Boundary layer and surface pressure distributions behavior over a submarine nose model with two different nose shapes

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Abstract

Surface pressure distributions and boundary layer profiles are measured over the nose surface of a submarine model in a wind tunnel. The tests are conducted for two different nose shapes in order to study the effects of nose shape on the flow field around the model. The influence of Reynolds numbers, which are $0.5 \times 10^6$, $0.8 \times 10^6$ and $10^6$, and pitch angles, $\alpha = 0, 5, 10$ and $15^\circ$, on the surface pressure distribution over the surface of two nose shapes are investigated. Furthermore, the effect of the longitudinal pressure gradient on the boundary layer velocity profiles and the probability of the separation in the plane of symmetry of the nose are studied. It is found that the Reynolds number does not have a significant influence on the nose surface pressure distribution at all pitch angles. The results show that the presence of the adverse pressure gradient in major portion of the blunter nose shape causes the non-dimensional velocity profiles of boundary layer in locations of $0.1 \leq X/L \leq 0.23$ are deviated from the log layer profile. Therefore the separation on the blunter nose shape is more likely than the other nose at high pitch angle manoeuvres.

Keywords: nose shape, submarine model, boundary layer properties, separation, wind tunnel

1 Introduction

The main body of airplanes, submarines, torpedoes and etc., with axisymmetric nose is a body of revolution. The flow field over these bodies especially their nose presents motivating features due to the existence of both longitudinal and circumferential pressure gradients Pantelatos and Mathioulakis [1]. The variation of the boundary layer features (e.g., transition and separation) that are dependent to the body shape and the pressure gradients may decrease the efficiency of such vehicles. For instance, design of a submarine with higher speeds and lower noise levels needs a careful geometrical design. An improper body shape can cause extreme drag, noise, and instability Paster [2]. Present authors in their recent study Saeidinezhad et al. [3] investigated the hydrodynamic behavior of a submarine model with a non-axisymmetric nose in pitch maneuver. The measured drag coefficient of the model showed a nearly parabolic trend by increasing the pitch angle with a relatively high slope. In addition, their flow visualisation result depicted that the location of the flow separation for the non-axisymmetric nose shape is closer to the nose tip than the symmetric nose at high angle of attack. Hence, the behaviour of the drag coefficient versus pitch angle was attributed to the nose shape of the model.
A number of other experimental investigations have focused on flows over the bodies of revolution at incidence. Some of these researches conducted comprehensive investigation about the pressure distributions and boundary layer development on the surface of bodies of revolution Patel et al. [4], however, few of them investigated the details of the flow field around a submarine model and especially its nose.

Previous boundary layer researches mostly focused on the after-body part of the bodies of revolution where the boundary layer has thickness with the same order of the local radius of the body Patel et al. [4]. Their results showed that transverse (or lateral) curvature affects the boundary layer behavior which is usually neglected in thin boundary layer theory. The boundary layer over a submarine rapidly thickens when the submarine moves in a straight line, while the boundary layer over the fore-body part of the submarine is still thin and can be treated by the conventional techniques Patel et al. [4].

Patel et al. [4] studied the pressure distributions, mean velocity profiles and Reynolds stresses across the thick axisymmetric turbulent boundary layer near the tail of a six-to-one prolate spheroid model in a wind tunnel. Their result showed that the thick boundary layer is characterized by significant variations in static pressure across it which is associated with a strong interaction between the boundary layer and outside potential flow. Also, the low level of turbulence in the boundary layer was attributed to the transverse surface curvature.

Ramaprian et al. [5] and Patel and Baek [6] investigated the three-dimensional turbulent boundary layer on the plane of symmetry of a body of revolution (a hemispherical nose with a hemispheroidal rear) at incidence angle equal to 15°. The surface pressure distributions were measured along the entire length of the body, but the reliable distributions of the velocity vector of the boundary layer were measured just in the longitudinal distance of \(0.2\leq X/L\leq0.8\). The model was suspended stationary in the test section by wires which were connected to the model nose and tail tip. The wires on the nose tip induced some disturbance in the velocity vectors for distance range of \(0 \leq X/L \leq 0.2\).

