Hydrodynamics & Hydroelasticity

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The University of Southampton

The Lloyd’s Register Educational Trust (LRET)
Marine & Offshore Research Workshop
16-18 February, 2010 at Engineering Auditorium, NUS
Hydrodynamics & Hydroelasticity.

LRET Marine & Offshore Research Workshop

National University of Singapore, 16-18 February 2010

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The Presentation

• Predicting Fluid-structure interactions
• Rogue waves
• Hydroelasticity: effect of structural discontinuity (antisymmetric case)
• Viscous hydrodynamics & hydroelasticity
• Parametric Roll resonance in regular waves
• Sloshing
Predicting fluid-structure interactions.
The context

- A range of marine structures in offshore, energy, aquaculture etc
- Larger ships; faster ships; new ship types & forms
- Survivability of damaged conditions
- Operations in more extreme environments, e.g. large waves, ice
- Use of numerical prediction methods within the *Goal Based Standards* framework
- Use of numerical prediction methods for design of marine structures with improved performance and efficiency, for a better environment
The requirements

Methods capable of dealing with:
• large waves; steep waves
• large motions
• large deformations; material nonlinear behaviour
• extreme events – e.g. slamming, sloshing, green water
• multi-fluid structure interactions, e.g. air-water; ice; ice-water
• arbitrary geometries, e.g. multi-hulls, nets, air lubricated hulls; kite-propelled vessels
• multi-scale modelling
• global and local loads

Verified & Validated methods
The tools

• Potential flow
• RANSE
• Linear and nonlinear structural analysis
  beams, shells, multi-layered structures
The methods

- Potential flow 2D nonlinear
  relatively simple; efficient;
  limitations; evidence it works
- Potential flow 3D nonlinear
  various levels of nonlinearity,
  e.g. body-nonlinear
  various velocity potentials, e.g.
  Rankine, time domain Green’s
  various treatment of free surface
  boundary conditions, e.g. flat
  surface deformed body, MEL,
  ALE
  forward speed effects

LINEAR Material Behaviour

Heave & Pitch motions:
S175 Container Ship,
Regular Head waves
Black dotted line : Linear
All other lines: Nonlinear
Marks: Experimental results
The methods

- RANSE – Particle methods
  (SPH) Smoothed particle hydrodynamics
  (MPS) Moving particle semi-implicit
  - developed by researchers
to suit their needs;
  - suitable for violent flows,
  e.g. sloshing, slamming

- RANSE – commercial software
  - some allow for structural flexibility
  - suitable for violent flows,
  e.g. sloshing, slamming

LINEAR Material Behaviour
Rogue waves.
Overview of presentation

- Background
- Modelling rogue waves
- Wave-structure interactions
- Summary
- Future work
Rogue Wave Characteristics

- Much taller than the surrounding sea state
- Vertical and horizontal asymmetry
- Very tall crest preceded or followed by a very deep trough

The Draupner New Year Wave record

Rogue Wave Definition

\[ AI = \frac{H_{\text{max}}}{H_S} \geq 2.0 \quad \text{CI} = \frac{\eta_{\text{max}}}{H_S} \geq 1.2 \]

\[ L_OA \leq \frac{L_OA}{H_{\text{max}}} \leq 10.0 \]
Rogue Wave Models

- Isolated rogue wave: NewWave theory

\[ \eta(t) = \eta_{\text{max}} \frac{\sum_{n=1}^{N} [S(\omega_n)\delta\omega] \cos(\omega_n t)}{\sigma^2} \]

NewWave with \( H_s = 0.10 \text{m}, T_p = 1.45 \text{s} \) and \( AI = 2.36 \) (model scale)
Rogue Wave Models

- Rogue wave in a random seaway: optimisation

\[ \frac{H_s}{H_{\text{max}}} \quad \frac{T_p}{\eta_{\text{max}}} \rightarrow \eta(t) = \sum_{n=1}^{N} A_n \cos(\omega_n t + \phi_{\text{random}}) \rightarrow \eta(t) = \sum_{n=1}^{N} A_n \cos(\omega_n t + \phi_{\text{optimised}}) \]

Optimised sea with \(H_s=0.10\text{m}, T_p=1.45\text{s}\) and \(A_I=2.36\) (model scale)
Wave-Structure Interactions

• **Experiments** (scale 1:43.62)
  – Naval frigate used as a representative ship
  – Rigid and flexible models

• **2D linear hydroelasticity**
  – Timoshenko beam idealisation
  – Summation over N regular waves and R distortion modes

