# Sea Effects Simulation in Submarine Autopilot Design

G. Cherio, M. Manzo – *Automation System – Avio S.p.A. – Italy*
S. Crupi – *Consultant - Italy*

**Abstract**

The developed autopilot is based on the theory of the Optimal Control and Kalman filtering, and provides computation for optimal Trim and Compensation to be actuated in order to minimise ship's drag. During depth change the ship moves along its main speed direction, the other components being zero.

**Improved performance** in depth keeping can be obtained by cost/effective reactions of the Autopilot to the external disturbances as the Sea State.
**Energy saving,** Rudder Machinery **low usage** and **noise reduction** can also be improved.

The wave motion causes some effects on the boat, the most significant being the forces applied to the hull and noise on the depth measurement.

The forces generate an actual movement of the boat, while the wave height added to average depth gives a non-true depth change, not corresponding to actual boat movement.

The investigation of these phenomena allows the design of high accuracy autopilot, minimising the activity of the control surfaces.

The simulation of these phenomena in the laboratory allows repeatability and observation of boat behaviour in autopilot control: for this reason, submarine and wave motion simulation are developed.

Sea simulation is based on the potential flow theory; it is possible to select the wave spectrum (Pierson-Moskowitz, Bretshneider, JONSWAP) and sea state (force); the simulated sea was applied to a specific submarine's hull modelled by the 3D Panel Modelling technique.

These studies give the possibility to identify any periodical movement of the boat: in autopilot design stage this allows to avoid any non-necessary controller reaction, saving energy, reducing useless rudders machinery wear and noise generation.

## 1 Sea State theory

Wave motion can be represented through a statistical approach. Waveheight is a random phenomenon that was classified in statistical mode through the waveheight power spectrum.

Historically, the waveheight and the period were observed in different ocean locations and appropriate power spectra were identified, whaich represents, through a random process, the statistically waveheight observed.

Different types of spectra were proposed:

- One parameter spectrum: that proposed by Pierson-Moskowitz, in which the significant waveheight is specified;

- Two parameters spectrum: that proposed by Bretschneider, in which the significant waveheight and period are specified.

  Even if the two significant wave's parameters, its height and its period, can be specified, they are not completely independent: they are correlated to each other, so it is not possible to specify a very high waveheight and, at the same time, a very small wave period (or a very small wave length).

The computation provides sea waves of an irregular, non-sinusoidal, single directional sea state.

### 1.1 Statistical Waves description

#### 1.1.1 Pierson-Moskowitz sea spectrum

A "one parameter" spectrum: the significant waveheight; it is for a fully developed wind-driven sea; it is defined by the following equations:

$$\varphi_\zeta = \frac{A}{\omega^5} e^{\frac{-B}{\omega^4}} \qquad [m^2 s]$$

where

A = 8.10e-3g$^2$ =0.779

$$B = \frac{3.11}{{H_{1/3}}^2}$$

### 1.1.2 Bretschneider Sea Spectrum

A "two parameter" spectrum: the significant waveheight and the modal period; it is defined by the following equations:

$$\varphi_\zeta = \frac{1.25}{4} \frac{{H_{1/3}}^2}{\omega \left( \frac{\omega T_s}{2\pi} \right)^4} e^{\frac{-1.25}{\left( \frac{\omega T_s}{2\pi} \right)^4}} \qquad [m^2 s]$$

where:

$$\frac{2\pi}{T_s} = 0.4 \sqrt{\frac{g}{H_{1/3}}}$$

that is:

$$T_s = \frac{2\pi}{0.4 \sqrt{\frac{g}{H_{1/3}}}} = \frac{2\pi}{0.4} \sqrt{\frac{H_{1/3}}{g}} = 5.015 \sqrt{H_{1/3}}$$

The spectrum becomes of "one parameter" type and coincident with that of Pierson-Moskowitz. The connection between the significant waveheight and its period has to be in accordance with the previous relationship.