The results of Ramaprian et al. [5] exhibited the interaction between viscid and inviscid, cross-flow separation and formation of the longitudinal vortices in the boundary layer. The results of Patel and Baek [6] identified the influence of the external flow convergence and/or divergence on the turbulence and the overall development of the boundary layer.

Groves et al. [7] designed and constructed an axisymmetric model with the name of DARPA SUBOFF. The systematic tests were performed on this model to obtain some experimental data in order to validate the results.
obtained from a numerical simulation. Huang and Liu [8] measured the pressure, velocity, skin friction, and Reynolds stress in the boundary layer of the stern region of a SUBOFF model with and without appendages in a wind tunnel. The results showed the effects of the various appendages on the thick turbulent boundary layers over the stern. The results of this work were used by many researchers for numerical results validation. However, the flow field around the SUBOFF model nose has not been studied so far and needs a special consideration.

The review of the relevant literature show that most of the experimental investigation measured the surface pressure, shear stress distributions and boundary layer profiles along the mid-body and/or after-body of a body of revolutions equipped with a known nose shape but none of them investigated the effect of nose shape on the flow behaviour around a submarine nose.

Javad et al. [9] studied the influence of bow shapes (tango and standard bows) on the behaviour of a submarine in the towing tank free surface motion tests. The present authors in their previous works Abedi et al. [10] and Saeidinezhad et al. [11] studied the separation and vorticity fields around a body of revolution at incidence angle. Saeidinezhad et al. [11] investigated the effect of nose shape on the cross-flow separation and vortex formation around SUBOFF submarine model by smoke and oil flow visualization methods. In addition, the both longitudinal and circumferential surface pressure distributions on the submarine model with the two nose shapes at $\alpha = 15^\circ$ are presented to support the nature of the flow structure and the separation patterns that are observed qualitatively in the flow visualization experiments.

The present work is devoted to study the boundary layer and surface pressure profiles behaviour measured along the nose of a submarine model at its symmetry plane for two different nose shapes and at various pitch angles. The main purpose of the present experiments is to investigate the effect of pressure gradient on the development of the boundary layer over a submarine nose. These results can give quantitative detailed data for the efficient design of a nose shape. This data can form the basis for further theoretical studies of the flow over the submarine models, especially two well-known DARPA SUBOFF (Submarine model was generated in Submarine Technology Program (STP) office of the Defense Advanced Research Project Agency of USA) and DRDC (Standard submarine model of Defence Research and Development Canada) submarine models. The DRDC nose shape is blunter than SUBOFF nose. In the present work, the influence of Reynolds numbers, $Re = 0.5 \times 10^5, 0.8 \times 10^5$ and $10^6$ and pitch angles $\alpha = 0, 5, 10$ and $15^\circ$ on the surface pressure distributions are studied for two nose shapes. In addition, the velocity profiles characteristics
across the boundary layer developed over these two nose shapes are investigated for three pitch angles of $\alpha = 0$, 5 and 10° and for $\text{Re} = 10^6$.

The present experimental tests are conducted in the wind tunnel. The captive model tests of an ocean vehicle are usually performed in a wind tunnel or within a towing tank apparatus. There are some differences between these two test environments. In the towing tank medium, all submersible conditions can be examined. The deep or semi-submersible tests of submersible models have been performed in the towing tank Javadi et al. [9], Roddy [12] and Van Randwijk and Feldman [13] and Zhang et al. [14]. Also, the resistance of the ship models is studied in a towing tank Akbarzadeh et al. [15] and Ram et al. [16]. Wind tunnels do not have free surface and therefore only fully submerged conditions (such as immersed submarine) can be simulated Saeidinezhad et al. [3], Huang and Liu [8], Park et al. [17] and Watt et al. [18]. Also the sailboat study of the ships can be achieved in the wind tunnel and towing tank Altosole and Francescutto [19] and Hajizadeh et al. [20]. In the experiments of submersible vehicle, two principal dimensionless numbers are Reynolds and Froude numbers. Javanmardi et al. [21] studied the effect of moving pressure source and channel parameters on the generated waves in a water channel both numerically and experimentally. Their investigation shows that the generated wave height is independent of water depth for supercritical depth Froude numbers at a given Reynolds number. Also, the blockage factor of water channel has higher influence at supercritical Froude depth values, while at subcritical Froude values; it is negligible compared with water depth. As an underwater vehicle usually operates far away from the free surface, the Froude scaling is no longer concerned and the most important similarity parameter for this case is the Reynolds number.

