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Experimental Investigation of a Hemisphere in a Thin Flat Plate Boundary Layer

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Abstract

Wind tunnel experiments of the flow past a hemisphere in a thin flat plate boundary layer were conducted over a range of Reynolds numbers, based on hemisphere diameter from 6.36×10^4 to 1.55×10^5. Mean and unsteady surface pressure measurements, in conjunction with surface flow visualisation, were used to characterise the flow over the hemisphere and near-wake region. A frequency analysis of the surface pressure at a Reynolds number of 1.25×10^5 indicated broadband spectral activity in the Strouhal number range 0.12 to 0.18.

Introduction

Aircraft geometries can include a range of external protuberances which may adversely affect aerodynamic performance or lead to structural vibration issues. The flow past a hemispherical protuberance involves complex three dimensional interactions between multiple flow structures. A necklace vortex forms at the base of the hemisphere as the spanwise pressure gradient causes the upstream boundary layer to move around the hemisphere [1]. An adverse pressure gradient in the streamwise direction causes this necklace vortex to detach from the hemisphere on either side and form legs that extend downstream [1]. In the wake of the hemisphere the free shear layer comprised of vortical structures that form closed loops which are stretched as they are shed from the hemisphere and swept downstream [2, 3]. The necklace vortex interacts with the base of these vortex loops which adds streamwise vorticity into the wake [4].

Vortex shedding has previously been observed over the top of a hemisphere in the Reynolds number range 5.5×10^2 to 1.6×10^3 at Strouhal numbers of 0.45 to 0.87 [3] while the necklace vortex structure stretched downstream in the wake rather than being shed.

In this experiment the Reynolds number, $Re=\rho u_\infty D/\mu$, and Strouhal number, $St=fD/u_\infty$, were based on hemisphere diameter, D, and freestream velocity u_∞.

Experimental Details

The wind tunnel experiments were conducted in an open circuit suction wind tunnel with an octagonal working section 620 mm high and 800 mm wide, as shown in figure 1. The inlet had a bell mouth shape followed by a settling chamber and two turbulence reducing screens. There was a 4:1 contraction before the working section and the maximum velocity of the wind tunnel was 25 m/s. The boundary layer thickness at the upstream pole of the hemisphere was measured using a 0.8 mm pitot tube and a wall mounted static port. The boundary layer was found to be turbulent and the non-dimensional boundary layer thickness, $(D/2)/\delta$, was between 2.9 and 3.1, where δ was the height when the flow velocity reached 99% of the freestream velocity.

The coordinate system for this experiment is defined in figure 1, with the origin at the base of the hemisphere centre and the elevation angle, ϕ, and azimuthal angle, θ, defined counter-clockwise from the upstream x axis.

Two hemisphere models were used in this experiment, both with 2mm thick aluminium shells of 100mm diameter. The first model did not contain pressure tappings and was used for surface flow visualisation. The second model had 37 pressure tappings along a centreline spaced at 5° intervals between $5° \leq \phi \leq 175°$ with a further two ports located at ϕ of 1° and 179°. In order to obtain pressure measurements over the whole surface of the hemisphere it could be rotated using a stepper motor positioned underneath the model outside the wind tunnel. The hemisphere was mounted on the lower wall of the wind tunnel, on a ground plate which contained 123 pressure ports both radially upstream and in a 50 × 25mm grid downstream.

The surface pressure field on the hemisphere and ground plate was recorded using a Pressure Systems Inc (PSI) System 8400 with two 32 channel 8400 scanner digitizer interface system scanners. These scanners acquired pressure data at approximately 227 Hz and had a maximum uncertainty of ±3 Pa over the range ±6.9kPa. A Kulite pressure transducer with a sensitivity of 2.6 mV/kPa and a range of ±34 kPa was used to provide fluctuating pressure spectra with a sample rate of 10 kHz. The Kulite transducer was connected to one pressure port at a time by approximately 30mm of tubing. This length of tubing was deemed to have a negligible effect on the pressure attenuation over the range of frequencies to be investigated [5] and, as such, the pressure spectra were not corrected.

