Propulsion control and thrust allocation on marine vessels

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• Introduction
• Ventilation model and anti-spin thruster control
• Propulsion controllers
• Anti-spin thrust allocation
• Singularity avoidance
• Conclusions
Introduction

- The high demand for oil and gas leads to exploration and exploitation at increasingly deeper waters.
- This favors the use of Dynamic Positioning (DP) or Position Mooring (PM) systems for station keeping.
- Continuous demand for increased accuracy, safety and efficiency.
- The focus in this work has been on:
  - Propulsion/thruster control
  - Thrust allocation
Introduction

Ventilation and in-and-out-of events

Ventilation

- Air is sucked down from the surface into the propeller
- Rapid and time varying
Ventilating ducted propeller

Video 1.wmv

Ruth et al. (2005)
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Ventilation model and anti-spin thruster control

Motivation:
On vessels conducting DP or PM operations in harsh environment, ventilation and in-and-out-of water effects may lead to unacceptable behavior of the thrusters. This may result in reduced efficiency, accuracy and safety of the DP or PM system.

Objective:
Determine the differences between fixed pitch propellers and consolidated controlled propellers as regards ventilation, in-and-out-of water effects and anti-spin thruster control.

Contributions:
- A summary of scaling laws was presented (Ruth & Smogeli 2006).
- A dynamic model of propellers subject to ventilation and in-and-out-of water effects for use in simulations was developed (Ruth & Smogeli 2006).
- Reducing the pitch ratio, at the cost of increasing the shaft speed, reduces the likelihood and severity of ventilation (Ruth & Smogeli 2006).
Ventilation model for consolidated controlled propellers

• Extensive model tests (more than 1000 combinations) were conducted. (Master Thesis)

• A quasi static ventilation model was developed. (Master Thesis)

• The model was extended to a dynamic model by:
  – Introducing rate limitations (Wagner effect).
  – Accounting for response time of water flowing through propeller disk.

• The proposed model is valid for the particular propeller with:
  – $P/D=[0.4,1.3]$
  – $h/R=[-1,\infty]$

• It is however assumed that the model will be suitable for other propellers with a different set of parameters.
Ventilation experiments

Verification of dynamic model:

- Shaft speed control
- Sinusoidal desired thrust
- Sinusoidal submergence ratio

- Combined control (power control)
- Stepwise desired thrust
- Sinusoidal submergence ratio

\[ \beta_T \] - Thrust loss factor
\[ \beta_Q \] - Torque loss factor
\[ n \] - Shaft speed
\[ h/R \] - Relative submergence

Graphs showing experimental and simulated data for various parameters over time.
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Motivation:
Propulsion control of DP vessels by use of torque or power control was suggested by Sørensen et al. (1997). How will they perform at higher advance speeds?

Objective:
Evaluate the performance of torque and power control, compared to other control methods, in transit operation.

Contributions:
• A new \( \tau \) parameter is proposed for:
  – Comparison of propellers in equal environmental conditions.
  – Determination of optimal propeller diameter.
  – Determination of optimal pitch ratio.
  – Comparison of different propulsion controllers as regards efficiency and thrust sensitivity (Ruth et. al. 2006).

• Different propulsion control methods for surface vessels was compared with respect to:
  – Thrust sensitivity (Ruth et. al. 2006).
  – Efficiency (Ruth et. al. 2006).
The $\tau$ parameter

Advance number: \[ J_A = \frac{V_A}{nD} \]

is not a suitable parameter for comparing efficiency and thrust sensitivity of different controllers since the controllers may operate at different shaft speeds.

Therefore the $\tau$ parameter was proposed:

\[ \tau = \frac{J_A}{\sqrt{K_T}} = \sqrt{\rho D} \frac{V_A}{\sqrt{T}} \]

This parameter makes it possible to:

- Compare efficiency of different propellers and controllers at equal environmental conditions (equal $V_A$).
- Determine the optimal pitch ratio.
- Determine the optimal propeller diameter.
Propulsion controllers

• One control variable:
  – Shaft speed control
  – Torque control
  – Power control
  – Combined control
  – Pitch control

• Consolidated controlled propellers (two controlled variables):
  – Torque/pitch ratio controller
  – Shaft speed/pitch ratio controller
  – Torque/Shaft speed controller
Propulsion controllers

Comparison of efficiency for different pitch ratios:

\[ \tau = \rho^{0.5} D V A^{0.5} \left[ \frac{T}{T^*} \right] \]
Propulsion controllers

Comparison of efficiency for different controllers:

\[
\eta_0/\eta_{0\text{optimal}} [-] \quad \tau = \rho^{0.5} D V_A / T^{0.5} [-]
\]

- Torque/pitch ratio
- Torque/shaft speed
- P/D = 1.4 (FPP)
- P/D = 0.58 (FPP)
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Anti-spin thrust allocation

Motivation:
Vessels conducting DP operations are usually over actuated. This should be exploited in the case of ventilation and in-and-out-of water events in order to increase efficiency, safety and positioning accuracy.

