High Performance Computations in Ship Hydrodynamics

Dr. Igor. V. Tkachenko, Nikita V. Tryaskin, Sergey I. Chepurko
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Introduction

State Marine Technical University of St. Petersburg

- Faculty of Naval Architecture and Ocean Engineering
- Faculty of Natural and Social Sciences and Humanities
- Faculty of Marine Engineering
- Faculty of Marine Electronics and Control Systems
- Faculty of Business and Management

Faculty of Naval Architecture and Ocean Engineering:
- Departments - 10;
- Laboratories – 9;
- Research Institutes – 1;
- Research Educational Centers – 1.

The value of scientific financing - 3d place in Saint-Petersburg
CFD and Education

- **Disciplines:**
  - Boundary and layer theory;
  - Modern turbulent models;
  - Numerical Methods in fluid dynamics;
  - High Performance Computations in ship hydrodynamics.

- **Software:**
  - Ansys CFX, Fluent;
  - OpenFOAM.

- **Students works:**
  - Lab works;
  - Project works;
  - Diploma works.

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Example of laboratory work

Flow past step
Numerical investigations

- Homogeneous and heterogeneous flows past an bodies;
- Dynamics of bodies;
- Hydrodynamics of bodies near the solid and liquid boundaries;
- Ships propellers;
- Compressible flows;
- Internal flows;
- Geophysical flows.
Features of simulation of flows past marine objects in natural conditions

- High Reynolds number (Re > 10^7);
- Gas-liquid interface
- Stratification
- Interaction with ice

=> Turbulence modeling, grid resolution > 10^7
=> Wave motion, cavitation
=> Mixing, internal waves
=> Ice model
Mathematical models, hardware and services

- **Mathematical model:**
  - Unsteady Reynolds Averaged Navier-Stokes equations (URANS), Large Eddy Simulations (LES) equations, Hybrid Methods (DES);
  - URANS models (k-eps, k-omega, SST), LES models (Smagorinsky, DSM, DMM);
  - Volume of Fluid (VoF) and mixture fraction methods.

- **Hardware:**
  - University cluster of the SMTU (130 cores, 450 Gb RAM);
  - UniHub (Clusters of the ISP RAS, JSCC RAS, HP, 512-1024 cores).

- **Services:**
  - Open source SALOME - CAD;
  - Open source [OpenFOAM](http://openfoam.org) + ParaFOAM (FVM, SIMPLE, PISO, unstructured grids, MPI, CUDA) + Cloud Services;
  - Inhouse code [FlowFES](http://flowfes.org) + Paraview (FEM, projection method, unstructured grids, MPI).
Simulation of homogeneous flows past an bodies
Homogeneous flow past the cylinder

OpenFOAM, laminar flow, 2D, cylinder

Vector diagram

Re=4000

Velocity field

Steady laminar flow vs. Transient laminar flow for the mesh = 9600 cells
OpenFoam solver's: SimpleFoam & IcoFoam

C_

Re
Homogeneous flow past the sphere

Re=14062

Filed of the turbulent viscosity

Re=1.14 \times 10^6

Drag coefficient

<table>
<thead>
<tr>
<th>Re</th>
<th>$C_D^{\text{calc.}}$</th>
<th>$C_D^{\text{exp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>14062</td>
<td>0.36</td>
<td>0.4</td>
</tr>
<tr>
<td>1140000</td>
<td>0.179</td>
<td>0.12-0.18</td>
</tr>
</tbody>
</table>

FlowFES, LES-Smagorinsky, 3D, sphere

01.12.2017

Moscow, RAS
Homogeneous flow past the airfoil

OpenFOAM, RANS, 2D, Airfoil
Göttingen 92

Drag Coefficient $C_x$

Lift Coefficient $C_y$

$Re = 10^5$
Homogeneous flow past the wing

FlowFES, LES, 3D, NACA 0018, Ratio 1

Re=2.5\times10^6
Homogeneous flow past the spheroid

\( \alpha = 10^\circ \)

\( \alpha = 20^\circ \)

\( \alpha = 30^\circ \)

FlowFES, LES, 3D, spheroid 6:1

\( \text{Re} = 4.2 \times 10^6 \)

Vortex separation angle

Coefficient of the normal force

01.12.2017

Moscow, RAS
The motion of Wigley body on free surface

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>0.0046</td>
<td>0.0048</td>
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01.12.2017

Moscow, RAS
Simulation of the dynamics of marine vehicles
Pitch up maneuver of the spheroid

Vorticity

\[ \omega \]

FlowFES, Reference frame, LES, 3D, Spheroid 6:1

\[ u_0 \]

\[ \text{Re}=4.2 \times 10^6 \]

Tracers

\( t=0.92 \text{ sec} \)

\( t=2.08 \text{ sec} \)

\( t=3.09 \text{ sec} \)
Pitch up maneuver of the spheroid

\[ \alpha(t) = 0 \div 30^0 \quad \text{LES, Smagorinsky} \]

Evolution of the coefficients of normal force \( C_n \) and pitch-up moment \( C_m \).

