

# Under the Reattaching Shear Layer

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## ABSTRACT

The occurrence of high negative peak pressures on the streamwise surfaces of bluff bodies under a reattaching shear layer in turbulent flow is discussed in relation to the causal mechanisms. An hypothesis by Melbourne (1975), as to the cause of these pressures, is revisited to see how it is working out in the light of new knowledge and what modifications and additions might be appropriate. In particular, it is concluded that whilst the process and pressures are very dependent on the magnitude of the freestream turbulence and scale, it is the generation, stretching and convection of vortices under the reattached shear layer which constitute a vital link in the chain of events leading to the occurrence of the high negative peak pressures.

## INTRODUCTION

Through earlier studies, in particular Melbourne (1975) and (1979) and in this conference series Melbourne (1980), the effects of turbulent flow on bluff body aerodynamics as they pertain to wind engineering applications have been pursued. One of the dominant features of these flows is the process of shear layer reattachment on the streamwise surfaces, because the behaviour in this region gives rise to the highest local pressures and often the critical response condition. The process of shear layer reattachment is known to be very dependent on the incident turbulence, although not too much is known about the relative contributions of scale and intensity. Melbourne's hypothesis (1975) on the effect of turbulence on the highest negative surface pressures referred to an instability process in the intermittent generation of high negative pressures, but did not recognise a significant three-dimensional effect in the process which later became apparent. It is the object of this paper to summarise what knowledge we have about the three-dimensional effects and what is happening under the shear layer and in so doing add a little to the hypothesis.

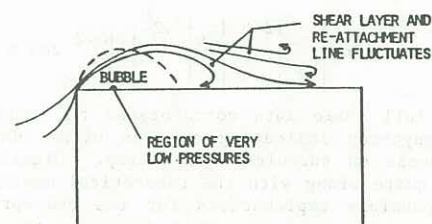
## THE HYPOTHESIS TO 1980

Throughout the seventies there had been increasing evidence of the occurrence of very high negative pressures on streamwise surfaces near a leading edge from which a shear layer is separating. This phenomenon had led to failure of flat roofs on low rise structures and window panels on tall buildings. In both cases, full scale and model measurements confirmed the existence of very high negative pressures occurring in the region near the leading edge under the separating shear layer. Melbourne (1975) advanced an hypothesis suggesting that the high negative pressures, which are often of an intermittent nature, could be due to an instability under certain conditions as follows:

"The shear layers and pressure underneath fluctuate. For certain conditions of freestream turbulence, angle of attack, (and radius of leading edge curvature) the shear layer commences to occasionally reattach onto the wall. As this occurs the cavity region under the shear layer is no longer vented and any decrease in pressure causes the initial radius of curvature of the shear layer to decrease further which in turn increases the local freestream velocity

outside the shear layer and further decreases pressure. This is an unstable process which proceeds until the shear layer breaks up into a complete separation again and the cavity becomes vented. During this unstable process, very low, intermittent pressures can occur on the surface under the shear layer near the leading edge."

The development of this hypothesis, shown diagrammatically in Figure 1, was influenced by the earlier work of Gartshore (1973), which led to the observation that if the freestream turbulence is increased, the increased rate of entrainment into the shear layer would cause earlier reattachment; the smaller radius of curvature of the shear layer further increases local freestream velocity outside the shear layer which decreases the pressure on the surface under the shear layer separation bubble. The combined effects of high freestream turbulence and the instability process hypothesised are suggested as being the major causes of the very high negative pressures being experienced under shear layers which are reattaching and which have led to roof and window glass failures.



1. SHEAR LAYER RE-ATTACHMENT EFFECTIVELY SEALS OFF BUBBLE FROM DIRECT VENTING TO FREESTREAM.
2. FREESTREAM FLOW OVER THE FRONT OF THE SHEAR LAYER ACCELERATES, THE INCREASED VELOCITY IS ACCOMPANIED BY A DECREASE IN PRESSURE.
3. THE COMBINED EFFECTS OF ENTRAINMENT INTO THE SHEAR LAYER FROM INSIDE THE BUBBLE AND THE DECREASE OF PRESSURE AT THE BOUNDARY CAUSES THE SHEAR LAYER TO MOVE TO REDUCE BUBBLE VOLUME AND INTERNAL PRESSURE (DOTTED LINE).
4. THIS PROCESS CONTINUES IN AN UNSTABLE WAY TO REDUCE SURFACE PRESSURES UNDER THE BUBBLE UNTIL IT IS VENTED BY BURSTING OR BY ARTIFICIAL MEANS.

