# CHAPTER 1 GENERAL

## Section 1 GENERAL PROVISIONS

### 1.1.1 General requirements

1.1.1.1 The Guidelines specify a direct calculation method for nonlinear ship wave loads based on viscous flow computational fluid dynamics (hereinafter referred to as "CFD").

1.1.1.2 The Guidelines apply to conventional ship types requiring direct nonlinear wave load calculations according to China Classification Society (hereinafter referred to as "CCS") rules or guidelines, including bulk carriers, oil tankers, ore carriers, container ships, liquefied gas carriers, cruise ships, etc.

1.1.1.3 The Guidelines assume that the hull is rigid and employ incompressible free-surface flow simulation with water and air as media; wind and current effects are generally not considered.

1.1.1.4 The Guidelines are applicable to the calculation of the following wave load components:

(1) hull girder wave loads;

(2) hull motion;

(3) hydrodynamic pressure on the hull shell;

(4) slamming pressure;

(5) green water pressure.

1.1.1.5 The Guidelines are based on viscous flow CFD method of the Reynolds-averaged Naiver-Stokes (RANS) equations, capable of accounting for the following physical phenomena:

(1) viscous effects and boundary layer flow;

(2) free-surface liquid flow;

(3) wave breaking and splashing;

(4) strong interactions between ship waves.

### 1.1.2 Miscellaneous

1.1.2.1 Alternative methods for calculating nonlinear ship wave loads that differ from those specified in the Guidelines may be used provided they are supported by appropriate theoretical justification, model test validation, or recognized standards, subject to CCS approval.

## Section 2 DEFINITIONS

### 1.2.1 General Requirements

1.2.1.1 Unless otherwise specified, the main ship dimensions and parameters defined in the Guidelines are as follows:

(1) Ship length $L$ (m): refer to 1.1.2.1, Section 1, Chapter 1, PART TWO of CCS Rules for Classification of Sea-going Steel Ships.

(2) Ship breadth $B$ (m): refer to 1.1.2.2, Section 1, Chapter 1, PART TWO of CCS Rules for Classification of Sea-going Steel Ships.

(3) Structural draft $d$ (m): refer to 1.1.2.4, Section 1, Chapter 1, PART TWO of CCS Rules for Classification of Sea-going Steel Ships.

(4) Block coefficient $C_b$: refer to 1.1.2.5, Section 1, Chapter 1, PART TWO of CCS Rules for Classification of Sea-going Steel Ships.

(5) Speed $V$ (m/s): refer to 1.1.2.27, Section 1, Chapter 1, PART TWO of CCS Rules for Classification of Sea-going Steel Ships.

### 1.2.2 Definition of Main Symbols

1.2.2.1 Unless otherwise specified, the definitions of main symbols used in the Guidelines are shown in Table 1.2.2.1:

**Definitions of Main Symbols** **Table 1.2.2.1**

| Symbol Name | Meaning | Unit |
|---|---|---|
| $Fr$ | Froude number, $Fr=V/\sqrt{gL}$ | - |
| $Re$ | Reynolds number, $Re=VL/\nu$ | - |
| $\lambda$ | Wave length | m |
| $H$ | Wave height | m |
| $k$ | Wave number, $k=2\pi/\lambda$ | rad/m |
| $\omega$ | Wave angular frequency, $\omega=2\pi/T$ | rad/s |
| $\rho$ | Fluid density | kg/m³ |
| $\nu$ | Kinematic viscosity of water | m²/s |
| $M_y$ | Vertical wave bending moment | Nm |
| $M_z$ | Horizontal wave bending moment | Nm |
| $M_x$ | Wave torque | Nm |
| $Q_z$ | Vertical wave shear force | N |
| $Q_y$ | Horizontal wave shear force | N |
| $Q_x$ | Longitudinal wave shear force | N |

### 1.2.3 Coordinate System Definitions

1.2.3.1 Unless otherwise specified, the Guidelines adopt a right-handed Cartesian coordinate system as shown in Figure 1.2.3.1:

Origin (AE): intersection point of the midship section, aft end of ship length $L$, and baseline;

X-axis: longitudinal axis, positive from stern to bow, in m;

Y-axis: transverse axis, positive from starboard to port, in m;

Z-axis: vertical axis, positive upward from the baseline, in m.

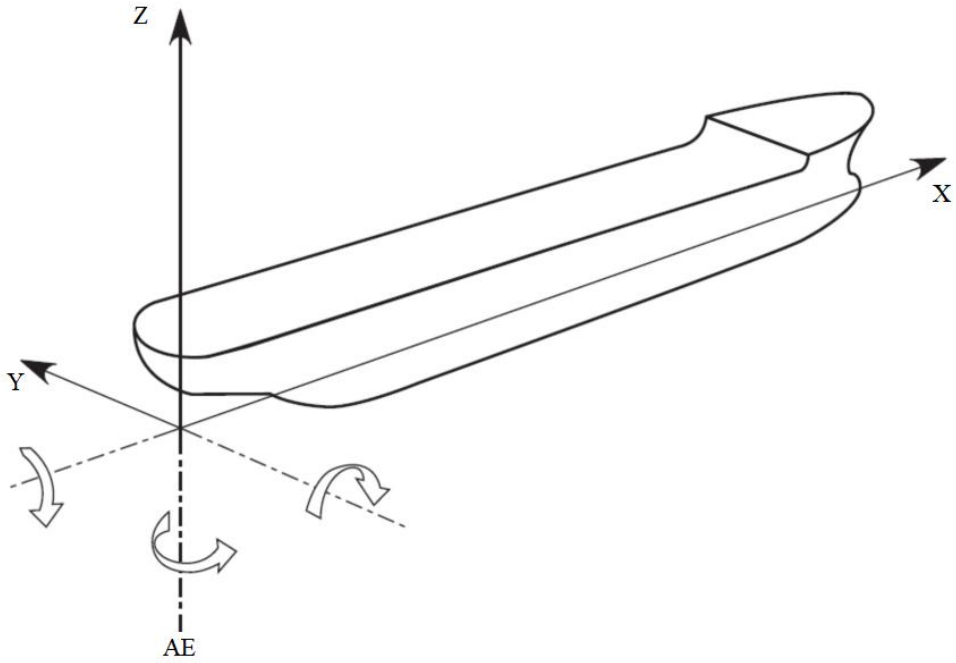



**Figure 1.2.3.1 Definitions of Coordinate System**

### 1.2.4 Definitions Related to Computational Fluid Dynamics

1.2.4.1 Reynolds-Averaged Naiver-Stokes (RANS) equations: by time-averaging the transient Naiver-Stokes equations, the following governing equation set is obtained to describe the mean turbulent motion (incompressible Newtonian fluid):

$$\rho\overline{u}_j\frac{\partial\overline{u}_i}{\partial x_j}=-\frac{\partial\overline{p}}{\partial x_i}+\mu\frac{\partial^2\overline{u}_i}{\partial x_j\partial x_j}-\rho\frac{\partial\overline{u_i'u_j'}}{\partial x_j}+\rho f_i$$

where: $\bar{u}_i$ —— time-averaging velocity component, in m/s;

$\rho$ —— fluid density, in kg/m$^3$;

$\overline{u}_i,\overline{u}_j$ —— time-averaging velocity components ($i$, $j$=1, 2, 3, corresponding to x, y, z directions), in m/s;

$\overline{p}$ —— time-averaging static pressure, in Pa;

$\mu$ —— dynamic viscosity of fluid, in Pa·s;

$x_i,x_j$ —— spatial coordinate components of dynamic viscosity ($i$, $j$=1, 2, 3, corresponding to x, y, z directions), in m;

$f_i$—— components of body force per unit mass of fluid, in m/s$^2$;

$\overline{u_i'u_j'}$ —— Reynolds stress term, in Pa.