## 1.2 Waveheight and wave velocity

### 1.2.1 Instant waveheight generation

The waveheight and other parameters are generated at a point of defined coordinates adding the contribution of single sinusoids with different amplitude (obtained from the amplitude spectrum), different frequency and different phases.

The amplitude of the sinusoid $\omega_i$ is defined by:

$$\zeta_{ai} = \sqrt{2 S(\omega_i) \Delta\omega} = \sqrt{2 \int_{\omega_i - \frac{\Delta\omega}{2}}^{\omega_i + \frac{\Delta\omega}{2}} S(\omega) d\omega}$$

The instantaneous surface elevation is defined by:

$$h(x,t) = \sum_{i=1}^{N} \zeta_{ai} \cos(k_i x - \omega_i t + \phi_i)$$

where

$$k_i = \frac{2\pi}{\lambda_i} = \frac{{\omega_i}^2}{g} \qquad \text{wave number}$$

and

$\phi_i$ is the phase of the component at frequency $\omega_i$ and it is selected in random way ;

The sea direction $\psi_{sea}$ means:

- The direction 0 means the sea is oriented from south to north, and so it develops along the X axis fixed to ground.
- The direction $\frac{\pi}{2}$ [rad] means the sea develops to east;
- The direction $\pi$ [rad] means the sea develops to south, an so on.

Figure 1 provides the used reference system.

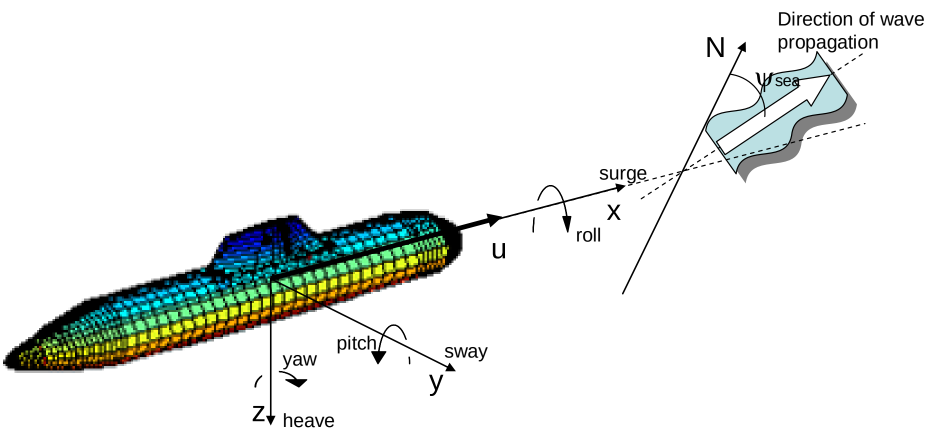


**Figure 1 - Reference systems for waveheight definition**

### 1.2.2 Wave velocity generation

The velocity vector, by its components u,w along the axes, at each point under the surface identified by its coordinates x,y,z, is evaluated by the following formulae:

$$u(x,z,t)=\sum_{i=1}^{N}\zeta_{ai}\omega_i e^{-k_i z}\cos(k_i x-\omega_i t+\phi_i)$$

$$w(x,z,t)=\sum_{i=1}^{N}\zeta_{ai}\omega_i e^{-k_i z}\sin(k_i x-\omega_i t+\phi_i)$$