Fig. 1 Diagrammatic representation of the 1975 hypothesis on the cause of high negative pressures near the leading edge under a separating and reattaching shear layer.

A step towards validating Melbourne's hypothesis was made by Sharp (1980), who showed that the peak negative pressures under a reattaching shear layer occur near the leading edge, when the oscillating reattachment line of the shear layer is closest to the leading edge from which the separating shear layer originated. Sharp further investigated the effect of venting on the instability process by showing that the peak negative pressures could be substantially reduced (in magnitude) if the bubble under the reattaching shear layer was vented. Melbourne (1979a) also showed that venting of the leading edge regions, with devices such as a slotted eave, substantially reduced the magnitude of the maximum negative pressures in this region.



This type of venting has practical applications in respect of reducing loads on low pitched roofs of buildings, and on cantilevered grandstand roofs; two examples of the latter have been built.

#### EVIDENCE OF THREE-DIMENSIONAL EFFECTS

The earlier flow visualisation of the reattachment phenomenon was restricted to a two-dimensional streamwise slice through the flow. Hence, whilst it was possible to see the changing reattachment position and its relationship with pressure under the shear layer, it was not possible to see what was happening across the flow, that is parallel to and just behind the leading edge from which the shear layer was originating. However, there was evidence back in 1973 of some increased lateral coherence from such incidents as the sequence of glass failure on the Boston Hancock Building and the model measurements of the response of the cable-stayed West Gate Bridge, (Melbourne, 1979b).

Both the model and full scale measurements of the response of the West Gate Bridge have been extended to include a look at the correlation of pressures along the leading edge. However, first we must look at the evidence which lead to this later work (Melbourne 1982). From the model tests in turbulent flow in two levels of turbulence intensity and theoretical estimates by Holmes (1975) it was concluded that most of the cross-wind excitation for this slender deck could be attributed to incident turbulence with some lesser contribution from broad band wake excitation. However, one aspect which did not tally with the theoretical estimates was the effect of turbulence on the deck response for which the theory predicts linear dependence of response with turbulence intensity. The full bridge model data was fitted by the following equation showing the functional dependence of the vertical response, at centre deck,  $z$ , normalised by deck width,  $c$ , on reduced velocity, turbulence intensity, damping and wind angle to the deck normal.

$$\frac{z}{c} = 0.0176 \left| \frac{-u}{n_o c} \right|^{2.5} \left| \frac{\sigma}{u} \right|^{2.2} \left| \frac{1}{\zeta} \right|^{0.2} \cos \beta \quad (1)$$

The full scale data corroborated the model evidence, if anything indicating an even higher dependence of response on turbulence intensity. Clearly something was quite wrong with the theoretical model. A number of possible explanations for the underprediction of response in more turbulent flows by the theoretical model were followed up by the author. The explanation appears to relate to the quasi-steady assumption that the lateral correlation of the fluctuating lift forces is directly related to the lateral correlation of the incident flow longitudinal or vertical components. Knowledge of the mechanism by which negative pressures are created under reattaching shear layers leads to the conclusion that the lateral correlation of these pressures, along the leading edge, might not be directly related to the lateral correlation of the incident turbulence as assumed by the theory. Measurements at both model and full scale of the lateral coherence of deck pressures and longitudinal velocity components confirmed that there was a significant difference between the velocity and pressure correlation as shown in Figure 2, with the pressures showing much higher correlation.

Other evidence we have of strong three-dimensional effects comes from some qualitative observations of the response of aeroelastic models of large cantilevered roofs. Several of these model have been built and tested, one in particular to further explore the load reduction resulting from slotting the leading edge to vent the bubble under the reattachment. This is a different story, but sufficient to say that two full scale grandstand cantilevered roofs have now been built incorporating the slotted leading edge. Watching the way in which these cantilevered roofs respond in turbulent flow, it is apparent that when a major disturbance (i.e. upward displacement) occurs at some point, this disturbance is then seen to travel like a low frequency ripple, or wave, along the leading edge. These roofs tend to have very weak leading edge beam connections, such that the structural influence of

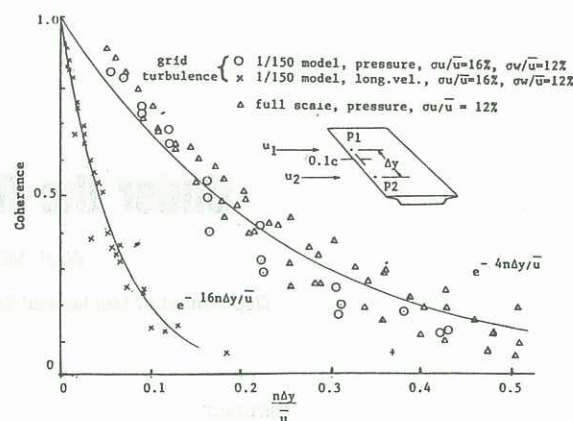


Fig. 2 Lateral coherence of deck pressures and longitudinal velocity component in model and full scale.

adjacent bays (each containing a major cantilever beam element) is small, typically 25% and 5% for one and two bays away. Hence, the travelling wave observed along the leading edge has to be related to an aerodynamic load. This, in turn, would seem to be related initially to a relatively local event which spreads laterally along the leading edge.