1.2.4.2 Volume of Fluid (VOF): a technique for simulating two or more immiscible fluids by solving a set of momentum equations and tracking the volume fraction of each phase within the computational domain.

1.2.4.3 $y^+$ value: a dimensionless wall distance defined as follows, used to evaluate boundary layer mesh resolution:

$$y^+=\frac{yu_\tau}{v}$$

where: $y$ —— distance from the first grid node to the wall;

$u_\tau$ —— friction velocity, $u_\tau=\sqrt{\tau_w/\rho}$, where: $\tau_w$ is the wall shear stress and $\rho$ is the fluid density.

For low-Re turbulence models, $y^+\approx1$ is required; for wall function approaches, $30 < y^+ < 100$ is required.

1.2.4.4 Reynolds number (*Re*): a dimensionless number characterizing the flow regime in a flow field, calculated using the following formula:

$$Re=\frac{VL}{v}$$

where: $\nu$ —— kinematic viscosity of water, in m²/s, with a reference value of $0.89\times10^{-6}$ m²/s at 25℃.

1.2.4.5 Froude number (*Fr*): a dimensionless number representing the wave-making condition of ship navigation according to the following formula:

$$Fr=\frac{V}{\sqrt{gL}}$$

where: $g$ —— gravitational acceleration, to be taken as 9.81 m/s².

1.2.4.6 Turbulence model: additional differential equations introduced beyond the RANS equations to make the equation closed. Turbulence models can be classified into zero-equation models, one-equation models, two-equation models, and multi-equation models based on the number of differential equations.

1.2.4.7 Boundary conditions: in the process of ship hydrodynamic calculations, boundary conditions are usually applied around the computational domain and on the hull surface. Common boundary conditions generally include:

(1) velocity inlet: specifies velocity distribution and fluid properties;

(2) pressure outlet: specifies outlet pressure conditions;

(3) symmetry boundary: normal velocity is zero, and gradients of other variables are zero;

(4) solid wall condition: impermeable surface satisfying either no-slip or slip conditions.

1.2.4.8 Overlapping grids (dynamic mesh): the overlapping grid technique couples different regions by exchanging data between receiver cells in one region and donor cells (i.e., active cells) in another region. A typical overlapping simulation takes the entire solution domain as the background region and define the region surrounding a rigid body (e.g., hull) as the overlapping region. The outer surface of the overlapping region is defined as the overlapping boundary.

1.2.4.9 Degrees of freedom: the hull motion in waves involves six degrees of freedom (6 DOF), including surge, sway, heave, roll, pitch and yaw.

## Section 3 PLANS AND DOCUMENTS

### 1.3.1 General Requirements

1.3.1.1 The drawings and documents referenced in the Guidelines include, but are not limited to:

(1) Lines and offsets;

(2) Frame lines;

(3) Bilge keel structure and arrangement;

(4) General arrangement;

(5) Shell expansion;

(6) Capacity plan;

(7) Hydrostatic calculations;

(8) Loading manual (including section weights, centers of gravity, etc.);

(9) Typical cross-sectional area;

(10) Calculation data files (including mesh, calculation results, and post-processing);

(11) Three-dimensional geometry model database.

# CHAPTER 2 NUMERICAL CALCULATIONS FOR VISCOUS FLOW

## Section 1 GENERAL PROVISIONS

### 2.1.1 General Requirements

2.1.1.1 This section presents the fundamental principles of numerical calculations based on viscous flow, providing theoretical explanations primarily in terms of mass conservation, momentum conservation, free surface capturing, and fluid-structure interaction calculations.

2.1.1.2 The viscous flow calculations of ship motion in waves and wave loads essentially involves solving a coupled system of equations for unsteady, viscous, multi-phase flow fields and rigid body motion.

2.1.1.3 For viscous flow calculations, the finite volume method is generally used to discretize the governing equations. The core set of equations generally includes: the continuity equation for incompressible fluids, the RANS momentum equations, the VOF free surface tracking equation, and the six-degree-of-freedom (6 DOF) rigid body motion equations.

## Section 2 GOVERNING EQUATIONS

### 2.2.1 Continuity Equation (Law of Mass Conservation)

2.2.1.1 For the simulation of ship wave motion, the fluid can be considered as incompressible fluid (with a constant density of ρ). The core of mass conservation is that the rate of change of fluid mass within a control volume is equal to the net mass flux passing through its boundaries. By taking any infinitesimal control volume $V_1$, with boundary S being a closed curve surface. the following integral form of the conservation of mass equation is established based on the law of mass conservation:

$$\frac{\partial}{\partial t}\iiint_{V_1}\rho dV_1+\iint_S \rho u\cdot n dS=0$$

where: $\rho$ —— fluid density, in kg/m³;

$t$ —— time, in s;

$V_1$ —— infinitesimal control volume, in m³;

$S$ —— curve surface of control volume boundary, in m²;

$u$ —— fluid velocity vector, in m/s;

$n$ —— external normal vector to the control volume boundary.

For ships, assuming the encountered fluid is incompressible, the above equation can be further simplified to:

$$\rho\frac{\partial}{\partial t}\iiint_{V_1} dV_1+\rho\iiint_{V_1}\nabla\cdot u dV_1=0$$

where: $\nabla$ —— divergence operator.

### 2.2.2 Turbulence Model

2.2.2.1 When a ship moves in waves, the flow field around the hull is unsteady, viscous, and turbulent. Viscous flow solvers typically employ Reynolds Averaging to average the instantaneous Naiver-Stokes equations, separating mean quantities from fluctuating components, thereby addressing the turbulent flow calculation issues, as described in expression 1.2.4.1.

2.2.2.2 The RANS equation contain the Reynolds stress tensor $\tau_{ij}^{R}$, which makes the equation unclosed. To close the equation, turbulence models are used to establish relationships between the Reynolds stresses and the time-averaged velocity. In ship wave motion simulations, the k-ω SST (Shear Stress Transport) turbulence model is commonly adopted. This model combines the high accuracy near walls of the k-ω model with the good far-field stability of the k-ε model. By solving the transport equations for turbulent kinetic energy $k_1$ and specific dissipation rate $\omega_1$, it achieves closure of the Reynolds stresses.

### 2.2.3 Reynolds Stress Closure Assumption

2.2.3.1 The k-ω SST model adopts the Boussinesq assumption, relating the Reynolds stress tensor to the mean velocity gradient via the following expression:

$$\tau_{ij}^{R} = \mu_t \left( \frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} \right) - \frac{2}{3} \rho k_1 \delta_{ij}$$

where: $\mu_t$ —— turbulent viscosity coefficient, in Pa·s;

$k_1$ —— turbulent kinetic energy, in m²/s²;

$\delta_{ij}$ —— Kronecker delta (δ=1 for $i=j$, δ=0 for $i \neq j$);

$\frac{2}{3}\rho k \delta_{ij}$ —— isotropic pressure term due to turbulent kinetic energy.

2.2.3.2 The turbulent viscosity coefficient $\mu_t$ is determined by the turbulent kinetic energy $k_1$ and the specific dissipation rate $\omega_1$:

$$\mu_t = \rho \frac{k_1}{\omega_1}$$

The physical meaning of turbulent kinetic energy $k_1$ is the turbulent fluctuation energy per unit mass of fluid. Its transport equation is derived by subtracting the instantaneous momentum equation from the Reynolds-averaged momentum equation, taking the dot product with the velocity fluctuation component, and then performing time averaging. The final equation is:

$$\frac{\partial k_1}{\partial t} + \overline{u}_j \frac{\partial k_1}{\partial x_j} = \nabla \cdot \left( \left( \nu + \frac{\nu_t}{\sigma_k} \right) \nabla k_1 \right) + P_k - \rho \omega_1 k_1$$

where: $\sigma_k$ —— turbulent kinetic energy diffusion coefficient;

$\nabla$ —— divergence operator;

$\rho\omega_1 k_1$ —— turbulent kinetic energy dissipation term, representing the process by which turbulent fluctuation energy is dissipated into thermal energy;

$\omega_1$ —— specific dissipation rate, in 1/s.