2 Experimental setup

2.1 Wind tunnel and Model

The experiments in the present work are conducted in a closed loop subsonic wind tunnel with a test section size of 370×280×1200 mm. The axial fan of the tunnel provides airflow with maximum speed of about 30 m/s and turbulence intensity level of 0.25 % in the test section. The test section has 45 degree corner fillets which enlarge the cross-sectional area gradually in downstream direction to maintain a constant static pressure along the test section, therefore decreasing the buoyancy effects Barlow et al. [22]. Figure 1 shows the schematic of the lower half part of the wind tunnel test section as well as the full shape of the model positioned in the test section.
A submarine model with two different nose shapes is selected in the present work. A 1:152 scale model of DARPA SUBOFF bare hull submarine Groves et al. [7] with a length \((L)\) of 0.687 m and a maximum diameter \((D)\) of 0.08 m is considered as the base model. The results of the pressure coefficient measured over this model are compared with other works available in the literature for validation purposes. This model consists of three detachable parts, a nose (fore-body), a mid-body and an after-body with the lengths of \(L_n/L=0.23\), \(L_m/L=0.51\) and \(L_a/L=0.26\) respectively. To study the effect of nose shape on the flow characteristics around the nose, the SUBOFF nose is replaced with DRDC submarine nose Watt et al. [18]. Two noses selected have the same length, \(L_n\). The geometry of the SUBOFF model and DRDC submarine nose (the blunter nose) are shown in Figure 2. All parts of the models were machined from aluminium with accuracy of ±0.5 mm.

The submarine model is mounted in the middle of the test section by an aluminium tube with diameter of 10 mm working as the main strut which attaches to the model at \(X/L=0.5\) (Figure 1). The main strut also exports the pressure tubes from the body to pressure sensor box. The pitch angle \((\alpha)\) of the model is changed by a linkage which is attached to the model as shown in Figure 1. The pressures and velocities are measured upstream of the support location and therefore the effect of support on these results is neglected.

A trip strip is attached on the nose surface to simulate the turbulent boundary layer flow around the model. A wire as trip strip with a diameter of 0.6 mm was attached to the model nose circumferentially. For SUBOFF model the trip is placed at \(X/L = 0.05\) based on the work of Huang and Liu [8] and for the DRDC model wire trip is placed at \(X/L = 0.03\) based on the recommendation of Watt et al. [18].

The combined blockage ratio due to the model and its support is below 5% at zero pitch angle. For higher pitch angles, the measured pressure coefficients and boundary layer velocities are corrected by employing Equation (1) and (2). In this equation, \(C_{pv}\), \(U\), and \(q_{\infty}\) are measured pressure coefficient, velocity and dynamic pressure and \(C_P\) and \(U\) are the corrected ones, respectively. Also, the parameter \(\varepsilon\) is the correction factor and BR is the blockage ratio which are presented in Equation (3) and (4) [22]. The parameter, \(P\) (Pa), is the local pressure on the surface; \(P_{\infty}\) (Pa) and \(U_{\infty}\) (m/s) are the free-stream static pressure and velocity that are measured at the wind tunnel nozzle outlet by a pitot-static tube and \(\rho\) (Kg/m³) is the airflow density.

\[
C_P = \frac{P - P_{\infty}}{\frac{1}{2} \rho U_{\infty}^2} = \frac{P - P_{\infty}}{q_{\infty}(1 + 2\varepsilon)} = \frac{C_{pv}}{(1 + 2\varepsilon)} \quad (1)
\]
\[
U = U_{\infty} \sqrt{(1 + 2\varepsilon)} \quad (2)
\]
\[ \varepsilon_i = \frac{1}{4} \times \text{BR (Blockage Ratio)} \]  

(3)

\[ \text{BR (Blockage Ratio)} = \frac{\text{Model and support front area}}{\text{Wind tunnel test section area}} \]  

(4)

2.2 Experimental procedure and instruments

The surface pressure distributions are measured by nine pressure taps positioned along the nose and five taps mounted along the mid-body. All pressure taps are connected to a multi-channel pressure box (pressure sensor Honeywell, DC005NDC4) with the measuring range of ±1245 Pa and with the accuracy of ±3 Pa.

