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Review of Micro Vortex Generators in High-Speed Flow

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A review of the state-of-the-knowledge of micro vortex generators (MVGs) and their effect on separated shock/boundary-layer interactions is provided. MVGs are thought to be effective for reducing the separation zone. However, details of how they affect the separation zone remain to be understood properly. In addition, metrics on how the MVGs affect the separation have not been well developed. Suggestions for further study are provided.

I. Introduction

THE desire to control the boundary layer such as to reduce or remove separation zones, drag reduction and to improve flow quality is as old as the boundary layer concept itself. Practical requirements of flow control techniques, for example, robustness, ease of implementation, light weight and simplicity, tend to favor passive devices such as vortex generators, vanes, fences and the less developed large-eddy breakup units or riblets, instead of active ones although active devices have their attractions.[1–6] Generally, for aircraft applications, the incoming boundary layer is also turbulent.

A boundary-layer flow control technique that has seen much recent interest is to distribute an array of micro vortex generators (MVGs), also known as "low-profile" or "sub-boundary layer" vortex generators, whose height is less than the boundary layer thickness, ahead of a region with adverse flow conditions. MVGs are also suggested as being able to improve the "health" of the boundary layer. As shown in Fig. 1,[7] there is more than one kind of MVG. For flow control, such miniature, passive devices have obvious advantages of low profile drag, lack of intrusiveness and robustness. These devices, being passive, have no need for actuation systems with their related complications. Initial studies of MVGs for flow control were conducted at low speeds.[7] These devices have also been proposed for practical configurations.[8–14] MVGs are thought to operate in the same manner as conventional vortex generators in energizing the boundary layer fluid through entrainment of the freestream by trailing vortices.

Lately, MVGs have been proposed as being able to alleviate or overcome the adverse effects of separated shock/boundary layer interactions (SBLIs) over transonic wings and supersonic inlets. As is well-known, SBLIs can significantly reduce the quality of the flow field by inducing large-scale separation, causing total pressure loss, flow distortions, localized peak heating and pressures, and unsteadiness, the consequences being to degrade the performance of the wing or engine.[1,15] These high-speed studies generally were conducted with an impinging shock.[16–34] Numerical simulations have been made on MVGs for comparative studies

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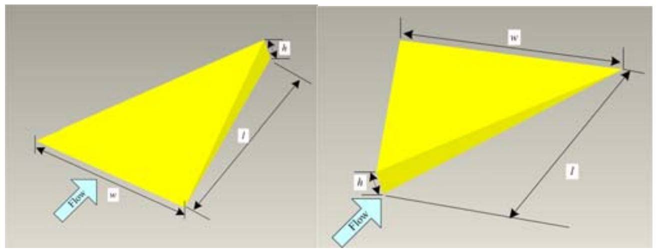
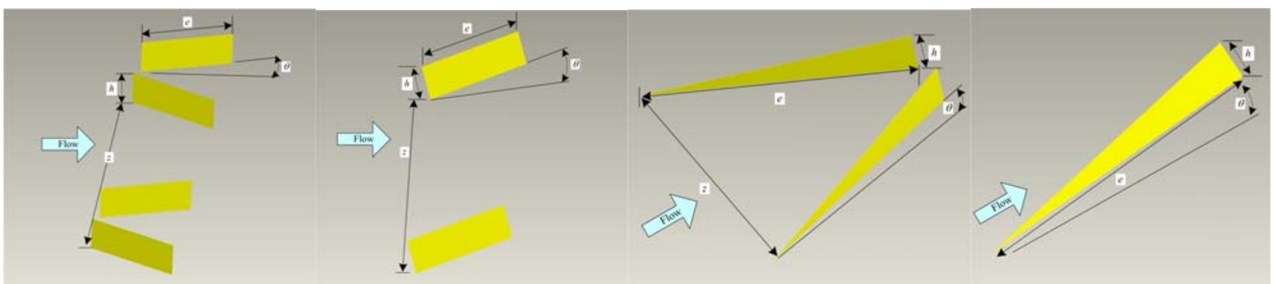
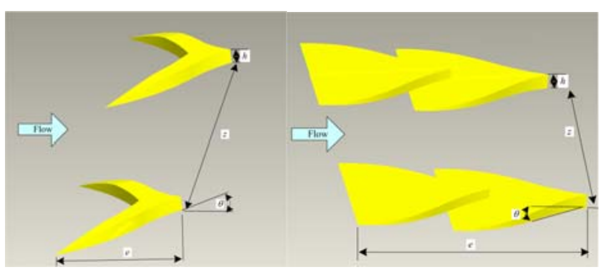


(a) Forward- and backward-facing wedge.