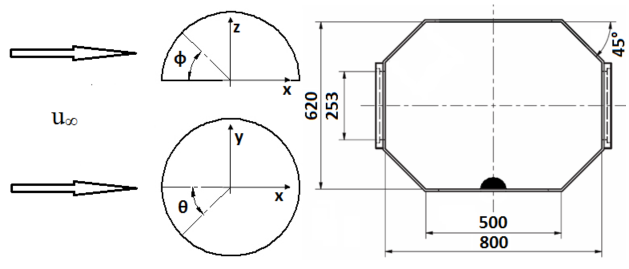

Figure 1. Hemisphere model geometry coordinate system, side and top view and cross section of the wind tunnel working section with a hemisphere of diameter D = 100 mm mounted on the lower wall

Surface Flow Visualisation

Qualitative surface skin friction flow visualisation was undertaken using a kaolin clay, oleic acid and kerosene mixture painted on the blank hemisphere and ground plate covered with black vinyl contact paper. Once the model and ground plate were painted the wind tunnel was ramped up to the desired freestream velocity and the kerosene was given approximately five minutes to evaporate, leaving the surface flow pattern. These flow patterns can be seen in figure 2, where regions of high shear appear darker because the clay has been swept away while regions of low shear appear brighter as the clay accumulates.

The flow over the hemisphere in the range of Reynolds numbers investigated was transitional with a different behaviour as the Reynolds number increased. At Re = 6.36×10^4, shown in figure 2(a, b), a laminar boundary layer formed over the front of the hemisphere which separated near ϕ = 80° along a well-defined