• **3D partly nonlinear seakeeping model**
  – Currently regular waves only
  – Heave and pitch
  – Instantaneous wetted hull surface at time $t$ accounts for nonlinearities
Zero-speed results

- Responses at zero speed with $H_s=4.36\text{m}$ and $T_p=9.58\text{s}$, full scale

Heave response in irregular sea

Heave response in optimised sea (AI=2.36)

Pitch response in irregular sea

Pitch response in optimised sea (AI=2.36)
Zero-speed results

Variation in maximum heave with maximum wave height in all seaways at zero speed (presented full scale)

Variation in maximum pitch with maximum wave height in all seaways at zero speed (presented full scale)
Influence of forward speed

Motion of model through optimised sea at zero speed

Motion of model through optimised sea at service speed
Influence of forward speed

- Ship response variation with forward speed in an optimised sea with $H_s=4.36m$, $T_p=9.58s$ and $AI=2.36$ (full scale)
Summary and Future Work

- Rogue waves modelled successfully using NewWave and optimisation techniques
- 2D linear hydroelasticity shows good agreement with experimental heave and pitch results at zero speed
- More significant differences are seen between the experimental results and 2D linear hydroelasticity as forward speed increases
- Experimental testing of flexible model for assessment of vertical bending moments
- Extension of 3D partly nonlinear model to include an irregular and rogue seaway
Hydroelasticity: effect of structural discontinuity on antisymmetric response.
Background – Technical issues

- Flexural direct stress, due to bending is augmented with sectorial direct stress induced by constraint in cross sectional warping

- The structural discontinuity at the transitions between open/closed parts of the ship results in changes to its antisymmetric dynamic characteristics

- Past work showed differences between shell FE and beam (not accounting for these effects) idealisations

Twisting moment on a bulk carrier in regular quartering waves;
Structural models account for deck strips between holds

Hirdaris et al Marine Structures, 2003 16, 627-658
## Theoretical background

### Warping function as an independent variable

<table>
<thead>
<tr>
<th>Variables</th>
<th>Bishop &amp; Price</th>
<th>Pedersen</th>
</tr>
</thead>
<tbody>
<tr>
<td>v, θ, φ, γ, M, V, T, M&lt;sub&gt;w&lt;/sub&gt;</td>
<td>v, θ, φ, χ, γ, M, V, T, M&lt;sub&gt;w&lt;/sub&gt;</td>
<td></td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Sectional characters</th>
<th>μ, EI, KAG, I&lt;sub&gt;Z&lt;/sub&gt;, I&lt;sub&gt;C&lt;/sub&gt;, GJ, EI&lt;sub&gt;ww&lt;/sub&gt;</th>
<th>μ, EI, KAG, I&lt;sub&gt;Z&lt;/sub&gt;, I&lt;sub&gt;C&lt;/sub&gt;, GJ, EI&lt;sub&gt;ww&lt;/sub&gt;</th>
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<td>Z&lt;sub&gt;C&lt;/sub&gt;, Z&lt;sub&gt;S&lt;/sub&gt;</td>
<td>Z&lt;sub&gt;C&lt;/sub&gt;, Z&lt;sub&gt;S&lt;/sub&gt;</td>
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<table>
<thead>
<tr>
<th>Longitudinal displacement</th>
<th>u</th>
<th>wφ' − yθ</th>
<th>− wφ - yθ</th>
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<thead>
<tr>
<th>Bimoment</th>
<th>M&lt;sub&gt;w&lt;/sub&gt;</th>
<th>− EI&lt;sub&gt;ww&lt;/sub&gt;θ&quot;</th>
<th>− EI&lt;sub&gt;ww&lt;/sub&gt;χ'</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Shear strain</th>
<th>γ</th>
<th>v' − θ</th>
<th>v' − θ − [Z, ϕ]'</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Shear Force</th>
<th>V</th>
<th>KAGγ</th>
<th>KAGγ + GI&lt;sub&gt;ph&lt;/sub&gt;(ϕ' − χ)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Torsion moment</th>
<th>T</th>
<th>GJϕ' − [EI&lt;sub&gt;ww&lt;/sub&gt;ϕ&quot;]</th>
<th>GJϕ' − [EI&lt;sub&gt;ww&lt;/sub&gt;χ']</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Boundary conditions</th>
<th>M = 0 = V = T</th>
<th>M = 0 = V = T</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M&lt;sub&gt;w&lt;/sub&gt; = 0</td>
<td>M&lt;sub&gt;w&lt;/sub&gt; = kχ</td>
</tr>
<tr>
<td></td>
<td>at the ends</td>
<td>at the ends</td>
</tr>
</tbody>
</table>

| Number of dynamic equations | 3 | 4 |
Application to a 750 TEU feeder containership