The longitudinal pressure distributions over the range of 0 ≤ X/L ≤ 0.23 on the nose surface are recorded along with the circumferential direction in the range from 0° to 180° with 15° increment by rotating the nose along its axis. The origin of circumferential direction (φ = 0°) is at the symmetry plane in the windward side of the model where the flow meets. The pressure data are collected for 105 locations on the one-half of nose surface 0° ≤ φ ≤ 180° as shown in Figure 3 (black spots). Also, Figure 3 shows the dimensions of the nose and the positions of the pressure data collections.

The pressure measurements are performed for three values of Reynolds numbers (based on the overall length of the model) i.e., \( Re = 0.5 \times 10^6, 0.8 \times 10^6 \) and \( 1 \times 10^6 \) corresponding to three free stream velocities of \( U_\infty = 12, 18 \) and 24 m/s respectively and for various pitch angles \( \alpha = 0, 5, 10 \) and 15°. The origin of the body coordinate system is located at the nose tip. The \( X \) axis corresponds to the axis of symmetry of the model and is positive in the downstream direction. The direction of the \( X \) and \( Y \) axes are also shown in Figure 3.

The boundary layer velocity profiles in the plane of symmetry on the leeward side (\( \phi = 180° \)) of the submarine nose were measured by using a single probe hot wire anemometer. The single probe with 0.5 mm tungsten wire is connected to a constant temperature anemometer (CTA). The probe is mounted on a three-dimensional traverse system with movement accuracy of 0.01 mm. To measure the boundary layer accurately, the probe moves logarithmically in a line normal to the model surface and controlled by a computer software and the data are acquired during 5 second for each location. The CTA (constant temperature anemometer) has a temperature corrective probe that is placed in the flow and applies the effect of temperature variation during airflow measurement. The velocity measurement results are obtained for model with both nose shapes for \( Re = 1 \times 10^6 \) at three pitch angles \( \alpha = 0, 5 \) and 10° with trip strip on the nose. The measuring parameters and their corresponding uncertainties are listed in table 1.
3 Results and Discussion

In this study, the effects of the nose shape on the flow behaviour over the nose surface of an axisymmetric submarine model are investigated and discussed for various pitch angles. The first part of the results focuses on the variations of the surface pressure coefficients with Reynolds number and pitch angles. Then, the effects of nose shape on the surface pressure distribution are investigated. In the second part, the effects of pressure gradient on the boundary layer velocity profiles are studied at various pitch angles in the plane of symmetry on the leeward side of the model ($\phi = 180^\circ$). Moreover, the experimental results obtained for employing the SUBOFF model are compared with the available results in the literature.

3.1 Surface pressure coefficient

Pressure coefficient ($C_p$), which is calculated from measuring surface pressure over the model, is defined by Equation (5).

$$C_p = \frac{P - P_{\infty}}{\frac{1}{2} \rho U_{\infty}^2}$$

In this equation, $P$ (Pa.) is the local surface pressure; $P_{\infty}$ (Pa.) and $U_{\infty}$ (m/s) are the free-stream static pressure and velocity that are measured at the wind tunnel nozzle outlet by a pitot-static tube and $\rho$ (kg/m$^3$) is airflow density.

Figure 4 shows the longitudinal distribution of the surface pressure coefficient on the SUBOFF model along the leeward plane ($\phi = 180^\circ$) at $Re = 1 \times 10^6$ and for zero pitch angle. In addition, the SUBOFF model body curve is drawn in this figure. The present result is compared with the experimental result of Huang and Liu [8] reported for $Re = 12 \times 10^6$. It is seen that present result is in a good agreement with the result of Huang and Liu [8] in spite of the difference in the Reynolds number values. This is due to the presence of the fully turbulent boundary layer on the model surface. The pressure distribution near the nose tip ($0 \leq X/L \leq 0.035$), where the minimum of pressure takes place, is not measured by Huang and Liu [8].

