COMPARISON OF EXPERIMENTAL TOWING TEST AND CFD ANALYSIS OF A BARE HULL MODEL SUBMARINE ON THE SURFACE

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SUMMARY

In designing submarines, hull form selection, resistance, and powering are key aspects. The bare hull form of a submarine can be considered according to five parameters. Surface resistance is important should it be necessary to operate at relatively high Froude Numbers. Due to the complex nature of the flow around the hull, model experiments are still the most reliable approach to determining surface resistance. CFD simulations enable surface condition analysis using FINEMarine. The towing mechanism must be taken into account and so this was designed to fix the pitch motion and measure the hydrodynamic forces. This paper outlines the towing method, comparing the model test and the CFD results, as well as providing a comparison of wave formation from the towing test and the CFD results. The results show that resistance increased significantly above a model speed of 1.4 m/s. Furthermore, above this speed, as the resistance of the model rose, the downforce gradually decreased.

NOMENCLATURE

D_H	Hull Diameter (m)
L_B	Bow length (m)
L_C	Cylinder length (m)
L_{CS}	Conical Stern length (m)
LOA	Length overall (m)
LWL	Length waterline (m)
R_t	Total resistance (N)
T	Draught (m)
V	Speed of vessel (m/s)
Δ	Displacement (tonnes)
γ	Conical Stern angle (degree)

1. INTRODUCTION

Hull form selection, resistance, and powering are important in designing submarines. Model testing was carried out to predict the resistance and power in near-surface conditions. The model was a bare hull form, without any appendages, although the effect of appendages must be considered when predicting the resistance.

CFD tools are widely used for the prediction of ship resistance and powering. As such, CFD codes were also used for comparison with the model test results. The model experiments were carried out in the Ship Model Towing Tank (SMTT) at Marine Hydrodynamics Centre, Myanmar Maritime University (ITTC, 2011). The SMTT is 60m in length, 4m in breadth, and 4m in depth, with a water level of 3m. The maximum carriage speed of the SMTT is 4 m/s.

2. OBJECTIVE

This paper analyses the surface resistance of a submarine bare hull and compares the results with CFD simulation results. The towing mechanism was arranged so as to test the model without a running trim.

3. STUDY AREA

Despite being primarily designed for optimal performance when submerged, submarines must also be able to operate well on the water surface. Modern submarine hulls are inefficient when operating on the surface, resulting in poor resistance performance. Submarines have a low freeboard compared to normal ship surfaces, meaning the majority of the hull sits below the water surface. As such, when operating at relatively high Froude Numbers, wave making resistance becomes dominant.

Conducting an experimental study of this condition requires the development of a compatible model. To this end, the resistance can be measured using a towing scale model, which, when appropriate scaling laws are applied, enables the full-scale resistance of the vessel to be predicted.

Initially, a 1.5m long wooden model was manufactured and tested in the model basin of the Myanmar Maritime University. A CFD simulation was carried out to compare the vessel's resistance and wave formation.

The CFD solver is capable of calculations with multi-phase flows and moving grids. In the multi-phase continuum, considering the incompressible flow of viscous fluid under isothermal conditions, the mass, momentum, and volume fraction conservation equations can be written as (FINE™ / Marine 9.1, Theory Guide) –

$$\frac{\partial}{\partial t}\int_V p dV + \int_S p(\vec{U} - \overrightarrow{U_d})\vec{n} dS = 0 \qquad (1)$$

where V is the domain of interest, or control volume, bounded by the closed surface S, with a unit normal vector $\vec{n}$ directed outward. $\vec{U}$ and p represent the velocity and pressure fields, respectively.

When the grid is moving, the so-called "space conservation law" must also be satisfied:

$$\frac{\partial}{\partial t}\int_V dV = \int_S \overrightarrow{U_d}\,\vec{n}\,dS = 0 \qquad (2)$$

4. STUDY APPROACH

4.1 Determining the main dimensions

The propeller-hull interaction results in the submarine bare hull form being based on the following five parameters (Burcher & Rydill, 1995):

- The fineness ratio
- Prismatic coefficient
- Nose radius
- Tail angle and
- The position of the maximum section.

The dimensions of a submarine model with the parallel middle body form are described in table 1. The limitation of the test arrangement and the CNC model results in an L/D relation of 8.3. The vessel design consists of an elliptical main hull and a conical stern (Figure 1).

Table 1: Main particulars of model at design condition.