$L_{pp}=124.9\text{ m}$, $B=20.8\text{ m}$, $D=10.4\text{ m}$, $\Delta=19623\text{ tonnes}$, $T=9\text{ m}$

Warping Constant

Torsional constant

Basaran et al, OMAE 2008, paper 57401
Hirdaris et al 5th Int. Conf. Hydroelasticity, 2009, 57-68
Application to a 750 TEU feeder containership

Dry Hull Natural Frequencies (rad/s)

<table>
<thead>
<tr>
<th>Modal index (r)</th>
<th>Model A</th>
<th>Model B (D)</th>
<th>Model C (D)</th>
<th>Model C1 (D)</th>
<th>Model C1 (EIw-B) (D)</th>
<th>Model C1 (WD)</th>
<th>3D FE</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 (1T)</td>
<td>6.51</td>
<td>7.45</td>
<td>5.80</td>
<td>5.77</td>
<td>6.25</td>
<td>5.56</td>
<td>7.82</td>
</tr>
<tr>
<td>4 (2T)</td>
<td>10.77</td>
<td>10.45</td>
<td>9.22</td>
<td>9.01</td>
<td>10.00</td>
<td>9.09</td>
<td>11.88</td>
</tr>
<tr>
<td>6 (2HB)</td>
<td>19.46</td>
<td>22.79</td>
<td>18.65</td>
<td>18.79</td>
<td>19.86</td>
<td>18.94</td>
<td>26.01</td>
</tr>
<tr>
<td>7 (4T)</td>
<td>26.92</td>
<td>28.48</td>
<td>26.20</td>
<td>25.75</td>
<td>26.60</td>
<td>22.90</td>
<td>29.94</td>
</tr>
</tbody>
</table>

- Model A = No structural discontinuities, except as in structural properties (Price et al model);
- Model B (D) = structural discontinuities, but shear strain effects omitted;
- Model C (D) = structural discontinuities, shear strain & rate of twist angle all considered;
- Model C1 (D) = same as C but shear strain & rate of twist angle not considered;
- Model C1 (WD) = same as C but structural discontinuities neglected.
- Models A, B, C, C1 consider the structure between the main holds
- Model C1(EIw-B) assumes open deck structure for warping and structure between holds
- Model 3D FE consists of 6966 ANSYS SHELL 63 FE and lumped mass elements
Application to a 750 TEU feeder containership

Horizontal Bend. Moment

Horizontal Shear Force

Twisting Moment

Bi Moment

\[ \omega_e = 0.72 \text{ rad/s} \]
\[ L/\lambda = 1.04 \]
Speed = 16 knots
Heading 135°

Large differences & discontinuity effects
Conclusions

- Inclusion of structural discontinuities has an important influence on natural frequencies, mode shapes and modal internal actions.

- For the feeder containership, differences in the modal characteristics appear to have small influence in the predicted antisymmetric wave-induced loads in waves of the same length as the ship.

  The torsional moment and bi-moment are the exceptions, which is to be expected.

- Comparisons against 3D FE structural models is not particularly easy. This is due to the fundamental differences in their structural behaviour, by comparison to beams.

  Nevertheless comparisons should continue to be carried out.

- Further work is required for confirming the observations through applications to other ship types.
Viscous hydrodynamics & hydroelasticity.
2D hydrodynamics/hydroelasticity using RANS – viscous effects

- Effects of viscosity can be included using “RANS” Computational Fluid Dynamics (CFD) codes
- Tackling the three-dimensional problem directly using such codes is still computationally intensive
- Alternative: “Strip Theory”, whereby hydrodynamic forces on each section are obtained using a RANS code.
- Also applicable to 2D hydroelasticity
Meshing strategy for RANS (2D)

- Hybrid mesh
- High quality hexahedral elements in vicinity of section:
  ¼ wave length longitudinally
  ½ wave length vertically
- Coarse prismatic elements elsewhere
- 25% less elements than structured mesh
Sensitivity analysis for RANS (2D)

- Rectangular section
- Mesh refinement
  normal to wall
tangent to wall; corners
Pressure & shear stress distributions examined
- Time step refinement
- Turbulence model
  Laminar
  K-ε
  Shear stress Transport (SST)

