21st Australasian Fluid Mechanics Conference
Adelaide, Australia
10-13 December 2018

Characterisation of suction effects on a submarine body operating near the free surface

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Abstract

Submarines operating near the free surface will experience a depth and speed dependent heave force. This force can have a significant impact on the submarine causing it to either broach the surface or descend if it is insufficiently controlled. In this condition, a submarine generally has limited control due to typically low operating speeds and small control surfaces. Therefore, in the design process, it is critical to be able to accurately predict how the heave force changes with varying speeds and depths to ensure the trim tanks and control surfaces that are typically utilised in this condition are effective. Moreover, when developing simulation models of a submarine, correct characterisation of the heave force is essential in order to guarantee representative behaviours close to the free surface.

Using Reynolds Averaging Navier Stokes (RANS) computational fluid dynamics (CFD) simulations, this paper presents data at varying depths and speeds typical for a submarine operating near the free surface for the evolved DST Group/MARIN generic BB2 submarine at model scale [9]. The non-dimensional depth (H^*) tested ranged from H^* = 1.4 up to H^* = 3.0 with Froude number between 0.16 and 0.31. At these depths, the heave force is directed upward towards the free-surface, increasing the risk of a submarine broaching. However, it is shown that small changes to either the depth or the speed will result in a significant change in heave force, which could lead to instabilities in the control of the submarine. The hydrodynamic heave force coefficient is presented independently of buoyancy and mass.

Introduction

Due to operational requirements, submarines are often required to operate close to the free surface. To reduce the risk of detection during these times, vessel speed is generally slow and thus, vessel manoeuvrability and control is limited [1]. Accurately modelling the free surface effects as a submarine approaches the free surface is critical in determining changes in propulsion, trim tanks and control surface angles required to maintain control during low speed near surface operations.

As the distance between a submarine and the free surface decreases, the total resistance on the vessel significantly increases as wave making effects are introduced and become significant in proportion to the overall resistance acting on the vessel. This increase in total resistance must be accounted for in both manoeuvring and powering analysis - the outcomes of which are critical to calculate operational speed and vessel range. Furthermore, the bow wave and wake generated in this condition cause a combination of heave force and pitching moment. Understanding these effects is essential in order to accurately size submarine trim tanks, and to understand manoeuvring effectiveness.

The free surface effect can be characterised as a function of depth below an equivalent flat free surface (d) and Froude number (Fr). In this paper the depth is non-dimensionalised by the maximum diameter of the submarine's pressure hull (D) and presented as a non-dimensional depth (H^*), defined by equation (1)

$$H^* = \frac{d}{D} \tag{1}$$

There have been several publications investigating the free surface effect with a range of experimental and numerical approaches. Examples of experimental and numerical approaches using the Joubert and SUBOFF geometries with and without appendages at a range of depths ranging from H^* = 1.1 to H^* = 5.5 with Froude numbers ranging from 0.1 to 0.65 were published by Dawson [2] and Renilson [3]. Moonesun et. al. [4] showed that the wave making resistance can contribute more than 50% of the total resistance and snorkelling speeds close to the free surface at H^* = 2.0. Dawsone [2] and Jackson [5] concluded that at depths deeper than H^* = 3.0, the wave making resistance can be considered negligible for an un-appended body for the speeds tested. This was also studied by several others to determine a "deeply submerged" condition [6-8] at which there is no further free-surface effects acting on the submarine.

Therefore, in order to capture the free-surface effects, H^* values were tested between 1.4 and 3.0 using the fully appended BB2 geometry that was used for the MARIN free running experiments [9]. This ensured an in-depth analysis was conducted in the depth range in which there is significant change to the forces acting on the submarine. In addition to the drag force discussed by the majority of the publications listed above, this paper aims to focus on both the vertical force generated by the free-surface interaction and the changes in free-surface elevation with varying speed and depth.