Main particulars	Unit
Overall length, LOA (m)	1.500
Hull vertical diameter, D_{VH} (m)	0.210
Hull horizontal diameter, D_{HH} (m)	0.180
Displacement, Δ (tonnes)	0.028
Bow length, L_B (m)	0.333
Cylinder length, L_C (m)	0.590
Conical stern length, L_{CS} (m)	0.576
Draught, T (m)	0.170
Conical stern angle, γ (degree)	20.20

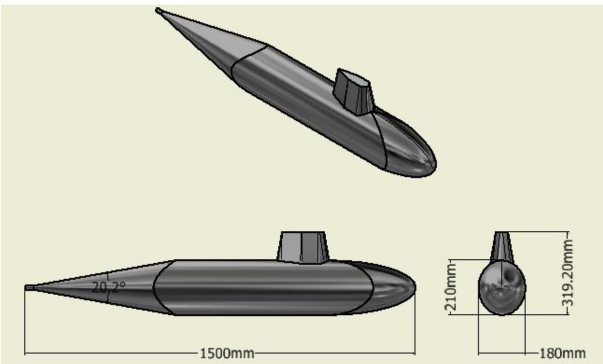


Figure 1: Model of submarine.

4.2 Model making and towing mechanism

Figure 2: Fabricated wooden model without appendages.

The model without appendages (Figure 2) was tested in the towing tank on the surface condition, with the observation being made that even keel conditions could not be controlled (Tun & Htun, 2021). The CFD simulation was also carried out for even keel using FINEMarine. The pressure distribution on the hull is shown in Figure 3. As a result, the towing mechanism was designed to fix the pitching motion of the model (Figure 4). The towing mechanism components are detailed in Table 2.

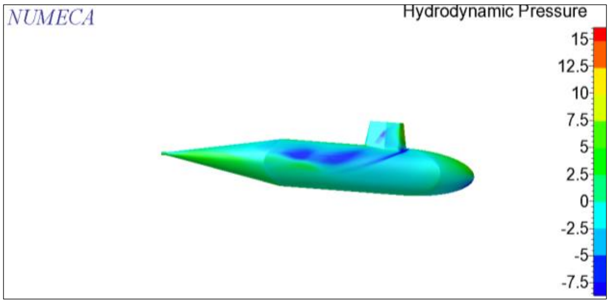


Figure 3: Hydrodynamic effect of the model.

Table 2: Towing mechanism components.

Symbol	Items	Function
	Load cell (strain gauge)	To measure the downforce or lift force
	Guide arm fit pins	To ensure the straight-line position on flow (2 numbers for bow and stern)
	Load cell (strain gauge)	To measure the resistance of the model (attached to model)
	Vertical slipway or towing post	To measure the heaving motion and tow the model by carriage.

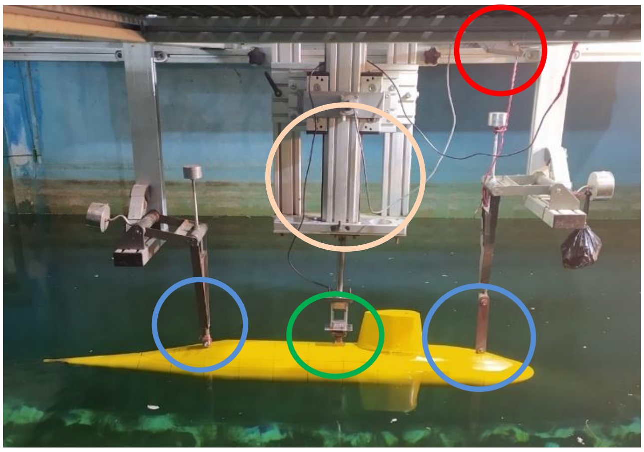


Figure 4: Towing mechanism arrangements.

4.3 Experimental approach

The towing tests were conducted over a 0.6 to 1.8 m/s speed range (Table 3). The test conditions were: zero trim, 0.170m of draught, and the towing tank water level was 3m.

Table 3: Model resistance test.

Speed of vessel V (m/s)	Total resistance of model R_t(N)	Downforce (N)
0.6	0.800	0.720
0.8	2.187	2.764
1.0	4.522	6.129
1.2	7.937	10.796
1.4	7.457	10.446
1.6	12.497	8.794
1.8	18.015	7.363

4.4 Numerical approach

The flow around the ship's hull is complex, so model experiments are still regarded as the most reliable data source to determine ship resistance. However, numerical methods have strongly advanced in this field, meaning a combined use of both model tests and CFD codes can be very effective in aiding ship design and for understanding ship hydrodynamics (Watson, 1998). FINEMarine with the k-omega turbulence model (SST-menter) and Solidworks 2020 Flow Simulation with turbulence only were used to perform numerical computations. The initial mesh had an X axis of 24, a Y axis of 16, and a Z axis of 12, with the total cells being 843146 (Figure 5). The minimum mesh width was 0.00135m. The computed first layer thickness/the distance of the nearest grid point to the wall (Y_{wall}) was 0.001839m.