A more recent observation on the three-dimensionality of the process occurred during pressure measurements by one of the authors, on a model of a tall building to which horizontal window sun shades were fitted. The maximum negative pressures under the reattaching shear layer went from  $C_p = -4.8$  to  $C_p = -3.5$  with the addition of the horizontal sun shades. It was thought that the horizontal flat plates acted somewhat like the boundary layer fence on an aircraft wing in that they acted to inhibit lateral flow under the reattaching shear layer.

There has also been a considerable amount of research since the early 1980s on separation bubbles generated on the sides of blunt plates by Hillier and Cherry (1981), Cherry & Hillier (1984), Cherry, Hillier and Latour (1983), (1984), Kiya and Sasaki (1983), (1985), and with acoustic interaction by Welsh and Gibson (1979 and later). Whilst much of this work has been in smooth flow and all of it on plates with long afterbodies, where the flow is always eventually reattached, there are many similarities with the intermittent reattachment on short afterbody sections in very turbulent flow. In particular, the observations of these researchers with respect to the flapping of the shear layer and the presence of vortices are very relevant. Cherry et al (1984) noted that there is "a weak tendency for out-of-phase shear layer flapping motions to develop over spanwise separations of  $0.6 X_R$ , and this probably indicates that some unsteady lateral venting of the fluid within the cavity region (bubble) is part of the low frequency process, "where  $X_R$  is the mean reattachment length from the leading edge. Cherry and Kiya both comment about the convection of vortices downstream being the major source of the pressure fluctuations, which may be more relevant to the long afterbody geometry and low turbulence. However, Kiya and Sasaki noted that "a pair of counter-rotating streamwise (or longitudinal) vortices probably exist in the reattaching zone. The spanwise distance between the streamwise vortices is approximately  $0.6 X_R$ . A flow visualisation study suggests that they are ends of a hairpin vortex."

All these model and full scale observations lead one to think that the occurrence of the high negative peak pressures is more related to the vortex behaviour under the reattached shear layer. The way in which vortices are generated, stretched and convected downstream are all relevant to the process and contribute variously to the generation of the high negative peak pressures. The existence of horseshoe vortices is consistent with the continuity of the process, inasmuch as earlier observations of the way in which the bubble tightened up (i.e. reattachment moved



towards the leading edge) indicated that fluid in the bubble had to move laterally as there seemed no evidence of significant flow across the reattached shear layer. There seems little doubt now that a lateral flow and accompanying vortex stretching process is occurring in the bubble along the leading edge and that this occurs concurrently with the tightening up of the bubble under the reattached shear layer. There is also the evidence that the pressure fluctuations are related to the convection of the vortices downstream, seemingly quite separate to any stretching processes. It is not yet obvious where or when in the complex process of vortex generation, stretching or convection that the high negative peak pressures occur, nor is it obvious why the increase of free-stream turbulence and scale should cause an increase in the magnitude of the negative peak pressures which occur. The problem now is to explore these phenomena in more detail and the remainder of this paper will describe moves in this direction. Before leaving this section, the authors wish to acknowledge helpful discussions on the subject with Dr. R. Britter in 1984.

#### LOOKING FOR THE THREE-DIMENSIONAL EFFECTS

The first experiments related to the three-dimensional effects measured the correlation of spanwise pressures, such as shown in Figure 2. Whilst these provided some confirmation of what was thought to be happening, it became apparent that conditional sampling techniques would have to be employed. This is because the averaging process obfuscates the impact of the extreme event, which may be highly intermittent, and which is the event of interest in that it leads to the occurrence of the high negative pressures. Not only is it necessary to conditionally sample the more extreme events, it is also necessary to employ flow visualisation techniques both streamwise and spanwise to capture these events with sufficient resolution. This work is currently proceeding with the use of a 5 W laser and high speed photography coupled with pressure and velocity measurements. It is proposed, in the short space remaining, to present examples of the conditionally sampled data.