Computational Approach

Computational fluid dynamics (CFD) was the chosen approach for calculating the free surface effects. The Reynolds Averaged Navier-Stokes (RANS) with the k-ω Shear Stress Transport (SST) model was used with the Volume of Fluid (VOF) equations. Fluent was the selected CFD software with Pointwise used to generate the mesh. In order to minimise the damping of the free surface due to turbulence effects, *Fluent's* interface modelling was selected as 'sharp' as well as 'Interfacial Anti-Diffusion' enabled.

The mesh of the modelled flow volume shown in Figure 1 was generated in two sections: an internal box and an external box with a non-conformal interface to reduce the number of cells and thus reduce computational requirements. The total size of the modelled flow volume was selected such that its width captured the Kelvin wake generated by the submarine with an outlet positioned three boat lengths aft of the submarine. The refined inner domain extended half a boat length forward and aft of the submarine. In order to reduce the computational requirements, only the port side of the total flow volume was modelled with a symmetry boundary applied at its plane of symmetry. The grid consisted of fully structured hexahedral cells utilising and O-C topology around the hull and appendages with an H topology to create a refinement layer for the free surface. A range of depths were tested from H^*=1.4 to H^*=3.0, with a grid sensitivity study conducted at H^*=1.4 focusing on drag and heave forces. It was found that a mesh density of approximately 10 million elements using the above flow volume was required to accurately capture the free-surface effects. Validation, not presented in this paper, was carried out against previously published data [9] and will be further discussed in a future publication.

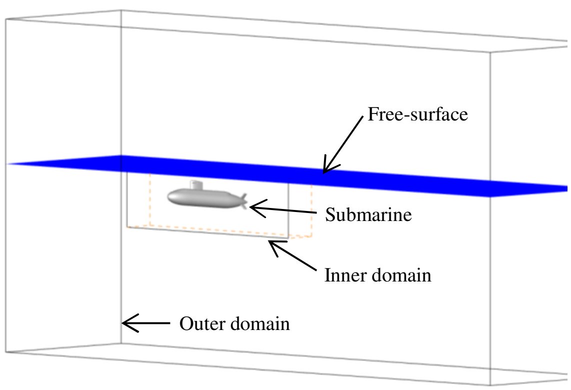

Figure 1: Numerical domain used for predicting free-surface and drag forces acting on the submarine body

Results

The surge (X) and heave force (Z) are non-dimensionalised according to Equation 2. Boat speed is presented as a Froude number (Fr) defined by Equation 3. In both equations: ρ is the density of the water, V is the boat speed, L is the length of the boat and g is the acceleration due to gravity. V is the boat speed.

$$X' = \frac{X}{\frac{1}{2}\rho V^2 L^2}\ , \qquad Z' = \frac{Z}{\frac{1}{2}\rho V^2 L^2} \tag{2}$$

$$Fr = \frac{V}{\sqrt{gD}} \tag{3}$$

These forces are defined relative to a body fixed coordinate system. A positive surge force indicates a force acting forward and aligned with the centreline of the hull, a positive sway force acts toward starboard and a positive heave force is perpendicular to both the surge and sway forces according to the right-hand rule (in the direction of the keel).

Figure 2 displays the surge force coefficient plotted against the non-dimensional depth of the submarine (H^*) with each line representing a different Froude number. Using the same format, Figure 3 plots the heave force against H^*. The heave force was calculated by removing the buoyancy force generated by the displacement of the submarine from the total vertical force predicted from the CFD simulations. Note that in both figures the negative of the surge and heave force coefficients are plotted and these represent the resistance and suction force, respectively.

