The comparison on resistance performance and running attitude of asymmetric catamaran changing shape of tunnel stern exit region

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Abstract. Catamaran vessels have been used for various purposes such as leisure craft and research vessel. Especially, asymmetric catamaran has a half of the symmetrical hull and flat side of facing inward demi-hull, and has feature of planing hulls such as hard chine, spray rail. Therefore, these vessels can travel at high speed with better stability and resistance performance. However, these features cause asymmetric catamaran to have large trim angle at high-speed condition, which cause problem on vessel’s operation performances such as visibility and dynamic instability motion. To overcome these negative effects, tunnel shape in stern has been introduced. By applying this shape, trim angles are also suppressed because large dynamic lift developed on the exit region of tunnel stern. In this research, tunnel stern was applied on the asymmetric high-speed catamaran to evaluate vessel’s hydrodynamic performance by numerical method, and the tunnel stern types are distinguished by slope of tunnel exit region: flat or narrow types. Consequently, it is confirmed that the total resistance of tunnel types is lower about 1.6–5.0% than the bare hull in the wide speed range while showing almost same phase with the bare hull after $FnV=2.3$. Also, narrow type improves resistance performance further than flat type. On the other hand, trim angles show different trend with each tunnel type. In case of narrow type, the trim angle is stabilized after $FnV=1.8$ while that of flat type show an increasing trend as ship speed increase. These indicated that the narrow type has better resistance and operation performance than others.

1. Introduction

Recently, there has been a significant increase on the use of catamaran vessels for various purpose such as sail yacht, ferries, leisure craft and research vessel. The advantages of this vessel compared to mono-hull are that they have better transverse stability, more attractive layout accommodation [1]. Furthermore, catamarans often have a shallower draft and better resistance performance than comparably-class mono-hulls. There are two types of catamaran hull, such as Symmetric and Asymmetric Hull. Symmetric hulls have symmetric demi-hull and usually are used sail yacht and leisure boat which need to be comfortable. On the other hand, asymmetric hulls have a half of the symmetrical hull and flat side of facing inward demi-hull with hard chine, spray rail like planing hulls. Therefore, these vessels can travel at high speed with better stability and have been widely used for fast vessels. However, these vessels usually build with some degrees of shaft angle due to the engine and gearbox inside the hull. This has known to cause loss of propeller. Moreover, the large trim angle at high-speed condition also cause problem on vessel’s operation performances such as visibility and
dynamic instability motion. To overcome these negative effects on operation performance of vessel, tunnel stern which is round shape in stern has been introduced. By applying this shape in stern, shaft angle can be reduced, and trim angles are suppressed because large dynamic lift developed on the stern.

In this research, we applied tunnel stern on the asymmetric high-speed catamaran and evaluated resistance performance and running attitude. Also, we monitored flow characteristic according to changes exit region of tunnel sterns. The tunnel stern types are distinguished by slope of tunnel exit region: flat or narrow type. The performance of catamaran was estimated by using commercial CFD software, STAR-CCM+. Reynolds averaged Navier-stokes equations with an SST turbulence model was used along with the volume of fluid method to describe the two-phase flow of water and air around the hull. Furthermore, running altitude of the planing hull was used via an overset method. Validation of this simulation was performed with Warped hull.

2. Numerical simulation
The governing equations of fluid were discretized by Finite Volumes Methods[2][3]. The discrete form is shown in equation 1, and continuous integral form of the RANS equation is represented in equation 2.

\[
\frac{d}{dt}(\rho x V) + \sum_f \{ \rho \phi (v \cdot a - G) \}_f = \sum_f (\Gamma \nabla \phi \cdot a)_f + (S \phi V) \quad (1)
\]

\[
\frac{d}{dt} \int_V \rho x \phi dV + \int_A \rho \phi (v - u_\phi) \, da = \int_A \Gamma \nabla \phi \, da + \int_V S \phi \, dV \quad (2)
\]

where \( \rho \) and \( \phi \) are a density and scalar quantity in continuum, respectively. \( v \) and \( u_\phi \) are velocity and grid velocity, respectively. \( \Gamma \) and \( S \) are the face diffusivity and source coefficient, respectively. This equation is composed of unsteady term, convection flux, diffusion flux and the volumetric source term, in sequence.

The unsteady term represents growth rate of variation \( \phi \) over time on control volume and is only included in transient calculation. There are two temporal discretization: First-order and second-order temporal scheme. Generally, second-order scheme with relatively coarse grid ensures same accuracy to first-order scheme with relatively fine grid, and second-order scheme is used in this research.

2.1. Computational domain
The mesh was divided into one stationary background region and one moving overset region close to the hull. Both parts were meshed with trimmed, predominantly hexahedral cells with local refinements at the free surface and the wake. In the overset region, the mesh was same size with background region where the hull is located, and prism layer mesh constructed around the hull. To resolve the free surface accurately, a high mesh density was used in the region around the free surface in vertical direction where induced wakes by hull were expected to be present. The whole mesh consists of a total of about 2.16 million of cells, where the inner region has about 898,000 cells and the outer region has about 1,268,000. The height of the first cell layer around the hull was set to \( Y^+ \approx 75 \). The computational domain and boundary conditions are illustrated in figure 1.