Figure 5 illustrates the pressure coefficient versus circumferential angle in two longitudinal locations at $\alpha = 10^\circ$, $Re = 10^6$ and for SUBOFF model. The circumferential pressure distributions of the present work are compared with the same results of Hosder and Simpson [23] at $Re = 2.5 \times 10^6$. The results of Hosder and Simpson are measured at position $X/L = 0.11$ and $X/L = 0.14$ but the present surface pressure data are measured in position $X/L = 0.105$ and...
The observed slight discrepancy between our results and the results of the Hosder and Simpson study in location $X/L=0.11$ is because of this difference between the locations of the measurements.

3.2 The effect of Reynolds number and pitch angle on the pressure results

Detailed surface pressure measurements along the circumferential and longitudinal directions over the nose surface are achieved by rotating the nose around its axis. Figure 6 shows the contour of the pressure coefficient over the surface of SUBOFF nose at $Re = 0.5 \times 10^6$, $0.8 \times 10^6$ and $1 \times 10^6$ and for four pitch angles of $\alpha = 0, 5, 10$ and $15^\circ$. The pressure data are obtained only at one half of the nose surface $0^\circ \leq \phi \leq 180^\circ$ (see Figure 3) then these data are considered for the other half part of the nose $180^\circ \leq \phi \leq 360^\circ$ due to the asymmetry of the nose and flow field. At zero pitch angle, the pressure field has the axial symmetry over the nose surface (as shown in Figure 6a-6c). The longitudinal pressure gradient is dominant in the flow around the nose. The pressure coefficient has maximum value ($C_P=1.0$) at incident point where the flow stagnates ($X/L = 0$) and decreases along the nose until a minimum value ($C_P=-0.26$). The pressure distribution has a favourable gradient in this portion. Then the pressure increases (adverse pressure gradient) and stays close to zero towards the nose end.

The effect of Reynolds number on the nose surface pressure at zero pitch angle is depicted in Figure 6a-6c. No significant variation in the surface pressure coefficient is seen as the Reynolds number is changed. As the pitch angle is increased, the circumferential pressure gradient appears on the nose surface between windward and leeward side, although the longitudinal pressure gradient is also present. In the leeward symmetry plane ($\phi = 180^\circ$), the longitudinal pressure gradient becomes stronger and the minimum pressure coefficient decreases (increases in absolute value) when the pitch angle is increased. The minimum of $C_P=-0.26$ at $\alpha = 0^\circ$ is changed to $C_P=-1.0$ at $\alpha = 15^\circ$ the on leeward side of the model at the same longitudinal position. On the windward symmetry plane ($\phi = 0$) pressure takes its maximum value near to the tip and then increases due to the flow acceleration towards the nose end.

Figure 7 shows the contour of pressure coefficient over the surface of SUBOFF and DRDC noses at $Re = 1.0 \times 10^6$ and for four pitch angles of $\alpha = 0, 5, 10$ and $15^\circ$. For both noses, the pressure coefficient has maximum value at incident point and decreases along the nose until a minimum value. The place and the amount of minimum value of pressure coefficient strongly depend on the nose shape. The adverse longitudinal pressure gradient is observed for both noses after minimum pressure location, however, the pressure recovery on the SUBOFF nose is
more pronounced after its minimum value and stays close to zero afterward. The pressure coefficient results at $\alpha = 10^\circ$ are presented in Figure 7e-7f. It is seen that the greater portion of the DRDC nose is subjected to a positive pressure gradient at high pitch angles.

3.3 Boundary layer behaviour on the symmetry plane at pitch angle

In this section, the characteristics of velocity profiles of boundary layer on the symmetry plane of the submarine nose ($\phi = 180^\circ$) are studied for $Re = 10^6$ at three pitch angles of $\alpha = 0$, 5 and 10$^\circ$. The boundary layer profiles are measured at five longitudinal locations of $X/L = 0.05, 0.09, 0.14, 0.19$ and $0.23$ along the nose in the leeward plane of symmetry ($\phi = 180^\circ$) by a hotwire anemometer.

