'We thought we were gone' says cruise passenger
Importance of Roll Motions

• Hard to predict accurately.
• Roll motions have an effect on:
  – Top sides foundations
  – Risers or their end fittings
  – Turret bearing loads
  – Efficiency of process equipment
  – Crew comfort/wellness
  – Helicopter operations
  – Loading/unloading of supply vessels
  – Shlossing loads in FLNG membrane tanks
Basics of Roll Motion

• Resonant motion amplitude dominated by amount of damping at the natural frequency.
• Roll natural period of typical FPSO between 10-15s -> right in the range where wave spectrum has significant energy.

• Excitation Factors:
  – Relative Wave Angle
  – Separation Tn & Tp
  – Wave Spreading
  – Spectral Peakedness
  – Water Depth
  – Other

• Damping Sources:
  – Skin friction
  – Wave making
  – Eddy generation
  – Moorings & Risers
  – Internal waves in tanks
  – Other
Effect of loading condition

• Wave Condition:
  – $H_s = 6.7 \text{m}$
  – $T_p = 11.4 \text{s}$
  – Direction = 270deg

• Loading Condition:
  – Ballast, $T_n = 11.7 \text{s}$
  – Full, $T_n = 14.1 \text{s}$
Effect of Loading Condition - cont’d

- Test Results:
  - Full, stdev = 1.5deg; mpm = 6.6deg
  - Ballast, stdev = 3.9deg; mpm = 13.3deg

![Graph showing frequency response](image)
Effect of Bilge Keel Width

- **Wave Condition:**
  - $H_s = 6.7m$
  - $T_p = 11.4s$
  - Direction = 270deg

- **Loading Condition:**
  - Ballast, Roll natural period = 11.7s

- **Caveats:**
  - Very shallow draft condition
  - Damping from lower riser balcony
Effect of Bilge Keel Width - cont’d

- Test Results:
  - 1.0m x 185m, stdev = 4.3deg; mpm = 14.5deg
  - 1.5m x 205m, stdev = 3.9deg; mpm = 13.3deg
Effect of Bilge Keel Width - cont’d
Long Term Response Analysis
Long Terms vs Short Term Response Analysis

Short-term environment
Design Storm

Short-term response analysis

Short-term Design Response

≠

Long-term environment
e.g. Hindcast Database

Long-term response analysis

Long-term Design Response
Example Long Term Response Analysis

- Turret moored tanker in GOM
- Hurricane hindcast database
- FD Mooring Analysis using SPMsim
- Resulting 100-year MPM Roll Amplitude
- Response Based Design Criteria
Joint Distribution: Hs – Relative Wave Heading

significant wave height (m)
Joint Distribution: Roll – Relative Wave Heading

MPM roll amplitude w/o wave spreading
Joint Distribution: Roll – Relative Wave Heading

MPM roll amplitude w/ wave spreading

relative wave-ship heading (degrees)
100-yr Cumulative Distribution of Roll

- turret @ 75 m
- turret @ 85 m
- turret @ 95 m
- turret @ 85 m w/ wave spreading
MPM Roll from 100yr Storm vs 100yr Roll MPM

100yr Design Environment
• $H_s = 12.2\,\text{m}$
• $T_p = 14.2\,\text{s}$
• $V_w = 36.5\,\text{m/s} @ 30\,\text{deg}$
• $V_c = 1.75\,\text{m/s} @ 45\,\text{deg}$

MPM from 100yr storm = 5.8deg

MPM 100yr Roll = 9.9deg

100yr Roll Environment
• $H_s = 8.9\,\text{m}$
• $T_p = 14.5\,\text{s}$
• Relative Heading = 135deg
Local Conditions that affect Roll Motions
Seasonal swell direction Northwest Shelf, Australia
Seasonal wind direction Northwest Shelf, Australia
Relative Swell Heading, Northwest Shelf, July
Wave and Current Rose, July, Offshore Ghana
Brazil
Example of CFD for Roll Motions

- 2D CFD using EOLE™ by Principia
- Comparison of 6 configurations
- Forced oscillations at Tn = 14s with 5° and 10° amplitudes
- Quadratic damping extracted from moment time series
- Moment around center of roll integrated on 1m wide section: 2D
- Removal of linear damping using 3D diffraction analysis
## Configurations Studied