![Figure 1. Computational domain.](image)

2.2. Numerical method
We applied established coordinate system and numerical methods [4] for incompressible and viscosity of fluid to calculate performance of planing hull, and table 1 listed key features of numerical models. The commercial CFD code used in this study was STAR-CCM+.

**Table 1.** Key features of numerical models.

| Model                          | Governing Equation | Time                  | Turbulent Model | Wall Treatment | Spatial Discretization | Velocity/Pressure Coupling | Free Surface Model | Body Motion  |
|--------------------------------|--------------------|-----------------------|------------------|----------------|------------------------|---------------------------|-------------------|-------------|
|                                | Reynolds-Averaged  Navier-stokes | Implicit Unsteady     | SST (Menter) $k$-$w$ | All $Y^+$ Treatment | Cell Centered FVM        | SIMPLE Algorithm          | Volume of Fluid method | High-Resolution Interface Capturing |
|                                |                    |                       |                  |                |                        |                           |                   | Overset Grid Method |

3. **Principle dimension of asymmetric catamaran and tunnel stern**

Table 2 lists the principle dimension of asymmetric catamaran hull applied in this study while figure 2 illustrates the model profiles. The model has a hard chine and flat side on inward of demi-hull.

| Dimension        | Value |
|------------------|-------|
| Length$_{BP}$ (m) | 1.803 |
| Breath (m)       | 0.69  |
| Draft (m)        | 0.0905|
| Displacement (kg)| 48.7  |
| Speed($F_{nv}$)  | 0.85~2.57|

The rear and longitudinal views of tunnel stern are illustrated in figure 3. Generally, tunnel stern is composed of three regions; entrance, propeller and exit region[5]. Among these areas, the exit region starts from edge of propeller region to transom and has an important impact on the trim angle of the vessel. The dynamic lift developed on the exit region can result in the bow-down trim[6][7]. The principle of tunnel stern in the present study is shown in table 3. The bare hull represents base hull without tunnel stern while same shape and height is applied on the exit and propeller region in flat type, the inclination angle was set so that tunnel become narrows throughout exit region.
Figure 3. Conceptual design of tunnel stern (Left: Rear view, Light: Bottom and side view).

Table 3. Principle of the tunnel stern models.

| Shape | Dimensions | Flat type | Narrow type |
|------|------------|-----------|-------------|
|      | L\(_{\text{ENT.}}\) | 12.2\%L\(_{\text{BP}}\) | 12.2\%L\(_{\text{BP}}\) |
|      | L\(_{\text{PROP.}}\) | 5.0\%L\(_{\text{BP}}\) | 5.0\%L\(_{\text{BP}}\) |
|      | L\(_{\text{Exit}}\) | 8.9\%L\(_{\text{BP}}\) | 8.9\%L\(_{\text{BP}}\) |
|      | H\(_{\text{PROP.}}\) | 33.6\%T | 33.6\%T |
|      | B\(_{\text{PROP.}}\) | 18\%B | 18\%B |
|      | \(\alpha_{\text{ENT}}\) | 6° | 6° |
|      | \(\alpha_{\text{Exit}}\) | 0° | 3° |
|      | \(\beta_{\text{Exit}}\) | 0° | 3° |

4. Result and discussion

4.1. Validation of the numerical method

In this paper, the experiment and numerical results from the Warped hull 2, were used to validate a CFD model[8]. Table 4 lists the principle dimensions of the Warped hull 2 while figure 4 illustrates the concept and geometry of the model.

Figure 4. Geometric view of the Warped Hull 2 [9].

Table 4. Principal dimensions of Warped Hull 2.

| Dimensions          | Values       |
|---------------------|--------------|
| Length\(_{\text{OA}}\) (m) | 1.9          |
| Length\(_{A-B}\) (m)  | 1.5          |
| Breath (m)           | 0.424        |
| Draft\(_{AP}\) (m)    | 0.11         |
| Displacement (kg)    | 32.73        |
| Speed(F\(_{\text{nV}}\)) | 1.92–3.57   |
The results were compared with experimental and CFD data for the total resistance, trim and wetted surface area as given in figures 5–7. Qualitatively, overall numerical predictions were reliable with experimental values but there were slightly underestimations about 2–8% of the total resistance, 3.5–4% of the trim angle and 5–7.2% of the wetted surface for all ranges of \( F_nV \), quantitatively.

**Figure 5.** Comparison of total resistance.

**Figure 6.** Comparison of trim angle.

**Figure 7.** Comparison of wetted surface area.

### 4.2. Resistance performance

Numerical analysis was performed with bare hull and two types of tunnel stern. The frictional, residuary and total resistances were shown as dimensionless form by weight and compared in figures 8–10. In total resistance performance, the tunnel types demonstrate good performance about 1.6–5.0% than bare hull over wide-range of \( F_nV \) while showing same performance after \( F_nV=2.3 \). For comparing details of the resistance performance, the total resistance was divided into the frictional and residual resistance. The residual resistance was improved when applied the tunnel types, and it was improved by 5.2–7.3% for the narrow type and 3.1–4.6% for the flat type. The frictional resistances show equivalent performances except that the narrow type shows poor performance after \( F_nV=2.0 \).

