DESIGN OF HYBRID MARINE CONTROL SYSTEMS
FOR DYNAMIC POSITIONING IN EXTREME SEAS
AND IN ICE

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Outline

- Introduction
- Control design for different environmental conditions
- Hybrid control from calm to extreme seas
- Hybrid DP in ice
- Switching control between station keeping and transit
Introduction – Dynamic positioning

• Keep floating structure in fixed position and heading as well as to precisely maneuver predetermined track exclusively by means of vessel’s propulsion system
Introduction – Thruster-assisted position mooring

• Thruster-assisted position mooring system:
  – ATA/TA POSMOOR (DNV)
  – PM

• Main objective of PM
  – Control position
  – Control line tension

• Turret, spread, single point, etc.
Introduction – Challenges

- Harsh environmental conditions
  - Strong current: Gulf of Mexico, Northern England, Southern Norway, and South Africa
  - Long and high wave: North seas
  - Strong wind with gust: North Atlantic
  - Ice: Arctic areas
Introduction – Challenges

- All-year operation
- Vessel Operational Conditions
  - Control objective
  - Speed
  - Environmental condition

Shuttle tanker, station keeping in calm seas

Ferry during transit at high speed in calm seas

Ferry maneuvering at port
Introduction – Hybrid concept motivation

- Design of control system for changes of vessel operational conditions (VOCs)
- One unique nonlinear controller
  - complicated or maybe impossible
  - difficult to satisfy many control objectives
- Hybrid controller (combine and switch among different controllers)
  - simpler solution
  - satisfy different control objectives
Introduction – Hybrid concept motivation

• Flight control:
  – Gain scheduling (McLean, 1990; Wang and Balakrishnan, 2002; Oosterom and Babuška, 2005)
  – Switching in Nonminimum Phase Nonlinear Systems for VSTOL Aircraft (Oishi and Tomlin, 1999 and 2000)

• Vehicle control:
  – Local network control (Hunt et al., 1997).
  – Hybrid car: Toyota Prius

• Marine control system:
  – Hybrid thruster controller (Smogeli et al., 2004).

• Supervisory control: (Hespanha, 2001; Hespanha et al., 2003).
Control design

- Supply chain management
- Plant diagnostics and condition monitoring
- Guidance systems
- Optimal setpoint chasing
- DP control
- Power management
- Ballast control
- Thruster control
- Motor and drive control

Marine Control System Structure
(Sørensen, 2005)
Total motion = \( \text{Wave frequency motion} + \text{Low frequency motion} \)

### Normal env.
- Compensates LF motion
- Feedforward (Wind)
- PID controller
  - P: Position
  - D: Velocity
  - I: drift motion

### Harsh env.
- Compensates WF + LF motion
- Feedforward (Wind)
- PID + ABF controller
  - PID
  - Acceleration feedback
DP: Hybrid control from calm to extreme seas

- Compensate WF+LF motion
  - Output-PID and AFB controller

- Compensate LF motion
  - Output-PID controller

Environment:
- Extreme
- High
- Moderate
- Calm

Main function:
- Transit
- Low speed maneuvering
- Station keeping

Speed (m/s):
- 20
- 10
- 6
- 4
- 2

Output:
- Compensate WF+LF motion
- PID controller
- AFB controller

DP: Hybrid control from calm to extreme seas
• Hybrid control system
  – continuous state multi-controllers, and
  – discrete state logics
Mirroring the diagram:

- **Models/Estimators**
  - **Input:** $y$, $u$, $\omega_{0p}$
  - **Output:** $y_p$

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DP: Switching control from calm to extreme seas
### Controllers

<table>
<thead>
<tr>
<th>State</th>
<th>Controller Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm</td>
<td>Output-PID</td>
<td>Compensate low frequency (LF) motion</td>
</tr>
<tr>
<td>Moderate</td>
<td>Output-PID</td>
<td>Compensate LF motion</td>
</tr>
<tr>
<td>High</td>
<td>Smooth transition of moderate and extreme controllers</td>
<td>Smooth transition of moderate and extreme controllers</td>
</tr>
<tr>
<td>Extreme</td>
<td>Output-PID+AFB</td>
<td>Compensating both WF and LF motions</td>
</tr>
</tbody>
</table>

