Study on Heel Stabilization for Cruise Ship by using Active Fin and Anti-Rolling Tank

Jae-Han Kim and Yonghwan Kim

Department of Naval Architecture and Ocean Engineering,
Seoul National University, Korea

22 December 2012
Wind-Induced Heel of Cruise Ship

• Wind-induced heel of cruise ship
  – Large superstructure of cruise ship makes her vulnerable to lateral wind load.
  – Wind-induced heel of cruise ship is considered in the seakeeping point of view.
  – Heel stabilization is recommended to improve passenger comfort and seakeeping performance.

• Prediction of heel moment
  – Wind-induced heel moment to the ship is computed numerically.
  – Wind speed profile: DNV Recommended Practice C205 (October 2010)
  – Calculation of heel moment (Fujiwara & Ueno, 2006)
  – Heel moment coefficient from wind tunnel experiment in Fincantieri (Serra, 2002)

• Stabilization of heel effect
  – Actuator: Stabilizing fin, anti-rolling tank (U-tube tank)
  – Linear optimal control algorithm: LQG
**Computational Program**

- **WISH-CRUISE**
  - Computational methods of heel moment and motion stabilization integrate to the program WISH-CRUISE.
  - WISH-CRUISE is extension based on WISH (computer program for nonlinear wave induced load and ship motion) which is developed in Seoul National University.
  - Assessment of seakeeping performance of cruise ship in time domain can be carried out by using the program WISH-CRUISE.
Prediction of Wind-Induced Heel

I. Model cruise ship

II. Wind speed profile model

III. Computation of heel moment
• **Similar cruise ships to model cruise ship**

  - Caribbean Princess, computational model cruise ship, experimental model cruise ship

<table>
<thead>
<tr>
<th></th>
<th>Model Cruise Ship</th>
<th>Caribbean Princess</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (LBP)</td>
<td>242 m</td>
<td>242 m</td>
</tr>
<tr>
<td>Breadth</td>
<td>36 m</td>
<td>36 m</td>
</tr>
<tr>
<td>Depth</td>
<td>8.3 m</td>
<td>8.4 m</td>
</tr>
<tr>
<td>Displacement</td>
<td>51,000 ton</td>
<td>52,000 ton</td>
</tr>
</tbody>
</table>

  - Specification and shape of superstructure are necessary to obtain the heel moment accurately.

  → **Superstructure of Caribbean Princess is considered in the present study.**
Parameters for Computation of Wind Load

• **Coordinate system for numerical computation**
  - Apparent wind velocity is computed from vector summation of true wind velocity and forward speed of ship.

• **Definition of parameters**
  - Parameters for wind load computation are obtained from specifications of the superstructure of Caribbean Princess.

### Definition of parameters for calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall, ( L_{OA} )</td>
<td>275.7 m</td>
</tr>
<tr>
<td>Breadth, ( B )</td>
<td>36.0 m</td>
</tr>
<tr>
<td>Frontal projected area, ( A_F )</td>
<td>1738.3 m(^2)</td>
</tr>
<tr>
<td>Lateral projected area, ( A_L )</td>
<td>9093.0 m(^2)</td>
</tr>
<tr>
<td>Height of top of superstructure, ( H_{BR} )</td>
<td>46.2 m</td>
</tr>
<tr>
<td>Height from calm water surface to center of lateral projected area ( C ), ( H_C )</td>
<td>17.3 m</td>
</tr>
<tr>
<td>Mean height of the ship (equal to ( A_L/L_{OA} )), ( H_L )</td>
<td>33.0 m</td>
</tr>
<tr>
<td>Air density (kg/m(^3)), ( \rho_A )</td>
<td>1.2754 kg/m(^3)</td>
</tr>
</tbody>
</table>
Wind Speed Profile

- Wind speed profile for heel moment
  - Logarithmic wind speed profile model
  - DNV (2010), “Wind loads”, Recommended Practice C205, Section 5
  - The 10 minutes mean wind speed at 10m height above the still water level is to be used as a wind parameter U(H).

\[
U(z) = \frac{1}{k_a} \ln \frac{z}{H} + \frac{1}{k_a} \sqrt{\kappa} \ln \frac{z}{H}
\]

κ: surface friction coefficient
\( \kappa = \frac{k_a^2}{(\ln \frac{H}{z_0})^2} \)