2.2.3.3 The specific dissipation rate $\omega_1$ is defined as the ratio of turbulent kinetic energy dissipation rate to turbulent kinetic energy. Its transport equation is derived from the transport equation of $k_1$ and the definition

of $\omega_1$, combined with the blending function of the k-ω SST model, resulting in the following final equation:

$$\frac{\partial \omega_1}{\partial t}+\bar{u}_j\frac{\partial \omega_1}{\partial x_j}=\nabla\cdot\left(\left(\nu+\frac{\nu_t}{\sigma_\omega}\right)\nabla\omega_1\right)+\alpha\frac{\omega}{k_1}P_k-\beta\rho\omega_1{}^2+\gamma(\nabla k_1\cdot\nabla\omega_1)$$

where: $\sigma_\omega$ —— diffusion coefficient of specific dissipation rate;

$\nabla$ —— divergence operator;

$\alpha\frac{\omega_1}{k_1}P_k$ —— generation term of specific dissipation rate, $\alpha$ being the generation coefficient (third term on the right-hand side);

$-\beta\rho\omega_1^2$ —— dissipation term of specific dissipation rate, $\beta$ being the dissipation coefficient;

$\gamma(\nabla k_1\cdot\nabla\omega_1)$ —— cross-diffusion term, used to enhance model stability in adverse pressure gradient flows, $\gamma$ being the cross-diffusion coefficient.

2.2.3.4 The core advantage of the k-ω SST model lies in its ability to automatically switch between the k-ω and k-ε models via a blending function $F_1$. In the near-wall region ($y^+ \leq 100$), the k-ω model is employed to ensure accuracy in boundary layer calculations; in the far field ($y^+ > 100$), the k-ε model is employed to improve flow field stability. The blending function $F_1$ is derived based on the wall distance $y$, and its equation is given below:

$$F_1=\tanh\left(\left(\min\left(\max\left(\frac{\sqrt{k_1}}{0.09\omega_1 y},\frac{500\nu}{y^2\omega}\right),\frac{4\rho k_1}{\mu_t C_{dk}y^2}\right)\right)^4\right)$$

where: $y$ —— wall distance, in m;

$C_{dk}$ —— constant, $C_{dk}=0.075$.

When $F_1 = 1$, the model operates entirely in k-ω mode; when $F_1 = 0$, it operates entirely in k-ε mode. In intermediate regions, a linear interpolation of $F_1$ ensures a smooth transition between the two modes.

## Section 3 VOF FREE SURFACE

### 2.3.1 General Requirements

2.3.1.1 The viscous flow calculation of ship motion in waves and wave loads involves two-phase air-water flow, with the key being accurate capture of the gas-liquid interface (free surface). Typically, the Volume of Fluid (VOF) method is employed, which defines volume fractions to describe the distribution of the two phases and thereby derives the free surface transport equation.

### 2.3.2 Water Phase Volume Fraction α

2.3.2.1 The water phase volume fraction $\alpha$ is defined as the ratio of the water volume within a control volume to the total volume of the control volume, calculated as follows:

$$\alpha=\frac{V_w}{V_f}$$

where: $V_w$ —— water phase volume within the control volume, in $m^3$;

$V_f$—— total volume of the control volume, in $m^3$.

When $\alpha = 1$, the control volume is pure water phase; when $\alpha = 0$, the control volume is pure air phase; and when $0 < \alpha < 1$, the control volume is a mixed region of air and water phases, i.e., the free surface zone. Meanwhile, the air phase volume fraction $\alpha_a$=1-$\alpha$ satisfies $\alpha+\alpha_a=1$.

### 2.3.3 Rate of Change of Water Phase Mass

2.3.3.1 According to the mass conservation law, the rate of change of water phase mass equals the net mass flux of the water phase across the boundaries of the control volume. The integral form of water phase mass conservation is expressed as:

$$\frac{\partial}{\partial t}\iiint_{V_1}\rho\alpha dV_1+\iint_S\rho\alpha u\cdot ndS=0$$

where: $\rho$ —— fluid density, in $kg/m^3$;

α —— water phase volume fraction;

$dV_1$—— fluid infinitesimal volume;

$dS$ —— infinitesimal surface area;

$u$ ——fluid velocity vector, in m/s;

$n$ —— external normal unit vector on the surface.

Disregarding water compressibility, the following equation can be obtained:

$$\rho\left(\iiint_{V_1}\frac{\partial\alpha}{\partial t}dV_1+\iiint_{V_1}\nabla\cdot(\alpha u)dV_1\right)=0$$

where: $\rho$ —— fluid density, in $kg/m^3$;

$\nabla$ —— divergence operator;

$\alpha$—— water phase volume fraction;

$dV_1$—— fluid infinitesimal volume;

$u$—— fluid velocity vector, in m/s.

Due to $\rho\neq 0$ , and the control volume is infinitesimal, the VOF free surface transport equation can be derived as:

$$\frac{\partial\alpha}{\partial t}+\nabla\cdot(\alpha u)=0$$

where: $\alpha$ —— water phase volume fraction;

$\nabla$ —— divergence operator;

$u$ —— fluid velocity vector, in m/s.

In Cartesian coordinates, this equation expands to:

$$\frac{\partial\alpha}{\partial t}+\frac{\partial(\alpha u_x)}{\partial x}+\frac{\partial(\alpha u_y)}{\partial y}+\frac{\partial(\alpha u_z)}{\partial z}=0$$

where: $u_x$, $u_y$, $u_z$ —— components of the two-phase mixture velocity field, in m/s.

### 2.3.4 Miscellaneous

2.3.4.1 To avoid numerical diffusion of the free surface and ensure the steepness of the wave surface, a high-resolution interface capturing form (e.g., HRIC) can be used to discretize this equation so as to effectively suppress interface diffusion and accurately capture complex free surface features such as wave breaking, peak, and valley.

## Section 4 SIX DOF RIGID BODY MOTION

### 2.4.1 General Requirements

2.4.1.1 When a ship moves in waves, it can be considered as a rigid body undergoing six DOF motion under the influence of hydrodynamic forces, gravity, buoyancy, and other external forces. Viscous flow calculations achieve bidirectional coupling between the flow field and hull motion through dynamic fluid-solid interaction, with the core being the solution of the six DOF rigid body dynamics equations.

2.4.1.2 A body-fixed coordinate system ($x'$, $y'$, $z'$) is established with its origin at the ship's center of mass, moving along with the vessel. The X'-axis aligns with the longitudinal direction of the hull (forward), the Y'-axis with the transverse direction (to port), and the Z'-axis with the vertical direction (upward). According to rigid dynamics theory, translational and rotational motions of the hull follow Newton's second law and Euler's rotation equations, respectively.

### 2.4.2 Translational Motion Equations

2.4.2.1 The fundamental principle of the hull's translational motion is that the acceleration of the center of mass is proportional to the net external force acting on the hull—i.e., Newton's second law:

$$m\frac{d^2X_c}{dt^2}=\sum F$$

where: $m$ —— mass of the hull, in kg;

$X_c$ —— position vector of the hull's center of mass in the inertial coordinate system, in m;

$\sum F$—— resultant external force vector acting on the hull, in N.

2.4.2.2 The total external force acting on the hull mainly consists of the total hydrostatic pressure $F_{hydro}$, gravity $G$, and other external forces $F_{\text{ext}}$ (such as propeller thrust, mooring forces, etc.), i.e.,

$$\sum F = F_{\text{hydro}} + G + F_{\text{ext}}$$

where: $G$——gravity, $G$=-$mgk_z$, $k_z$ being the unit vector along the z-axis of the inertial coordinate system.

