

Numerical Simulation of Cavitation Phenomena for Hybrid Contra-Rotating Shaft Propellers

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Abstract. This paper deals with a numerical simulation of cavitation flow around a hybrid contra-rotating shaft propeller operating in wake field. The simulation for the cavitating flow is performed for straight operating and turning condition of podded propeller located behind the main propeller using unsteady Reynolds-Averaged Navier-Stokes. The behavior of the main propeller is almost similar regardless of the turning angle. In contrast, the cavitation behavior of the podded propeller depending on the turning angle appears to be entirely different due to the change of the load distribution on the podded propeller. At the large angle of the turning condition, the unstable cavity flow due to the large amount of cavitation and the hub vortex separated from the forward propeller as well as face cavitation is observed. Thus, a great caution on the cavitation phenomena is needed when designing and operating the HCRSP.

1. Introduction

Some EU projects show a possibility of a Hybrid Contra-Rotating Shaft Propeller (HCRSP, Figure 5) to reduce both operating cost and CO₂ emission. In a TRIPOD project [1], an attempt which combined a CLT-type propeller and HCRSP has been tried and achieved energy savings of 9-11 percent at model tests. In an ENVIROPAX project [2], the HCRSP concept including various hydrodynamic issues like power split, propeller design, powering performance evaluation has been investigated. Along with a study of the HCRSP, a Japanese ROPAX Ferry has been equipped with an ABB hybrid CRP-POD system claiming energy savings of 13 percent in full scale [3].

Nonetheless of a success on energy savings, an application of the HCRSP is still reluctant to attempt due to the high cost of the system, the uncertainty of propulsive performance in full scale and uncertain cavitation phenomena, especially in turning condition of a podded propeller. In this study, therefore, cavitation flow around the HCRSP is numerically simulated in order to investigate a characteristic of the cavitation behavior in turning conditions as well as a straight operating condition.

2. Numerical Method

Governing equations for incompressible turbulent flow are an instantaneous conservation of mass (continuity equation) and momentum (Reynolds averaged Navier-Stokes equation, RANS). Reynolds stresses are important to predict turbulent flow, especially in high Reynolds number flow. To close the transport equations, a k- ω SST turbulent model [4] is applied because the model is suitable for highly adverse pressure gradient flow such as propeller and turbine blades. For a calculation of cavity flow on propellers, a multi-phase mixture model assuming that a working medium is a single fluid with a



homogeneous mixture of two phases (liquid and vapor) is used. Schnerr and Sauer model [5] is used for the cavitation model for the simulation.

A grid system is filled with unstructured mesh by STAR-CCM+. The meshes around leading edge and trailing edge are refined to capture steep pressure gradient. A size of the numerical domain for a numerical cavitation tunnel is determined to have the same size with a medium-sized cavitation tunnel ($0.6 \text{ m} \times 0.6 \text{ m}$). In order to simulate wake field in the cavitation tunnel, an axial wake distribution which was numerically computed in full scale, is applied to a velocity inlet condition of the domain.

3. Cavitation Simulations of HCRSP

3.1. Design of HCRSP

A HCRSP system has been designed for a 7,000 TEU container. Power ratio between a forward propeller and a podded propeller is divided equally and RPM ratio is determined to be 1:1.45. At all the speeds, the HCSRSP requires about 10% of less power assumption than a conventional propulsion system. A tendency to save more energy at low speeds is observed through the results of the model tests. In order to perform cavitation simulations of the HCRSP, a thrust coefficient is calculated for the forward propeller from the results of the model tests. A rotation rate of the podded propeller is determined as a RPM ratio between two propellers.

The forward propeller rotates counter-clockwise while the podded propeller rotates clockwise when looking downstream with 0° of blade position defined at top position. The turning angle of the podded propeller is defined as the angle between the rotation axis of the forward and podded propeller.

3.2. Cavitation Simulation of HCRSP in straight operating condition (0° of turning condition)

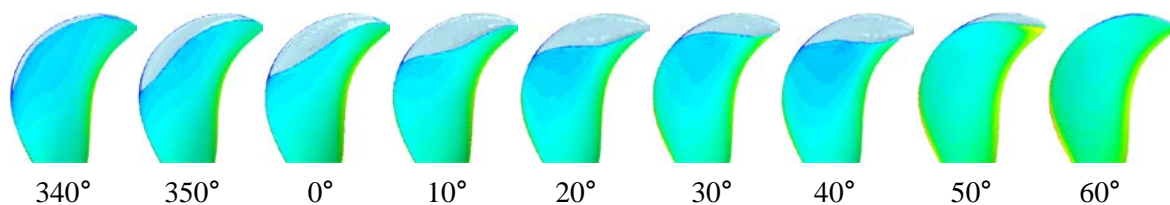


Figure 1. Cavitation patterns of forward propeller in straight operating condition