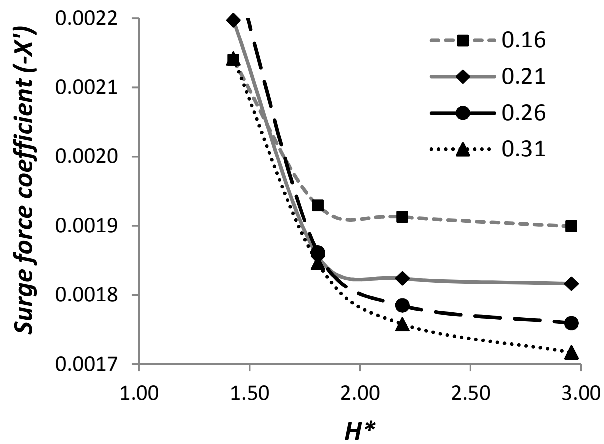

Figure 2: Surge force coefficient (X') at different depth (H^*) for a range of Froude numbers from 0.16 to 0.31

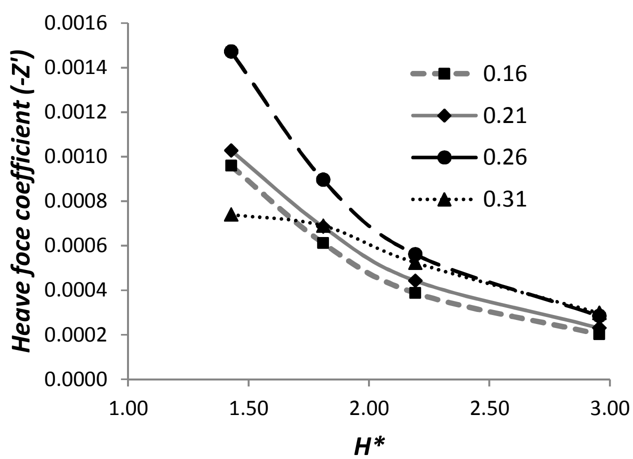

Figure 3: Heave force coefficient (Z') at different depth compared to depth (H^*) for a range of Froude numbers from 0.16 to 0.31

Figures 4 to 7 plot the free-surface elevation as a function of *x/L* at a range of H^* values at constant speed at a lateral location corresponding to the centreplane of the boat. The free-surface elevation has been non-dimensionalised with respect to submarine diameter (λ/D), where λ refers to wave height in metres. The reference point is located at the stern of the submarine with positive x-values forwards, i.e. the bow at $x/L = 1$.

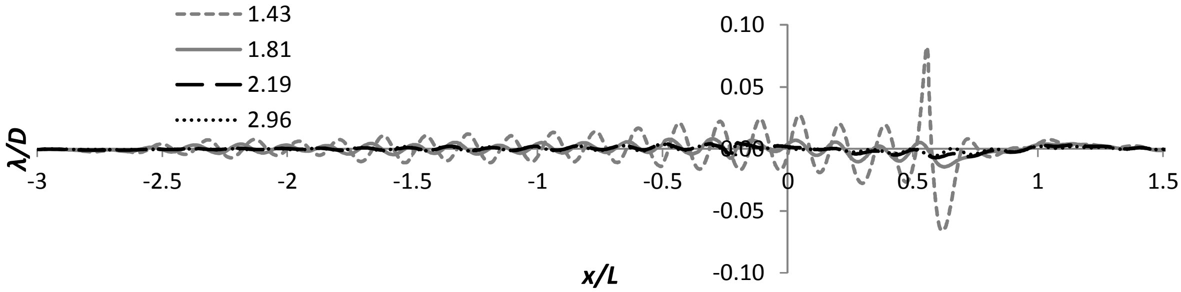

Figure 4: Free-surface elevation plotted against the longitudinal distance, x/L, for a range of H^* values at $Fr = 0.16$

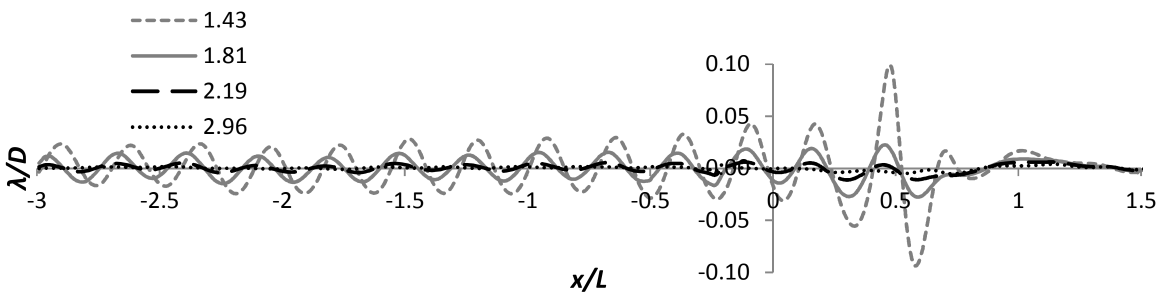

Figure 5: Free-surface elevation plotted against the longitudinal distance, x/L, for a range of H^* values at $Fr = 0.21$