### 2.4.3 Rotational Motion Equations

2.4.3.1 The rotational motion of the hull follows Euler's rotation law: the angular acceleration about the center of mass is proportional to the resultant external moment acting on the rigid, expressed as:

$$I\dot{\Omega}+\Omega\times(I\Omega)=\sum M$$

where: $I$—— moment of inertia tensor of the hull around its center of mass, in kg·m²;

$\Omega$ —— angular velocity vector of the hull, in rad/s;

$\dot{\Omega}$ —— angular acceleration vector of the hull, in rad/s²;

$\sum M$ —— resultant external moment vector acting on the hull, in Nm;

$\Omega\times(I\Omega)$ —— Coriolis moment generated by centrifugal effects due to the rigid rotation.

2.4.3.2 In the hull-fixed coordinate system, the moment of inertia tensor is a diagonal matrix (disregarding products of inertia), i.e.:

$$I=\begin{pmatrix} I_{x'x'} & 0 & 0 \\ 0 & I_{y'y'} & 0 \\ 0 & 0 & I_{z'z'} \end{pmatrix}$$

where: $I_{x'x'}$ —— moment of inertia about the x'-axis (roll), in kg·m²;

$I_{y'y'}$ —— moment of inertia about the y'-axis (pitch), in kg·m²;

$I_{z'z'}$ —— moment of inertia about the z'-axis (yaw), in kg·m².

2.4.3.3 The total external moment acting on the hull mainly includes the hydrodynamic moment $M_{\text{hydro}}$, the restoring moment $M_{\text{rest}}$ caused by gravity and buoyancy, and the moments from other external forces (such as propeller forces, mooring forces, etc.) denoted as $M_{\text{ext}}$. The relationship is given by:

$$\sum M = M_{\text{hydro}} + M_{\text{rest}} + M_{\text{ext}}$$

where: $M_{\text{hydro}}$ —— hydrodynamic moment, in N·m, obtained by integrating pressure and viscous shear stress over the wet surface of the hull;

$M_{\text{rest}}$ —— restoring moment, in N·m, resulting from the lever arm difference between gravity and buoyancy, serving as the primary restoring moment for roll and pitch motions;

$M_{\text{ext}}$ —— moment of other external forces, in N·m, (propellers, mooring forces, etc.).

By solving the above-mentioned equation sets, the displacement, velocity, attitude angles, and angular velocities of the hull at any given time can be determined. If required, sectional loads can also be obtained by means of similar equilibrium relationships involving forces and moments.

## Section 5 WAVE GENERATION AND ABSORPTION THEORY

### 2.5.1 General Requirements

2.5.1.1 The viscous flow calculation of ships moving in waves and wave loads is to generate incident waves that are in line with actual working conditions, effectively absorb out of domain waves, and avoid reflected waves interfering with the flow field. Wave generation is mainly based on the regular and irregular waves of linear wave theory (Airy waves) and nonlinear wave theory (Stokes waves), which suppress wave reflection and maintain waveform stability through damping or wave force methods.

### 2.5.2 Linear Waves (Airy Waves)

2.5.2.1 Linear wave theory (Airy waves) is applicable for small wave steepness ($H/\lambda\leq 0.05$, where $H$ is wave height and $\lambda$ is wavelength). Wave motion is described by velocity potential satisfying the following dispersion relation:

$$\omega^2 = gk\tanh(kh)$$

where: $\omega$ —— wave circular frequency, in rad/s;

$h$ —— water depth, in m;

$k$ —— wave number, in rad/m;

$g$ —— gravitational acceleration, taken as 9.81m/s²;

$\tanh(kh)$ —— hyperbolic tangent function. In deep water ($h \geq \lambda/2$), $\tanh(kh) \approx 1$, and the dispersion relation simplifies to $\omega^2 = gk$; in shallow water ($h \leq \lambda/20$), $\tanh(kh) \approx kh$, and the dispersion relation simplifies to $\omega^2 = gk^2 h$.

2.5.2.2 The free surface wave height $\eta(x,t)$ is expressed as:

$$\eta(x,t) = \frac{H}{2}\cos(kx - \omega t)$$

where: $H$ ——wave height, in m;

$k$ —— wave number, in rad/m;

$\omega$ —— wave circular frequency, in rad/s;

$t$ —— time, in s.

**2.5.3 Nonlinear Waves (Fifth-Order Stokes Waves)**

2.5.3.1 When wave steepness is large ($H/\lambda > 0.05$), linear wave theory (Airy waves) introduces significant errors, and requires the use of nonlinear wave theories, of which, the fifth-order Stokes wave theory can be used to correct the velocity potential, wave height and velocity field due to high accuracy and the adaptability to medium to high wave steepness ($H/\lambda \leq 0.12$) by taking the considering of nonlinear wave interactions. The free surface wave height $\eta(x,t)$ for the fifth-order Stokes waves is given by:

$$\eta(x,t) = \frac{H}{2}\cos\theta + \frac{3}{8}\varepsilon H\cos 2\theta + \frac{15}{64}\varepsilon^2 H\left(1 + \frac{3}{2}\cosh^2(kh)\right)\cos 3\theta + \frac{35}{256}\varepsilon^3 H\left(2 + 5\cosh^2(kh)\right)\cos 4\theta + \cdots$$

where: $\theta$ —— wave phase, in rad, $\theta = kx - \omega t$;

$\cosh(kh)$ —— hyperbolic cosine function; other parameters are the same as in linear wave theory. This expression can accurately describe the nonlinear characteristics of peak sharpening and valley flattening through high-order nonlinear correction, which is more in line with the actual wave shape.

2.5.3.2 The velocity potential $\phi(x,z,t)$ for the fifth-order Stokes waves is expanded up to $\varepsilon^5$ terms as follows:

$$\phi(x,z,t) = \frac{gH}{2\omega}\frac{\cosh[k(z+h)]}{\cosh(kh)}\cos\theta + \frac{3gH\delta}{8\omega}\frac{\cosh[2k(z+h)]}{\cosh^2(kh)}\cos 2\theta + \frac{15gH\delta^2}{64\omega}\frac{\cosh[3k(z+h)]}{\cosh^3(kh)}\left(1 + \frac{3}{2}\cosh^2(kh)\right)\cos 3\theta + \cdots$$

where: $\phi$ —— velocity potential, in m²/s;

$g$ —— acceleration of gravity, taken as 9.81m/s$^2$;

$H$ —— wave height, in m;

$k$ —— wave number, in 1/m;

$\omega$—— wave circular frequency, in rad/s;

$\theta$—— phase, in rad, taken as $\theta = kx - \omega t$ ;

$\delta$ ——wave steepness, taken as $\delta = kH / 2$ .

### 2.5.4 Irregular Waves

2.5.4.1 The actual sea conditions are mostly irregular waves, characterized by a series of regular waves with different frequencies, wave heights, and phases superimposed. Irregular wave generation is generally based on the principle of linear superposition, combined with Pierson Moskowitz (P-M) spectrum or JONSWAP spectrum, to generate irregular waves that conform to actual sea conditions.

2.5.4.2 Linear superposition of irregular waves. The wave height $\eta(x, t)$, velocity potential $\varphi(x, z, t)$, and velocity components $u(x, z, t)$ and w$(x, z, t)$ of irregular waves are obtained by superposing $N$ regular waves with different frequencies. Linear Airy waves are usually used, while Stokes waves can be used in nonlinear scenarios.

$$\eta(x,t) = \sum_{n=1}^{N} \eta_n \cos(k_n x - \omega_n t + \varepsilon_n) \ , \qquad \text{for wave height superposition}$$

$$\phi(x,z,t) = \sum_{n=1}^{N} \phi_n(x,z,t) = \sum_{n=1}^{N} \frac{g\eta_n}{\omega_n} \frac{\cosh[k_n(z+h)]}{\cosh(k_n h)} \cos(k_n x - \omega_n t + \varepsilon_n) \ , \quad \text{for velocity potential superposition}$$

where: $N$—— number of superposed regular waves, usually ranging from 50 to 200; larger $N$ yields a more accurate representation of actual sea conditions;

$\eta_n$—— wave height of the $n^{\text{th}}$ regular wave;

$k_n$—— wave number of the $n^{\text{th}}$ regular wave;

$\omega_n$—— angular frequency of the $n^{\text{th}}$ regular wave;

$\varepsilon_n$—— random phase of the $n^{\text{th}}$ regular wave (uniformly distributed between 0 and 2π), used to simulate the randomness of irregular waves.

