The influence of aft control surface configuration of a submarine on the submerged operational performance

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## Agenda

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
</tr>
<tr>
<td>2</td>
<td>Construction of the SOE</td>
</tr>
<tr>
<td>3</td>
<td>Control surface configuration</td>
</tr>
<tr>
<td>4</td>
<td>SOE limits</td>
</tr>
<tr>
<td>5</td>
<td>Actuation architecture</td>
</tr>
<tr>
<td>6</td>
<td>SOE boundaries</td>
</tr>
<tr>
<td>7</td>
<td>Concluding discussion</td>
</tr>
</tbody>
</table>
Submarine control surfaces (i)

- A submerged submarine is required to manoeuvre in both the vertical and horizontal planes.
  - Horizontal plane = higher agility, high rates of turn → low tactical diameters.
  - Vertical plane = lower agility required because:
    - High agility generates large pitch angles and depth excursions.
    - If a malfunction in the hydroplane control system occurs (a “jam”), this could place the submarine in danger in broaching or exceeding the maximum depth.

- Traditionally, control surfaces consist of a set of forward and aft hydroplanes and rudders in a cruciform configuration.
  - Large rudders, Smaller hydroplanes with stabilisers.

- However alternative configurations for the aft control surfaces are possible:
  - X-plane: - has been adopted by many SSKs.
  - Inverted Y: - no in-service examples.
  - Pentaform: - no in-service examples.
Submarine control surfaces (ii)

• However, recently X-planes have also been proposed for a number of larger nuclear powered submarine projects:
  – Ohio replacement SSBN (Columbia Class) USA.
  – Vanguard Successor SSBN (Dreadnought Class) UK.
  – Barracuda SSN (Suffren Class) France.

• Nuclear powered submarines traditionally have a higher degree of safety analysis conducted on the designs.

• Vertical plane manoeuvring and control is mitigated by a Safe Operating Envelope (SOE).
  – An x-y plot of speed vs depth.
  – Provides guidance to operators on safe combinations of speed and depth, if an incident were to occur.
  – Incidents considered are hydroplane jams and floods.
  – Calculated using a mathematical model – batch processing 1000’s of trajectories to derive the SOE.
Safe Operating Envelope (i)

- Jam line boundaries on a typical SOE are a composite of results from a number of different hydroplane jam scenarios:
  - Jams to rise and dive.
  - Different hydroplane jam combinations.

- An SOE is most often considered for in-service submarines.
  - Mitigating against the risk of platform loss, if an incident occurs at sea.

- SOEs can also be used as part of the design process for a new submarine. The SOE can:
  - Influence the design process.
  - Ensure the final design is able to meet the required concept of operations.
    - Highlights if there is a need to change the:
      - Hydrodynamics of the platform.
      - Systems that actuate the hydroplanes.
Safe Operating Envelope (ii)

- Typically two types of jam scenario:
  - Jam limitations: multiple sets of similar scenarios with increasing severity.
    - In the main body of the SOE.
    - A single isolated failure depends on actuators and linkages → a single aft hydroplane or two aft hydroplanes if they are linked on a common stock.
    - A permanent failure – backup systems cannot override the jam.
  - Jam maximum boundary: a single scenario of maximum severity.
    - A case that bounds the limits of the SOE.
    - Potentially multiple failures depending on the mechanical, hydraulic and electrical linkages or the control logic of the steering and diving control system.
    - A temporary jam – backup systems can override the jam and regain control.
  - The final SOE is a composite of these two scenarios.
Control surface configuration impact on jam limitation case

• The configuration of the aft control surfaces can have a significant impact on the type of jam incidents that need to be assessed for defining the SOE limitations.

• Some examples of common arrangements for the cruciform and X-plane designs are shown below:

Linked cruciform (2xCS)
- Port and starboard hydroplanes linked by a common stock.
- Upper and lower rudder linked by a common stock.
- One set of control surfaces for each manoeuvring axis.
- No redundancy.
- Permanent double sternplane jam.

Linked X-plane (2xXP)
- Diagonally opposite planes linked by a common stock.
- Both sets of control surfaces act in both manoeuvring axes.
- Some redundancy as the opposite pair can still affect depth/pitch & heading.
- Permanent X-plane diagonal pair jam.

Independently actuated cruciform (1xCS)
- Port and starboard hydroplanes have individual actuator & stock.
- Control surfaces for each manoeuvring axis (rudder as above).
- Some redundancy as the actuator only controls a single sternplane.
- Permanent single sternplane jam.

Independently actuated X-plane (1xXP)
- Each plane has its own actuator & stock.
- All four control surfaces act in both manoeuvring axes.
- Significant redundancy as the remaining planes can all affect depth/pitch & heading.
- Permanent single X-plane jam.
SOE jam limitation – normal operating condition

• If the submarine operates with all sternplanes fully functional, but then experiences a permanent single sternplane failure:

  • 2xCS arrangement has the smallest operational area (30%) and lowest allowable maximum speed (36%).

  • 2xXp configuration is better with a slightly bigger operational area 45% and speed 56%.

• 1xCS and 1xXp arrangements have the best performance (area 56% vs 64% and speed 79% vs 83% respectively).
  
  – Only one possible recovery strategy for 1xCS:
    – Put the working hydroplane in the opposite direction to the jam.
  