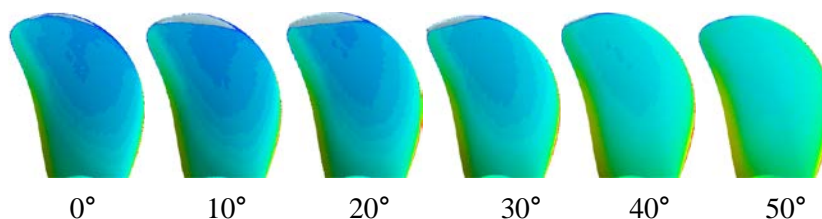


Figure 2. Cavitation patterns of podded propeller in straight operating condition

Figure 1 and 2 show the cavitation patterns of the forward propeller and podded propeller in the straight operating condition (0° of the turning condition). Back sheet cavitation starts appearing from 340° on a surface of the forward propeller. A maximum volume of cavitation appears on an upper side of the surface at 20° position and the cavitation disappears from 60° . The cavitation disappears smoothly around the tip region. Thus, there is no momentarily high value of the index indicating the erosion risk. From 70° to 330° , the propeller is wholly free from the sheet cavitation.

The cavitation volume of the podded propeller is relatively small even if the power density (power per unit area) of the podded propeller is larger than that of the forward propeller, because of a relatively low gradient wake field into the podded propeller. The back sheet cavitation starts appearing from 0° and disappearing from 50° . Likewise with the cavitation behavior of the forward propeller, the sheet cavitation stably behaves and shows no erosive cavitation.

3.3. Cavitation Simulation of HCRSP in turning condition

Table 1. Summary of cavitation observation results

| Turning Angle | Back Cav. (Forward) | Face Cav. (Forward) | Back Cav. (Pod) | Cav. due to hub vortex (Pod) | Face Cav. (Pod) |
|------------------|---------------------|---------------------|------------------|------------------------------|-----------------|
| -10 ° (Port) | 340° ~ 50° | none | 0°~10°/185°~325° | 210° ~ 275° | 355° ~ 95° |
| -8 ° (Port) | 340° ~ 55° | none | 0°~15°/185°~315° | 220° ~ 275° | 5° ~ 90° |
| -6 ° (Port) | 340° ~ 60° | none | 0°~25°/215°~290° | 235° ~ 260° | 65° ~ 80° |
| -4 ° (Port) | 340° ~ 60° | none | 0° ~ 25° | none | none |
| -2 ° (Port) | 340° ~ 60° | none | 0° ~ 35° | none | none |
| 0 ° (Straight) | 340° ~ 60° | none | 0° ~ 50° | none | none |
| 2 ° (Starboard) | 340° ~ 60° | none | 355° ~ 50° | none | none |
| 4 ° (Starboard) | 340° ~ 60° | none | 345° ~ 90° | none | none |
| 6 ° (Starboard) | 340° ~ 60° | none | 340° ~ 90° | 70° ~ 85° | 195° ~ 265° |
| 8 ° (Starboard) | 340° ~ 60° | none | 340° ~ 120° | 45° ~ 85° | 160° ~ 265° |
| 10 ° (Starboard) | 340° ~ 65° | none | 345° ~ 140° | 40° ~ 85° | 155° ~ 265° |

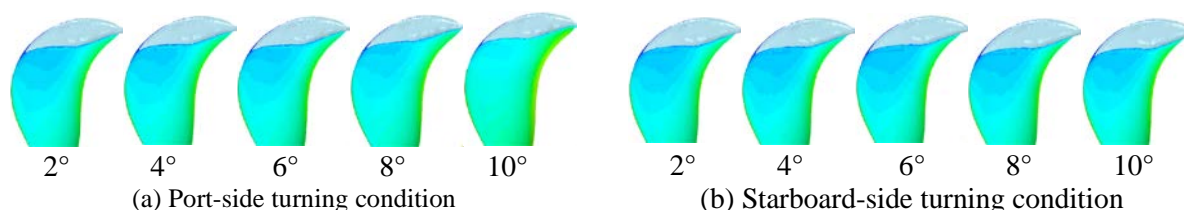


Figure 3. Patterns of sheet cavitation of forward propeller in turning condition (20° of blade position)