2.5.4.3 Wave Spectrum. The energy distribution of irregular waves is determined by the wave spectrum, generally by the means of either the P-M spectrum or the JONSWAP spectrum.

(1) The expression for the P-M spectrum is as follows:

$$S(\omega) = \frac{5}{16} H_s^2 \omega_p^4 \omega^{-5} \exp\left\{ -\frac{5}{4} \left( \frac{\omega}{\omega_p} \right)^{-4} \right\}$$

where: $S(\omega)$—— wave spectrum density, in m²·s;

$H_s$ —— significant wave height, in m;

$\omega_p$ —— spectral peak frequency, in rad/s;

$T_p$ —— spectral peak period, in s;

$\omega$—— wave circular frequency, in rad/s.

(2) The expression for the JONSWAP spectrum is as follows:

$$S(\omega) = (1 - 0.287\ln\gamma)\frac{5}{16}H_s^2\omega_p^4\omega^{-5}\exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right)\gamma^{\exp\left(-\frac{(\omega-\omega_p)^2}{2\sigma^2\omega_p^2}\right)}$$

where: $\omega_p$—— spectral peak frequency, in rad/s;

$\gamma$—— spectral peak enhancement factor, $\gamma$=1.0~7.0;

$\sigma$—— spectral width parameter, $\sigma$ = 0.07 for $\omega \leq \omega_p$, $\sigma$=0.09 for $\omega > \omega_p$.

# CHAPTER 3 DIRECT CALCULATION OF NONLINEAR SHIP WAVE LOADS

## Section 1 GENERAL PROVISIONS

### 3.1.1 General Requirements

3.1.1.1 This Chapter specifies the detailed requirements for calculating nonlinear ship wave loads based on CFD methods.

3.1.1.2 For viscous flow-based ship wave load calculations, CCS-recommended software is generally to be used. If other software or solvers are employed, prior agreement from CCS is required.

3.1.1.3 Viscous flow-based ship wave load calculations are generally to provide time history curves of motion response and hydrodynamic pressure, and combine these with mass distribution data to determine sectional wave loads.

3.1.1.4 The specific flowchart for viscous flow-based ship wave load calculations is shown in Figure 3.1.1.4. The process mainly includes:

(1) pre-processing: establishing the geometry model and performing initial settings;

(2) basic setup during calculation: defining the computational domain, boundary conditions, environmental inputs, loading conditions, attributes of ship's center of gravity moments of inertia, as well as input and output monitoring parameters;

(3) post-processing after calculation: extracting hydrodynamic pressures, analyzing segment load conditions, processing motion and load data, so as to obtain wave load time history curves.

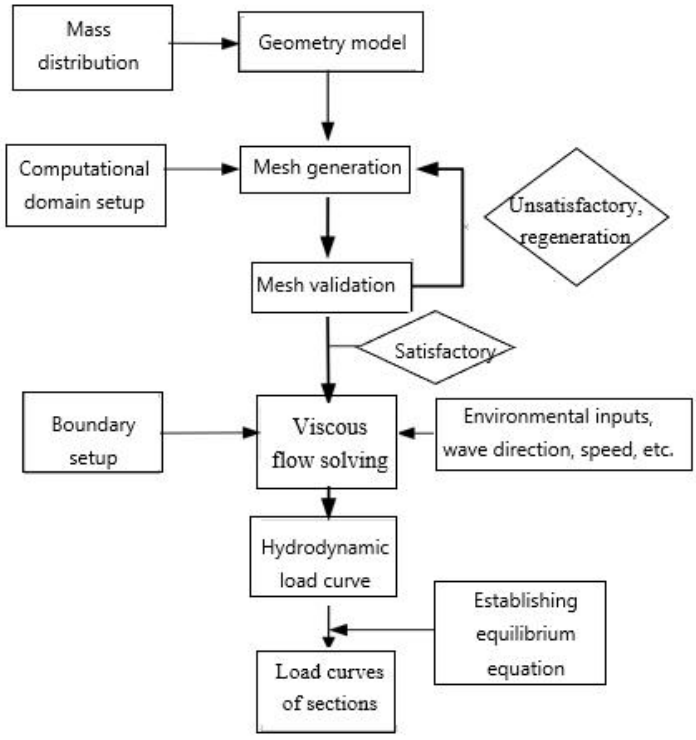



**Figure 3.1.1.4 Calculation Flowchart**

## Section 2 COMPUTATIONAL GEOMETRY MODEL AND SETUP

### 3.2.1 Computational Geometry Model

3.2.1.1 A geometry model is to be established first for viscous flow numerical calculations. In general, the geometry model is to be accurately modeled in three dimensions according to ship's line diagram, offsets, general arrangement, etc. to precisely reflect the ship's liner characteristics and appendage arrangements (such as anti-rolling fins and keels). The model surfaces are to ensure smooth continuity, forming a fully enclosed solid to avoid computational errors caused by geometric defects. The geometry model is to be in a standard 3D data format such as STEP, IGES, or STL.

3.2.1.2 If green waves, side slamming, or fluctuating pressure effects need to be considered, corresponding geometric models of superstructures and above-deck sections are to be established.

3.2.1.3 For model-scale calculations, the scale ratio is to be determined according to calculation objectives, generally referring to the ship model scale used in tank test. For the calculation of actual ship scale, a full-scale model is to be established, with appropriate wall treatments applied based on conditions such as Reynolds number.

### 3.2.2 Computational Domain Setup

3.2.2.1 The purpose of calculation for the ship in calm water domain is to determine the hydrostatic loads and model configuration under initial conditions. The calm water domain settings are shown in the following table (using symmetric boundaries).

**Computational Domain Settings (Calm Water)** **Table 3.2.2.1**

| Boundary | Recommended Dimension | Minimum Dimension |
|---|---|---|
| Inlet (forward of bow) | 1.5~2.0 *L* | 1.0 *L* |
| Outlet (aft of stern) | 3.0~5.0 *L* | 2.0 *L* |
| Side boundary | 1.5~2.0 *L* | 1.0 *L* |
| Bottom boundary | 1.5~2.0 *L* | 1.0 *L* |
| Top boundary | 0.5~1.0 *L* | 0.3 *L* |

3.2.2.2 When considering wave propagation, the computational domain can be divided according to the Practical Guidelines for Ship CFD Applications recommended by ITTC (International Towing Tank Conference), taking into account the computation time and resource availability. A recommended domain layout with overlapping grids is illustrated in Figures 3.2.2.2 and Table 3.2.2.2. A damping and attenuation zone is to be provided at the outlet of the background mesh, with a length of at least 1.5 times the wavelength. Either force-based or viscous damping methods may be selected to prevent wave reflections at the boundaries from affecting the flow field simulation. Where wave attenuation is significant, a wave amplification region may be introduced to enforce desired wave behavior; this region is recommended to be 1.0–1.5 times the

wavelength.