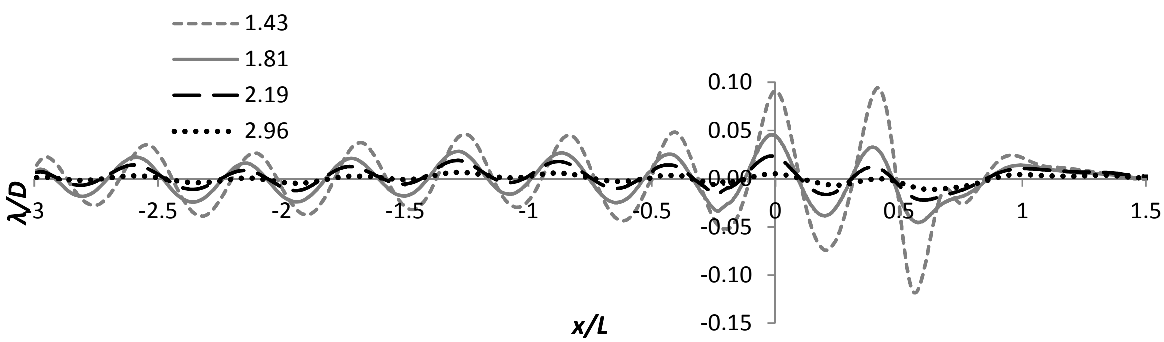

Figure 6: Free-surface elevation plotted against the longitudinal distance, x/L, for a range of H^* values at $Fr = 0.26$

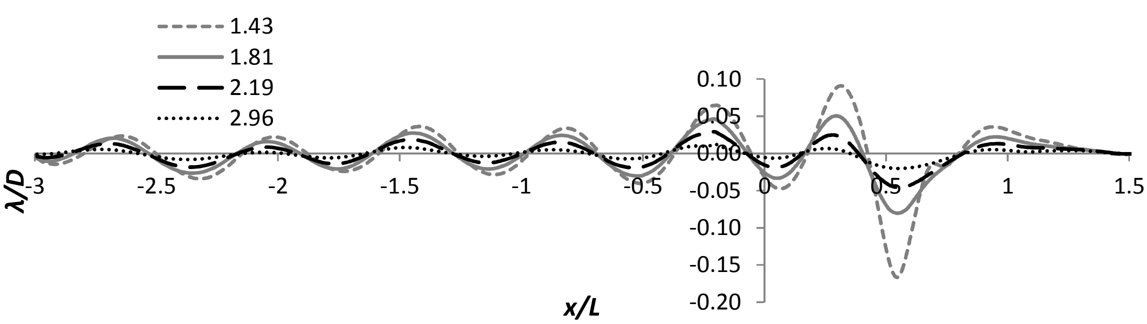

Figure 7: Free-surface elevation plotted against the longitudinal distance, x/L, for a range of H^* values at $Fr = 0.31$

Discussion

The change in surge force coefficient presented in Figure 2 shows the significant impact the wave making resistance adds to the total drag of the submarine, in particular for H^* values less than 2.0. It can also been seen that the change in drag coefficient between H^*=2.0 and H^*=3.0 at Fr=0.16 is only 2.5% suggesting at the lower speeds, a depth corresponding to $H^* = 3.0$ is approaching a deeply submerged condition, as defined in the introduction. However, for the same depth range ($2.0 < H^* < 3.0$) at an increased velocity such that $Fr = 0.31$, a change in drag coefficient of approximately 6% is recorded that indicates there is a significant affect from the free surface at the higher Froude numbers.