- Terrain roughness parameter \( z_0 \)
- DNV RP C205, Table 2.1: to consider difference between open sea and coastal area
- Constant terrain roughness parameter
  - \( z_0 = 0.0001 \) (for open sea)
  - \( z_0 = 0.001 \) (for coastal areas with onshore wind)

The height of model cruise ship is over 40m, therefore, difference should be considered.
Heel Moment

- Prediction of heel moment
  - Regression analysis of wind-tunnel experimental results has been carried out.
  - Estimated formulation of heel moment by wind load

\[
K_A = C_H(\phi) C_{AK}(\psi_A) q_A A_L H_L
\]

where
- \(C_H(\phi)\) heel effect coefficient
- \(C_{AK}(\psi_A)\) heel moment coefficient
- \(\phi\) heel angle
- \(\psi_A\) apparent (relative) wind direction
- \(A_L\) lateral projected area
- \(H_L\) mean height of the ship
- \(k_q\) empirical parameter

Calculation of pressure component by wind load

\[
q_A = \frac{1}{2} \rho A U^2 + k_q \left\{ \frac{1}{H_L} \int \frac{\rho_A}{2} U_T^2 dz_A \right\} + (1-k_q) \left\{ \frac{\rho_A}{2} U_T^2 \right\}
\]

pressure in the actual sea wind condition

\[
q_A = \frac{1}{2} \rho A U^2 + k_q \left\{ \frac{1}{H_L} \int \frac{\rho_A}{2} U_T^2 dz_A \right\} + (1-k_q) \left\{ \frac{\rho_A}{2} U_T^2 \right\}
\]

\[
+ 2 \cos(\psi + \beta) \left\{ \frac{1}{2} \rho A U^2 - k_q \left\{ \frac{1}{H_L} \int \frac{\rho_A}{2} U_T^2 dz_A \right\} + (1-k_q) \left\{ \frac{\rho_A}{2} U_T^2 \right\} \right\}
\]

Computed wind profile for prediction of heel moment (open sea)

Heel moment by wind direction

International Research Exchange Meeting of Ship and Ocean Engineering in Osaka
Coefficients for Heel Prediction: $C_H$, $C_{AK}$

- **Heel effect coefficient: $C_H$**
  - Heel moment variation by heel angle
  - Wind tunnel experiment using modern cruise ship model by Fincantieri: Model No. 1852 (Caribbean Princess)

\[
C_H(\phi) = \begin{cases} 
-0.00738\phi + 1.0 & \text{for } -20 \leq \phi < 0 \text{ (deg)} \\
-0.00757\phi + 1.0 & \text{for } 0 \leq \phi \leq 20 \text{ (deg)}
\end{cases}
\]

- **Heel moment coefficient: $C_{AK}$**
  - Heel moment variation by apparent wind direction
  - Heel moment coefficient

\[
C_{AK}(\psi_A) = \begin{cases} 
C_{AY} \cdot 0.0737 \left( \frac{H_C}{L_{OA}} \right)^{0.821} & \text{for } \frac{H_C}{L_{OA}} \leq 0.097 \\
C_{AY} \cdot 0.500 & \text{for } \frac{H_C}{L_{OA}} > 0.097
\end{cases}
\]

\[C_{AY}(\psi_A) = C_{CF} + C_{YL}, \text{ lateral wind force coefficient}\]
\[H_C: \text{height from waterline to center of lateral projected area (m)}\]
Analysis of Heel Stabilization

I. Stabilization using stabilizing fin

II. Stabilization using U-tube tank
Controller Design: Stabilizing Fin

- **Controller design of stabilizing fin**
  - State-space equation is derived from equation of roll motion to apply the linear optimal control algorithm LQR (linear quadratic regulator).
  - Equation of roll motion
    \[
    (I_{44} + I_{a,44})\ddot{\phi} + b_{44}\dot{\phi} + c_{44}\phi = M_{Ext} + M_{Fin}
    \]
  - Effective angle of attack (lift force)
    \[
    \alpha_E = \tan^{-1}\left(\frac{\dot{z} + \phi l_v - \partial l_x - v_w}{V_S - u_w}\right) + \theta + \delta
    \]
  - State-space equation
    \[
    \begin{bmatrix}
    \ddot{\phi} \\
    \dot{\phi}
    \end{bmatrix} = \begin{bmatrix}
    0 & 1 \\
    -\frac{c_{44}}{I_{44} + I_{a,44}} & -\frac{b_{44}}{I_{44} + I_{a,44}}
    \end{bmatrix}
    \begin{bmatrix}
    \phi \\
    \dot{\phi}
    \end{bmatrix}
    + \begin{bmatrix}
    1 \\
    \frac{1}{2} \rho S \frac{dC_L}{d\alpha} \cos \alpha_0 \left\{ \frac{(V_S - u_w)^2}{I_{44} + I_{a,44}} + \left(\dot{z} + \phi l_v - v_w\right)^2 \right\} I_Y
    \end{bmatrix}
    \begin{bmatrix}
    0 \\
    0
    \end{bmatrix}
    \]