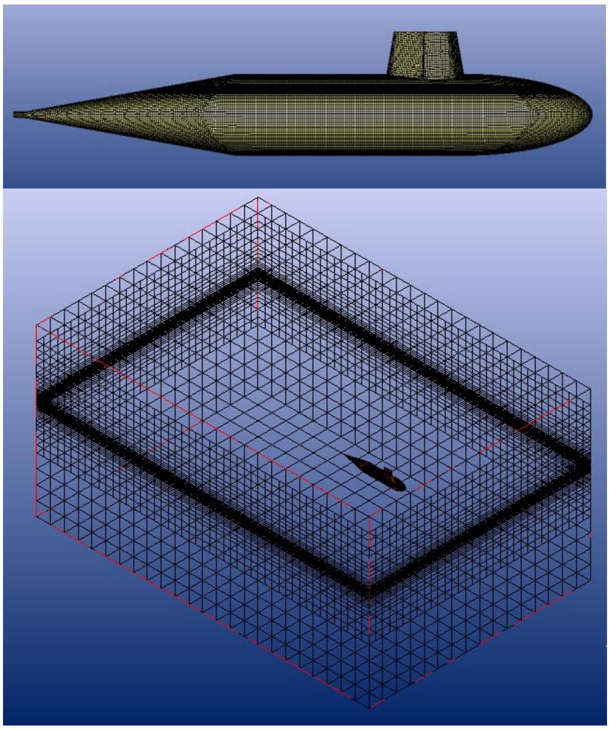


Figure 5: Generated mesh of the whole model.

The physical parameters were greater than the mesh parameters in terms of the boundary type of each surface. HEXPRESS™ took these conditions into account when computing a mesh in accordance with the future flow. For instance, a boundary layer mesh was computed to properly capture the flow next to the wall using a turbulence model. This highlights the importance of defining the boundary conditions during mesh setup. By default, each physical boundary is defined as a SOLID. Boundary conditions are listed in Table 4 (FINE™ / Marine 9.1, Theory Guide).

Table 4: Boundary conditions.

Description	Boundary condition type	
zmin (bottom of domain)	External	Prescribed pressure
zmax (top of domain)	External	
xmin (outlet of domain)	External	Far field
xmax (inlet of domain)	External	
ymin (- side of domain)	External	
ymax (+ side of domain)	External	
Model	Solid	Wall function

The domain size for this application is defined based on the Froude number (Fn) and the body reference length (length overall LOA of the model). The default numbers are shown in Figure 6.

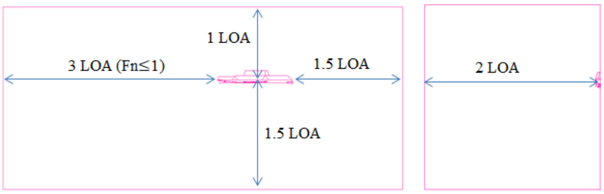
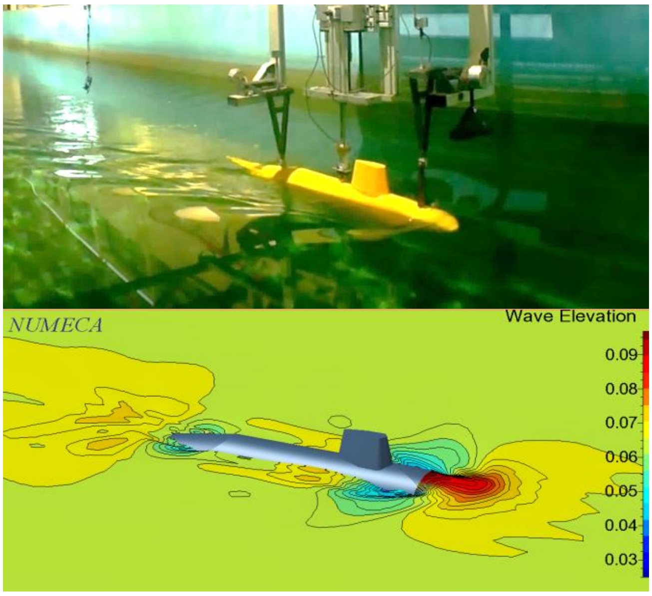
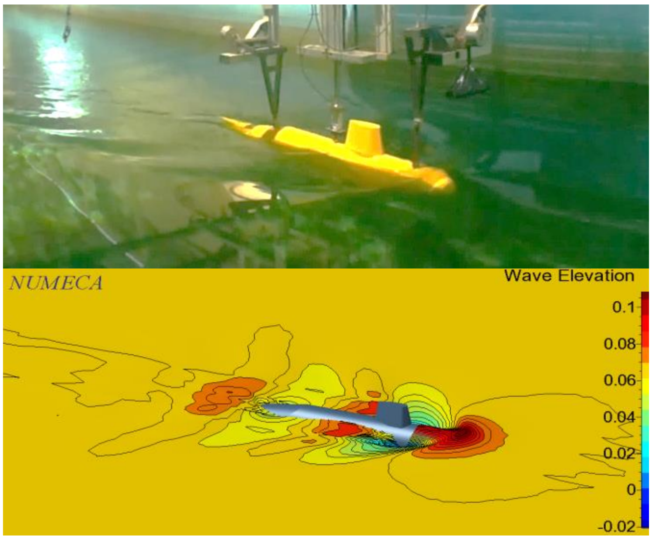


Figure 6: Computational domain size.

