Stationkeeping of moored structures in drifting ice

Li Zhou

May 28th, 2013
- Background
  - Numerical model
  - Ice model test
  - Validation
  - Extension: heading control
  - Conclusions & recommendations
Background

- Arctic and Subarctic regions
Background

- Types of structures

![Diagram showing different types of offshore structures](image-url)
Background

- **Main concerns of stationkeeping in ice:**
  - Dynamic global ice loads
  - Response of floating structures
  - Local ice loads for structure design
  - Concept design of hull lines & stationkeeping system
  - Ice management
Background

Research work

a) Introduced a numerical model for simulating ice–hull interaction in level ice

b) Did a series of model tests of icebreaking tanker in level ice

c) Modeled ice accumulation on the basis of ice loading process observed from the model tests

d) Compare simulated results with model test data and full scale data and made modifications.

e) Developed and simulated a heading control based stationkeeping concept
- Background
- **Numerical model**
- Ice model test
- Validation
- Extension: heading control
- Conclusions & recommendations
Numerical Model

General methods:

- Empirical formula
- Analytical solutions
- FEM
- DEM
- FEM-DEM
- CEM
Numerical Model

\[
(M + A) \cdot \ddot{x}(t) + B \cdot \dot{x}(t) + C \cdot x(t) = F(t)
\]

\[
F(t) = \begin{cases} 
R_{b1} + R_{s1} + R_{r1} + F_{m1} + F_{ow1} + 0 + m \cdot v \cdot r \\
R_{b2} + R_{s2} + R_{r2} + F_{m2} + F_{ow2} + 0 - m \cdot u \cdot r \\
R_{b6} + R_{s6} + R_{r6} + F_{m6} + F_{ow6} + M_{\psi} + 0 
\end{cases}
\]

Coordinate system

A step-by-step numerical integration method is applied.
Numerical Model

Ice forces: icebreaking force & ice submersion / accumulation forces

- The icebreaking force is invoked when ice and structure collides.
- The broken ice force is exposed to structure during submersion.
Numerical Model

- Simulating ice breaking force
  - Field observations on ice breaking pattern: circular crack & radial crack

Taken on icebreaker YMER in Baltic Sea, March, 2011
Numerical Model

- Simulating ice breaking force
  - Model test observations on ice breaking pattern: circular crack

Taken in ice basin of Aalto university, Feb, 2012
Numerical Model

Simulating ice breaking force

- The basic geometrical model including waterline of ship and edge of ice, are both discretized.

- Numerical Model
  - detect contact zones around the hull
  - calculate contact areas, normal crushing forces, friction forces
  - calculate vertical forces $F_v$
  - check if $F_v >$ Bending capacity $P_f$?
    - Yes: update ice wedge
    - No: keep ice wedge
  - Next step
Numerical Model

- Simulating ice submersion/accumulation force

Three alternatives:

- Broken ice floes clear away;
- Only one layer of broken ice floes contacts with the structure;
  - Lindqvist’s formulation
  - Croasdale’s 2-D solution
- Ice accumulation occurs;
  - Croasdale’s 3-D solution
Numerical Model

• Lindqvist’s formulation (1989)

Parameters: main dimensions, hull form, ice thickness, friction and ice strength

\[ R_i = (R_c + R_b)(1+1.4\frac{v}{\sqrt{gh_i}}) + R_s(1+9.4\frac{v}{\sqrt{gL}}) \]

- crushing
- breaking
- submersion
Numerical Model

- Croasdale’s 2-D solution (1980)

1) Assume: good ice clearing

\[ H = l_s \delta \rho h_i g (\sin \alpha + \mu \cos \alpha) \left( \frac{\sin \alpha + \mu \cos \alpha}{\cos \alpha - \mu \sin \alpha} + \frac{\cos \alpha}{\sin \alpha} \right) \]
Numerical Model

- Croasdale 3-D: Sequence of ice rubble buildup

![Diagram of ice rubble buildup sequence](image-url)
Numerical Model
Numerical Model

- Croasdale 3-D solution

\[ H = H_P + H_R + H_L \]

\( H_P \): force needed to push ice sheet horizontally through rubble
\( H_R \): force needed to push ice blocks down the slope through rubble
\( H_L \): force required to submerge ice rubble under ice sheet prior to breaking it
**Numerical Model**

- Ice–structure interaction geometries

b) Observed at initial stage

c) Observed at steady state stage
Numerical Model

- Calculating $F_m$

  RIFLEX (2003) is used. The relation between restoring forces and offsets can be pre-calculated before simulation starts.

