PARADIGM FOR DEVELOPMENT OF SIMULATION BASED DESIGN FOR SHIP HYDRODYNAMICS

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ABSTRACT

SBD for ship hydrodynamics merges traditional fields of resistance and propulsion, seakeeping, and maneuvering, which with inclusion of environmental effects will revolutionize the design process and offers possibility for innovative out-of-the-box concepts for future ships to meet the challenges of the 21st century. Development of SBD involves a new paradigm for hydrodynamics research in which CFD, EFD, UA are conducted simultaneously for benchmark geometries and conditions using an integrated approach along with optimization methods, all of which serve as internal engine guaranteeing simulation fidelity. Present paper describes research at IIHR in major components of SBD for ship hydrodynamics through overview the status of their application to traditional fields and future directions. Prognosis for realization practical applications is also discussed.

1. INTRODUCTION

Rapid advancements in simulation technology are revolutionizing engineering practice, including ship design, as simulation-based design (SBD) and ultimately virtual reality are replacing current reliance on experimental observations and analytical methods. It is not unreasonable to expect a major shift in how scientific method forms its basis of conceptual truth, a shift from reliance on observations, based on experiments, to reliance on logic, based on simulation with profound similarities and differences to transition from Aristotelian to Galilean scientific methods, as occurred in 16th-18th centuries. SBD covers a broad range from computerized systems to solutions of physics based initial boundary value problems. Of interest here is the latter specifically for ship hydrodynamics.

SBD for ship hydrodynamics merges traditional fields of resistance and propulsion, seakeeping, and maneuvering, which with inclusion of open-ocean and littoral environmental effects offer the possibility for innovative out-of-the box concepts for future ships to meet the challenges of the 21st century. Development of SBD involves a new paradigm for hydrodynamics research in which computational fluid dynamics (CFD), experimental fluid dynamics (EFD), and uncertainty analysis (UA) are conducted simultaneously for benchmark geometries and conditions using an integrated approach along with optimization methods, all of which serve as internal engine guaranteeing simulation fidelity. The traditional design process relies on repeated building and testing of candidate designs, which is a very expensive and time-consuming process that suffers from inability to scale up to full-scale ships (Fig. 1a). In contrast, the SBD approach replaces this with a simulation-based optimization technology, together with minimal validation testing, which once developed and validated offers quick and inexpensive consideration of many operating conditions with the capability of scaling up to full-scale performance (Fig. 1b).

Present paper describes research at IIHR in major components of SBD for ship hydrodynamics (CFD, EFD, UA, and optimization) through overview the status of their application to traditional fields (resistance and propulsion, seakeeping, and maneuvering) and future directions. Prognosis for realization practical applications is also discussed.
Fig. 1 Design processes: (a) build and test; and (b) simulation-based design.

2. PARADIGM SBD FOR SHIP HYDRODYNAMICS

Fig. 2 shows block diagram of SBD for ship hydrodynamics, including major and sub components and their interrelationship. As apparent from Fig. 2, achievement of SBD for ship hydrodynamics requires considerable research in numerical methods and optimization; physics and modeling; measurement systems, and UA.

The research and development process for SBD for ship hydrodynamics involves integrated CFD, EFD, and UA, which is a new paradigm for hydrodynamics research. CFD is used to guide EFD, EFD is used for model development and validation, and lastly CFD is validated and fills in sparse EFD data for complete diagnostics and documentation of flow for specified benchmarks. A building block approach is used whereby successive steps based on previous knowledge. Both idealized and practical geometries are used for physics and model development and benchmarking for practical applications, respectively. Surface-piercing flat-plate with upstream horizontal submerged foil used for studies of wave boundary layer and wake interactions and free surface effects on turbulence. Surface-piercing NACA 0024 foil used for studies of wave-induced separation. Surface combatant DTMB 5415 used for studies for practical applications, as described presently. Presumably, sufficient number of benchmarks will provide confidence for related applications. International collaborations are attractive from diverse ideas, resource, and ground-truth points of view.