  – Several possible recovery strategy options for a 1xXP configuration:
    – Use the three remaining X-planes in the opposite direction to the jam (shown in figure).
      – High manoeuvrability can result in large pitch angles during recovery.
    – Order a turn, neutralising the jam’s tendency to cause a depth excursion, with the bowplanes being used for depth control.
      – Benign vertical plane manoeuvre results in little pitch – but not as efficient in recovery.
  
  – SOE performance of 56% area and 74% speed.

Non dimensional area = SOE area / max speed x max depth.
Non dimensional speed = SOE max speed / platform max speed.
SOE jam limitation – degraded operating condition

- If the submarine continues to operate with an existing non-functioning sternplane and experiences a further permanent single sternplane failure:
  - 2xCS has no redundancy against a stern hydroplane jam. Any failure must be immediately rectified at sea if the submarine is to continue submerged operations.
  - 1xCS configuration has an SOE performance of 40% for area and 53% for speed, a reduction of 16% and 26% respectively compared with the normal condition.
    - The existing non-functioning control surface must be regained for the recovery action to occur.
  - 2xXP arrangement has an SOE performance of 31% area and 39% speed, a reduction of 17% and 14% respectively compared with the normal condition.
    - The existing non-functioning control surface must be regained for the recovery action to occur.
  - 1xXP configuration has an SOE performance of 48% area and 58% speed, a reduction of 16% and 25% respectively compared with the normal condition.
    - Does not require the regain of the degraded control surface.

Key

Non dimensional area = SOE area / max speed x max depth.

Non dimensional speed = SOE max speed / platform max speed.
Control surface actuation architecture impact on jam max boundary

• The SOE jam maximum boundary case is highly dependent on what possible failure modes could exist, which itself is a function of the architecture of the steering and diving control system.

• Some examples of common arrangements for the cruciform and X-plane designs are shown below:

Linked cruciform

• Minimal automation of control systems – flight yoke primary interface.
• Basic autopilot for heading and depth (only used occasionally).
• Temporary double sternplane jam.

Independently actuated cruciform

• Increased levels of automation, designed to be used extensively under autopilot control.
• A steering and diving control system interfaces between the planesman input and the actuators.
• Temporary double stern & bow plane jam.

Linked X-plane

• Minimal automation of control systems – flight yoke primary interface.
• Basic autopilot for heading and depth (only used occasionally).
• Temporary X-plane diagonal pair jam.

Independently actuated X-plane

• Increased levels of automation, designed to be used extensively under autopilot control.
• A diving and steering control system interfaces between the planesman input and the actuators.
• Temporary four X-planes and two bowplanes jam.
SOE maximum boundary jam – normal operating condition

• If the submarine operates with all sternplanes fully functional, but then experiences a temporary failure of multiple hydroplanes:

• 2xCS arrangement has the smallest maximum boundary operational area (42%) and speed (50%).

• 1xCS configuration has the largest maximum boundary operational area (75%) and speed (100%).

• The 1xXP and 2xXP results are both of a similar magnitude, for area (65% vs 67% respectively) and for speed (86% vs 85% respectively).
  – 1xCS result is better where “all planes jam” i.e. double bow and stern.
  – 1xXP result is worse for “all planes jam” as its 2x bow + 4x stern.

Key

Non dimensional area = SOE area / max speed x max depth.

Non dimensional speed = SOE max speed / platform max speed.
Concluding discussion (i)

• This presentation has shown comparisons of SOE areas and speeds for different aft control surface configurations for a submerged submarine. This has showed that:
  – Traditional cruciform designs have a limited SOE area, because of the architecture and the control systems for the arrangement.
    – Simple systems, often operated in manual control
  – Improving the architecture and control systems results in a significant increase in the SOE area, whilst maintaining the overall cruciform arrangement.
    – More complex systems, often operated in autopilot control
  – Changing the cruciform arrangement to that for an X-plane, but not improving the architecture and control systems, results in a modest improvement to the SOE area.
    – Simple systems, often operated in manual control, but requiring a improved understanding by operators
  – Changing the cruciform arrangement to that for an X-plane and improving the architecture and control systems results in an SOE has minimal impact on the intact SOE, but has a significant impact on the ability to recover from a degraded plane condition.
    – Very complex systems that are heavily reliant on autopilot control and electronic safe guards
Concluding discussion (ii)

- An **evolution** in the design of both the control surface configuration and the actuation can result in a **revolution** in platform operability for nuclear powered submarines.

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<th>Cruciform</th>
<th>X-plane</th>
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<td><strong>Linked</strong></td>
<td>Traditional submarine design.</td>
<td>Medium improvement to the SOE (normal)</td>
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<td>Small SOE, no redundancy</td>
<td>Can cope with degraded condition, but small SOE. (If degraded plane can be regained for recovery)</td>
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<tr>
<td><strong>Independently actuated</strong></td>
<td>Large improvement to the SOE (normal).</td>
<td>Medium improvement</td>
</tr>
<tr>
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<td>Can cope with degraded condition, with medium SOE. (If degraded sternplane can be regained for recovery.)</td>
<td>- to the SOE (normal &amp; degraded).</td>
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<tr>
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<td>(Degraded plane does not need to be regained)</td>
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