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Locating Cross-Flow Separation by Surface-Pressure Fluctuations: A Case Study on a Hemispherical Protuberance

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Abstract

Cross-flow separation plays a key role in the performance of many aerodynamic systems. This work is set out to use surface-mounted pressure transducers to ascertain the effectiveness of using surface-pressure fluctuations in locating cross-flow separation. The interpretation of the results will be compared to China-clay flow-visualisation data and previous measurements of surface-pressure fluctuations over the same body.

Analysed herein is a select region of fluctuating surface pressure ports on a hemisphere's longitudinal meridian in the vicinity of the separation. Tests were conducted at two different Reynolds numbers (Re_D, which describes the ratio between the inertial and viscous forces present within the fluid); $Re_D = 6.36 \times 10^4$ and 1.55×10^5 based on the diameter of the hemisphere D. The Strouhal number ($St = fD/u_\infty$) describes the oscillatory nature of pressure fluctuations, and is found using frequency (f), characteristic length (D), and free-stream wind speed (u_∞). Spectral power peaks at low Strouhal numbers (<1.0) at or near separation locations were detectable by Kulite sensors. Findings signified the presence of high-amplitude low-frequency pressure fluctuations near the flow separation location. The "China clay" visualisation technique demonstrated later separation with increased Reynolds number, which was corroborated by fluctuating pressure measurements as spectral activity concentration (vortex shedding location) shifted leeward in the same flow case. At the higher Reynolds numbers possible local flow reattachment post-separation was identified near Strouhal number 0.25.

Introduction

Cross-flow separation is a key topic in the study of fluid-structure interactions. Flow fields developed around streamlined and bluff bodies will have streamlines with three-dimensional characteristics. Cross-flow separation over a body produces longitudinal vortices due to the roll up of a separated boundary layer. These longitudinal vortices usually form complex flow field characteristics downstream of the separation location which in turn contribute to unsteadiness of flow over the surface. One of the main contributions to this unsteady behaviour is due to vortices which form from the free stream flow that interact with the shear layer separation over a body, termed hairpin vortices [1]. A bluff or streamlined body immersed in a turbulent boundary layer will result in three-dimensional streamlines and may be subjected to cross-flow separation as flow travels from the windward side to the leeward side. An example of induced cross-flows are hemispherical protuberances immersed in a turbulent boundary layer; these are a common feature on aircraft, other vehicles, and can help model large scale domes in the atmospheric boundary layer. The detection of the existence and location of separation is an important step towards characterising the flow and identifying regions of strong turbulence. With a hemispherical protuberance, the periodicity of hairpin vortex shedding due to cross-flow separation near the hemisphere apex produces distinct pressure field oscillations [11]. It is hoped that by measuring these surface-pressure fluctuations, the location of cross-flow separation on the hemisphere meridian can be determined.

Vorticity in the near-wake region is introduced as the shear layer rolls up [9]. Experiments with hot-wire and large-eddy simulation show that a boundary layer immersed hemisphere at $Re_D = 5 \times 10^4$ had a spectral activity peak associated with shear-layer instability near the separation line [12]. In the case of flow separation and reattachment in the presence of an adverse pressure gradient, observations have identified strong spectral activity at low frequencies for fluctuating pressures [5, 6]. The presence of oscillations in the separation region has been attributed to vortex shedding caused by the previously discussed shear layer instabilities. At $Re_D = 5.5 \times 10^2$ to 1.6×10^3 vortex shedding was observed near the hemisphere apex at Strouhal numbers of 0.45 to 0.87 [9]. It is also interesting to note that for a Reynolds number greater than 2×10^3 the Strouhal number for vortex shedding has been seen to decrease with increasing Reynolds number [10].

The present study aims to investigate feasibility of locating cross-flow separation on a hemispherical protuberance immersed in a turbulent boundary layer from pressure fluctuations. The technique is made possible because the separation-reattachment process results in velocity fluctuations near the surface: differential pressure sensors resolve these fluctuations allowing analysis of the boundary layer state [5].