(b) Counter- and co-rotating vane.



(c) Wishbone and doublet type Wheeler vanes.

Figure 1. Types of MVGs, adapted from [7].

with experiment and to support applications, using RANS, hybrid RANS/LES and monotone integrated large eddy simulations, e.g., see [25, 32, 35] and some of the afore-cited references.

As a sidenote, there has been at least one previous study of conventional vortex generators placed ahead of a variety of shock generators.[36,37] Barter and Dolling[36] found that Wheeler doublet vortex generators placed upstream of a two-dimensional ramp-induced separation produce significant three-dimensionality, reduce the upstream influence and the length of the region of separation shock motion. These generators decrease the maximum rms value of wall pressure unsteadiness and shifts the fluctuations to higher energy. These authors attribute the effects to be due to a fuller boundary-layer profile, a weaker separation shock[a] and increased turbulence in the boundary layer, the last causing increased separation shock jitter. Subsequently, Barter and Dolling noted that the vortex generators reduce the loads on moderately swept compression ramps but not on blunt fins.[37] The authors concluded that SBLIs which are sensitive to the incoming boundary-layer properties are favorably influenced by vortex generators.

MVGs appear to reduce the size of the separation zone. However, no satisfactory explanation of how the MVGs affect the separation zone has been offered. It should be noted here that conventional, vane-shaped vortex generators are well established. They function by producing tip vortices which entrains freestream fluid, thereby energizing the boundary layer. In high-speed flow, they have seen application in diffusers and are visible on the wings of many types of transonic aircraft. Conventional vortex generators do not appear to have been used for high-speed inlets to mitigate the adverse effects of SBLIs and there appears to be only limited studies into such applications. Perhaps a serious consideration with high-speed applications is the possible adverse effects of wave drag from the vortex generators themselves that mitigate their advantages.[38]

Following Lin's review,[7] numerous studies been done at different institutions, both experimentally and numerically, on MVGs in supersonic flow to warrant another review of the state-of-the-knowledge. The emphasis of the review is on the flow physics around the MVG and on the effect of the MVG wake on separated shock/boundary layer interactions. The review is organized as follows: §II reviews the flowfield around MVGs, followed by §III which reviews the effects of MVGs on SBLIs in the transonic and supersonic regime. As far as we are aware, there has not been any studies of MVGs at hypersonic Mach numbers. The review ends with an outlook of what further work needs to be done to understand the physical mechanisms of MVGs and on other potential areas of interest.