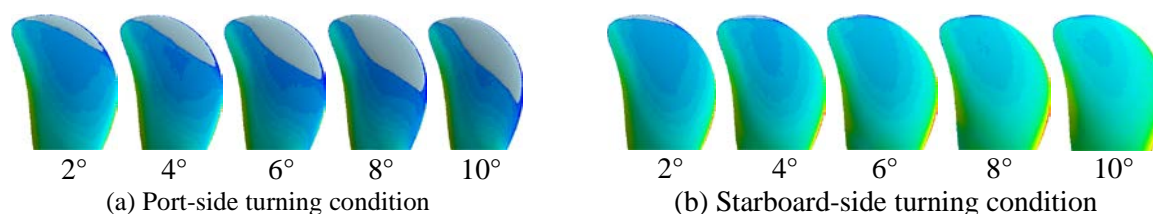


Figure 4. Patterns of sheet cavitation of podded propeller in turning condition (20° of blade position)

The positions of cavitation occurrences of the HCRSP are summarized in table 1. The cavitation phenomena of the forward propeller are almost similar regardless of turning angle of the podded propeller. As depicted in figure 3, which shows the cavitation patterns at 20° of blade position for the forward propeller in turning condition of the podded propeller, the cavitation pattern and volume of the forward propeller maintains almost similarly regardless of the turning angle, except that the cavitation volume gets slightly bigger as turning angle goes towards starboard-side from port-side turning.

Unlike with the cavitation phenomena of the forward propeller, those of the podded propeller are entirely different depending on the turning angle of the podded propeller. The load of upper side becomes larger and that of lower side becomes smaller as the running angle gets bigger, which makes the cavitation volume get bigger at the upper side of the propeller because the actual pitch angle of the upper side becomes larger due to the turning angle. Directly contrary to the port-side turning condition, the cavitation of upper side gradually gets smaller and fades away in starboard-side turning condition due to the reduced actual pitch angle at the upper side.

In a contrary with the upper side, the actual pitch angle at the lower side gets to be larger in the starboard-side turning condition. Consequentially, the cavitation on back side of the lower side begins to occur and gradually expands, from 6° of the port-side turning angle. In addition, the change of load distribution due to the turning angle also results in an occurrence of face cavitation. The face cavitation on the lower side appears in the port-side turning condition, while the face cavitation

appears on the upper side in the starboard-side turning condition. As the turning angle bigger, the occurrence range and volume of the cavitation gradually spreads out further and bigger.

From 6° of the port-side and starboard-side turning condition, moreover, the hub vortex separated from the forward propeller heats the surface of the podded propeller. The hub vortex induces the separated cavity on the blade surface near the root of the propeller. Since the behavior of the cavitation is quite unstable, the cavity flow could erode the blade surface by the hub vortex.

No sheet cavitation around the pod housing of the HCRSP at the turning condition is found regardless of the turning angle until 8°. In accordance with the turning angle increasing, it is found that the static pressure on the surface of the pod housing gradually goes down. At 10° of the port-side turning condition, eventually, the sheet cavitation is found on a fin located at the lower part of the pod housing.

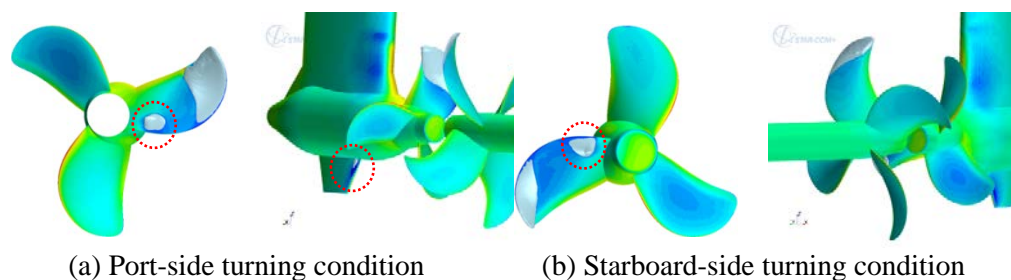


Figure 5. Cavitation pattern due to hub vortex and sheet cavitation of pod housing in turning condition

4. Conclusion

The cavitating flow is simulated from -10° to 10° of the turning angles for the podded propeller behind the forward propeller. Irrespective of the turning angle, the characteristics of the forward propeller remain almost similar. However, the pattern and volume of cavitation of the podded propeller is completely different because the load distribution of the podded propeller is entirely changed according to the turning angle. At the large angle of the turning condition, the unstable cavity flow due to the large amount of cavitation and the hub vortex separated from the forward propeller as well as face cavitation is observed. Thus, a great caution on the cavitation phenomena is needed because the cavitation pattern of the podded propeller is wholly different according to the turning angle.

Acknowledgement

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