**Figure 8.** Total resistance with tunnel types.

**Figure 9.** Residuary resistance with tunnel types.

**Figure 10.** Frictional resistance with tunnel types.

### 4.3. Running attitude and wetted surface area

The wetted surface, Sinkage and trim angle were shown in figures 11–13, and sinkage was represented as dimensionless form by initial draft. Figure 12 shows that tunnel types have similar draft and more submerge than bare hull over all \( F_nV \) range. However, Trim angle of tunnel types are different tendency with each other after \( F_nV=1.37 \). The flat type shows similar trend with bare hull but trim angles increase from 4.9% to 25.8% in general. However, the trim angles of narrow type peaks at \( F_nV=1.37 \) and has stabilized trend after \( F_nV=1.54 \). This indicates that changing tunnel exit region cause trim angle to suppress largely. Also, because of Sinkage and trim angle trend, the wetted surface area of tunnel stern increase from 0.97% to 2.89% than bare hull while flat type comes close to bare hull after \( F_nV=1.8 \).
4.4. Longitudinal and transverse pressure distribution

The longitudinal and transverse pressure distributions were evaluated for verifying the characteristic of tunnel stern, and its values were measured at 0.23m in transverse direction from centreline and 0.09–0.30m longitudinal direction from transom, shown as figure 14.

Figures 15–18 show longitudinal pressures of tunnel types around $Fn_V=1.20$–2.58. The bare hull and tunnel types has peak pressure point at bow. The areas where occurred maximum pressure distribution on the bow are from free surface to spray area. However, there are relatively low pressure distribution from tunnel entrance at the stern of tunnel type. These phenomena become more pronounced as the $Fn_V$ increases. Also, the pressures of tunnel types increase significantly after certain position of tunnel exit region and propeller and peak almost same with that of the bow.
Figure 17. Comparison of longitudinal pressure distributions at \( \text{Fn}_V = 2.06 \).

Figure 18. Comparison of longitudinal pressure distributions at \( \text{Fn}_V = 2.58 \).

These differences of pressure distribution can be confirmed clearly from transverse direction around the tunnel stern and shown as figure 19. The transverse pressure distributions were measured at four point from transom where located at 0.09, 0.19m in tunnel exit region, and 0.23, 0.3m where located in propeller region and tunnel entrance respectively.

Figure 19. Transverse pressure distribution at \( \text{Fn}_V = 2.57 \) / (a) Bare hull, (b) Flat type (c) Narrow type.

While the bare hull has uniform pressure distribution, it can be seen clearly that the entrance and propeller region have low pressure sections, and tunnel exit region have high pressure sections. In figure 19(b), exit region of flat type has high pressure section at 0.16m from stern, but the pressure distribution at 0.09m from stern is similar with that of bare hull. However, in cases of the narrow type, the pressure distributions at 0.09m from stern sharply increase than that of bare hull and flat type. This indicates that, increasing the slope of tunnel exit region, the overall pressure distributions of exit region also increased, and it suppress trim angle largely.

Figure 20 shows longitudinal wave profiles at stern. The amplitudes of first wave period of tunnel types are slightly lower than that of bare hull because the separation points of tunnel stern are located upper that of bare hull. figure 21~22 show Transverse wave profiles of 0.85 and 1.25m from the tunnel stern where are in first wave period of stern, this indicates that wave-making resistance of tunnel types is lower than that of bare hull.

Figure 20. Longitudinal wave profile of position 0.23m from the centreline at \( \text{Fn}_V = 2.58 \).
5. Conclusion and Future Work
In this study, a detailed analysis of the flow characteristics on stern tunnel type and the performances of asymmetric catamaran have been carried out via commercial software, STAR-CCM+. The validation was performed, and results were adequate for the prediction of performances in calm water. The following conclusions were drawn.

1) The numerical investigation indicated that there was a close dependency between resistance performance or running attitude and shape of tunnel stern. This implied that vessel performance could be adjusted by shape of tunnel stern.

2) Tunnel stern used in the study showed good performance of wave-making resistance reduction, the vessel applied tunnel stern are submerged slightly than bare hull because there is some loss of volume at stern.

3) The investigation showed that tunnel types produced better resistance performance than bare hull. In case of the running attitude, trim angle of each tunnel type shows the different trend. These trends could be confirmed by analysing the pressure distributions at the tunnel stern. It was showed that the pressure increased greatly in exit and propeller region with increasing inclination angle of tunnel exit region.

Future studies should further research the flow characteristics and performance of the stern tunnel with propeller. Furthermore, the parametric study on slope and length of tunnel exit region and needs for optimization on resistance performance and running attitude. To achieve this, it will be necessary to research the propeller of small crafts.

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