- Heading control
- Background
- Numerical model
- **Ice model test**
- Validation
- Extension: heading control
- Conclusions & Recommendations
Ice Model Test

The scope is to

a) observe icebreaking and ice accumulation processes
b) measure icebreaking length and dimension of ice pile
c) record corresponding ice forces
d) include effects of ice submersion or ice accumulation in numerical model
Ice Model Test

Ice basin of the Marine Technology Group in the Aalto University
Supported by the European Community's 7th Framework Programme and Aalto University

Ice basin: 40m X 40 m X 2.8 m
Ice Model Test

Ship model

MT Uikku

MT Uikku model (scale: 1:31.6)
Ice Model Test

Model test setup

- Compact 6-component force transducer
- One-directional load cell
- Dynamic measurement unit (DMU)
- Two cameras
# Ice Model Test

## Test matrix (full scale)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>$V_i$ [m/s]</th>
<th>$\psi$ [deg]</th>
<th>Measured parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>0.2</td>
<td>90</td>
<td>Ice force, accelerations, dimension of ice pile</td>
</tr>
<tr>
<td>102</td>
<td>0.5</td>
<td>90</td>
<td>Ice force, accelerations, dimension of ice pile</td>
</tr>
<tr>
<td>103</td>
<td>0.2</td>
<td>0</td>
<td>Ice force, accelerations</td>
</tr>
<tr>
<td>104</td>
<td>0.5</td>
<td>0</td>
<td>Ice force, accelerations, size of ice cusp</td>
</tr>
<tr>
<td>105</td>
<td>0.2</td>
<td>45</td>
<td>Ice force, accelerations, dimension of ice pile</td>
</tr>
<tr>
<td>201</td>
<td>0.2</td>
<td>90</td>
<td>Ice force, accelerations, dimension of ice pile</td>
</tr>
<tr>
<td>202</td>
<td>0.5</td>
<td>90</td>
<td>Ice force, accelerations, dimension of ice pile</td>
</tr>
<tr>
<td>203</td>
<td>0.2</td>
<td>45</td>
<td>Ice force, accelerations, dimension of ice pile</td>
</tr>
<tr>
<td>204</td>
<td>0.5</td>
<td>45</td>
<td>Ice force, accelerations, dimension of ice pile</td>
</tr>
<tr>
<td>205</td>
<td>0.2</td>
<td>0</td>
<td>Ice force, accelerations, size of ice cusp</td>
</tr>
<tr>
<td>206</td>
<td>0.5</td>
<td>0</td>
<td>Ice force, accelerations, size of ice cusp</td>
</tr>
</tbody>
</table>
Ice Model Test

- 0° heading cases: Test 103, Test 104, Test 205, Test 206

- There was no ice accumulation.
- Ice most often failed in flexure at bow.
- Some cusps at shoulder area experienced re-breaking.
- The ice failure was asymmetric on the both sides of the hull.
Ice Model Test

- 90° heading cases: Test 101, Test 102, Test 201, Test 202

- The ice drift speed significantly affected ice accumulation. At low speed (201), severe ice accumulation occurred while almost no ice accumulation at high speed (202).

- Ice mainly failed in crushing and mixed failure modes at mid-hull, and bending at bow and stern.