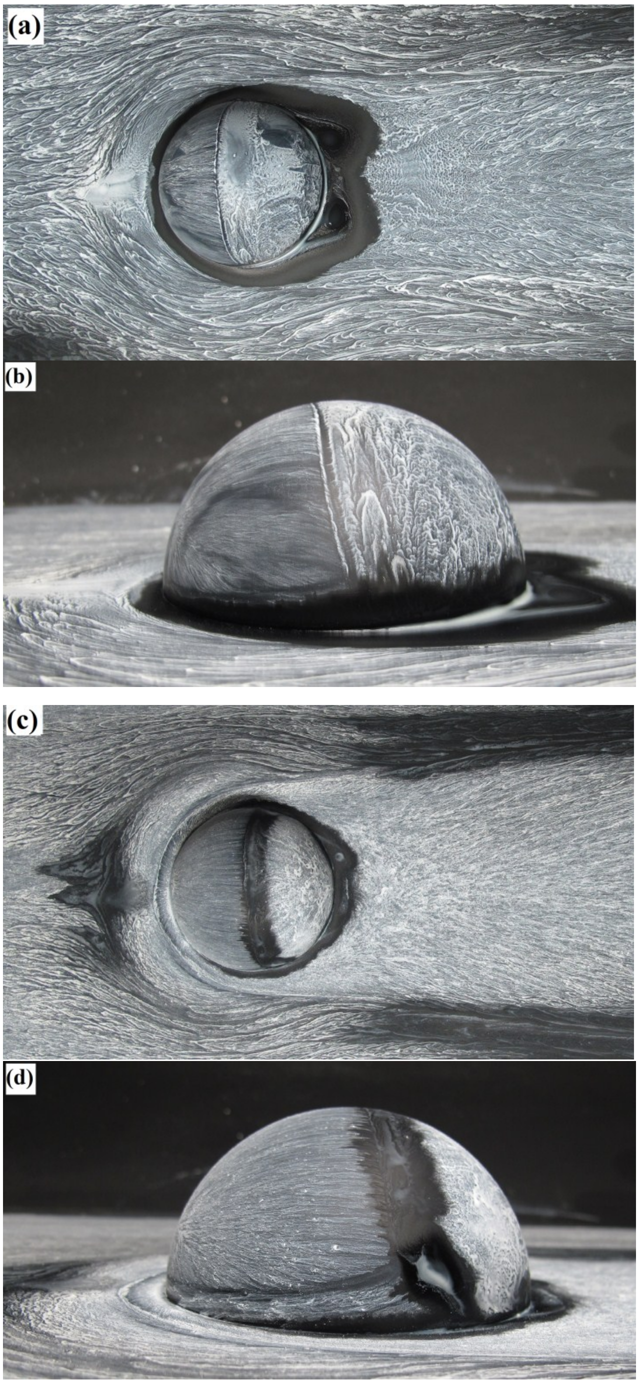

Figure 2. Top and side views of surface shear flow visualisation of flow over a hemisphere at (a, b) Re = 6.36×10^4 and (c, d) Re = 1.55×10^5. Freestream flow is from left to right.

laminar separation line. A previous study [6] recorded a single peak in the RMS pressure coefficient at ϕ = 81° for a Reynolds number of 6.6×10^4 in a smooth boundary layer, which is associated with the flow separation and a unsteady downstream flow. This laminar separation line is located in a similar position as that over a sphere [7].

At Re = 1.55×10^5, shown in figure 2(c, d), there was no sharp separation line with the laminar boundary layer separating at $\phi \approx$ 95°. The flow reattached at about 105° before separating again near 130°. A previous study [6] showed two peaks in the RMS pressure coefficient at similar locations to these for comparable Reynolds numbers, indicating the presence of a laminar separation bubble.

The primary necklace vortex at the base of the hemisphere extended 0.1 D from the upstream pole in both cases and was approximately 0.05 D high on the hemisphere. A bifurcation line, separating fluid which was entrained into the necklace vortex and that which passed over the top of the hemisphere, is evident in figure 2(b, d). As the flow moved azimuthally around the hemisphere, the surface flow indicated that the necklace vortex was swept up as it approached the laminar boundary layer separation region.

Behind the hemisphere figure 2(a) shows distinct rotating structures in the near wake at Y/D of approximately ±0.25 for the Reynolds number of 6.36×10^4. At the higher Reynolds number, figure 2(c), these structures were much smaller but in both cases they were slightly larger in the positive Y direction.

Mean Surface Pressure

The mean surface pressure coefficient,

$$c_p = \frac{p - p_\infty}{q_\infty}, \tag{1}$$

along the line of symmetry of the hemisphere, θ = 0°, was obtained for a range of Reynolds numbers between 6.36×10^4 and 1.55×10^5 and is shown in figure 3. In equation (1) p, p_∞ and q_∞ are the surface static pressure, freestream static pressure and the free stream dynamic pressure respectively. The region, ϕ < 20°, on the upstream side of the hemisphere shows that the mean pressure coefficient to decrease slightly as Reynolds number increased.

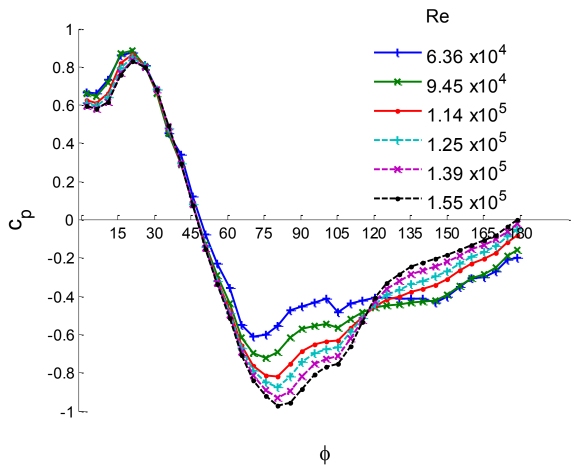

Figure 3. Mean surface pressure coefficient over the hemisphere line of symmetry for Reynolds number between Re = 6.36×10^4 and 1.55×10^5