The CFD code is CFDSHIP-IOWA (Paterson et al.), which is a general-purpose unsteady Reynolds-averaged Navier-Stokes (RANS) research CFD code developed for support of student thesis and project research at IIHR as well as transition to Navy laboratories, industry, and other universities. The approach is open source; commented modular coding with revision control; Fortran 90/95; architecture which supports model development; portable high-performance computing; and online distribution of source code, examples, and documentation. Modeling includes prescribed and predicted 6DOF motions; incident waves; blended k-ω turbulence model; free-surface tracking method through solution of the exact nonlinear kinematic and approximate dynamic conditions; and inertial and non-inertial coordinate systems. Numerical-methods include structured, higher-order, finite-difference discretization; advanced iterative solvers (PETSC toolkit); inner iterations for fully implicit coupling of free-surface, velocity–pressure, and ship motions; and conservative treatment of convective and viscous terms. High performance computing includes portable, multi-level parallelism for dynamic load balance. Commercial grid generation is used with CHIMERA overset grids for complex geometries.
Fig. 2 Block diagram of simulation-based design for ship hydrodynamics.
The EFD is conducted in the IIHR towing tank, which is 100 m long, 3.048 m wide and deep, and equipped with a drive carriage, plunger-type wavemaker, and moveable wave dampener system. The drive carriage houses a personal computer (PC), and data-acquisition instrumentation and pushes a 5.5-m trailer used for installation models and measurement systems. The wave-maker is hydraulically driven and controlled with an MTS controller and LabView software, and is capable of producing a wide range of wavelengths ($\lambda=0.5$-6.0m) and wave steepness ($Ak=0.025$-0.3), and can also generate irregular waves. The wave dampeners are raised and lowered from the carriage before and after runs and enable twelve- and twenty-minute intervals for steady and unsteady tests, respectively. Measurement systems include 6DOF Krypton motion tracker; resistance, pitch and heave, and free roll mounts; 3-component load cell; capacitance-wire and servo wave gauges; pressure transducers for surface pressure taps and 5-hole pitot; and 2D towed PIV. Steady and unsteady (phase averaged) data-acquisition and reduction procedures for global and local measurements.

Acceptance of SBD rests on quality assurance, which requires standard UA methods and procedures for both EFD and CFD. The situation for EFD is better than for CFD; since, standard UA methods and procedures are available, although adoption is not wide spread. Work on EFD UA focuses on rigorous implementation for typical towing tank tests (Longo et al., 1998) through collaboration International Towing Tank Conference (ITTC, 1999) and developments for advanced measurement systems as described below and for identification of facility biases through international collaborations (Stern et al., 2000). Although all agree of the need and importance for establishing credibility of CFD simulations and codes through verification and validation (V&V) and certification methods and procedures, there are many viewpoints covering all aspects ranging from basic concepts to definitions to detailed procedures. Work on CFD UA focuses on development V&V methods and procedures along with examples through collaboration colleagues (Stern et al., 2001, Wilson et al., 2001, 2002) and ITTC (ITTC, 1999) and certification approach (Stern et al., 2003) based on results Gothenburg 2000 Workshop on CFD for Ship Hydrodynamics (Larsson et al., 2003).

International collaborations focus on benchmark EFD validation data for surface combatant DTMB 5415 and estimation facility biases with Naval Surface Warfare Center (formerly, DTMB), Bethesda, USA and Italian Towing Tank (INSEAN), Rome, Italy (Stern et al., 2000); CFD-based optimization with Osaka Prefecture University (OPU), Osaka, Japan and INSEAN (Tahara et al., 2000); and RANS-based maneuvering simulations and EFD validation data with FORCE Technology (formerly, Danish Maritime Institute), Lyngby, Denmark (Simonsen et al., 2003).