Rounded corner, SST

Sharp corner, SST

Sharp corner, K-ε

Sharp corner, Laminar

Pressure Coefficient ($C_p$) contours & zero mass particle paths

Querard, 2010, PhD Thesis
Comparisons: 2D hydrodynamics

Rectangular

\[ \omega^* = \omega (B/2g)^{1/2} \]

Sway damping

Roll damping

Sway into Roll damping

Triangular

Querard, 2010, PhD Thesis
Flexible rectangular barge – 2D hydroelasticity

- Potential flow (Lewis & conformal mapping) vs RANS

Vertical Bending Moment VBM
Vertical Shear Force VSF

Horizontal Bending Moment HBM
Twisting Moment TM
Conclusions

- An engineering approach to examine suitability & applicability of RANS to 2D hydrodynamics & hydroelasticity has been successfully carried out.
- Sensitivity analysis for meshing, timestep and turbulence models produced guidelines for applying approach to practical ships.
- The adopted hybrid meshing is accurate and results in reduction of number of grid elements used.
- Choice of turbulence model is important to accurately capture boundary layer and vortical flows.
- The study showed that sway, as well as, roll damping and added mass coefficients are affected by viscosity.
Parametric roll resonance in regular waves.
Background

- Parametric Roll Resonance: Severe roll motions in waves, even in the absence of a transverse external exciting moment, i.e. longitudinal waves.

- Cause: Periodic changes in the transverse stability of the ship in waves, due to periodic changes in the underwater part of the hull, in other words, coupling between symmetric and antisymmetric motions.

- Example: Trawlers, modern Containerships with substantial bow flare and stern overhang.

Damage sustained by a Post-Panamax C11 Containership, due to parametric roll resonance
2D nonlinear method

- 2.5 dof system, comprising 1 dof roll equation of motion, together with input from heave and pitch motions, obtained from 3D linear or nonlinear methods.

- Parametric excitation is function of the instantaneous sectional breadth due to 1\textsuperscript{st} & 2\textsuperscript{nd} order terms for heave, pitch and wave passage.

- Non-linear Roll Restoring Moment: Evaluated using exact GZ curve (still water)

- Non-linear Roll Damping Coefficients: Evaluated using semi-empirical method for frictional, eddy and lift damping components

- The roll equation of motion is solved in the time-domain using a 4\textsuperscript{th} order Runge-Kutta method

- Applicable to any wave heading
3D nonlinear method

- 4 dof system in sway, heave, roll and pitch; surge neglected (requires evaluation of added resistance in waves); yaw neglected (requires addition of auto pilot to control heading).

- Radiation and diffraction actions based on mean wetted surface; evaluated using Impulse Response Functions obtained from linear 3D potential flow analysis

- Incident wave and hydrostatic forces evaluated at instantaneous wetted surface

- Non-linear Roll Damping Coefficients: Evaluated using a semi-empirical method for frictional, eddy and lift damping components

- 4 dof system solved in time domain using 4th order Runge-Kutta method

- Applicable to any wave heading
Example – ITTC A1 Containership

- $L_{PP}: 150 \text{m}$, $\Delta: 23710 \text{ t}$, $T=8.5 \text{m}$, $GM=1.0 \text{m}$
- Comparison 2D & 3D methods
- Experimental $\phi_S: 12.9^\circ$

Surface idealisation (2844 panels) up to main deck

![Graph showing Roll Angle vs Time for 2D and 3D Methods]

Following-waves, $F_n=0.08$, $wavamp=1.8 \text{ m}$, $We=0.5924 \text{ rad/s}=2.1W_n$
Example – Transom stern trawler

- $L_{PP}: 22.1\text{ m}, \Delta: 170.3\text{ t}, T=2.48\text{ m}, GM: 0.37\text{ m}$
- Comparison 2D & 3D methods
- Experimental $\varphi_S: 18^\circ$

Surface idealisation (984 panels) up to main deck
Conclusions

• Two non-linear numerical methods have been developed for the prediction of parametric roll in regular waves; a 2D Method based on simplified assumptions and a 3D partly nonlinear method.

• Extensive validations for a transom stern trawler, a C11 and an ITTC-A1 containerships demonstrate the capability of the two methods in simulating parametric roll in different operational conditions i.e. different headings, wave heights, encounter frequencies, forward speeds and loading conditions.

• Both methods compare well with numerical/experimental results available in the literature.

• An accurate prediction of damping, essential for realistic predictions.

• Extend current methods to account for parametric roll in irregular waves.
Sloshing.
Numerical Method

Two major issues need resolving to compute compressible two-fluid flows.