#### Experimental Setup

Fluctuating pressures were measured on the streamwise surface of a blunt flat plate mounted in the 30 kW wind tunnel at Monash University, with working section

1.22 x 0.92 m. The model (fitted with end plates) had dimensions of 50mm x 1m x 1m giving side and frontal aspect ratios of 20. The blockage ratio was 5.4%; measurements are uncorrected for blockage.

Two turbulence grids with bar widths (b) of 37mm and 70mm were used to provide a range of turbulence intensities and scales. Measurements described below were obtained in two flows with the same turbulence intensity ( $\sigma_u/\bar{u} \approx 8.0\%$ ) but different scales. Longitudinal integral scales ( $L_x$ ) were 0.13 m and 0.07 m for the large and small grids, respectively. Tunnel wind speed was approximately  $11 \text{ ms}^{-1}$  ( $Re \approx 3.5 \times 10^4$ ).

Honeywell 163 PC 1.0 psi pressure transducers were connected to pressure tappings with short lengths of plastic tubing. Restrictors in the tubing provided a flat frequency response ( $\pm 10\%$ ) up to 300 Hz. Data were sampled at 1000 Hz using a Data 6000 waveform analyzer.

#### Cross Correlation Results

Fluctuating pressures were measured at a distance  $x = 0.6D$  from the leading edge, where  $D$  is the frontal depth of the plate across the stream direction. This location was chosen because it is in the region of highest peak suction. Turbulence scale had a negligible effect on the mean reattachment length ( $X_R$ ), as noted previously by Hillier and Cherry (1981). For these experiments  $X_R \approx 2.5D$ , so the pressure measurements were obtained at  $x \approx 0.24 X_R$ .

Figure 3 shows typical pressure signals obtained simultaneously in the large scale flow. The lateral displacement of each transducer is  $0.8D$  giving a total displacement of  $2.4D$  for the four transducers. (Note: a negative pressure peak is indicated by an excursion in the positive direction.) High correlation is evident corresponding to the passage of large scale vortices. The large suction peak occurring at  $T = 0.32$  seconds is certainly well correlated over the length  $2.4D$ , and can probably be assumed to have been produced by a large vortex with a spanwise extent of  $4.0D - 5.0D$  or approximately twice the length of the separation bubble.

To determine how well these extreme events are correlated laterally, a conditionally sampled correlation coefficient ( $R'_{pp}$ ) was determined. A transducer mounted