For each case the pressure coefficient peaked at ϕ = 20° and then decreased as the flow accelerated over the hemisphere. This decrease in pressure coefficient showed very little Reynolds

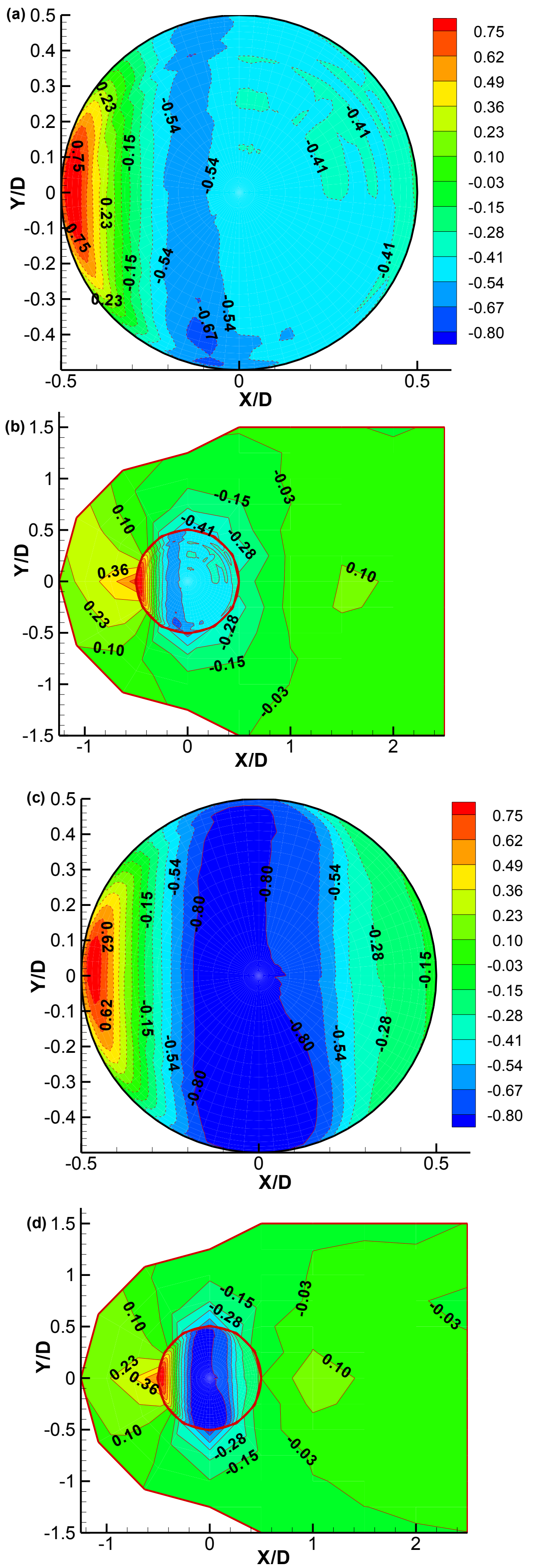

Figure 4. Mean surface pressure coefficient contours of hemisphere and ground plate at (a, b) Re = 6.36 × 10^4 and (c, d) Re = 1.55 × 10^5

number dependence until ϕ = 70°. The peak suction pressure coefficient increased from -0.6 to -0.98 as Reynolds number increased from 6.36 × 10^4 to 1.55 × 10^5. The pressure coefficient recovered more rapidly at higher Reynolds number to reach a value of -0.03 at ϕ = 180° when the Reynolds number was 1.55 × 10^5. This Reynolds number dependence in the mean pressure coefficient suggests the flow is in a transitional regime.

Cheng & Fu [6] recorded a similar spread in the pressure coefficient over the hemisphere centreline. They found that the centreline pressure coefficient plots did not collapse until Reynolds numbers of 3.0 × 10^5 for a hemisphere in a thin boundary layer, (D/2)/δ > 1 and 2.0 × 10^5 for a thick turbulent boundary layer, (D/2)/δ < 1, which were outside the range of this investigation.