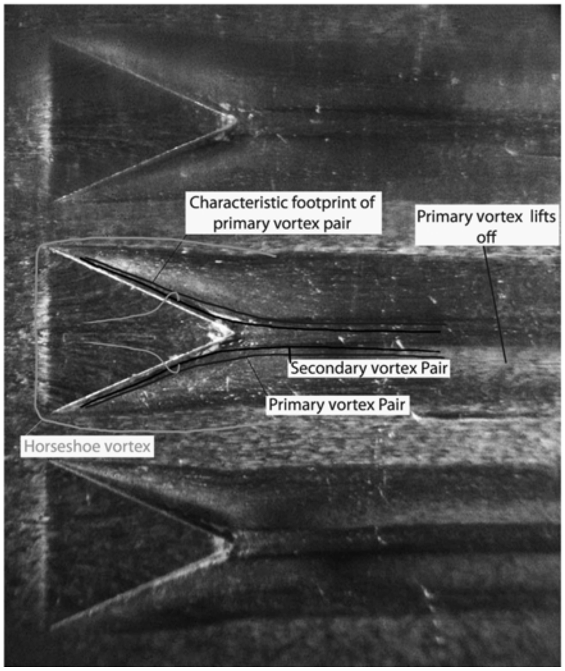
II. Supersonic Flow around an MVG

MVG studies in supersonic flow have focused on wedge and vane types, especially the former, in view of its robustness. This review therefore emphasizes the wedge type. Surface flow visualizations are shown in Figs. 2(a) and 2(b) of identical MVGs with a 24 deg leading edge, at Mach 1.4 and 2.5. These figures show that a leading-edge separation bubble forms due to a localized, two-dimensional shock/boundary layer interaction.

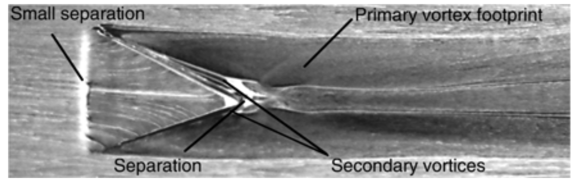
This separated flow past a submerged streamlined protuberance produces a weak horseshoe vortex, similar to those of protuberances whose height is approximately that of the boundary-layer thickness.[40] Experimental evidence for the horseshoe vortex has apparently been provided only from surface flow visualization thus far while numerical evidence came from high-order LES albeit at a lower Reynolds number, also from surface topology; see Fig. 2(c). It may be interesting to note that the surface flow visualization displayed in Fig. 2(a) shows no visible interference between the MVGs in spite of their proximity.

Getting closer to an MVG, despite its geometrical simplicity, the flow topology is extremely complex as revealed by a detailed analysis of surface and off-surface flow visualization.[41] This complexity may not be unexpected as three-dimensional geometries produce rich topologies. What is indeed surprising is that the complex flow is due to a tiny, sub-boundary layer protuberance. The dominant vortex pair shed by the MVG is not the aforementioned horseshoe vortex system but arises from the flow separating off the slant sides. Figure 3, including side views from experiment and high-order LES, together with video clips, identifies low

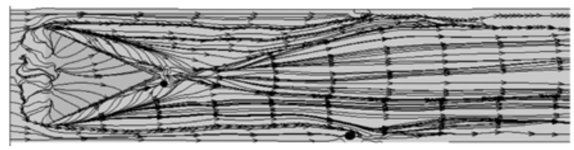
[a]The present authors consider that this may be a three-dimensional effect.



(a) From Herges et al.[31] ($M_\infty = 1.4$).



(b) From Babinsky et al.[25] ($M_\infty = 2.5$).



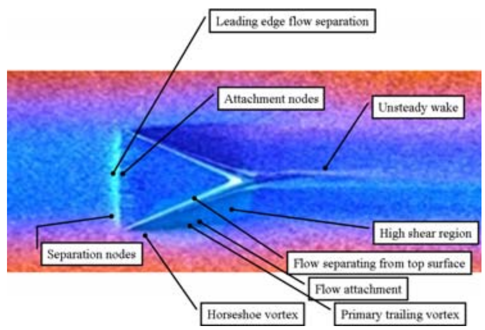
(c) From Li and Liu[39] ($M_\infty = 2.5$).

Figure 2. Experimental surface flow visualization and numerical surface streamlines from various investigators.

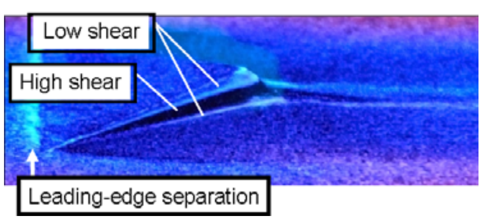
and high shear regions on the MVG sides, and on the flat plate. These regions are indications of a pair of large primary vortices. The surface streamline patterns are such that the horseshoe vortex system confines the primary vortex pair to trail downstream and intersect toward the rear. Moreover, Fig. 3(c) reveals singularities along the MVG leading edge which apparently have not been observed if at all experimentally.