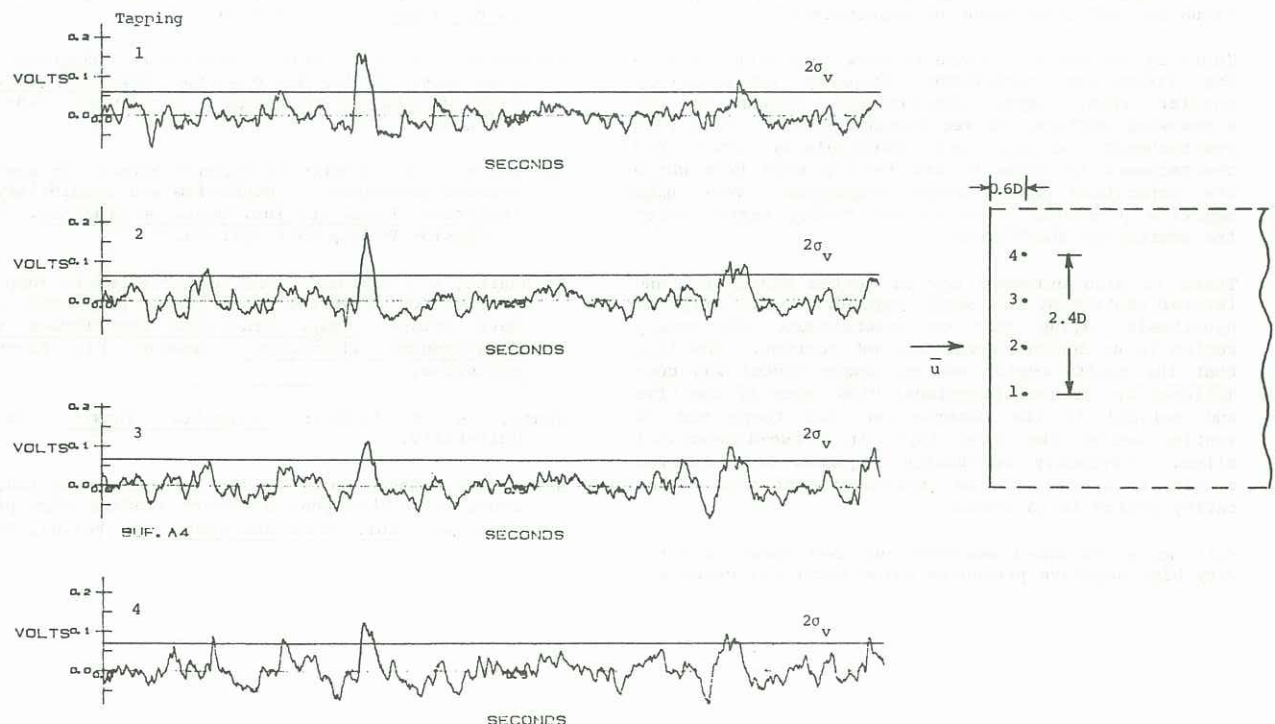


Fig. 3: Simultaneous pressure records for 4 laterally-spaced transducers in a relatively large scale turbulent flow ( $\sigma_u/\bar{u} \approx 8.2\%$ ,  $L_x/D = 2.6$ )



on the model centre line provided the conditioning signal. Whenever a negative peak  $2\sigma_v$  from the mean was measured at that location the corresponding signal at a displaced tapping was obtained. One hundred of these peaks were used to determine  $R'_{pp}$  for each lateral displacement.

Values of  $R'_{pp}$  and the average correlation coefficient  $R_{pp}$  are shown in Figure 4 for the two turbulent flows. A significant increase in correlation length is indicated by the use of conditional sampling. For the large-scale flow the integral correlation length ( $L = \int_0^\infty R_{pp} dr$ ) increases from 1.6D to approximately 2.1D when conditional sampling is used. An increase in  $L$  from 1.3D to 1.6D was obtained by conditional sampling in the small-scale flow.

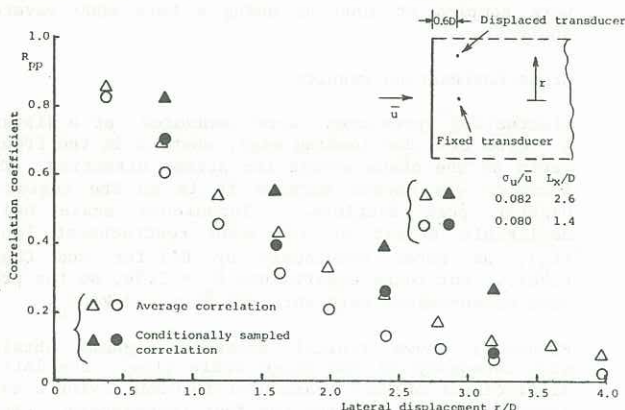


Fig. 4: Average and conditionally sampled cross correlation coefficients as a function of lateral displacement. [Conditional sampling based on 100 negative peak pressures  $> 2\sigma_v$  measured by a fixed transducer on the model centreline at  $x = 0.6D$ .]

#### CONCLUSIONS

With the knowledge gained over the decade since Melbourne's hypothesis was made, it seems reasonable to inspect how it is working out and what modifications and additions might be appropriate.

There is now ample evidence to show that with increasing freestream turbulence intensity progressively earlier shear layer reattachment occurs on the streamwise surfaces of rectangular prisms. When this reattachment occurs, and particularly when the reattachment is close to the leading edge from which the separating shear layer originated, very high negative pressures occur in the cavity region under the reattached shear layer.

There is also evidence now of vortex stretching and lateral venting of the cavity region. So the original hypothesis saying that on reattachment the cavity region is no longer vented was not correct. The idea that the cavity region was no longer vented was conditioned by the two-dimensional view taken at the time and related to the observation that there was no venting across the shear layer in a two-dimensional slice. Obviously continuity requires that lateral venting must occur if the cross-sectional area of the cavity region is to reduce.

Full scale and model observations have shown that the very high negative pressures which occur (i) under a

reattached shear layer have a higher lateral correlation than the longitudinal components of the incident turbulent flow (adding further to the significance of the three-dimensionality of the process), and (ii) that the magnitude of these negative pressures can be reduced by increasing the venting of the cavity region through the solid boundary and by interfering with the lateral flow along the cavity region.

Finally, it is necessary to add that the occurrence of the high negative peak pressures is very local, even within the bubble, and is likely to be more directly related to the generation, stretching and convection of vortices under the reattached shear layer than to the curvature of the shear layer and change in velocity outside the shear layer. However, whilst the vortex behaviour under the shear layer constitutes a vital link in the generation of the high negative peak pressures, it must still be noted that these pressures and the process are very dependent on the magnitude and scale of the freestream turbulence.

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