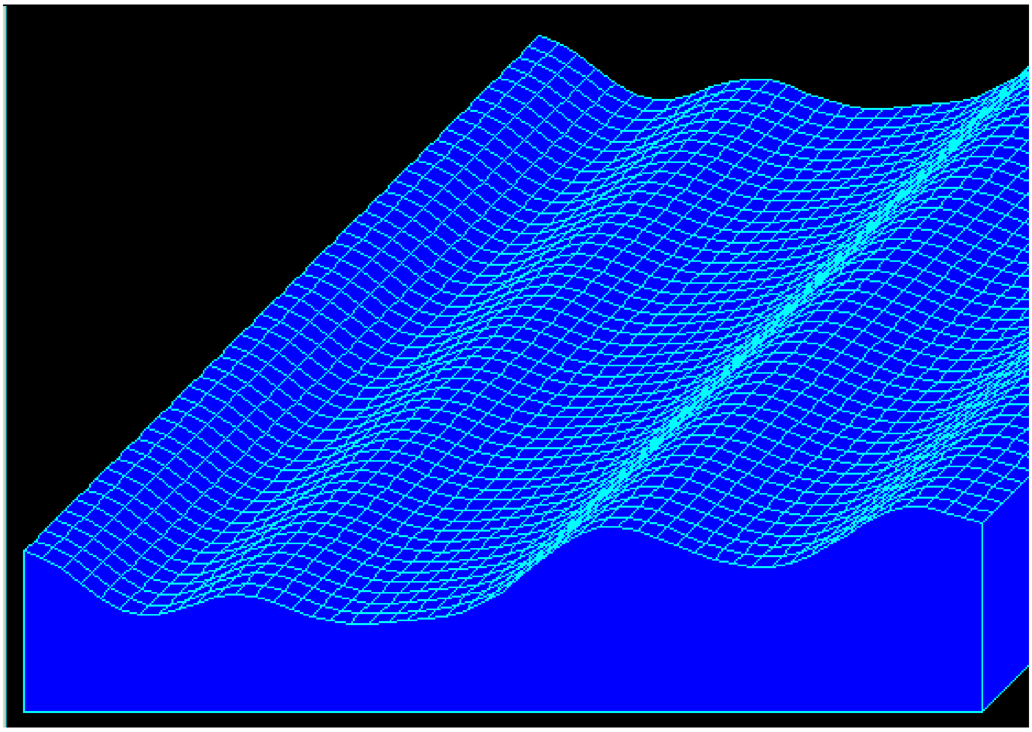

**Figure 2 – Snapshot of the Sea State real time simulation**

The graphical result of the Sea State simulation is shown in Figure 2, as from the Pierson spectrum, with a significant waveheight of 3m.

### 1.3 Sea load generation

The forces and moments due to the water on a rigid body are obtained from the integration of the pressure, *p*, over the submerged surface of the body:

$$\vec{F}=-\iint_S p\,\vec{n}\,dS$$

$$\vec{M}=-\iint_S p(\vec{r}\times\vec{n})dS$$

with

$\vec{n}$ = outward normal vector of the surface dS

$\vec{r}$ = position of the surface dS.

The waves are described by the velocity potential and have three components:

$$\Phi(x,y,z,t)=\Phi_r+\Phi_w+\Phi_d$$

$\Phi_r$ = radiation potential; represents the water movement and force (on the ship) due to the motion of a ship in calm water

$\Phi_w =$ undisturbed incident wave potential; represents wave movements without body

$\Phi_d =$ diffraction wave potential; represents wave deformation due to the body

The pressure is determined, via the linearised Bernoulli equation, from the potential theory by:

$$p = -\rho \frac{\partial}{\partial t}\Phi - \rho g z$$

$$p = -\rho\left(\frac{\partial}{\partial t}\Phi_r + \frac{\partial}{\partial t}\Phi_w + \frac{\partial}{\partial t}\Phi_d\right) - \rho g z$$

The forces and moments are:

$$\vec{F} = \rho \iint_S \left(\frac{\partial}{\partial t}\Phi_r + \frac{\partial}{\partial t}\Phi_w + \frac{\partial}{\partial t}\Phi_d + gz\right)\vec{n}\, dS$$

$$\vec{M} = \rho \iint_S \left(\frac{\partial}{\partial t}\Phi_r + \frac{\partial}{\partial t}\Phi_w + \frac{\partial}{\partial t}\Phi_d + gz\right)(\vec{r} \times \vec{n}) dS$$

that is:

$$\vec{F} = \vec{F}_r + \vec{F}_w + \vec{F}_d + \vec{F}_S$$

$$\vec{M} = \vec{M}_r + \vec{M}_w + \vec{M}_d + \vec{M}_S$$

Forces and moments have four components:

- Hydrodynamic forces (subscript *r*) or radiation forces
- Undisturbed incident wave or Froude-Krilov forces (subscript *w*)
- Diffraction wave forces (subscript *d*)
- Hydrostatic forces (subscript *s*)

The hydrostatic load is:

$$\vec{F}_S = \rho g \iint_S z\, \vec{n}\, dS$$

$$\vec{M}_S = \rho g \iint_S z(\vec{r} \times \vec{n}) dS$$

The forces are computed by discretisation of surface integrals.

The velocity potential for infinite water depth, for frequency $\omega_i$ and for undisturbed incident wave is:

$$\Phi_{wi} = -\frac{g\zeta_{ai}}{\omega_i} e^{-k_i z} \sin(k_i x - \omega_i\, t)$$

where:

$k_i = \frac{\omega_i^2}{g}$ is the wave number; this represents the connection between the wave number and the wave frequency.

Using the Bernoulli formula, the following formula representing the dynamic pressure (pressure variation) generated by the individual frequency of an undisturbed incident wave can be obtained:

$$p_{wi} = g\zeta_{ai} e^{-k_i z} \cos(k_i x - \omega_i\, t)$$

and its amplitude is independent from the ship's speed.

The dynamic pressure is in phase with the wave amplitude and decreases with the depth z by $e^{-k_i z}$.

The undisturbed incident wave on a surface gives the biggest part of wave excitation loads: the integral of the dynamic pressure on a wetted surface gives the force and the moment applied to the surface.

## 2 Hull Modelling by 3D Wireframe and Panels

The physical characteristics of a hull are given by the body plan. Based on the geometrical data available from these type of diagrams for a submarine, a finite element reticle was identified to generate a 3D wireframe of the hull, whose nodes positions were referred to a physical reference system with its origin located astern of the hull longitudinal axis.

Each node of the 3D wireframe was identified by its coordinates (x, y, z): the wireframe enabled the identification of 1564 elementary flat panels (quadrilateral elements in three dimensional problem) approximating the hull surface; there was no discontinuity among the panels, even if this is not important when the individual resultant force is applied to panel.

The number of panels was increased, and consequently their dimension was decreased, where the hull shape was quickly bending. The 3D wireframe covered the entire hull, the fin and the main appendages, while the hydroplanes were neglected**.**

Some views of the result of hull modelling are presented in Figure 3.

## 3 Sea Loads applied to the Submarine 3D Model

The resultant force evaluated for each panel was applied in its Centre of Gravity and oriented according to the normal unit vector of that panel.

The normal unit vector to the individual panel surface is defined to be positive when pointing into the fluid domain (outward the hull).

To have the full effect of the sea on the hull, together with the instant dynamic pressure effect, hydrostatic pressure was considered by its contribution ($-\rho g z$): this term influences hull movement on the z axis.

In the simulation the appropriate balance was given in order to make the submarine to reach its normal station while surfacing.

Sea loads are evaluated and applied to the hull model through the following process:

- The static and dynamic pressure caused by the wave motion is evaluated
- The pressure is applied to each elementary panel and the relevant force (for that panel) is evaluated
- The generated force is different from panel to panel, both in amplitude and direction, in order to consider its orientation in the three-dimensional-space, and it is evaluated taking into account the actual panel orientation
- The evaluation is extended to all the elementary panels defining the hull shape
- The resultant static force is obtained adding the contribution ($-\rho g z$) that provides the boats buoyancy, compensated by the boat weight
- The oscillating components, that are time-variant, are those providing the dynamic movement of the boat.