**Diagram:**
- **Operator**
- **Supervisory control**
- **Decision**
- **Model 1** to **Model 4**
- **Model set**
- **Controller 1** to **Controller 4**
- **Controller set**
- **Environment**
- **Marine vessel**
- **Switch**
- **Supervisor**
- **Switching signal**

**Legend:**
- **\( e_p \)**
- **\( \sigma \)**
- **\( y \)**

**Notes:**
- Compensate low frequency (LF) motion
- Compensate LF motion
- Smooth transition of moderate and extreme controllers
- Compensating both WF and LF motions
DP: Switching control from calm to extreme seas

Supervisory control:
- automatically switch to controller designed for that VOC
- scale-independent hysteresis switching logic: slow down switching to prevent chattering

Scale-independent hysteresis switching logic, Hespanha (2001)
DP: Switching control

- Experimental results
Estimated WPF and switching signal, $\sigma$
DP: Switching control from calm to extreme seas – Summary

• Switching control stabilized and improved performance of DP vessel in harsh environments
• Switching control expanded the weather operation window
DP in ice

• Motivation
  – Oil demand
  – Oil reservation in Arctic area
  – Global warming
Deepwater drilling in heavy sea ice
IODP Expedition 302, 2004

- Environmental condition
  - Waterdepth = 1200m,
  - Ice thickness = 1-3m, 9/10 icecover
  - Ice drift speed up to 0.154 m/s
- DP drilling vessel is Vidar Viking
- Experience instability of auto DP mode
- Manual station keeping based on captain’s experience
**DP in ice**

- **Challenges for control design**
  - Good enough model for ice loads
    - slush ice,
    - broken ice,
    - pack ice,
    - level ice,
    - ridges, and
    - Iceberg

- **Other challenges:** remoteness, coldness, darkness.

Intersection of the different disciplines:
- **Control theory**
- **Structure**
- **Ice and hydrodynamic load model**
DP in level ice

1. Initial contact
   - ice's velocity $v_{\text{ice}}$
   - vessel's velocity $v_{\text{vessel}}$
   - wave
   - hydrodynamic pressure
   - shear fracture
   - crushing
   - possible contact
   - normal friction

2. Crushing and plate deflection
   - wave
   - hydrodynamic pressure
   - shear fracture
   - crushing
   - possible contact
   - normal friction

3. Bending failure
   - flexural fracture
   - shear fracture
   - crushing
   - normal friction
   - hydrodynamic pressure

4. Rotation of broken ice fragment
   - ventilation begins
   - wave
   - normal friction

5. Impact between rotating ice fragment and vessel's hull
   - impact
   - wave
   - normal friction

6. Sliding & submersion and new contact
   - new contact
   - sliding and submersion
   - unbroken ice sheet
   - normal friction
   - hydrodynamic pressure

Top view of icebreaking

unbroken ice sheet
next bending failure
broken ice fragment
bending failure
DP in level ice - Modelling

Ice Data: $h_i$, $\sigma_t$, $\sigma_c$, $V$, ice edge before contact,

Dynamic Structure
Data: Mass, Damping, Stiffness and Effects of Control properties, contact surface.

Literature Review
Field Investigation
Laboratory Tests

Icebreaker
Drill rig
FPSO

Solve for each time step

Contact
Crushing
Bending failure
Clear away

$F_i(x, y, t_j)$, $F_{ew}(x, y, t_j)$

Vessel dynamics

$V_{v-i}(t_{j+1})$, $F_{w}(x, y, t_{j+1})$

Time History of Dynamic Ice Load and Vessel’s Response

Ice force vector
Ice edge geometry and location

Relative velocity
Water line location

$\tau_{\text{ice}} = \tau_{\text{crush}} + \tau_{\text{bending}} + \tau_{\text{submersion}} + \tau_{\text{velocity}}$
DP in level ice – Modelling

\[ \tau_{\text{crush}} = [R_b + R_s + R_v, 0, 0, 0, 0, 0]^\top \]

Simulated ice load
1: Local failure
2: Global failure
3: Maximum
4: Start of rotation
5: 2nd force peak
6: End of rotation