3. RESISTANCE & PROPULSION

Amongst the traditional fields, the first application of CFD was for resistance and propulsion initially motivated by need for prediction of viscous resistance and nominal wake, especially for tanker hull forms. More recently increased focus on high Froude number (Fr) conditions and wavemaking for container and surface combatant hull forms. Recent Gothenburg 2000 Workshop on CFD for Ship Hydrodynamics (Larsson et al., 2003) provides status for all three hulls. For container and surface combatant, the better codes at the workshop showed comparison error $E = D - S$ (where D and S are EFD and CFD values, respectively) for total resistance $C_T$ of about 5%D, whereas validation uncertainty $U_V$ [i.e., root sum square of experimental uncertainties} is also about 5%D such that better codes at the workshop nearly validated (condition for validation is $|E| < U_V$ ) at about 5%D. Unfortunately, no $C_T$ EFD validation data for tanker; however, similar interval $U_{SN}$ and interestingly 13 submissions exhibit normal distribution with 5%$C_T$ standard deviation. Qualitative validation for nominal wake and wave pattern shows very promising results for better codes, including prediction strong after-body bilge vortices (ABV) for tanker and container ship, sonar dome vortices and ABV for surface combatant, and wave patterns for both container and surface combatant. In general, turbulence is less resolved than mean velocity. Improvements are needed for non-isotropic turbulence models, surface capturing free-surface methods, and larger grids.

CFDSHIP-IOWA was one of the better codes at the workshop for the surface combatant. $C_T$ was validated at about 4%D (Table 1). Nominal wake at $x/L=0.435$ and wave pattern show good agreement EFD (Fig. 3). Average axial velocity along dashed horizontal line at $z/L=0.02$ in Fig. 3 validated at 6%$U_{in}$ (ship velocity). Average wave elevation along wave cut at $y/L=0.172$ not validated with $E=12%\zeta_{max}$ ($U_V=7.2%\zeta_{max}$, $U_D=4.7%\zeta_{max}$, $U_{SN}=5.5%\zeta_{max}$) due to under prediction shoulder wave height. Reynolds stresses and turbulent kinetic energy qualitatively show similar trends as EFD, excepting non-isotropy.
Applications of CFD including propulsor and/or appendages is less widespread than for bare-hull, but still many examples. Performance Committee of the

22\textsuperscript{nd} ITTC conducted a RANS/Panel Method Workshop (ITTC, 1999) for open water propeller at which CFDSHIP-IOWA was one of the better RANS codes. Recent work focused on ducted marine propulsor, including sub visual cavitation and acoustic modeling (Kim et al., 2003). Thrust $K_T$ not validated since $E=7\%D$ and $U_V=3\%D$, but torque $K_Q$ validated at $2\%D$ (Table 2). $U_{SN}$ intervals are similar as for bare hull $C_T$. $K_T$ and $K_Q$ V&V intervals are similar to those obtained previously for open water marine propulsors. Low pressures in trailing edge and especially tip-leakage vortices (Fig. 4a), structure and merging of trailing edge and tip-leakage vortices (Fig. 4b) and cavitation patterns (Fig. 4c) show good agreement EFD. Average radial velocity validated at $5\%V_{max}$, but under prediction gradients in vortex cores.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Validation of resistance CT for surface combatant.</th>
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<tbody>
<tr>
<td>$E$ (%D)</td>
<td>$U_T$ (%D)</td>
</tr>
<tr>
<td>$E=D-S$</td>
<td>3.1</td>
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Table 2 Validation of thrust $K_T$ and torque $K_Q$ for a ducted propulsor.

<table>
<thead>
<tr>
<th>$K_T$</th>
<th>$K_Q$</th>
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<tbody>
<tr>
<td>$E=D-S$</td>
<td>$E=D-S$</td>
</tr>
<tr>
<td>6.6</td>
<td>1.8</td>
</tr>
<tr>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>2.4</td>
<td>0.74</td>
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</table>

Fig. 3 Nominal wake (a), wave elevations (b), nominal wake turbulent kinetic energy (c) and free surface turbulent kinetic energy (d) for surface combatant.
Fig. 4 Surface pressure (a), trailing edge and tip-leakage vortices, and cavitation (c) for ducted marine propulsor.

Optimization is major component in SBD. Recent collaboration with OPU (Tahara et al, 2000) focused on development RANS-based SQP, high-performance-computing optimization module for minimizing transom stern waves (Fig. 5a), sonar dome vortices (Fig. 5b), and bow waves for surface combatant. Optimized hull shows reduced stern waves and flow separation, sonar dome vortices (10% reduction $\omega_{\text{ave}}$), and bow wave (13% reduction $\zeta_{\text{max}}$).