The computation of the undisturbed incident wave loads is executed in nearly real time, by a normal personal computer, with a submarine 3D model of 1564 panels.

The obtained result is a real time simulation of the boat behaviour under sea state as presented in the snapshot of Figure 4.

## 4 Improvement of real time simulator

The availability of a simulation of the load generated by the sea gives the possibility for upgrading the real time simulators by the additional forces and moments to be included in the mathematical boat model.

These additional terms act as sea disturbances in the mathematical equations describing the motion of the boat, providing a more realistic simulation of the boat behaviour under sea state.

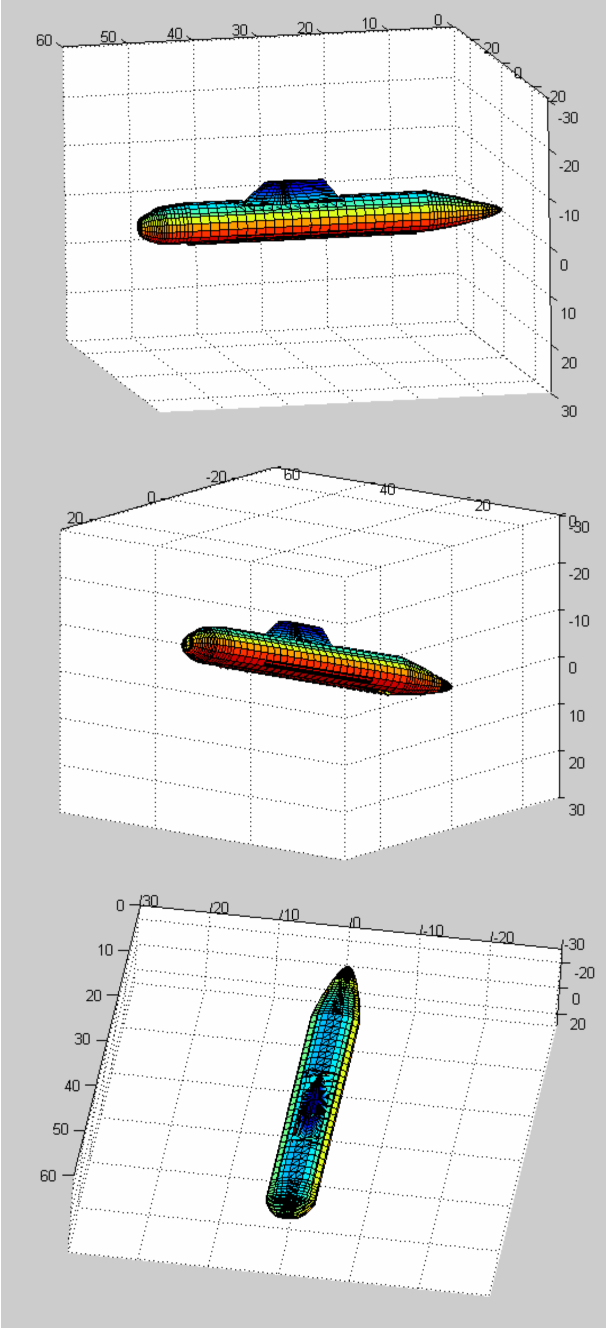

**Figure 3 – 3D Wireframe and Panelling of the Submarine Hull**

The simulation of sea state loads can be easily tuned to different hulls on the basis of the data available from the body plans for the specific projects. This activity basically consists in the adaptation of the wireframe to the specific hull geometry.