1. Standard methods for compressible flows based on the hyperbolic conservation laws are not efficient in the case of low Mach number or weak compressibility.

   A dual-time preconditioning technique is introduced to solve compressible two-fluid flows in a unified manner applicable to both incompressible and compressible flow regimes.

2. For any standard conservative, shock-capturing scheme to compute compressible multi-fluid flow systems, pressure oscillations exist near the interface.

   A preconditioned Split Coefficient Matrix Method (SCMM) is employed to eliminate pressure oscillations near interface.

   Free surface is implicitly captured based on a level set approach.
Numerical results – Rectangular Tank

- 90cm x 50.8cm; 44% filling level; Roll motion 4° at resonance 1.32s

Comparison of measured* and calculated pressure time histories
(blue lines: predictions; black with symbols: measured)

* Delorme et al 2009, Ocean Engineering, 36
Numerical results – Rectangular tank

- 90cm x 50.8cm, 18.3% filling level, Roll motion $4^\circ$ at 1.91s (resonance)

Pressures on wall at still free surface

MARSTRUCT European Network of Excellence

RANSE Uos: current method
SPH: Smoothed Particle Hydrodynamics
RANSE PRI: LS-DYNA
RANSE BV: FLOW3D
Numerical results – Chamfered Tank

- Filling level 20%; sway motion 152mm at 0.46Hz
- Flow simulation (velocities) during first impact event;
- Red: mean free surface; blue: free surface

\[ t_1: 2.35s \quad t_2: 2.575s \quad t_3: 2.675s \]

- \( t_1 \): Hydraulic jump with vertical wall forms & moves towards left wall
- \( t_2 \): Wave crest overturns due to high speed of wave front
- \( t_3 \): Impact takes place, just below free surface
- \( t_4 \): Liquid moves upwards along wall & forms a jet
- \( t_5 \): Rising jet drops due to gravity

\[ t_4: 2.693s \quad t_5: 3.0s \]
Numerical results – Chamfered Tank

- Filling level 20%; sway motion 152mm at 0.46Hz
- Predicted pressures during first & second impact events
- Positions 9, 10 are on the left wall, just above lower chamfer; 9r,10r are counterparts on right wall; 11, 12 located at right lower chamfer

Following first impact tank is moved in opposite direction. Behaviour of liquid similar to first impact, i.e. hydraulic jump, overturn & generation of cavities and/or bubbles; finally (second) impact with left wall & formation of high speed jet.

Magnitude and frequency of pressure oscillations different – probably due to different shape, size and location of cavities
Numerical results – Rectangular tank

- 600mm x 600mm, 83% filling level; sway motion 15mm at 1.2Hz

High speed camera images, showing air cavity trapped at top right corner

Rognebakke et al SNAME 2005

Computed free surface profiles (part of tank) at (a) 0.0 s, (b) 0.045s, (c)0.0475s, (d)0.05s, (e)0.13s showing formation of air pocket at top right corner

Chen & Price, Physics of Fluids, 2009, 21
Numerical results – Rectangular tank

- 600mm x 600mm, 83% filling level; sway motion 15mm at 1.2Hz

(a) Measured & (b,c) calculated pressures (b: 121x121 mesh; c: 151x151 mesh).
Locations 80: wall near top left corner, 82, 87: top near and farther from top left corner.
Predictions show more damping in pressures than measurements.
Conclusions

• Developed numerical method provides acceptable level of accuracy of pressure loads caused by liquid sloshing in containers;

This was demonstrated through illustration of modelling physical phenomena and comparisons with available measurements for a range of motions, tank shapes and filling levels.

The method provides correct order of magnitudes, of sufficient accuracy for preliminary design purposes.

• Investigation of air compressibility in violent sloshing motions provides improved insights and understanding of the complicated hydrodynamic phenomena;

Since air often is present as trapped bubbles or dispersed air, or most likely as a combination of both, a two-phase flow model is needed to reflect the complex mixture of liquid and air phase.
Recent Relevant Publications.
Publications since 1st LRET Marine Research Workshop


Publications (cont.)


• Schreier, Sebastian, Godderidge, Bernhard, Paschen, Mathias, Turnock, Stephen, Tan, Ming Yi and Cowlan, Nicholas (2009) Assessment of transient sloshing due to encounter of an LNG carrier with a steep wave. In, 28th International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2009), Honolulu, USA, 31 May - 05 Jun 2009. USA, American Society of Mechanical Engineers, 10pp.