Objective:
Develop an anti-spin thrust allocation system, capable of redistributing thruster force from heavily ventilated to less ventilated thrusters.

Contributions:
- A convex linearly constrained quadratic thrust allocator is proposed (Ruth et. al. 2007).
- Different methods for constraining the power consumption of the thrust allocator are proposed.
- A modification of the convex linearly constrained quadratic thrust allocator such that the power is proportional to $T^{3/2}$ is proposed (Ruth et. al. 2009).
- An anti-spin thrust allocation strategy is proposed leading to:
  – Power savings (Ruth et. al. 2009).
  – Reduced torque and power transients (Ruth et. al. 2009).
  – Improved positioning performance.
Anti-spin thrust allocation

Idea:
When you have many thrusters, redistribute thrust from ventilating to non-ventilating propellers.

Proposed solution:
Increase the cost of ventilating thrusters in the thrust allocator.

Benefits:
- Reduced power consumption.
- Reduces power and torque fluctuations.
- Increased positioning accuracy.
Anti-spin thrust allocation

1. Modify the cost function:
   \[
   \text{arg min}_{d, T_d} \left( \left\| \gamma W_s \right\|_2^2 + \left\| W_u T_d \right\|_2^2 \right)
   \]

   to:
   \[
   \text{arg min}_{d, T_d} \left( \left\| \gamma W_s \right\|_2^2 + \left\| \frac{W_u}{4 \sqrt{T_{d, prev}}} T_d \right\|_2^2 \right)
   \]

2. Increase the cost of the ventilating thruster:
   \[
   \beta_{Q1} = \begin{cases} 
   \beta_{Q1,j}, & \text{if ventilation occurs,} \\
   1, & \text{else.}
   \end{cases}
   \]
   \[
   \beta_{Q2,j} = \text{ratelimit}(\beta_{Q1,j}, \beta_{\lim,j}, -\infty)
   \]
   \[
   J_{M,j} = \beta_{Q2,j}^S \frac{W_{u,j}^2}{\sqrt{T_{d, prev,j}}} T_{d,j}^2
   \]
   \[
   S = 1 - \frac{3}{2m} \approx -1.31
   \]
Anti-spin thrust allocation

• Red_04b.avi
Anti-spin thrust allocation experiments

Anti-spin OFF
Anti-spin thrust allocation experiments

- Run_D.avi
Anti-spin thrust allocation experiments

Plots from animation:
Anti-spin thrust allocation experiments

Plots from animation:
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Singularity avoidance

Motivation:
On vessels with azimuthing thrusters, the directions of the thrusters significantly affect the maneuverability of the vessel. On vessels with slowly rotating thrusters, this may easily lead to loss of position.

Objective:
Determine a way of increasing the maneuverability on vessels with slowly rotating azimuths.

Contributions:
• A method for finding minimum gain from thruster forces to generalized forces for unidirectional thrusters are developed. This gain is a good indicator on the maneuverability of the vessel (Ruth & Sørensen 2009).
• A design loop for thruster configurations based on minimum gain from thruster forces to generalized forces is suggested. The method focus on maneuverability and thrust capability, and is capable of taking thruster or power bus failures into account (Ruth & Sørensen 2009).
• It is proposed how to find and visualize the minimum gain direction.
• Different methods for real time singularity avoidance are suggested.
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Conclusions

• A dynamic model of propellers subject to ventilation and in-and-out-of water effects for use in simulations was developed.
• Reducing the pitch ratio, at the cost of increasing the shaft speed, reduced the likelihood and severity of ventilation.
• The proposed τ parameter was suitable for:
  – Comparison of propellers in equal environmental conditions.
  – Determination of optimal propeller diameter.
  – Comparison of different propulsion controllers as regards efficiency and thrust sensitivity.
• Different propulsion control methods for surface vessels was compared with respect to:
  – Thrust sensitivity.
  – Efficiency.
Conclusions

• A new way of solving the thrust allocation problem by use of QP-solvers was presented.

• The anti-spin thrust allocation strategy resulted in:
  – Power savings.
  – Reduced torque and power transients.
  – Improved positioning performance.

• It was shown how the minimum gain from thrust to generalized forces can be determined for unidirectional thrusters.

• Real time singularity avoidance was demonstrated by experiments.
Thank you for your attention!
Bibliography


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