There are practical uses of a real time simulator including an effective simulation of the loads generated by the sea state:

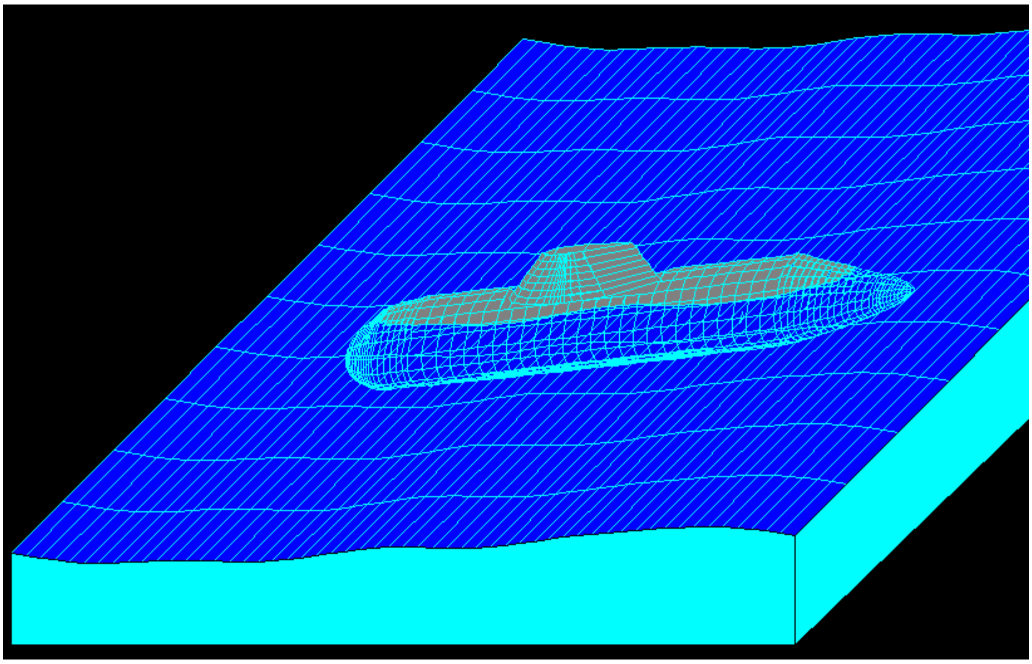

**Figure 4 - Snapshot of the 3D Submarine model under Sea State real time simulation**

- Control system design, to identify appropriate control strategy and for a more cost-effective tuning of the regulator under sea state, performed and preliminarily evaluated in laboratory

- Crew training by the dynamic simulators, for more effective training provided by simulation of the ship's behaviour more adherent to reality because of the improved mathematical model.

### 4.1 Controller design

A submarine under regular waves is subjected to different force components, the most significant being:

- First order wave forces, which produce an oscillatory motion about a mean level.

  These forces are an order of magnitude greater than the maximum force that can be exerted by the control surfaces; hence the submarine dominant motion in heave and pitch cannot be attenuated significantly by the control surfaces, unless the boat is at some distance from the surface and the effect of the waves is greatly attenuated.

  The autopilot has to be tuned to neglect these effects, because it would only cause a useless movement of the control surfaces, with ineffective hydraulic oil consumption and noise generation.

- Second order wave forces, which produce approximated constant force tending to broach the submarine.

  This force is comparable with the forces available from the control surfaces; in this case, autopilot reaction is appropriate and a small constant offset on the planes will counter this suction force: the boat will oscillate in depth about a constant mean driven by the first order forces.

The on board Depth Measuring System detects the water column over the sensor. The datum of the water column variation does not change either if it is due to the boat movement or to a wave.

A first rough distinction between the two causes can be obtained considering movement velocity: high frequency compared to the depth dynamic of the boat are certainly waves; the distinction is not so easy for frequency compatible with the depth dynamic of the boat.

In this case, sea state identification, its accurate estimation and filtering enable to distinguish the boat movement from that of the waves.

Furthermore it is possible to identify the oscillatory movement that cannot be compensated and in this case control surface movement is avoided.

The boat direction relative to the sea plays a fundamental role.

Low waveheight is generally associated to a short period: while a boat is moving in the same direction of the sea by a velocity comparable with that of the waves

these frequencies, that should be high, are detected by the boat sensors as comparable with the boat dynamic.