Methodology

Experiments were undertaken in an open return, suction-type wind tunnel with the hemisphere mounted in an octagonal test section 622mm high, 800mm wide, and 1196mm long. A 22-kW motor driving a 24-blade fan, coupled with a 4:1 contraction section, permit a maximum test-section wind speed of 25 m/s. Longitudinal free-stream turbulence intensity of the tunnel has been documented as less than 0.3% [4]. A differential pressure transducer connected to two circumferential rings of pressure taps before and after contraction measure the static pressure differential to determine average dynamic pressure in the downstream test section. Test Reynolds numbers $Re_D = 6.36 \times 10^4$ and 1.55×10^5 were selected for similarity to previous published results. The oncoming boundary layer was characterised as turbulent with a normalised thickness respective to the hemisphere diameter δ/D ranging from 0.158 to 0.173.

Two hollow aluminium hemispheres with outer diameter 100mm were used. Both had an anodised wetted surface and were mounted directly to the test section ground plane. One model had a uniform surface and was used for flow visualisation. The second hemisphere contained 35 pressure ports along the longitudinal meridian in 5° increments ranging from $5^\circ \leq \theta \leq 175^\circ$, and an additional two ports located at $\theta = 1^\circ$ and $\theta = 179^\circ$. The hemisphere geometry coordinate system in relation to flow direction as well as a representation of the ports along the centreline is show in figure 1.

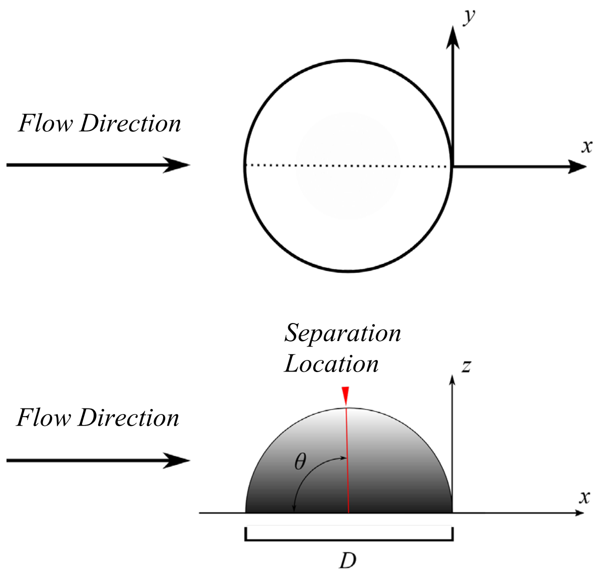

Figure 1. Hemisphere geometry, coordinate system, and stream-wise centreline.

Surface Flow Visualisation

The "China clay" technique was used on the hemisphere without surface pressure taps. Kaolin clay, oleic acid, and kerosene were mixed and applied to the surface of the hemisphere and ground plane. After being exposed to flow the mixture dried as the kerosene evaporated and the residual patterns photographed. These patterns are indicative of flow behaviour and structures near to the hemisphere surface. The purpose of the flow visualisation was to provide information on the location of where primary crossflow separation occurs over the hemisphere. Since the visualisation method is a time-averaged representation of flow over the hemisphere it does not provide any indication of flow unsteadiness.

Dynamic Pressure Measurement System

A Turbulent Flow Instrumentation 64-channel Dynamic Pressure Measurement System® (DPMS) measured pressure fluctuations along the longitudinal meridian. The DPMS is remotely located from the surface pressure tap, with tubing connecting the unit to each respective port on the hemisphere. Static pressures were measured at the hemisphere surface and sampled at a rate of 2.5 kHz for 60 seconds. Spectral plots were generated using Welch's power spectral density estimate with a discrete Fourier transform points and Hamming window size of 4096, and 2048 points of overlap between segments.

Kulite Differential Pressure Transducer

Two Kulite pressure transducers with respective sensitivities 2.6 mV/kPa and 2.9 mV/kPa with ±34.5 kPa range were used to measure pressure fluctuation frequency. Maximum uncertainty at full scale output for this type of sensor was considered too high for the RMS (root mean square) and mean pressure readings to be considered accurate. Data acquisition was undertaken simultaneously at two port locations ranging from $\theta = 60^{\circ}$ to $\theta = 135^{\circ}$ at a sample rate of 10 kHz for 60 seconds. Tests were repeated twice for each Reynolds number case at each port location. In comparison to the DPMS tubulation, pressure signal modulation was assumed as inconsequential for the frequencies of interest due to smaller tubing lengths (20mm) between the Kulite transducers and hemisphere ports [8]. As with the DPMS data, spectral plots were generated for the pressure coefficients using a discrete Fourier transform points and Hamming window size of 16384, and 8192 points of overlap between segments. The larger sizes were used to accommodate the higher sample rate of the Kulite sensors.