Exp - Wetzel, 1997, SST - Kim et al., 2003, DES - Kotatpati-Apparao et al., 2003
Impact the wedge into compressible liquid (slamming)

OpenFOAM, URANS, VoF, 2D
Heave and pitch motions of gas-tanker on regular waves
Heave and pitch motions of semi-submersible platform on regular waves

ROA of heave motion
Heave and pitch motions of Wigley body on regular waves

Heave and pitch motions at $Fr = 0.3$
Heave and pitch motions of Wigley body on regular waves: response amplitude operator (RAO)

ROA of heave motion  
ROA of pitch motion

Fr = 0.3
Heave and pitch motions of Wigley body on regular waves: phase shift

Phase shift of heave motion

Phase shift of pitch motion

Fr = 0.3
Heave and pitch motions of container ship S-175 on regular waves at drift angle 180°

Heave and pitch motions at Fr = 0.275

ROA of heave motion

ROA of pitch motion
Heave and pitch motions of container ship S-175 on regular waves at drift angle 150°

Heave, pitch and roll motions at Fr = 0.275

ROA of pitch motion

ROA of roll motion

ROA of heave motion
Heave and pitch motions of container ship S-175 on regular waves at drift angle 90°

Heave, pitch and roll motions at $Fr = 0.275$

ROA of heave motion

ROA of roll motion
Simulation of the flow past ship propellers
Ship propeller in uniform flow

Propeller Series B:
Blades - 5,
Expanded BAR - 0.6,
Nominal pitch - 0.6

TKE: 
\[ a - J = 0.1, \frac{k}{U^2} = 2; \ b - J = 0.3, \frac{k}{U^2} = 0.08; \ c - J = 0.5, \frac{k}{U^2} = 0.01 \]
Ship propeller in uniform flow

Thrust and torque coefficients

![Graphs showing thrust and torque coefficients for experiment and CFD simulations.](image-url)
Cavitation on ship propeller

Propeller Series E779

Experiment

CFD

Moscow, RAS
01.12.2017
The sea conditions and maritime technical objects: waves, stratification, ice
Stratified flow past the sphere

The turbulent wake

FlowFES, LES, MF, 3D, shpere

- Turbulent mixing
- Collaps of turbulent wake at small Fi
- Forming 2D pancake turbulent structures

$Fi = u / ND$

$\rho$, Kg/m$^3$

Instantaneous SGS viscosity

$Fi \rightarrow \infty$, $Re = 1.16 \cdot 10^6$

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Stratified flow past the sphere

Internal waves past sphere at different Froude numbers

Isopycnal surfaces

\[ Fi = 5 \]

\[ Fi = 40 \]
Stratified flow past the shere

Spectra of drag coefficient

Spectra of coefficient of drag force in homogeneous flow.
Experimental values of main frequency modes: 1st mode - $\text{St}=0.05-0.2$; high mode 2 - $\text{St}=1.1-1.3$ and mode 3 - $\text{St}=1.8-2.0$

Spectra of coefficient of drag force in stratified flow $\text{Fi}=5$.
Additional mode – $\text{St}=2.48$

<table>
<thead>
<tr>
<th>$\text{Fi}=5$, $\text{Re}=14062$</th>
<th>$C_D^{\text{calc}}$</th>
<th>$C_D^{\text{exp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.34</td>
<td>0.377</td>
</tr>
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Interaction of internal waves with moving sphere in stratified liquid

\[ Fr = \frac{U}{(gD)^{0.5}} = 0.6, \quad \omega = 0.628 \text{ rad/sec} \]
The sloshing in tank after impact interaction of the ship with ice

Speed of the ship after impact with ice

$t < 1$ сек

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Evolution of the liquid gas level in the tank after impact of tanker with ice

OpenFOAM, URANS, VoF, 3D

The sloshing

Evolution of the pressure field in the tank after impact of tanker with ice
The sloshing

Shallow water equations
Elizarova T.G. ¹, Saburin D.S. ²

Navier-Stokes equations
Tryaskin N., Tkachenko I. ³
Thank you for attention!
математическая модель

- Уравнение неразрывности
  \[
  \frac{\partial \bar{u}_i}{\partial x_i} = 0
  \]

- Уравнения Навье-Стокса
  \[
  \frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \nu \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \tau_{ij}^{SGS} \right] - \frac{1}{\rho_a} \frac{\partial p}{\partial x_i} + g_i \left( \frac{\rho - \rho_0}{\rho_a} \right)
  \]

- Уравнение переноса скаляра (объемной фракции жидкости VOF)
  \[
  \frac{\partial \tilde{f}}{\partial t} + \bar{u}_j \frac{\partial \tilde{f}}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ D \frac{\partial \tilde{f}}{\partial x_j} - J_j^{SGS} \right] - \frac{\partial \tilde{f}}{\partial t} + \bar{u}_j \frac{\partial \tilde{f}}{\partial x_j} = 0
  \]

- Модели турбулентности
  - **URANS**: \( k-\varepsilon \), SST, RSM, ...
  - **LES**: Smagorinsky, Dynamic Smagorinsky, Dynamic Mixed

Reynolds averaging (URANS):
\[
\bar{\phi}(\bar{x},t) = \frac{1}{T} \int_{t}^{t+T} \phi(\bar{x},t)dt
\]
Space filtering (LES):
\[
\bar{\phi}(\bar{x},t) = \int \int \int \phi(\bar{x} - \bar{s},t) F(\bar{s})d\bar{s}
\]