The mean pressure coefficient field on the entire surface of the hemisphere and ground plate is shown as a contour plot in figure 4. The plots show an area of high pressure at the front of the hemisphere and the stagnation point, taken to be the point of highest pressure coefficient, occurring consistently at ϕ = 20° and -5° < θ < 0°. The upstream side of the hemisphere shows contours spaced close together and are symmetrical about the streamwise centreline. Over the top and the downstream region of the hemisphere the mean pressure coefficient was not symmetrical. The mean pressure coefficient increased more rapidly when Y/D was positive. The flow upstream of the hemisphere was asymmetric with higher pressures visible on the ground plate for positive Y/D. The cause of this slight asymmetry requires further investigation.

The azimuthal mean pressure coefficient at constant ϕ is shown in figure 5 for Re = 1.55 × 10^5 along with the potential solution for flow past a sphere [8], given by the equation:

$$c_p = 1 - \frac{9}{4}\sin^2\theta. \tag{2}$$

At θ ≈ 100° and ϕ ≥ 15° the azimuthal pressure coefficient plot flattens slightly and eventually develops a similar profile to that observed for the flow past a cylinder exhibiting laminar separation and turbulent reattachment [9]. This indicates that the laminar separation bubble formed above the necklace vortex, which from the flow visualisation occurs approximately for ϕ > 6° and there was no reattachment for ϕ < 6°.

Figure 5 indicates that a pressure minimum occurs for ϕ = 5° at θ = 90°, which shifts slightly upstream towards the front of the hemisphere as ϕ increases. The potential solution for flow over a sphere also has a pressure minimum at 90°.

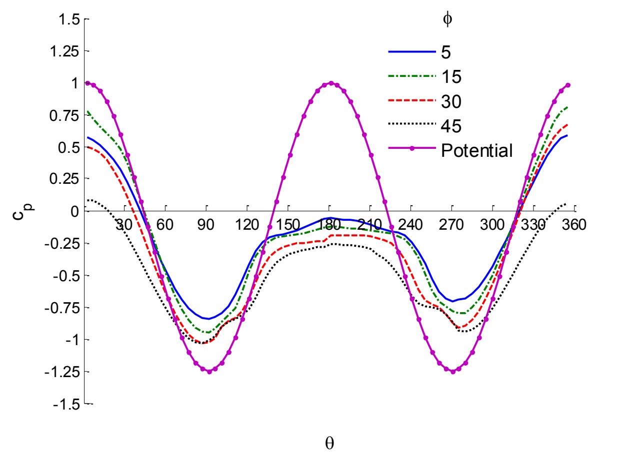

Figure 5. Azimuthal mean surface pressure coefficient at constant ϕ for Re = 1.55 × 10^5. Also shown is to the potential solution for flow over a sphere.

Pressure Fluctuations

The power spectral density (PSD) of the pressure fluctuations were analysed at specific locations in the flow at a Reynolds number of 1.25×10^5. The flow at this Reynolds number had similar flow features to the flow at Re = 1.55×10^5 including the laminar separation bubble.

A background spectrum, shown in figure 6, was measured on the ground plate with no hemisphere in the wind tunnel. This background spectrum showed the first and second harmonics of the wind tunnel fan blade passing frequencies, corresponding to multiple peaks at Strouhal numbers starting at 1.5 and 3. This was well above the region of interest, corresponding to Strouhal numbers less than one. Background noise in this range had significant peaks at Strouhal numbers of 0.08, 0.23 and 0.25.