Results and Discussion

Spectral analysis was used to analyse the relationship between oscillatory flow frequency and elevation angle. As vortex shedding oscillations generally occur at a low Strouhal number, it was necessary to focus on the lower end of spectral data collected. As a means of identifying separation location, spectral analysis allows direct comparison of surface pressure fluctuation activity at each elevation angle. This also assists in the analysis of streamwise locations which allow separation characteristics such as reattachment to be observed. Frequency data were non-dimensionalised via the Strouhal number ($St = fD/u_{\infty}$). Spectral analysis of pressure field fluctuations over the longitudinal meridian focussed on a Strouhal number less than 1.0. High level spectral activity occurred predominantly at low frequencies, except for blade passing frequencies along with their harmonics surrounding $St \approx 1.7$ and $St \approx 3.5$. To evaluate background noise levels the hemisphere was removed from the wind tunnel test section, and analysis of background spectra was undertaken with sensors placed directly on the ground plane at all test Reynolds numbers. In the region of interest, background peaks were observed at Strouhal numbers of 0.05, 0.68 and 0.8 for $Re_D = 6.36 \times 10^4$, and Strouhal numbers of 0.2, and 0.88 for $Re_D = 1.55 \times 10^5$. Background peaks at Strouhal numbers 0.68 for $Re_D = 6.36 \times 10^4$ and 0.88 for $Re_D = 1.55 \times 10^5$ correspond to sub-harmonics of the blade passing frequencies. DPMS measurements of the same region ($60^{\circ} \leq \theta \leq 135^{\circ}$) are used for comparison. The DPMS data has been provided by DST (Defence Science & Technology) with a methodology similar to [7]. The power level has been recorded as a simple high-low scale for simplification of the trend comparison.

Analysis: Reynolds Number 6.36×10^4

Flow visualisation over the hemisphere at a Reynolds number of 6.36×10^4 shows a clear separation line at an elevation angle of approximately $\theta \approx 80^{\circ}$ with no evidence of flow reattachment on the hemisphere body. This is in alignment with the Kulite acquired spectral data later discussed at the same Reynolds number.

Figure 2. Flow visualisation of hemisphere using 'China clay' technique. Separation line is represented by the dashed line and elevation angle is overlayed. $Re_D = 6.36 \times 10^4$.

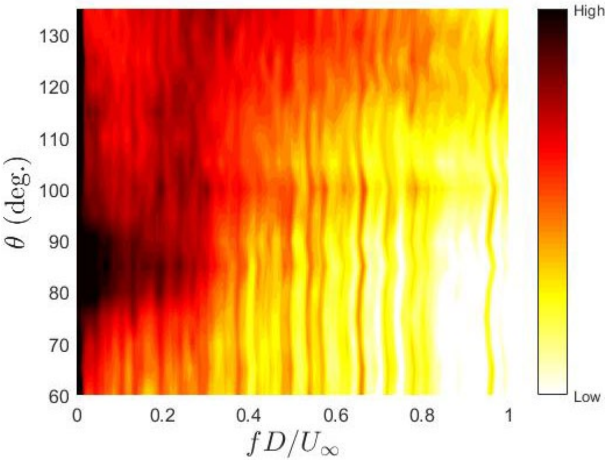

Figure 3. Kulite power spectra over hemisphere (60° < θ < 135°) for Re_D = 6.36 × 10^4

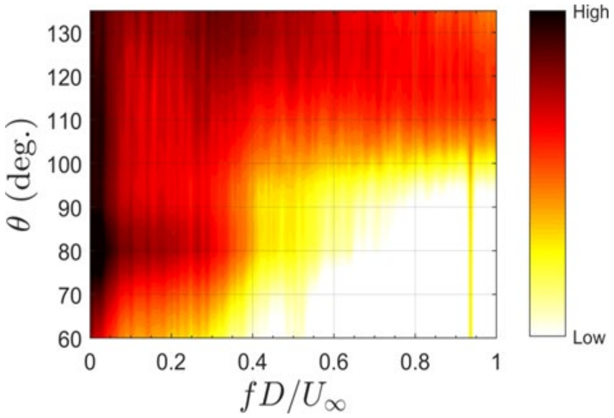

Figure 4. DPMS power spectra over hemisphere (60° < θ < 135°) for Re_D = 6.36 × 10^4.