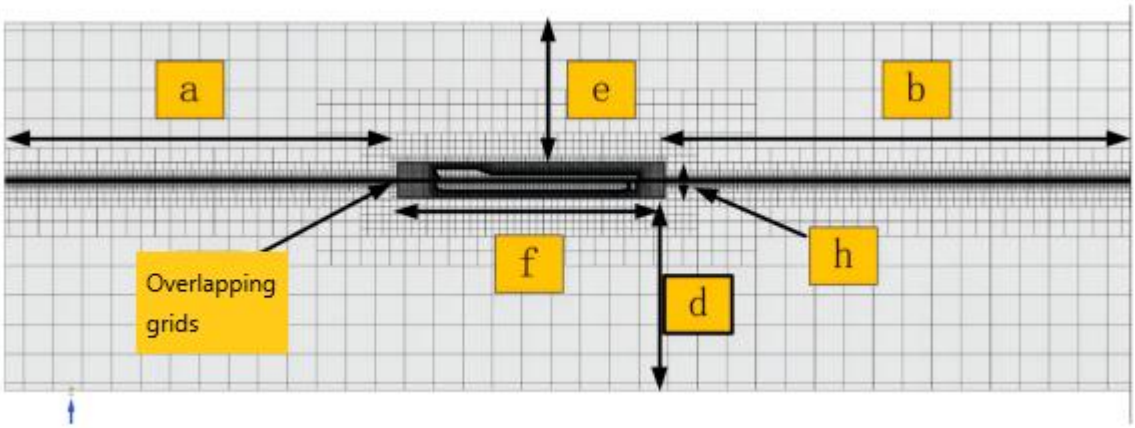



Figure 3.2.2.2(1) Longitudinal Schematic of Computational Domain

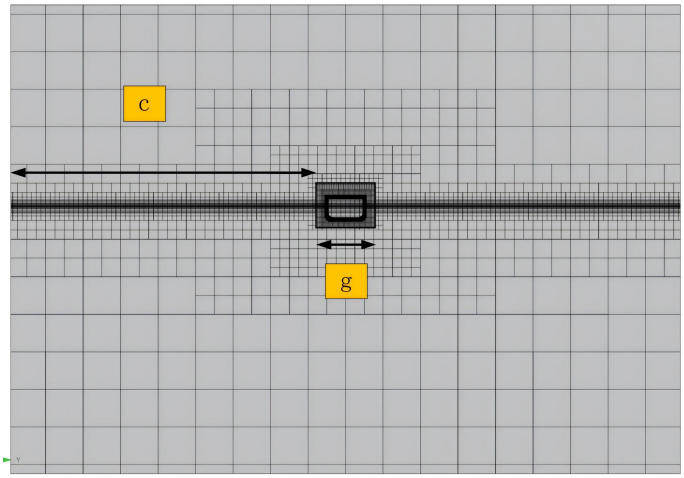



Figure 3.2.2.2(2) Transverse Schematic of Computational Domain

**Computational Domain Settings (Waves)** **Table 3.2.2.2**

| Boundary | Recommended Dimension | Minimum Dimension |
|---|---|---|
| Inlet (ahead of overlap region) a | 1.1~2.0 *L* | 1.0 *L* |
| Outlet (aft of stern) b | 3.0~5.0 *L* | 2.0 *L* |
| Side boundary c | 1.5~2.0 *L* | 1.0 *L* |
| Bottom boundary d | 1.5~2.0 *L* | 1.0 L |
| Top boundary e | 0.5~1.0 *L* | 0.5*L* |
| Overlap region (*x*-direction) f | 1.25~1.5*L* | 1.25*L* |
| Overlap region (*y*-direction) g | 1.5~3*B* | 1.5*B* |
| Overlap region (*z*-direction) h | 2~6*D* | 2*D* |

## Section 3 MESH GENERATION AND VALIDATION

### 3.3.1 General Principles of Mesh Generation

3.3.1.1 The mesh serves as a discretized spatial solution element, with types including structured grids (multi-block structured grids), unstructured grids, and hybrid grids. Mesh element types include tetrahedra, hexahedra, wedges, and pyramids. It is recommended to use a cutting-body mesh generator to construct the hexahedral elements of target dimensions, thereby achieving improved computational accuracy and convergence.

3.3.1.2 Meshing is to accurately resolve all important features of the flow field, including wall boundary layers, free-surface wave patterns, bow breaking waves, and stern wake, etc. Generally, it is recommended that the mesh size on the hull surface Δs be taken as $(0.002\sim 0.005)L$.

3.3.1.3 For regions with significant geometric variations (e.g., bulbous bow, bilge, rudder) and critical flow field regions (e.g., free surface, boundary layer, wake zone), mesh refinement is to be applied to accurately represent the geometry and capture the critical flow characteristics. Boundary layer mesh, with 5-15 layers and a growth rate of 1.1-1.5, can be adjusted appropriately according to the selected turbulence model.

3.3.1.4 The mesh in the free-surface region is to meet the requirements specified in Table 3.3.1.

**Free-Surface Meshing** **Table 3.3.1.4**

| Parameter | Recommended Value | Maximum Value |
|---|---|---|
| Mesh size in *x*-direction | 1/80 to 1/150 of wavelength | 1/40 of wavelength |
| Mesh size in *y*-direction | 1/80 to 1/150 of wavelength | 1/40 of wavelength |
| Mesh size in *z*-direction | 1/12 to 1/40 of wave height | 1/8 of wave height |

### 3.3.2 Mesh Quality Requirements

3.3.2.1 Mesh quality is to be checked to ensure no negative volumes or excessively distorted mesh, and that orthogonality and volume variation rate remain within acceptable ranges. Common CFD mesh evaluation criteria are shown in Table 3.3.2.1.

**MESH EVALUATION CRITERIA** **Table 3.3.2.1**

| Quality Indicator | Ideal Range | Acceptable Range | Undesirable Range |
|---|---|---|---|
| Aspect Ratio | <10 | <100 | >1000 |
| Distortion | <0.25 | <0.7 | >0.85 |
| Orthogonality | >0.9 | >0.2 | <0.1 |
| Volume variation rate | <2 | <5 | >10 |

### 3.3.3 Mesh Convergence Verification

3.3.3.1 At least three different mesh sets — coarse, medium, and fine — are to be used for convergence verification in numerical calculations. The coarse mesh is used for preliminary analysis. The medium mesh serves as the reference grid and can be generated by scaling up $1/\sqrt{2}$ the coarse mesh. The fine mesh is primarily used for convergence assessment and can be generated by scaling up $1/\sqrt{2}$ the medium mesh. Mesh convergence is mainly determined by ensuring that changes in key physical quantities (such as moments) are less than 2% and that the Grid Convergence Index (*GCI*) is below 5%. *GCI* is calculated by the following formula:

$$GCI=\frac{F_s|\varepsilon|}{r^p-1}$$

where: $\varepsilon$ —— coefficient, $\varepsilon=(f_2-f_1)/f_1$;

$f_2$ —— physical quantity from medium mesh;

$f_1$ —— physical quantity from fine mesh;

$f_3$ —— physical quantity from coarse mesh;

$F_s$ —— safety factor, typically to be taken as 1.25;

$r$ —— mesh refinement ratio, to be taken as $\sqrt{2}$ . The convergence order $p$ is obtained by the following formula:

$$p=\frac{In\left|\frac{f_3-f_2}{f_2-f_1}\right|}{Inr}$$

3.3.3.2 A grid convergence study is to be conducted for at least one condition to assess the dependence of calculation results on mesh resolution, thereby establishing an optimal meshing.

## Section 4 CALCULATION CONDITION SETUP

### 3.4.1 General Requirements

3.4.1.1 The basic calculation conditions for ship wave load analysis include regular wave and irregular wave conditions under typical loading cases.

### 3.4.2 Loading Conditions

3.4.2.1 Generally, at least one condition is to be selected based on the loading manual such that the maximum hogging or sagging bending moment in still water is achieved, to serve as the calculation condition.