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
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<tbody>
<tr>
<td>bare hull</td>
<td>hull with one bilge keel of 1 meter length</td>
<td>hull with one bilge keel of 2 meters length</td>
<td>hull with the lower riser support &quot;box&quot; and one bilge keel of 2 meters length</td>
<td>hull with the lower riser support &quot;box&quot; (without bilge keels)</td>
<td>hull with two bilge keels of 1 meter length</td>
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</tbody>
</table>
Vortex Development induced by Appendages

Case 1

Case 2

Case 3
Forced roll oscillation
Amplitude = 10°

Case 4

Case 5

Case 6

SOFEC
Estimated Roll RAOs for the various cases

RAO in roll with damping

Case 1: User damping: Linear = 0.0, Quadratic = 1.458e11
Case 2: User damping: Linear = 0.0, Quadratic = 3.56e11
Case 3: User damping: Linear = 0.0, Quadratic = 4.78e11
Case 4: User damping: Linear = 0.0, Quadratic = 5.48e11
Case 5: User damping: Linear = 0.0, Quadratic = 4.24e11
Case 6: User damping: Linear = 0.0, Quadratic = 3.52e11
Effect of Mooring and Risers on Roll Motions

- Water Depth: 2140m
- VLCC, Ballast Draft = 8.8m
- Mooring Configuration:
  - Spread mooring, 24 mooring lines
  - Turret mooring, 9 mooring lines
- Riser configuration:
  - 24 catenary risers
  - Total FZ ~ 5500 metric tons
- Beam Sea Condition 1-yr RP:
  - Hs = 4.5m
  - Tp = 9.9s
Effect of Risers on Roll RAO

Roll RAO - Effect of Mooring and Risers, 270deg

- Mooring Lines + Risers
- Mooring Lines
- No Mooring Lines

Roll RAO (deg/m) vs. wave period (s)
Effect of Riser Balcony Location

Roll RAO - Effect of Riser Porch Location

- waves @ 90deg
- waves @ 270deg
Effect of Riser Balcony Location

RAO of vertical motion at the riser hang-off point, amidships

Z-motion at riser hang-off (m/m)

wave period (s)
Effect of Mooring Configuration

Roll RAO, Turret vs Spread Mooring

![Graph showing Roll RAO (degrees/meter) versus wave period (seconds) for Turret and Spread Mooring configurations. The graph peaks at different wave periods for each configuration.]
Second Order Roll Motions

Motions at Roll Natural Period
driven by
difference frequency moments
Second Order Roll Motions

• Example
  – 170,000 DWT FPSO – Purpose Built
  – No bilge keels
  – Roll Period: Full = 25.2s; Ballast = 23.7s

• Test setup:
  – Horizontal mooring
  – Scale 1:60
  – 3-hr duration

• Simulation setup:
  – HOBEM 3D diffraction
  – Second order roll moment spectrum
Separation between Roll period and wave period

![Graph showing separation between Roll RAO and wave frequency]

- **Roll RAO (solid line)**
- **Wave Spectrum (dashed line)**

**Axes:**
- **Horizontal (x-axis):** Wave frequency (rad/s)
- **Vertical (y-axis):** S (m²/s) and Roll RAO (deg/m)
Second order Roll Moment Spectrum

![Graph showing the relationship between difference frequency and roll moment spectrum.]

- **SMx**: Roll RAOs
- **Roll RAOs**
## Second Order Roll Motions – Simulation vs Test

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<th>Mean (deg)</th>
<th>Max (deg)</th>
<th>Min (deg)</th>
<th>Stdev (deg)</th>
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<td>-1.4</td>
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<td>3.2</td>
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<td><strong>Ballast Draft Roll Motions</strong></td>
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<td>Simulation</td>
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<tr>
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<tr>
<td>Test</td>
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<tr>
<td>Total</td>
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<td>-11.9</td>
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Concluding Remarks

- Accurate Roll predictions still difficult
- Bilge keels are very effective in reducing roll
- For SPMs LTRA is necessary to find extreme roll
- Determine critical sea state and bilge keel before model test
- Bilge/bilge keel configurations can be compared using CFD
- If roll period is long don’t forget about second order roll
Thank you.
References

- FPSO roll damping prediction from CFD and 2D and 3D model tests investigations, ISOPE 2004 Toulon.
- On Second Order Roll Motions of Ships, OMAE2003-37022
- Extreme Responses of Turret Moored Tankers, OTC 12147
- FPSO Roll JIP, MARIN