Figures 3 and 4 show power spectra measured by the Kulite transducers and DPMS respectively along the centreline of the hemispheres at Re_D = 6.36 × 10^4. Across all Reynolds numbers, high-activity regions for $\theta > 70^\circ$ show distinct unsteady pressure fluctuations near the suspected boundary layer separation location over the hemisphere. At Reynolds number 6.36 × 10^4 spectral activity wideband peaks between Strouhal numbers 0.01 and 0.20 are observed across elevation angles $\theta = 80^\circ$ to $\theta = 90^\circ$ for both DPMS and Kulite spectra. The presence of low Strouhal number pressure fluctuation activity appears to correspond to the vortex shedding, attributed to flow separation near the apex of the hemisphere [6]. This is further supported by wideband activity and a 'flat' region of relatively high-power fluctuations across $90^\circ \leq \theta \leq 135^\circ$. This low Strouhal number activity of high intensity can be attributed to flow turbulence and recirculation downstream of the separation line as θ increases. A difference in the power regions for both pressure transducer types is observed as the Kulite spectra shows a high-power region near $\theta = 85^\circ$ and the DPMS spectra shows the corresponding region centred at $\theta = 80^\circ$.

Analysis: Reynolds number 1.55 × 10^5

Flow visualisation over the hemisphere at the increased Re_D = 1.55 × 10^5 demonstrates movement of the separation line downstream to $\theta \approx 95^\circ$. Farabee and Casarella [5] and Cherry et al. [3] measured fluctuating surface-pressure of separating and reattached boundary layers over a backward and forward-facing step; and airfoil geometry respectively. Both studies identified large-amplitude, low-frequency fluctuations associated with shear layer unsteadiness and vortex shedding. Broadband spectral activity seen in figure 6 between $\theta = 95^\circ$ and $\theta = 110^\circ$ shows two distinct regions with a dead zone near $\theta \approx 100^\circ$, which does not correspond to visible regions over the hemisphere. The 'flat' region of relatively high-power fluctuations at the higher Reynolds number across $90^\circ \leq \theta \leq 135^\circ$ in the spectral plots can be attributed to the recirculation of fluid on the leeward side of the hemisphere seen in both figures 2 and 5.

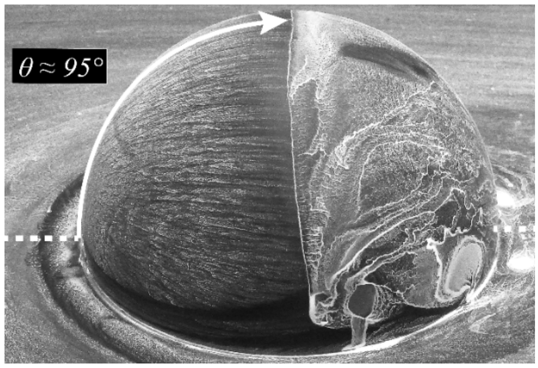

Figure 5. Flow visualisation of hemisphere using 'China clay' technique. Separation line is represented by the dashed line and elevation angle is overlayed. Re_D = 1.55 × 10^5.

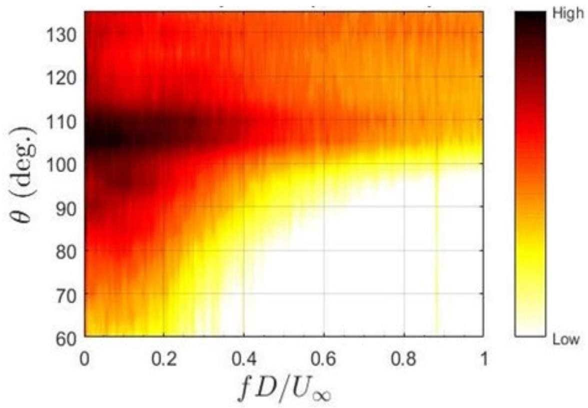

Figure 6. Kulite power spectra over hemisphere (60° < θ < 135°) for Re_D = 1.55 × 10^5

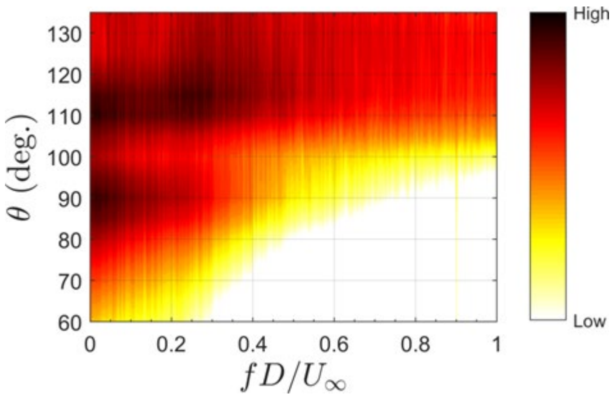

Figure 7. DPMS power spectra over hemisphere (60° < θ < 135°) for Re_D = 1.55 × 10^5.