3.4.2.2 The comparison data between three-dimensional hull geometry model and hydrostatic calculations are to be provided, with comparison data including at least waterline length, breadth, molded depth, wetted surface area under the calculation condition, molded displacement volume, longitudinal position of the center of buoyancy, vertical position of the center of buoyancy, and hydrostatic bending moment. The relative error of the molded displacement volume is not to exceed 0.3%, and the absolute error of the longitudinal position of the center of buoyancy is not to exceed 0.1%*L*. Additionally, the mass distribution and hull moments of

inertia need be verified to ensure consistency, so that the relative error of the maximum hydrostatic bending moment does not exceed 5%.

### 3.4.3 Regular Wave Calculation Conditions

3.4.3.1 Regular wave conditions are be defined according to actual engineering requirements, including wave direction angle, ship speed, wave height, time step, and total duration.

3.4.3.2 Regular waves may be generated by means of either first-order Airy wave theory or fifth-order Stokes wave theory. For small-amplitude waves, reference can be made to 2.5.2 of the Guidelines regarding linear waves (Airy waves). If nonlinear effects are considered, fifth-order Stokes waves are recommended; specific details can refer to 2.5.3 of the Guidelines on nonlinear waves (fifth-order Stokes waves).

3.4.3.3 The minimum simulation duration is generally to be 20 wave cycles. Unstable time periods are to deducted according to the output time history curve.

### 3.4.4 Irregular Wave Calculation Conditions

3.4.4.1 Irregular wave conditions are to be defined according to actual engineering needs, including wave direction angle, ship speed, significant wave height, spectral peak period, number of frequency samples, time step, and total duration.

3.4.4.2 Generation of irregular waves is described in 2.5.4.1 and 2.5.4.2 of the Guidelines.

3.4.4.3 The sea conditions are to be selected by means of IACS Rec. 34 North Atlantic wave scatter diagrams or region-specific wave scatter diagrams, or alternatively, based on actual operating sea areas and regional wave spectra. Commonly used wave spectra are listed in 2.5.4.3 of the Guidelines.

3.4.4.4 For full-scale calculations, the minimum simulation duration is generally to be 30 to 60 minutes, with a statistical convergence period covering at least 200 wave cycles. For model-scale calculations, the minimum simulation duration is to be converted according to similarity criteria. Unstable time periods are to deducted according to the output time history curve.

## Section 5 SOLUTION SETUP

### 3.5.1 General Requirements

3.5.1.1 When calculating ship wave loads, boundary conditions, time step, turbulence models, and other parameters are to be properly set, and convergence of the solution is to be assessed.

### 3.5.2 Boundary Condition Setup

3.5.2.1 Boundary conditions are primarily determined based on the type of solver and computational requirements.

3.5.2.2 For inflow boundaries, velocity inlet is generally recommended; pressure outlet is specified at the outlet boundary. The ship surface is to be treated as a no-slip wall, while velocity inlets are to be applied to both sides, bottom, and top of the computational domain. If symmetric computation is required, the symmetry plane of the geometry in the simulation is to be defined as a symmetrical boundary. Water depth is to be setup according to 3.2.2 of this Chapter.

3.5.2.3 If overlapping regions are defined, the outer boundary of the overlapping mesh is to be set as an overlapping mesh boundary.

3.5.2.4 Damping and attenuation zones are to be applied at outlet boundaries to suppress wave reflections. A damping and attenuation zone with a length of 1.5 to 2 times the wavelength is generally recommended. If the wave region includes wave force amplification features, additional wave forces can be applied along the perimeter boundaries. Wave height monitoring is to be conducted near the hull, and correction are to be made to the wave inputs and settings accordingly.

3.5.2.5 Motion constraints: Releasing degrees of freedom during ship motion in waves allows calculation of loads on any cross-section via force and moment balance. However, releasing too many degrees of freedom often leads to instability and increased computational resources. Different constraint configurations yield different load results — for example, releasing heave and pitch enables calculation of vertical bending moment and shear force. If all six degrees of freedom are released, rudder force is to be applied at the stern to maintain equilibrium.

**3.5.3 Time Step Setting**

3.5.3.1 In viscous flow-based nonlinear ship load calculations, the Courant–Friedrichs–Lewy (CFL) number for time step selection is to satisfy the following condition:

$$CFL = \frac{|u_C|\Delta t}{\Delta x} < 1$$

where: $u_C$ —— relative velocity, in m/s;

$\Delta t$ —— time step, in s;

$\Delta x$ —— grid spacing in the $x$-direction, in m.

3.5.3.2 While ensuring that the CFL number remains below 1, the time step is to be further adjusted according to actual needs.

3.5.3.3 If monitoring loads (slamming, green waves, etc.) is required, the time step is to be further reduced.

**3.5.4 Turbulence Model**

3.5.4.1 For viscous flow-based wave load calculations, the SST k-ω model is generally used. Alternatively, RNG (Renormalization Group) k-ε, realizable k-ε, or partial LES (Large Eddy Simulation) models may also be used.

**3.5.5 Solve Convergence Criteria**

3.5.5.1 In the process of viscous flow-based ship wave load calculation, convergence can be determined by analyzing residual changes in the calculation process. Common residuals include turbulent kinetic energy, dissipation rate, velocity, etc.. When a ship moves in waves, residuals usually cannot be reduced to very low level, so convergence is also to be evaluated by other physical quantities such as motion and moments.

3.5.5.2 Under regular waves, monitoring points for fluctuating pressure on the hull surface, free-surface wave height, and slamming/green waves are to approach periodic steady-state behavior.

3.5.5.3 Force/moment monitoring under regular waves: the resultant force and moment acting on the hull vary periodically and stably over time, without significant drift.

3.5.5.4 Periodic convergence under regular waves: For regular wave simulations, at least 5 to 10 wave cycles are to be computed to ensure that the motion response reaches a periodic steady state.

3.5.5.5 For irregular waves, specific determination is to be made based on the time history curve, and requirements in 3.4.4.3 are to be met.

### 3.5.6 Monitoring Point Setup

3.5.6.1 Monitoring points are generally to be set up according to the required monitoring items. Fluctuating pressure monitoring is to be conducted near the midship waterline; a series of wave height sensors are to be installed for monitoring at *L*/2 forward from the bow and around the ship; slamming monitoring is to be carried out on both sides of the bow, the bottom forward area, and the stern plate; and green water monitoring is to be carried out on the deck surface and superstructure walls.

3.5.6.2 The locations of monitoring points may be supplemented or adjusted as needed based on actual conditions.

## Section 6 WAVE LOAD OUTPUT

### 3.6.1 General Requirements

3.6.1.1 After completing the ship's wave load calculations, the hydrodynamic pressure on the shell surface, time history curves of ship motion and acceleration, and time history cuves of hull girder loads are generally to be output.

### 3.6.2 Hydrodynamic Pressure

3.6.2.1 Pressure monitoring points are generally to be arranged along the hull surface in the concerned areas. The time history curves at these points are to be statistically analyzed, and combined with computational results such as pressure contour plots for comprehensive evaluation, mainly including:

(1) Fluctuating pressure: pressure caused by hydrodynamic forces on the hull surface,generally mild;

(2) Slamming pressure: pressure resulting from intense relative motion between the ship and waves, commonly occurring at the bow, sides, and bottom forward;

(3) Green water pressure: impact pressure generated when water surges onto the deck or superstructure.