As expected, the suction force presented in Figure 3 follows the trend in which the higher the Froude number and the lower the H^* value, the suction force as a result of the free-surface is increased. There is a significant cross over at $H^* \approx 1.75$ at $Fr = 0.31$. Whilst this requires further simulation at lower H^* values to establish the trend through this non-linear region, it is hypothesised that it is due to the larger bow wave generated and longer wave length, which results in a significantly longer trough that occurs on the aft corner of the sail (around amidships) resulting in the change in heave force without significant impact on the drag coefficient. A Froude value of 0.31 is, however higher than typical submarine operating conditions whilst near the surface and therefore not critical to developing submarine analytical models.

Figures 2 and 3 also indicate the surge and heave forces have a non-linear characteristic at values of $H^*<2.0$, but are much less sensitive to the presence of the free-surface between $H^* = 2.0$ and 3.0. This highlights the importance of understanding the changes in forces acting on the submarine whilst operating in this narrow depth range.

Figures 4 to 7 show the displacement of the free-surface at the range of Froude numbers and H^* values tested. Similar to the drag data discussed from Figure 1, it can be seen that at $Fr = 0.16$ and $H^* = 3.0$, the bow wave generated by the submarine has an amplitude with a non-dimensional value (λ/D) of approximately 0.002 and a peak wave height aft of the submarine of less than $\lambda/D = 0.003$. When these λ/D values are compared to the values predicted from the $H^* = 1.4$ case, there is a 97% decrease in the bow wave height when operating at the deepest depth at the same Froude number. Furthermore, the change in peak wave elevation between $H^* = 3.0$ and $H^* = 2.2$ was only 2% indicating that the majority of the reduction in wave amplitude occurs between $H^* = 1.4$ and $H^* = 2.2$. This further reinforces the trend shown in Figures 2 and 3, which suggested that the free-surface effect is minimal at $H^* = 3.0$, hence, the submarine is close to operating under 'deep submerged' conditions.

At $Fr = 0.31$, the reduction in bow wave and wake is significantly less between $H^* = 1.4$ and $H^* = 3.0$. The reduction in peak wave height is only 92%. This implies that the higher the boat speed is, the greater is the interaction with the free surface. Furthermore, if a line of best fit is applied and extrapolated to the drag coefficient at $Fr = 0.31$, a deeply submerged condition would be achieved before an H^* value of 5.0. This agrees with the experimental work conducted by Dawson [2] who showed that a deeply submerged condition at $\mathrm{Fr} = 0.29$ is achieved between $H^* = 3.3$ and 5.5.

It should also be noted in Figures 4 - 7, the change in wave length between the four Froude numbers tested. With varying wave lengths, the location in which the centre of vertical force is acting will move and thus change the pitching moment at different velocities. Whilst not discussed in this paper, the change in pitching moment should be the next parameter studied to further improve the accuracy of submarine control when operating near the free-surface.

Conclusions

This paper aimed to show the free-surface effect acting on the BB2 submarine geometry across a range of depths and speeds. The Froude number range and H^* values were selected based on previously published data to capture the area in which the free-surface effect was greatest and transitioning to a 'deeply submerged' condition. The 'deeply submerged' condition is considered when there is no longer a change to either the heave or surge force with increasing depth.

This paper compared the surge and heave force coefficients and free surface elevation across a range of Froude numbers and non-dimensional depths in order to demonstrate the effect of the free-surface. All three of these parameters suggest that the free-surface effect is minimal at $H^* = 1.43$ and $Fr = 0.16$. A deeply submerged condition could theoretically be achieved at a shallower depth with a lower Froude number, however, that would represent unrealistic operating conditions for a submarine. Furthermore, greater values for H^* are required to establish the deeply submerged conditions at higher Froude numbers.

It has been shown that the free-surface effect must be correctly modelled as it is proportional to both velocity and depth. This is essential when developing numerical models to characterise the behaviour of submarines operating near the surface.

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