In comparison with the DPMS spectra at Reynolds number 1.55 × 10^5, Kulite spectra show similar regions of power near $\theta = 105^\circ$, although there are also clear differences. The region of power near the suspected separation point is much more distinct in the DPMS spectra in comparison to the Kulite data. Surrounding $\theta = 90^{\circ}$ the DPMS spectra shows a clear region of high power at Strouhal numbers < 0.2. In comparison, the Kulite data does not show a similar active region of similar magnitude, especially relative to the second high-activity region at $110^{\circ} \leq \theta \leq 115^{\circ}$. Reasons for this discrepancy were not identified, therefore the DPMS spectra is used in comparison with the flow visualisation to identify possible separation.

For the higher Reynolds numbers there is a lower concentration of spectral power at elevation angles $\theta < 70^{\circ}$. With the DPMS spectra, the cross-flow separation location is deemed Reynolds number dependent due to low Strouhal number activity appearing at increasing elevation angle from $\theta \approx 80^{\circ}$ to $\theta \approx 90^{\circ}$ with increasing Reynolds numbers. At $Re_D = 1.55 \times 10^5$ there is a clear sign of low Strouhal number activity in the region $90^{\circ} \leq \theta \leq 115^{\circ}$. The approximate range of this activity is $0.01 \leq St \leq 0.32$. A sharp drop in spectral density at all frequencies immediately downstream of $\theta \approx 110^{\circ}$ potentially signifies local flow reattachment as there is minimal fluctuation in pressure. This region of flow reattachment is only present at higher Reynolds numbers, as the decrease in pressure fluctuation is not observed at $Re_D = 6.36 \times 10^4$. Wood et al. [12] identified a peak at Strouhal number 0.27 which appeared to correspond to shedding of hairpin vortices triggered by shear layer instability at the separation line. A similar peak at Strouhal number ≈ 0.25 is observed at a Reynolds number of 1.55×10^5 at location $\theta = 115^{\circ}$, the suspected reattachment location. The background noise peak at $St = 0.88$ is again present, although again falls outside the region of interest.

Conclusion

Unsteady pressure fluctuation measurements of a boundary layer immersed hemispherical protuberance are investigated as a method of experimentally identifying cross-flow separation and its location. Differential surface-mounted pressure transducers recorded fluctuating pressure data near the separation location over a hemisphere. Spectral analysis of the frequency data quantifies oscillatory behaviour due to vortex shedding and cross-flow separation. The spectral data and results are then compared to flow visualisation and DPMS fluctuating pressure measurements.

Results showed good spectral similarity with both DPMS experimental data and surface shear flow visualisation at Reynolds numbers at 6.36×10^4. Low Strouhal number spectral activity near separation locations showed vortex shedding is the dominant contributor to surface pressure fluctuations near suspected separation locations. Regions of power post-separation at Reynolds number 6.36×10^4 suggest high turbulence and an absence of reattached flow. Although there were some differences in spectral activity locations between DPMS and Kulite spectra for $Re_D = 1.55 \times 10^5$, the differences appeared adequately minor and qualitative assessment of the separation location was still attempted. A strong peak in Strouhal number followed by a rapid drop in spectral density post-separation at Reynolds number 1.55×10^5 is theorised to correlate to local flow reattachment in the DPMS spectra.

DPMS and Kulite measurements showed levels of agreement that allow potential identification of the separation location over the hemispherical protuberance in the current study through spectral analysis. The agreement was further supported by qualitative comparison with flow visualisation techniques. These findings warrant further investigation into a standardised measurement method for use in spectral analysis for cross-flow separation location detection. Further experimental investigation into this method under varying Reynolds number and for varying boundary layer properties would be necessary to determine its effectiveness as a high-fidelity diagnostic technique

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