### 3.6.3 Forces and Moments Induced by Hydrodynamic Pressure

3.6.3.1 Forces and moments can be obtained by integrating the hydrodynamic pressure along the ship length using the following formula:

$$F_x(x) = \iint_{A(x)} p(x,y,z) n_x dA$$
$$F_y(x) = \iint_{A(x)} p(x,y,z) n_y dA$$
$$F_z(x) = \iint_{A(y)} p(x,y,z) n_z dA$$

$$M_x(x) = \iint_{A(x)} p(x,y,z)(z - z_{ref}) n_y dA$$
$$M_y(x) = \iint_{A(x)} p(x,y,z)(x - x_{ref}) n_z dA$$
$$M_z(x) = \iint_{A(x)} p(x,y,z)(x - x_{ref}) n_y dA$$

where: $A(x)$ —— wetted area of the cross-section at position *x*, in $m^2$;

$n_x$、$n_y$、$n_z$ —— vertical component of the normal vector;

$x_{ref}, y_{ref}, z_{ref}$ —— reference point for moment calculation, in m;

$p(x, y, z)$ —— hydrodynamic pressure, in Pa;

$F_i, i = x, y, z$ —— forces in three directions, in N;

$M_i, i = x, y, z$ ——moments in three directions, in Nm.

### 3.6.4 Motion and Acceleration

3.6.4.1 Based on the motion constraints defined in calculation conditions mentioned in 3.5.2.5, if a degree of freedom is released, the corresponding time history curve of motion can be output. Common motion time history curves at the ship's center of gravity include:

(1) translation and rotation: translation includes surge, sway, and heave; rotation includes roll, pitch, and yaw;

(2) velocity and angular velocity: velocity includes *x*-direction, *y*-direction, and *z*-direction velocities; angular velocity includes *x*-direction, *y*-direction, and *z*-direction angular velocities;

(3) acceleration and angular acceleration: acceleration includes *x*-direction, *y*-direction, and *z*-direction accelerations; angular acceleration includes *x*-direction, *y*-direction, and *z*-direction angular accelerations.

### 3.6.5 Hull Girder Wave Loads

3.6.5.1 Based on the ship's mass distribution, the forces and moments induced by hydrodynamic pressure, as well as the motion time history curves, the time history curves of wave loads at any cross-section of the ship can be determined by the following equilibrium equations:

$$\begin{pmatrix} Q_x \\ Q_y \\ Q_z \\ M_x \\ M_y \\ M_z \end{pmatrix} = -\begin{pmatrix} F_{extx} \\ F_{exty} \\ F_{extz} \\ M^A_{extx} \\ M^A_{exty} \\ M^A_{extz} \end{pmatrix} + \begin{pmatrix} m\left[\dot{u} + qw - rv - (x_G - x_A)(q^2 + r^2)\right] \\ m\left[\dot{v} + ru - pw + (x_G - x_A)(qp + \dot{r})\right] \\ m\left[\dot{w} + pv - qu + (x_G - x_A)(rp - \dot{q})\right] \\ I_x\dot{p} - I_{xy}(\dot{q} - rp) - I_{zx}(\dot{r} + pq) + (I_z - I_y)qr + I_{yz}(r^2 - q^2) \\ I_y\dot{q} - I_{yz}(\dot{r} - pq) - I_{xy}(\dot{p} + qr) + (I_x - I_z)rp + I_{zx}(p^2 - r^2) - m[(x_G - x_A)(\dot{w} + pv - qu)] \\ I_z\dot{r} - I_{zx}(\dot{p} - qr) - I_{yz}(\dot{q} + rp) + (I_y - I_x)pq + I_{xy}(q^2 - p^2) - m[(x_G - x_A)(\dot{v} + ru - pw)] \end{pmatrix}$$

where: $(\dot{u}, \dot{v}, \dot{w})$—— acceleration in the *x, y, z* directions, in m/s$^2$;

$(\dot{p}, \dot{q}, \dot{r})$ —— angular acceleration about the X, Y, Z axes, in rad/s$^2$;

$F_{ext}$—— external force due to hydrodynamic pressure, in N;

$M_{ext}$—— external moment due to hydrodynamic pressure, in Nm.

The symbols for vertical bending moment, vertical shear force, horizontal bending moment, horizontal shear force, and torque at any cross-section of the ship are shown in Figure 3.6.5.1, as described below:

(1) The vertical bending moment $M_y$ is positive when it induces tensile stress on the main deck (hogging moment), and negative when it induces tensile stress on the bottom (sagging moment).

(2) The vertical shear force $Q_z$ is positive when the resultant force acting behind the considered cross-section acts downward or when the resultant force acting ahead of the cross-section acts upward.

(3) The horizontal bending moment $M_z$ is positive when it induces tensile stress on the starboard side, and negative when it induces tensile stress on the port side.

(4) The torque $M_x$ is positive when the resultant moment behind the considered cross-section rotates in the

negative direction about the X-axis, or when the resultant moment ahead of the cross-section rotates in the positive direction about the X-axis.

(5) The horizontal shear force $Q_y$ is positive when the resultant force acting behind the considered cross-section acts toward the starboard side, or when the resultant force acting ahead of the cross-section acts toward the port side.

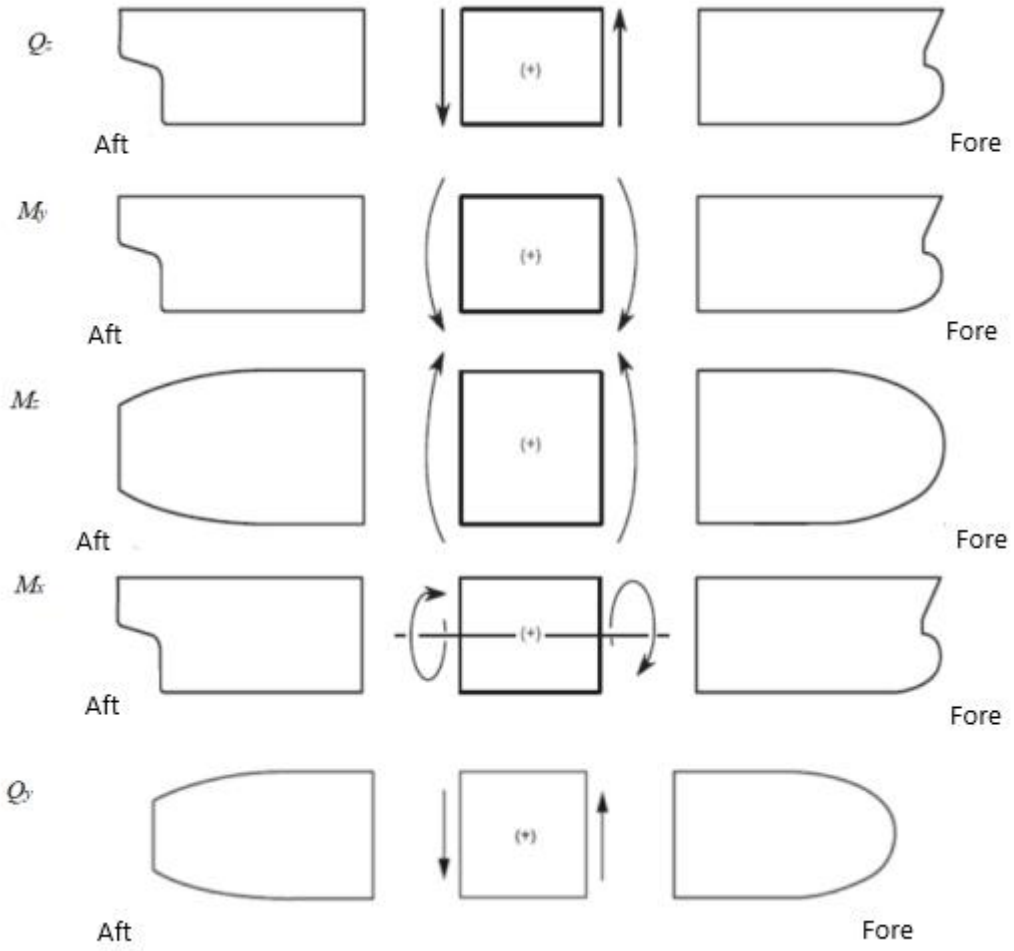



Figure 3.6.5.1 Symbols and Schematic Diagrams of Hull Girders at Any Transverse Sections