- **Stabilizing moment is calculated from lift and drag forces and applied into motion simulation instantaneously.**
- **Hydrodynamic effects of lifting surface such as stall and free surface effect are also considered.**

- **Two stabilizing fins are controlled simultaneously to reduce heel and roll motion.**
- **LQR controller is applied to determine the control inputs of two stabilizing fins in real time.**
Motion Stabilization: Control Algorithm

• **Optimal control algorithm: LQR**
  - LQR (linear quadratic regulator) control is an optimal control. Optimal control input \( u \) should minimize performance index \( J \).
  - Control performance is tuned by adjusting the state and control input weight matrices
    \[
    J = \int_0^\infty \begin{bmatrix} \tilde{x}^T(t) & \tilde{u}^T(t) \end{bmatrix} \begin{bmatrix} Q & R \\ R & 0 \end{bmatrix} \begin{bmatrix} \tilde{x}(t) \\ \tilde{u}(t) \end{bmatrix} dt
    \]
    where \( Q = \text{state weight matrix} \)
    \( R = \text{control input weight matrix} \)
  - Control input \( u \) is obtained by solving algebraic Riccati equation.
    \[
    PA + A^T P - PBR^{-1}B^T P + Q = 0
    \]
    Control input : \( u(t) = -R^{-1}B^T P x(t) \)

• **LQG (linear quadratic Gaussian)**
  - Application of LQG controller can make the robustness of the designed controller better by reducing the noise effect, so that the overall performance of the active stabilizing fin improves.

• **State observer: Kalman Filter**
  - Kalman filter is an optimal state observer based on the current and past measurement (Kalman, 1960).
  - Augmented state space equation includes the process and measurement noises.
  - State observer based on Kalman filter
    \[
    \dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L(y(t) - C\hat{x}(t))
    \]
    \( x(t_0) = x_0 \)
    \( \hat{x}(t) : \text{estimated state} \)
    \( L : \text{observer gain (Kalman filter gain)} \)

LQR + Kalman filter \( \rightarrow \) LQG (linear quadratic Gaussian)

Diagram of designed controller
Motion Stabilization: Stabilizing Fin

- Motion stabilization by using stabilizing fin
  - Wind + wave → roll + heel
  - LQG control algorithm (LQR + Kalman filter)
  - Wind-induced heel and wave-induced roll motion of the ship can be stabilized by applying stabilizing fins.
  - Stabilizing fins are effective when the ship is advancing with enough speed.
  - Saturation of control input is observed due to mechanical limitation of actuator.
  - Example of computation: model cruise ship, regular wave, Fn=0.211 wind speed=20m/s, wind direction=90°
Anti-Rolling & Heeling Tank: U-tube Tank

• Heel stabilization by using U-tube tank
  - U-tube tank is usually considered as anti-rolling tank.
  - U-tube tank can also be actuated as anti-heeling tank.
  - Internal fluid height in the tank can be controlled by using hydraulic pump or compressed air.
  - In the present study, pressure of actuator is considered as a control input.

• Dimension of tank
  - In general, volume of internal fluid in the tank is determined about 1~2% of ship displacement.
  - In the present study, arbitrary dimension of the tank is applied to perform the simulation.