Measured ice load

Advance of vessel in ice
DP in level ice – Modelling

- Time domain simulation
- Discretization of ice edge and vessel hull
• Validation
  – MESH 6: Comparison between mean simulated ice load and empirical ice resistance for different ice thicknesses and ice velocities.
DP in level ice – Modelling

• Compare with the empirical formulation (Lindqvist, 1989)
Control plant model for open water and ice

\[
\begin{align*}
\dot{p}_w &= A_{pw}(\omega_0)p_w + E_{pw}w_{pw}, \\
\dot{\eta} &= R(\psi)\nu, \\
\dot{b} &= -T_b^{-1}b + E_bw_b, \\
\dot{\tau}_{ice} &= -T_{ice}^{-1}\tau_{ice} + E_{ice}w_{ice}, \\
M\dot{\nu} &= -D\nu + R^T(\psi)b + \tau_c, \\
y &= \eta + C_{pw}p_w + v,
\end{align*}
\]

Observer design for open water and ice

Without ice-load measurements

\[
\begin{align*}
\dot{p}_w &= A_{pw}\dot{p}_w + K_1\dot{y}, \\
\dot{\eta} &= R(\psi)\dot{\nu} + K_2\dot{y}, \\
\dot{b} &= -T_b^{-1}\dot{b} + K_3\dot{y}, \\
\dot{\tau}_{ice} &= -T_{ice}^{-1}\dot{\tau}_{ice} + K_5\dot{y}, \\
M\dot{\nu} &= -D\dot{\nu} + R^T(\psi)(\dot{b} + \dot{\tau}_{ice}) + \tau_c + K_4R^T(\psi)\dot{y}, \\
\dot{y} &= \dot{\eta} + C_{pw}\dot{p}_w,
\end{align*}
\]

With ice-load measurements

\[
\begin{align*}
\dot{p}_w &= A_{pw}\dot{p}_w + K_1\dot{y}, \\
\dot{\eta} &= R(\psi)\dot{\nu} + K_2\dot{y}, \\
\dot{b} &= -T_b^{-1}\dot{b} + K_3\dot{y}, \\
\dot{\tau}_{ice} &= -T_{ice}^{-1}\dot{\tau}_{ice} + K_5(\tau_{ice}^{meas} - \dot{\tau}_{ice}), \\
M\dot{\nu} &= -D\dot{\nu} + R^T(\psi)(\dot{b} + \dot{\tau}_{ice}) + \tau_c + K_4R^T(\psi)\dot{y}, \\
\dot{y} &= \dot{\eta} + C_{pw}\dot{p}_w,
\end{align*}
\]
DP in level ice – Controller design

- Controller design

\[ \tau_c = \tau_{\text{PID}} + \tau_{\text{FF}}, \]

\[ \tau_{\text{PID}} = -K_p \eta_e - K_d \nu_e - K_i \int_0^t \eta_e \, dt, \]

\[ \tau_{\text{FF}} = -K_{\text{FF}} \hat{\tau}_{\text{wind}} - K_{\text{FF}} \hat{\tau}_{\text{ice}}, \]
DP in level ice – Controller design

- Controller design
DP in level ice – Simulation results

Vessel’s position

Open water

DP in Ice

Open water

Ice controller without ice-load measurements

Ice controller with ice-load measurements

Open water controller
Switching control between station keeping and transit

- **Motivation**
  - Different controllers for different tasks and different speed regimes
  - Time consuming if manually switch

- **Objective**:
  - Develop switching control for integrated station keeping control and transit
  - Illustrate feasibility of switching control system via shuttle tanker example
Switching control between station keeping and transit

- Model 1 - Transit
- Model 2 - Smooth transformation from transit to station keeping
- Station keeping
- Model 3 - DP
- Model 4 - Smooth switch between DP - PM
- Model 5 - PM

Switching signal $\sigma$

Marine vessel

Environment

Supervisor

Controller set

Observer 1 → Controller 1
Observer 2 → Controller 2
Observer 5 → Controller 5

Controller set

Decided by switching logic
Decided by operator

Switch
Switching control between station keeping and transit

- Switching between DP and PM (STL)

Submerged turret loading (STL)
Switching control between station keeping and transit
End of Presentation

• List of reference:
  
  
  
  
  
  
  