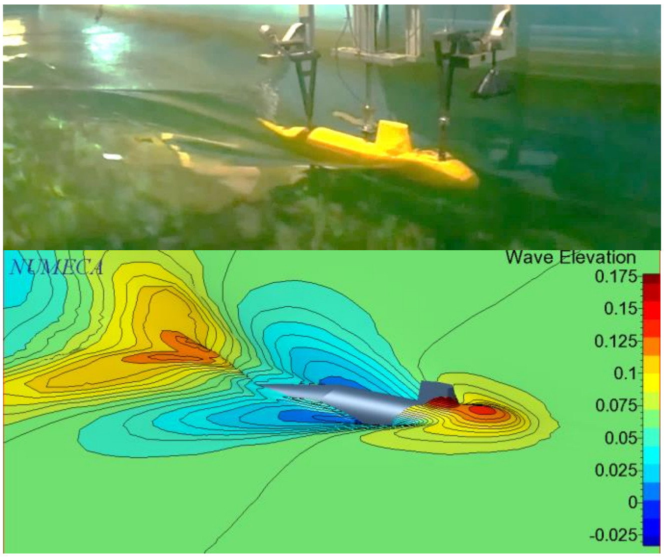
The CFD simulation covered a speed range of 0.6 to 1.8 m/s. As the model test had a fixed condition (locked for pitching motion), the CFD simulation was also conducted with the fixed model for the fixed trim and sinkage. Comparisons of a wave formation as a result of model testing and CFD simulation at various speeds are shown in Figure 7 (a to c).



(a) Towing tank test and CFD simulation with 0.8m/s.



(b) Towing tank test and CFD simulation with 1m/s.



(c) Towing tank test and CFD simulation with 1.8m/s.

Figures 7a-7c: Comparison of wave formation in the Towing tank test and CFD at various speeds.

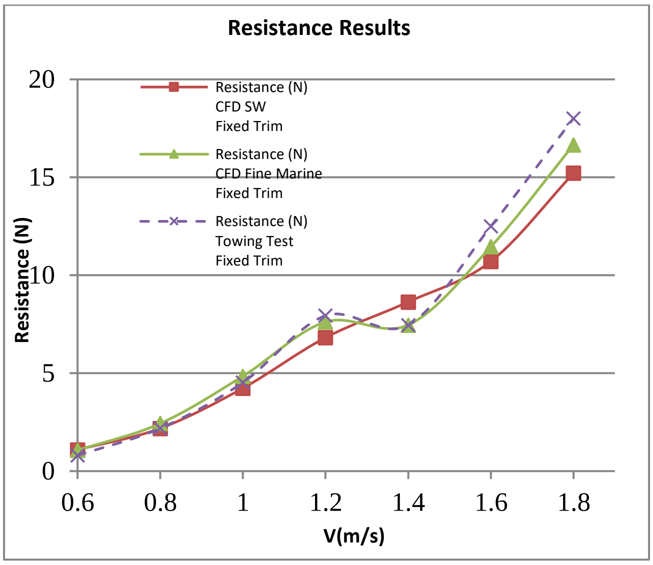


Figure 8: Comparison of CFD and Towing test of ship resistance without appendages.

5. RESULTS COMPARISON

Resistance and the wave forms were measured and compared over a speed range of 0.6 to 1.8 m/s. At a Froude Number of 0.33, the bow wave creates a trough at the stern, increasing the stern wave system as well as increasing the wave-making resistance followed by a resistance hump (Figure 8). The results show that the resistance of the vessel increases significantly when the vessel speed reaches and exceeds 1.4 m/s, the downforce gradually decreases at 8.09% per 0.1m/s reduction in forward speed.

6. CONCLUSIONS

The towing test and CFD simulation were conducted using a fixed trim condition and fixed model condition, respectively. The results were compared to the CFD results, with the comparison showing that they were well-matched with the surface conditions. At Fn=0.33, the hydrodynamic forces acting on the vehicle increased, but then decreased value beyond Fn=0.33 (see Table 3, Column 3 (Downforce (N)). Consequently, it was considered necessary in future to investigate the hydrodynamic effect on the model in free motion (see Figure 3 and Table 3). Hydroplanes would need to be attached following calculation of their hydrodynamic effect on the model, to ensure the even keel (no trim) condition.

7. ACKNOWLEDGEMENTS

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