<table>
<thead>
<tr>
<th>Dimension of U-tube tank</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of fluid in the tank</td>
<td>1025 kg/m³</td>
</tr>
<tr>
<td>Fluid height in the reservoir (h_r)</td>
<td>3.0 m</td>
</tr>
<tr>
<td>Width of vertical reservoir (w_r)</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Height of horizontal duct (h_d)</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Length between two reservoir (w)</td>
<td>30 m</td>
</tr>
<tr>
<td>Volume of internal fluid</td>
<td>860 m³</td>
</tr>
</tbody>
</table>
Controller Design: Active U-tube Tank

- **State-space model to design the controller of U-tube tank**
  - Controller of U-tube tank is also designed by adopting the LQG algorithm
  - Equation of motion: roll motion and U-tube tank
    \[
    (I_{44} + I_{a,44}) \ddot{x}_4 + b_{44} \dot{x}_4 + c_{44} x_4 = a_{44} \ddot{x}_r + c_{44} \dot{x}_r + F_{Ext}
    \]
    (Roll motion of the ship
    Moment by tank
    \[
    a_{rr} \ddot{x}_r + b_{rr} \dot{x}_r + c_{rr} \tau = -a_{r4} \ddot{x}_4 - c_{r4} x_4 + F_r \cdot r
    \]
    (Height variation of internal fluid in the tank
    Control input
    - Derivation of state-space equation to apply the LQR control

\[
\begin{bmatrix}
\dot{x}_4 \\
\dot{x}_r
\end{bmatrix} =
\begin{bmatrix}
-\frac{b_{44}}{A} & -\frac{1}{A}\left(\frac{a_{44}c_{44} + c_{44}}{a_{rr}}\right) & -\frac{a_{44}b_{rr}}{a_{rr}A} & -\frac{1}{A}\left(\frac{a_{44}c_{44} - c_{44}}{a_{rr}}\right) \\
1 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\dot{x}_4 \\
\dot{x}_r
\end{bmatrix}
\]

\[
\begin{bmatrix}
\frac{a_{44}b_{44}}{B(I_{44} + I_{a,44})} & \frac{1}{B}\left(\frac{a_{44}c_{44} - c_{44}}{I_{44} + I_{a,44}}\right) & -\frac{b_{44}}{B} & -\frac{1}{B}\left(\frac{a_{44}c_{44} - c_{44}}{I_{44} + I_{a,44}}\right)
\end{bmatrix}
\begin{bmatrix}
\dot{x}_4 \\
\dot{x}_r
\end{bmatrix}
\]

\[\begin{bmatrix}
A & 0 & 0 & 0 \\
0 & r & B
\end{bmatrix}
\begin{bmatrix}
\ddot{x}_4 \\
\ddot{x}_r
\end{bmatrix}
\]

\[F_r =
\begin{bmatrix}
\frac{1}{A} \\
0 \\
0
\end{bmatrix}
\]

\[F_{Ext} =
\begin{bmatrix}
0 \\
0 \frac{a_{44}}{B(I_{44} + I_{a,44})}
\end{bmatrix}
\]

where \(A = I_{44} + I_{a,44} + \frac{a_{44}a_{r4}}{a_{rr}}\), \(B = a_{rr} + \frac{a_{44}a_{r4}}{I_{44} + I_{a,44}}\)

- Stabilizing moment is calculated from height variation of internal fluid in the U-tube tank and applied into motion simulation instantaneously.
- Dynamics of internal fluid in the tank should be considered to obtain the stabilizing moment from the control input.
- Designed controller by using state-space equation integrates to the WISH-CRUISE.
- Control input from U-tube tank is applied simultaneously to reduce heel and roll motion.
Motion Stabilization: Active U-tube Tank

- Motion stabilization by using active U-tube tank
  - Wind + wave → roll + heel
  - LQG control algorithm (LQR + Kalman filter)
  - Wind-induced heel and wave-induced roll motion of the ship can be stabilized by applying U-tube tank.
  - Motion stabilization by using tank can be effective regardless of forward speed of the ship.
  - Performance of stabilization is dependent on the dimension of tank and capacity of actuator.
  - Example of computation: model cruise ship, regular wave, wind speed=20 m/s, wind direction=90°
Conclusions

• Computational methods to predict the wind-induced heel and to stabilize the motion of cruise ship are developed.

• Heel moment by wind load is computed using the estimated formulation. In this procedure, heel effect coefficient is corrected using another wind tunnel experimental result.

• Motion stabilizations by using stabilizing fin or active U-tube tank are considered based on linear optimal control algorithm LQG.

• These computational methods integrate to the time-domain seakeeping analysis program for cruise ship, called WISH-CRUISE.

• From result of numerical computations, it is observed that wind-induced heel of cruise ship can be reduced effectively by applying active fins or active U-tube tank.

• For more realistic simulation, mechanical limitation of control actuator will be considered appropriately.
Thank You