The encountered frequency is:

$$\omega_e = \omega_i - \frac{\omega_i^2 U}{g}\cos(\Psi_{Sea} - \Psi_{Ship})$$

with $\omega_e < \omega_i$ if the sea and the boat have the same direction, or even $\omega_e << \omega_i$ or $\omega_e < 0$ with the consequence that a low waveheight having an high natural frequency and a low relative frequency is detected as extremely low and assumed to be a boat movement.

Using depth sensors adequately located on the boat, and with the appropriate filtering of their signals will give the possibility of accurate sea state identification and, depending on the depth, it will be possible to avoid the tentative of wave following from the autopilot.

The availability of a simulator of wave motion enable to "measure" at convenient location of the boat the diving depth and to carry out the design stage of the regulator as we are on board.

The high repeatability of the simulated sea motion gives the possibility of accurate comparison sea for sea between different control strategies.

The sea motion estimation also gives the possibility to evaluate, while at periscope depth, the probability of uncontrolled emersion of the boat with the consequence of the boat being intercepted.

#### 4.1.1 Tuning of the controller gains

The availability of a real time simulation that takes into account the forces and moments generated by an irregular sea is useful to the control designer to better analyse the behaviour of the specific boat and to carry out a tuning stage of the autopilot to the different sea loads effects, and enabling to identify the best control strategy, simplifying the final tuning at the sea trial.

### 4.2 Sea State simulation for training

The real time simulation that takes into account the loads generated by an irregular sea can be satisfactorily used to drive the dynamic simulators for crew training .

The sea-load software is part of the software of the mathematical model of the boat; in this way the contribution of the sea loads are included in the calculation of the boat's motion, generating the appropriate control signals to drive the dynamic actuators for a realistic motion.

The additional sea effects as non-phenomenological aspect allows the training system to be more realistic. It allows more realistic training because the trainees have to "filter" the effects of wave motion as if they were on board.

The effect changes depending on boat speed, its direction relative to the wave motion and average depth.

Training at periscope depth is particular important: without wave motion simulation training would be downgraded to deep diving training.

The perfect repeatability allows recording, studying and evaluating trainees behaviour and eventually correct defective manoeuvres, repeating them reproducing exactly the environmental condition.

## 5 Impact on surface vessel control

The results of this development for submarines are easily applicable to surface ships.
In this case it is only necessary to tune the 3D wireframe to the specific geometry of the surface ship's hull under analysis. The simulation software will automatically apply sea loads to the newly identified hull's panels.

Sea loads simulation is useful for different applications in the field of the surface ships.

It is possible to estimate the oscillatory effects avoiding reacting by trying to compensate them; on the opposite the ship is left free to be rocked by the wave motion: this is particularly important for surface vessels in order to reduce rudders oscillations, in order to reduce rudders wear and increase cruising range, thus decreasing fuel consumption.

Time simulation of sea-keeping enables to obtain the forces distributed on the hull due to the ship's movement and wave effect.

It is possible to study the behaviour of the hull and its stability in extreme condition, and the strain to which the structure is subjected.

The improvement of the knowledge on this subject leads to evaluation programs of the structural strain based on the depth measurement carried out on board.

Sea state simulation is very important, also in the track-keeping, dynamic positioning and stabilisation problems.

## 6 Conclusion

Loads generated by the sea were implemented by real time simulation software on the basis of the potential flow theory.

A physical model of a submarine hull was defined by software on the basis of the panel technique.

Sea loads were applied to each individual panel of the modelled submarine hull.

The result is a real time simulator that represents submarine motion under sea state.

This simulator is useful for:

- Tuning of the submarine autopilot during the design stage in order to obtain better performance in depth keeping, decrease hydraulic oil consumption and reduce noise generation, and design appropriate control strategies while under sea state

- Driving the dynamic simulator used for crew training in order to reproduce more realistic vessel behaviour for effective training.

The application is easily extendable to the field of surface vessels for multiple applications.

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