Sidewall gap effects on oblique shock wave-boundary layer interactions

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I. Introduction

Constructing an experimental arrangement which can be considered two dimensional is common practice in fluid mechanics research, indeed it is often the aim, such that the assumption of two dimensionality in the resulting flow can be made, especially on the wind tunnel center-line. This is particularly true in many experimental investigations of shock wave-boundary layer interactions (SWBLI) [1,2].

SWBLIs are complex and important to the design of practical applications, for example air breathing supersonic aircraft. However, little research has been conducted on the extent to which a two dimensional experimental arrangement can be expected to generate two dimensional flow. Underscoring this are recent studies which suggest that nominally two dimensional experimental arrangements can result in flows featuring significant three-dimensional properties [3–5].

These studies and others point to the inclusion of sidewalls (unavoidable in internal supersonic flows and thus most experimental research), and their joining of side and floor boundary layers in the corners, as a possible source of three-dimensional flow components. Babinsky et al. [4] showed experimentally that corner flows which develop upstream of strong SWBLIs generate significant span-wise flow in the separation region.

While the effect of corner flows on SWBLIs are significant, previous work has shown that simple experimental geometry such as expansion fan placement relative to the SWBLI can have a large effect on the resulting flow [6]. These findings highlight the importance of understanding all the effects the experimental arrangement may have on the resulting flow. For example, a sharp wedge used to generate an oblique shock which is full span in a stream-normal direction will interact with the sidewall boundary layers. Researchers in general are well aware of this fact as it is inherent in the canonical swept SWBLI case. However, variations in the extent of sidewall interaction exist. For practical reasons of test article movement, some SWBLI studies have employed a small gap between the test article and sidewall [4,6–8], while others (including most numerical investigations due to meshing constraints) perform experiments with full span test articles [5,9–12].

Yet, the effect of a variation in sidewall gap on the resulting SWBLIs is largely unknown. The study presented here attempts to provide some understanding of the effect of sidewall gap by constructing three identical experimental arrangements, each featuring a different sidewall gap.

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II. Experimental Setup

Experiments have been conducted in the Imperial College London supersonic wind tunnel facility. The facility is a blowdown Mach 2 tunnel which exhausts to atmosphere. The test section measures 150 mm wide × 150 mm tall × 727 mm long and the unit Reynolds number is approximately $2 \times 10^7 \, \text{m}^{-1}$. More information can be found in [6].

A schematic diagram of the experimental arrangement appears in Fig. 1. An oblique shock generator is suspended from the ceiling of the wind tunnel test section by a sting with sharp leading and trailing edges (section A-A in Fig. 1).

Three different shock generators were manufactured, all with the same form as illustrated in Fig. 1, 15 mm thick × 337.7 mm long with a sharp 12° upstream facing wedge. The only difference between the three shock generators is the span-wise width which is 150, 144 and 130 mm, corresponding to sidewall gaps of 0, 3 and 10 mm.

The sting height and shock generator thickness were chosen based upon wind tunnel start-up constraints. During wind tunnel operation, an oblique shock originates from the tip of the shock generator impinging upon the wind tunnel floor where a boundary layer is present ($Re_\theta = 10100$, $\delta = 5.3 \, \text{mm}$, $\delta^* = 1.20 \, \text{mm}$, $\delta_\theta = 0.41 \, \text{mm}$). Obtained on centerline with LDV at $x = -42.8 \, \text{mm}$, no test article present.), resulting in a SWBLI. An expansion fan also originates from the corner on the underside of the shock generator, as illustrated in Fig. 1.

The flow resulting from three different shock generators was interrogated using Schlieren photography, high spatial resolution static pressure ports and surface oil flow visualization. The high spatial resolution static pressure measurements were made through a staggered array of 200 static pressure ports in the floor of the wind tunnel with a stream-wise resolution of $\Delta x = 1 \, \text{mm}$. Surface oil flow visualization was achieved by injecting a high contrast oil mixture over the wind tunnel floor upstream of the SWBLI and photographing it through a sidewall window (de-warped for camera perspective). All images presented in this study were obtained during the experiment to avoid any wind
tunnel shut down transient effects.

III. Results

![Schlieren photographs and topologies derived from surface oil flow visualization showing the effect of sidewall gap on the incident-reflected SWBLIs.](image)

Fig. 2 Schlieren photographs and topologies derived from surface oil flow visualization showing the effect of sidewall gap on the incident-reflected SWBLIs. \((M = 2, \theta = 12^\circ)\). Incident/reflected shock intersection and point of separation highlighted with white dashed lines and dots, respectively.

Schlieren photographs of each of the three gap cases are shown in Fig. 2. The photographs show that, as the sidewall gap \((g)\) is increased from \(0 \rightarrow 3 \rightarrow 10\) mm, the shock structure does not change significantly, however, the size of the SWBLI does reduce as indicated by the height of the incident/reflected shock intersection (denoted by a white dashed line). The reduction in SWBLI size is accompanied by downstream translation of the separation shock foot (denoted by a white dot).

A similar trend was seen with the upstream movement of the expansion fan by Grossman and Bruce [6] which is a two dimensional effect. However, as all three cases in the present study are identical in two dimensions and the expansion fan position unchanged, the observed reduction in SWBLI size is attributed to three-dimensional effects.