Moreover, the boundary layer profile in the location $X/L = 0.9$ is also measured to compare with Huang and Liu [8] results. Figure 8 shows the boundary layer velocity profile in location $X/L = 0.9$ on the leeward symmetry plane ($\phi = 180^\circ$) for SUBOFF model at zero pitch angle and for $Re = 10^6$. The result of Huang and Liu [8] is also shown in this figure. The non-dimensional boundary layer velocity profile ($U/U_c$) is depicted versus the non-dimensional distance from the surface ($Y-R_0/R_{Max}$). Comparing the present results with the Huang and Liu [8] experiments shows that the trend of the velocity profile of the boundary layer are very well predicted by the present work, but some differences between the results are seen in the range of $0.5 \leq (Y-R_0/R_{Max})$. In the present work, $U_c$ is the velocity at the edge of the boundary layer in at $X/L = 0.9$ while Huang and Liu [8] used the velocity of the flow outside of the boundary layer at $X/L = 0.75$ as the scaling velocity which its value is unknown. This might be the reason of the discrepancies between the both results presented in Figure 8.

3.4 The effect of pitch angle and pressure gradient on the boundary layer profiles

The boundary layer thickness on the nose surface is much less than the model diameter, therefore the effect of span-wise model curvature can be neglected Patel et al. [4]. The boundary layer in the plane of symmetry is intermediate in complexity between the axisymmetric boundary layer and the fully three-dimensional boundary layer Patel and Baek [6]. The flows in the plane of symmetry dose not experience the cross-flow but it undergoes the longitudinal pressure gradient. The longitudinal pressure gradient affects the shape of the two dimensional boundary layer profiles and the boundary layer might undergo the longitudinal separation. The effect of various pressure gradients on the non-dimensional turbulent boundary layer velocity profiles are shown in Figure 9 White and Corfield [24].
White and Corfield [24] noted that the boundary layer velocity profiles (as seen in Figure 9) with various strength of pressure gradients collapse into a single logarithmic law in the region of $35 < y^* < 350$, with the exception of the separating flow boundary layer. When the curves turn upward in the outer layer $y^* \geq 350$, the effect of pressure gradient on the boundary layer profiles is more pronounced and leads them to deviate from the logarithmic law.

In the present work, most of the boundary layer velocity profiles are logarithmically drawn with non-dimensional distance from the surface, $Y^*$, and non-dimensional velocity $U^*$ which are defined in Equation (6).

$$
Y^* = \left( \frac{Y - R_o}{\rho u^*} \right) \frac{\mu}{\sigma} , \quad U^* = \frac{U}{u^*}
$$

(6)

In addition, the profiles of the viscous sub-layer (Equation (7)), log layer (Equation (8)) and Spalding’s single formula for law of the wall (Spalding [25]) which is presented by Equation (9) are shown at each location. In Equation (9), $K$ and $C$ are constant parameters of the Spalding [25] equation. Initially, the value of the friction velocity $u^*$ is not known in Equation (6). Hence, its value is changed over an appropriate range until an optimum value is obtained which best matches the inner Spalding [25] boundary layer profile (Equation (9) with $K=0.4$ and $C=5.0$) to the non-dimensionalized outer layer measured data Demoss [26].

$$
U^* = Y^* \quad \text{Viscous sublayer}
$$

(7)

$$
U^* = \frac{1}{0.4} \ln(Y^*) + 5 \quad \text{The log layer}
$$

(8)

$$
\frac{y^*}{Y^*} = U^* + \frac{1}{e^{KC}} \left[ e^{KU^*} - \left[ 1 + KU^* + \frac{(KU^*)^2}{2!} + \frac{(KU^*)^3}{3!} \right] \right]
$$

(9)