4. SEAKEEPING

Based on success CFD for resistance and propulsion, extensions made for unsteady RANS. Following strip theory, forward speed diffraction and radiation, pitch and heave motions, and roll motion are used for code and measurement system development and validation. Extensions required significant research for both EFD and CFD. For EFD, measurement system and UA developments for incident waves, motion tracking, and phase-averaged wave elevation and nominal wake measurements (Gui et al, 2000, 2002, Longo et al, 2002). For CFD, code development for efficient time-accurate unsteady RANS, including incident waves and prescribed or free pitch and heave and roll motions (Wilson et al, 2002, Weymouth et al, 2003).

Fig. 5 Minimization of transom stern waves (a) and sonar dome vortices (b) for surface combatant.
CFD and EFD conducted for surface combatant in regular head waves (forward speed diffraction). UD intervals are similar as steady conditions. Good agreement first harmonic amplitude and phase for forces and moment (Table 3), wave pattern (Fig 6a), and nominal wake (Fig 6b). Resistance force and pitch moment are maximum when wave crest at fore-body shoulder, whereas heave force is maximum when wave crest at mid-ship. Diffraction wave pattern shows diverging waves off fore-body shoulder and transom corner with 90 deg lag outer wave, except near fore-body shoulder where 60 deg lead. Unsteady nominal wake shows maximum...
response in vortex core region, which is in phase with outer flow.

Table 3  EFD and CFD of axial force for surface combatant in regular head waves.

<table>
<thead>
<tr>
<th></th>
<th>CFD (x10^-3)</th>
<th>EFD (x10^-3)</th>
<th>E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{t,o}$</td>
<td>4.45</td>
<td>4.65</td>
<td>4.0</td>
</tr>
<tr>
<td>$C_{t,t}$</td>
<td>6.95</td>
<td>6.05</td>
<td>12.0</td>
</tr>
<tr>
<td>$\gamma_{t}$</td>
<td>20</td>
<td>70</td>
<td>11(%2\pi)</td>
</tr>
</tbody>
</table>

CFD conducted for Wigley hull in regular head waves for forward speed diffraction and radiation and pitch and heave motion conditions, including comparisons with available EFD, strip theory, and linear and nonlinear 3D potential flow methods. Intervals V&V similar as shown for steady conditions (Table 4). CFD is more accurate than strip theory (especially for high Fr and resonance conditions) and 3D potential flow (especially forward speed radiation). Fig 7 shows interaction waves and viscous flow.

Table 4 Validation of pitch and heave motions for Wigley Hull in regular head waves.

<table>
<thead>
<tr>
<th></th>
<th>$U_{SN}$</th>
<th>$U_D$</th>
<th>$U_Y$</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>21.63%</td>
<td>2.50%</td>
<td>21.77%</td>
<td>0.84%</td>
</tr>
<tr>
<td>$C_{1C}$</td>
<td>3.68%</td>
<td>2.50%</td>
<td>4.45%</td>
<td>0.15%</td>
</tr>
<tr>
<td>$Y_3$</td>
<td>6.02%</td>
<td>2.50%</td>
<td>6.52%</td>
<td>6.56%</td>
</tr>
<tr>
<td>$Y_{3C}$</td>
<td>1.52%</td>
<td>2.50%</td>
<td>2.92%</td>
<td>5.89%</td>
</tr>
<tr>
<td>$Y_5$</td>
<td>1.48%</td>
<td>2.50%</td>
<td>2.91%</td>
<td>2.28%</td>
</tr>
<tr>
<td>$Y_{5C}$</td>
<td>0.31%</td>
<td>2.50%</td>
<td>2.52%</td>
<td>1.28%</td>
</tr>
</tbody>
</table>

agreement CFD and EFD for roll decay at both low and medium Fr (Fig. 8). Fig 9 shows CFD wave and flow patterns for prescribed roll conditions. Roll induced waves due to both friction and pressure effects. Hull vortices undergo sinuous response with wavelength $\lambda=U_o\tau$ where $\tau$=prescribed roll period.

CFD and EFD conducted for surface combatant in free (and prescribed for CFD) roll motion. Good

Fig. 7 CFD unsteady interaction waves and viscous flow Wigley hull in regular head waves for pitch and heave motions.
5. MANEUVERING

General 6DOF motions and maneuvering are required for SBD. Following maneuvering simulation methods based on static and dynamic planar-motion-mechanisms (PMM) tests, static drift and rudder conditions are used for code and measurement system development and validation. V&V for dynamic PMM, rotating arm, and ultimately free-model test conditions are also required. Flow patterns for maneuvering ships are dominated by hull vortices, which are best explicated with reference to straight-ahead condition.