In the \(g = 0\) mm case, the incident oblique shock wave is seen to thicken as it propagates downward. This effect has been observed previously by Babinsky and Harvey [13] and is attributed to the swept SWBLIs between the incident oblique shock and the sidewall boundary layers. It is notable that as the sidewall gap is increased to \(g = 3\) mm and then \(g = 10\) mm the apparent thickening is reduced, suggesting a reduction in the out-of-plane swept SWBLI on the sidewall.

The separated region topologies in Fig. 2 are consistent with the Schlieren photographs. As the sidewall gap is increased, the separation length decreases, consistent with a smaller SWBLI. Increasing \(g\) from \(0 \rightarrow 3 \rightarrow 10\) mm causes
the separation width to grow from $113 \to 120 \to 121$ mm and the separation length to reduce from $44 \to 39 \to 30$ mm, respectively. This inverse relationship between separation length and width was also identified in the study of Grossman and Bruce [6], but was attributed to variations in the expansion fan position.

All three topologies feature the same number of critical points: 2 focus, 3 saddle and 1 dispersion node, where dispersion node is defined as a node with streamlines dispersing away from the node (denoted F, S and D, respectively in Fig. 2). As $g$ is increased, there is very little change in overall arrangement of the critical points or the general shape of the separated region. However, in the $g = 10$ mm case one of the saddle points shifts away from centerline and the separation and reattachment lines begin to neck down, suggesting that a further increase in sidewall gap may lead to a “pinching-off” and transition to multiple separation cells and a distinctly three-dimensional structure.

The $g = 10$ mm case exhibits less curvature in the reattachment line, resulting in a more planar reattachment shock. This is consistent with the Schlieren photograph Fig. 2c which features a more defined reattachment shock relative to Fig. 2a and Fig. 2b.

The normalized static pressure distributions for each case are presented in Fig. 3. The inviscid incident shock impingement point, separation and reattachment points, and expansion fan impingement point are annotated for each profile.

**Fig. 3** Average normalized static pressure distributions with varying sidewall gap

The largest profile corresponds to the $g = 0$ mm case. In this profile the reattachment point is very close to the inviscid incident shock impingement line. When the sidewall gap is opened from $0 \to 3 \to 10$ mm, the profile shrinks with the separation and reattachment points moving closer together as well as collectively translating downstream. In all three cases, the pressure rise to separation remains nearly the same, however the pressure rise to reattachment progressively decreases with the increase in sidewall gap.
Separation length has been defined in this study by the distance between the separation line, which is largely straight, to the farthest downstream extent of the reattachment line, which typically exhibits a degree of curvature. The largest amount of curvature in the reattachment line is seen to occur in the $g = 0$ mm case, whilst the least amount of reattachment line curvature occurs in the $g = 10$ mm case, suggesting that this configuration might arguably be the most two dimensional of all three SWBLIs. This is supported by the apparent thickening of the incident oblique shock as it propagates downward (i.e. the three-dimensionality of the incident-reflected SWBLI), which is smallest for the $g = 10$ mm case.

However, increasing $g$ from 3 to 10 mm also produced a large movement of the critical points within the topology along the reattachment line, a shift not seen when $g$ is increased from 0 to 3mm. Furthermore, the separation and reattachment lines in the $g = 10$ mm case began to “neck down”, suggesting that a further increase in sidewall gap may cause transition to multiple separation cells. This suggests that the most “two dimensional” configuration may lie between the $g = 3$ mm and $g = 10$ mm cases.

This trend is illustrated in Fig. 4 where the points $A \rightarrow C$ loosely represent these test cases considered here. $A$ corresponds to a ratio of sidewall gap to boundary layer thickness $g/\delta = 0$, $B$ corresponds to $g/\delta \approx 1$, and $C$ corresponds to $g/\delta > 2$. Case $A$ is inherently three-dimensional with a SWBLI that is influenced by strong well-developed swept SWBLIs on the sidewalls. As sidewall gap is opened up in Case $B$, the sidewall boundary layers are able to pass by the test article yielding a reduction in the swept interaction and with it a reduction in the three-dimensionality of the main SWBLI. When $g$ becomes too large, Point $C$, the incident oblique shock is no longer planar and the SWBLI takes on an increasingly three-dimensional structure with the transition to separation cells. Further increase of $g$ will cause the SWBLI to become even more three-dimensional and eventually surpass the level of spanwise variation seen in the original Case $A$.

![Fig. 4 Evolution of separation bubble with sidewall gap](image_url)
IV. Conclusion

The effect of sidewall gap ($g$) on a SWBLI has been explored experimentally with three identical shock generators with sidewall gaps of $g = 0$, 3 and 10 mm. It was found that an increase in $g$ was accompanied by several changes to the SWBLI characteristics: (1) a decrease in SWBLI incident/reflected shock intersection height, (2) a decrease in the size and strength of the swept SWBLI on the sidewall, (3) a decrease in separation length, (4) an increase in separation width, (5) a translation downstream of the separation and reattachment points, and (6) a decrease in the static pressure rise to reattachment while the pressure rise to separation remained unchanged.

A conceptual model for the influence of sidewall gap on SWBLI behavior which explains the observed trends is proposed. We postulate that the most two dimensional SWBLI is obtained when sidewall gaps on order of $g/\delta \approx 1$ are used, corresponding to a minimum strength swept SWBLI at the sidewalls, but that sidewall gaps which are too large lead to a break down in the planar incident oblique shock.

Acknowledgments

The first author gratefully acknowledges the support of the Imperial College President’s PhD Scholarship Scheme, supported by the EPSRC, for funding this research.

References