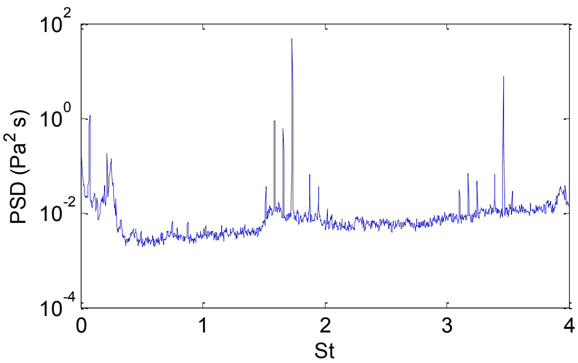

Figure 6. Background PSD of surface pressures in the wind tunnel with no hemisphere at Reynolds number 1.25×10^5.

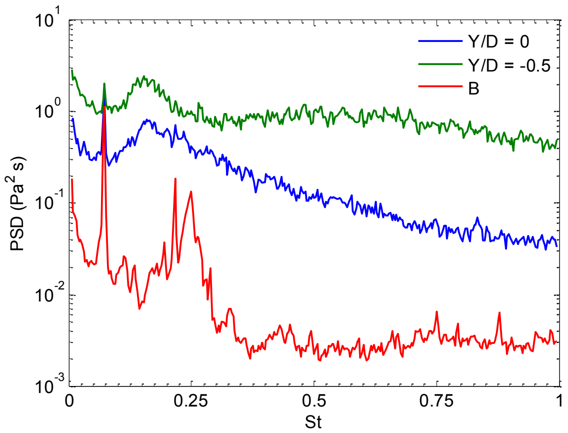

Figure 7. PSD plot of surface pressures at two positions on the ground plate for Re = 1.25×10^5. B denotes background spectrum.

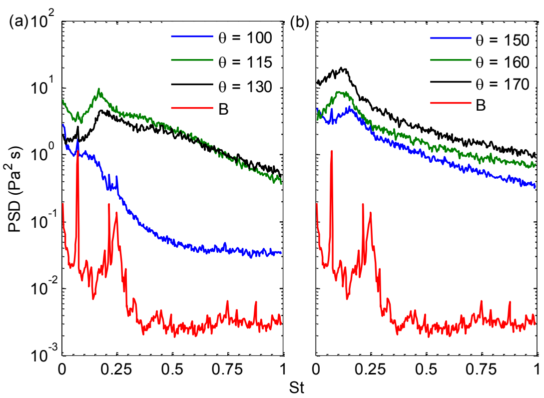

Figure 8. PSD plot of surface pressures for given azimuthal angle, θ, on the hemisphere at ϕ = 10°. Re = 1.25×10^5, B denotes background spectrum.

With the hemisphere installed, the PSD of the surface pressure on the ground plate at locations X/D = 1 and Y/D = -0.5 and 0 are shown in figure 7. A broad peak was recorded in both spectra near a Strouhal number of 0.15 and there was increased activity at all frequencies above the background level.

The PSD of surface pressure on the hemisphere at an elevation ϕ = 10° and azimuthal angles θ = 100°, 115° and 130° are shown in figure 8 (a), near the region of flow separation. These spectra again show no narrow peaks and increased activity at all frequencies above the background level. Two broad peaks occur for θ = 115° and 130° centred at Strouhal numbers of 0.17 and 0.18 respectively. In the separated region the pressure spectra, figure 8 (b), show a peak centred at Strouhal number of approximately 0.12 to 0.15 for θ = 150°, 160° and 170°.

Conclusions

The flow past a hemisphere protuberance in a thin flat plate boundary layer was investigated qualitatively using surface shear flow visualisation. This indicated that between Reynolds numbers of 6.36×10^4 and 1.55×10^5 the flow was in a transitional regime below the critical Reynolds number. Laminar separation took place at the lower Reynolds number while a laminar separation bubble occurred at the higher Reynolds number. The flow visualisation also indicated the necklace vortex was drawn upwards near the region of laminar flow separation.

Quantitative measurements of surface pressures indicated that the flow in this experiment was not symmetric. Broad low frequency spectral activity was recorded between Strouhal numbers of 0.12 to 0.18 over the hemisphere and in the near wake.

Acknowledgments

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