EFD and CFD conducted for Series 60 hull for low and medium Fr and straight-ahead and drift conditions (Longo et al, 2002, Tahara et al, 2002). Fig. 10 shows medium Fr axial vorticity and wave elevation for drift angle $\beta=0.0$ and 10 deg. For $\beta=0.0$, symmetric fore-body bilge vortices (FBV) and ABV are seen. For $\beta=10$ deg, asymmetric vortices, including FBV, fore-body keel (FKV), wave breaking (WBV), ABV, and after-body counter rotating (ABCV) vortices are seen. Fig. 11 shows vortex core properties for low and medium Fr and straight-ahead and 10 deg drift conditions. Low Fr vortices are similar to medium Fr, except absence of WBV. Wave pattern is also strongly affected by drift angle with increased/decreased amplitudes on windward/leeward sides. For medium Fr, plunging type breaking bow wave is seen, which induces the aforementioned WBV. Half-wave envelope $\alpha=22$ deg is same as for $\beta=0.0$ (and similar Kelvin wave value), but rotates with hull through drift angle $\beta$. Early version CFDSHIP-IOWA shows fair agreement EFD.
Recent collaboration with FORCE Technology (Simonsen et al., 2003) focused on CFD and EFD for hull-rudder-propeller interactions for Esso Osaka tanker hull for straight-ahead and static drift and rudder conditions. Intervals of validation for forces and moments show ranges of 4-9%D for the bare hull and 3-28%D and 6-37%D for the appended hull static rudder and drift conditions, respectively. Largest intervals correspond to largest rudder and drift angles due to larger $U_{SN}$ and $U_D$. Figs. 11a and 11b show axial vorticity and vortex core properties, respectively. Flow pattern similar Series 60 hull, but differences for appended tanker hull: additionally bilge (BV) and after-body side (ASV) vortices; and local effects at stern due to rudder.

Fig. 10 EFD axial vorticity and wave elevations (a) and vortex core properties (b) for Series 60 for low and medium Froude number and straight ahead and drift angle.

Fig. 11 CFD axial vorticity (a) and vortex core properties (b) for appended Esso Osaka for straight-ahead and static rudder and drift conditions.
6. FUTURE DIRECTIONS

Clearly much more research is needed in SBD for ship hydrodynamics to fully realize SBD for practical applications. CFD developments for two-phase flow level set free surface capturing methods and detached eddy simulation (DES) are in progress (Fig. 12). Former required for fixed grids, simultaneous air and water simulations, large motions, complex geometries and free surface topologies and breaking waves, interfacial mass transfer, etc. Latter required for massively separated flows. EFD developments for PMM and 3D towed PIV are also in progress (Fig. 13). Both required for measurement system development and EFD validation data for dynamic PMM test conditions. Additional benchmarks and certification methods also required for practical applications. Tokyo 2005 Workshop on CFD for Ship Hydrodynamics [http://www.nmri.go.jp/cfd/cfdws05/index.html] will be helpful in this regard as in addition to resistance and propulsion conditions forward speed diffraction and static drift conditions are being used for benchmarks.

![Fig. 12 CFD developments for two-phase flow level set free surface capturing methods (a) and detached eddy simulation methods (b).](image)

7. PROGNOSIS

No question inevitable and fast approaching reality of SBD. Already partially being done for next generation surface combatants such as US Navy DD21 and CVX concept designs. Near term (ca. 20 years) will focus on inclusion environmental conditions, which will enable “real life” simulations. Far term (ca. 50 years) will focus on extensions for ship structural materials and fluid-structure interactions.
interactions, weapon and power systems, and total ship systems integration for realization complete capability SBD. Very far term is real time simulations, i.e., virtual reality. Clearly lack of consensus on V&V and certification of CFD is a major stumbling block to progress. Also, lack of trained users needs to be addressed through educational materials development at undergraduate, graduate, and professional levels, e.g. (Stern et al., 2003).

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