Figure 10 shows the boundary layer velocity profiles at five locations of $X/L = 0.05, 0.09, 0.14, 0.19$ and 0.23 along the nose surface of DRDC and SUBOFF models at $\alpha = 0^\circ$. The streamwise component of the velocity ($U$) is non-dimensionalized with the velocity at the boundary layer edge ($U_e$). Also, the nose curvature and longitudinal pressure distribution of two nose shapes are shown in Figure 10. As it may be seen, the SUBOFF boundary layer velocity profiles in all positions have negative curvature due to negative pressure gradient along the nose with the exception of the profile at position $X/L = 0.05$. The sharp and deflective SUBOFF profile in location $X/L = 0.05$ is due to the presence of the trip strip in this position. The minimum of the longitudinal pressure coefficient for SUBOFF nose occurs in the range of $0.01 \leq X/L \leq 0.03$ while the pressure coefficient increases suddenly and stays
close to zero afterward and in the location range of \(0.03 < \frac{X}{L} \leq 0.23\). For DRDC nose, the pressure coefficient after the minimum location \((0.07 \leq \frac{X}{L} \leq 0.14)\), increases gradually along the nose \((0.14 < \frac{X}{L} \leq 0.23)\).

Figure 11 shows the non-dimensional boundary layer velocity profiles measured at five longitudinal locations of \(\frac{X}{L} = 0.05, 0.09, 0.14, 0.19\) and 0.23 along the nose surface for two DRDC and SUBOFF models at \(\alpha = 0^\circ\). In addition, the profiles of the viscous sub-layer, log layer and Spalding [25] are shown in each location. The effect of longitudinal pressure gradient is seen in Figure 11. The non-dimensional boundary layer profile deviates from the log layer profile (or Spalding profile) as \(\frac{X}{L}\) increases. However, for SUBOFF nose, this deviation is less pronounced than the DRDC nose one.

Figures 12 and 13 show the boundary layer velocity profiles along the nose surface of two models at \(\alpha = 5^\circ\). The surface pressure coefficient distribution is also presented in Figure 12. The surface pressure coefficient distributions along the two nose shapes show that the pressure gradient becomes stronger as pitch angle increased. The boundary layer velocity profiles for DRDC nose shape in longitudinal locations of \(0.1 \leq \frac{X}{L} \leq 0.23\) are more affected by the adverse pressure gradient at pitch angle \(\alpha = 5^\circ\) than \(\alpha = 0^\circ\).

Figures 14 and 15 show the boundary layer velocity profiles along the nose surface of two models at \(\alpha = 10^\circ\). Close look at the boundary layer velocity profiles on the surface of DRDC and SUBOFF nose shapes with different pressure distribution shows that the presence of the mild adverse pressure gradient in greater portion of the DRDC nose has greater influence than the sudden loss in pressure in small portion of the SUBOFF nose. Presence of adverse pressure gradient in greater portion of the DRDC nose indicates that the separation on the standard nose is more probable than the SUBOFF nose at high pitch angles. The flow visualization conducted by the same authors Saeidinezhad et al. [11] revealed the same evidence on the nose flow separation. The adverse longitudinal pressure gradient is greater for the DRDC nose (blunter nose) and therefore, the nose separation for DRDC nose occurs in smaller angle of incidence than the SUBOFF nose Saeidinezhad et al. [11].

4 Conclusions
In the present study the flow behaviour over two different nose shapes of a submarine model at various pitch angles manoeuvre is investigated. The surface pressure distributions and boundary layer profiles over the SUBOFF and DRDC noses are measured in a wind tunnel. The study presents the influence of Reynolds numbers, \(Re = 0.5 \times 10^6, 0.8 \times 10^6\) and \(10^6\), and pitch angles, \(\alpha = 0, 5, 10\) and \(15^\circ\), on the surface pressure contours for two nose shapes. The
boundary layer velocity profiles along the two nose shapes at three pitch angles of \( \alpha = 0, 5 \) and \( 10^\circ \) and at \( \text{Re} = 10^6 \) are also studied. The major conclusions of this study may be summarized as follows:

1. The comparison of measured longitudinal and circumferential pressure coefficients with the referenced experimental results of show a good agreement and reveals that the fully turbulent boundary layer profiles over the body length.

2. Reynolds number does not have a significant influence on the nose surface pressure distribution at all pitch angles considered.