- The rubble building process was very similar to that described by Croasdale, with main differences in cross sectional geometry.
Ice Model Test

- 45° heading cases: Test 105, Test 203, Test 204

- Ice accumulation occurred regardless of ice drift speed.
- The amount of ice pile increased from mid-hull to stern.
- The failure modes at different parts of the hull were similar to the 90° heading cases.
- Background
- Numerical model
- Ice model test
- Validation
- Extension: heading control
- Conclusions & Recommendations
Validation

- The Kulluk
Validation

Initial ice boundary
Numerical Model Validation

Simulated time history of ice forces and mooring force
($H_i=1.0 \text{ m}, V_i=0.6 \text{ m/s}$)
Validation

Comparison of ice loads from the simulation, full scale, and model scale measurements ($V_i=0.6$ m/s)

IIHR- Iowa Institute of Hydraulic Research; HSVA -Hamburg Ship Model Basin; ACL-ARCTEC Canada Limited;
Validation

Comparison of simulated and Full scale loads of Kulluk in level ice versus ice drifting speed ($H_i=1.0$ m)
Validation

- MT Uikku
Validation

Test 101: $\Psi=90^\circ$, $V_i=0.2$ m/s, $H_i=0.77$ m, accumulation
Validation

Test 102: $\Psi=90^\circ$, $V_i=0.5$ m/s, $H_i=0.77$ m, no accumulation
Validation

- Error between measured and simulated mean values

\[ e = \frac{\bar{F}_{\text{sim}} - \bar{F}_{\text{exp}}}{\bar{F}_{\text{exp}}} \times 100\% \]

<table>
<thead>
<tr>
<th>Heading</th>
<th>No.</th>
<th>( \sigma_- )</th>
<th>( \sigma )</th>
<th>( \sigma_+ )</th>
<th>( \sigma_- )</th>
<th>( \sigma )</th>
<th>( \sigma_+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>101</td>
<td>-8.8%</td>
<td>-3.1%</td>
<td>3.1%</td>
<td>F1</td>
<td>F2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>102</td>
<td>-2.8%</td>
<td>0.0%</td>
<td>10.4%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>201</td>
<td>2.8%</td>
<td>-2.0%</td>
<td>1.3%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>202</td>
<td>-11.9%</td>
<td>-8.0%</td>
<td>-3.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>105</td>
<td>5.5%</td>
<td>9.0%</td>
<td>32.0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>203</td>
<td>-5.7%</td>
<td>-5.4%</td>
<td>-4.0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>204</td>
<td>-12.1%</td>
<td>-8.7%</td>
<td>-2.1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>-14.6%</td>
<td>-5.4%</td>
<td>17.6%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>104</td>
<td>-28.2%</td>
<td>-6.2%</td>
<td>19.4%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>205</td>
<td>-7.8%</td>
<td>-5.0%</td>
<td>-2.7%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>206</td>
<td>-9.3%</td>
<td>-4.3%</td>
<td>0.4%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Validation

- Lindqvist formulation VS Croasdale’s 2D solution

Comparison of ice resistances from simulation and model test 103
- Background
- Numerical model
- Ice model test
- Validation
- Extension: heading control
- Conclusions & Recommendations
Extension: heading control

- Stationkeeping capability
  
  To evaluate the floating structure performance in level ice

- Setup
  
  1) Initial heading is 0°
  2) Heading control is used to change the heading to the constant ice drift angle (0° ~ 90° with interval 10°)
  3) 5% X 100 m = 5 m is the maximum offset allowed in stationkeeping operation.
Extension: heading control

Example: Heading change and Turret offset of moored tanker without HC

![Graph showing heading change and turret offset](image-url)
Extension: heading control

Capability plot
- Background
- Numerical model
- Ice model test
- Validation
- Extension: heading control
- Conclusions & Recommendations
Conclusions

A 2D numerical model for the interaction between level ice and a moored structure in the horizontal plane was developed:

a) ice-breaking
b) ice submersion
c) comparison with full scale measurements and experimental data

Then, the numerical model was extended by adding ice accumulation model:

a) The measured and simulated ice loads were compared.
b) Good agreement was achieved, although there were some deviations.

Heading control of a position-moored vessel operating in a level ice regime was simulated:

a) a heading control system based on a Kalman filter
b) a thrust allocation method
c) capability of the stationkeeping system
Recommendations

1) A randomly varying ice condition with probabilistic distribution of parameters, pressure–area relationship can be included.

2) More model tests are desirable to assist numerical simulation.

3) The model could be extended to 6 DOF and varying relative ice drift direction.

4) Ice breaking mechanism should be well studied.

5) Ice rubble transport and ice rubble action on the hull need to be modified.
References


Thank you!