3. Comparing the surface pressure coefficient distributions on the surface of SUBOFF and DRDC nose revealed that minimum pressure coefficient for two nose shape occurs at different locations. After the minimum locations, the pressure on the SUBOFF nose increases suddenly and stays close to zero. However, for the DRDC nose, major portion of the nose surface is subjected to a positive pressure gradient.

4. The non-dimensional boundary layer profile is seen to be affected by the longitudinal pressure gradients. For SUBOFF nose, the non-dimensional boundary layer velocity profiles in all longitudinal positions are not much deviated from the log layer profile along the nose. However, the non-dimensional boundary layer velocity profiles for DRDC nose in locations of \( 0.1 \leq X/L \leq 0.23 \) are more affected by the presence of adverse pressure gradient and deviated from the log layer profile (or Spalding profile).

5. The presence of the adverse pressure gradient in greater portion of the DRDC nose indicates that the separation on the DRDC nose is more likely than the SUBOFF nose at higher pitch angles. This is also supported by the flow visualization results of the same authors Saeidinezhad et al. [11] which confirm the boundary layer velocity profiles behaviour presented here.

**Nomenclature**

\[

c_{\text{C}} \quad \text{constant parameter of the Spalding equation} \\
c_{P} \quad \text{pressure coefficient} \\
c_{Pv} \quad \text{uncorrected pressure coefficient} \\
D \quad \text{maximum diameter of the model (m)} \\
K \quad \text{constant parameter of the Spalding equation} \\
L \quad \text{model length (m)} \\
Y \quad \text{vertical axis (m)} \\
Y^+ \quad \text{Non-dimensional distance from the surface} \\
\alpha \quad \text{pitch angle (deg)} \\
\mu \quad \text{dynamic viscosity} \\
\rho \quad \text{fluid density (kg/m}^3\text{)} \\
\phi \quad \text{circumferential direction (deg)}
\]
L\textsubscript{a} \quad \text{after-body length (m)}

L\textsubscript{m} \quad \text{mid-body length (m)}

L\textsubscript{n} \quad \text{nose length (m)}

P \quad \text{pressure (pa.)}

P\textsubscript{\infty} \quad \text{free stream pressure (pa.)}

P\textsubscript{SS}\textsubscript{\infty} \quad \text{free stream static pressure (pa)}

P\textsubscript{T}\textsubscript{\infty} \quad \text{free stream total pressure (pa)}

q\textsubscript{\infty} \quad \text{free stream dynamic pressure (pa.)}

q\textsubscript{\infty v} \quad \text{uncorrected free stream dynamic pressure (pa.)}

R\textsubscript{0} \quad \text{local radius of the model (m)}

R\textsubscript{Max} \quad \text{maximum radius of the model (m)}

Re \quad \text{model length Reynolds number}

U \quad \text{streamwise velocity (m/s)}

U\textsubscript{v} \quad \text{uncorrected streamwise velocity (m/s)}

u* \quad \text{friction velocity (m/s)}

U\textsubscript{\infty} \quad \text{free stream velocity (m/s)}

U* \quad \text{non-dimensional velocity}

X \quad \text{longitudinal axis along the model (m)}

\textbf{References}


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Table 1. The relations and uncertainty values of the parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Relation</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free stream velocity (m/s)</td>
<td>$V_u = \sqrt{\frac{2\Delta P}{\rho}}$</td>
<td>$\frac{u_{V_u}}{V_u} = 1.9$</td>
</tr>
<tr>
<td>Reynolds number</td>
<td>$Re = \frac{\rho V_u L}{\mu}$</td>
<td>$\frac{u_{Re}}{Re} = 2$</td>
</tr>
<tr>
<td>Mean velocity (m/s)</td>
<td>$U$</td>
<td>$\frac{u_U}{U} = 3$</td>
</tr>
<tr>
<td>Mean pressure (pa.)</td>
<td>$p$</td>
<td>$\frac{u_p}{p} = 2$</td>
</tr>
<tr>
<td>Pressure coefficient</td>
<td>$C_p = \frac{p - P_{\infty}}{q_{\infty}}$</td>
<td>$\frac{u_{C_p}}{C_p} = 3.4$</td>
</tr>
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$\Delta P = $ Pitot static tube differential pressure $= P_{\infty} - P_{S\infty}$

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