The high and low shear layer regions are also reflected in the surface pressure distributions. Time-averaged surface pressure distributions from high-order LES[33,39] show a high-pressure region lying ahead of the MVG, Fig. 4(a). This is a result of the localized shock/boundary layer interaction induced by the MVG leading edge. A slightly higher pressure is also present on either side of the MVG. However, extremely low pressures exist on the flat plate nearest to the MVG junction. This low pressure can be interpreted to be the result of the high-speed flow present in this region associated with an open, three-dimensional separation. The time-averaged result also shows an asymmetry downstream especially of the trailing edge, whether in the LES or in the experimental result, Fig. 4(b). While the asymmetry may be an artifact from the simulation or the data processing, it may also be evidence of unsteadiness.

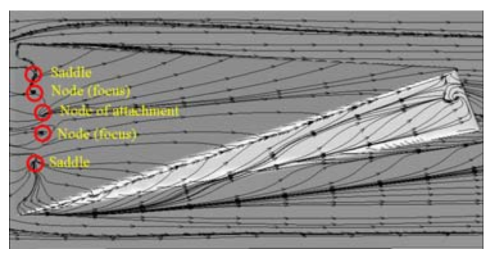
A further analysis of the high and low shear regions identify these to be due to the presence of secondary vortices, namely, one each at the corner of the MVG and flat plate and one each just just off the sides at the top. The presence of these secondary vortices satisfy topological rules.[41–43] Further, it is thought that when either the opposing primary or the secondary vortices impinge on each other, symmetry breaking occurs[44–47] which contributes to unsteadiness. These vortical interactions give rise to a large number of surface singularities as revealed by high-order LES, Fig. 5. Some of these singularities have subsequently been found experimentally. For example, Fig. 6 shows a pair of spiral points in both the LES and experimental results.[43] The experimental result was obtained through image processing of raw videos of surface flow



(a) Top view.[41]

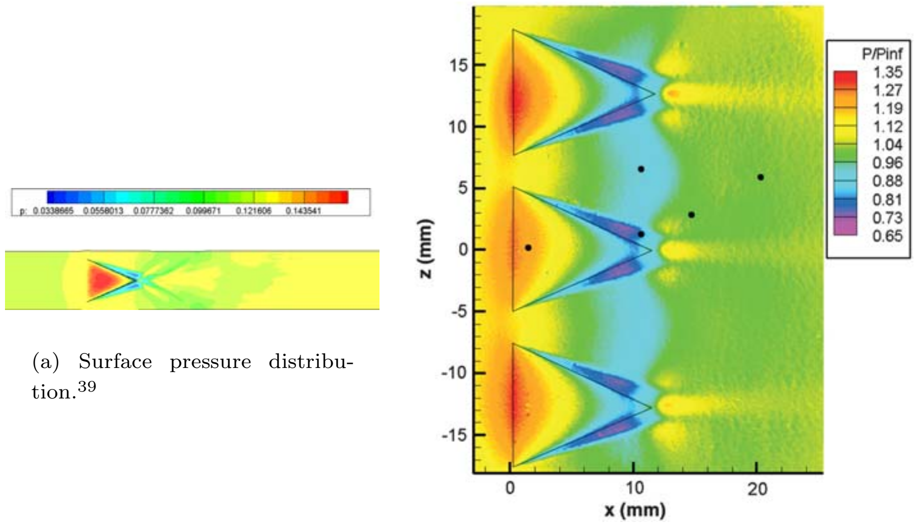


(b) Side view.[41]



(c) Side view.[33, 39]

Figure 3. Surface flow visualization showing various details.



(a) Surface pressure distribution.[39]

(b) From Herges et al.[31]

Figure 4. Surface pressure distribution around an MVG.

visualization. In passing, it can be noted that a synergistic approach in combining computations and experiments can yield great benefit.

In addition, a new visualization technique has revealed a connection between the spiral point SP5 in Fig. 5 and a flow feature that is tentatively identified as a vortex filament, Fig. 7. Numerical simulations confirm this feature. For example, Fig. 8 shows streamlines originating from SP5 at the same location as the experimental "tornado."

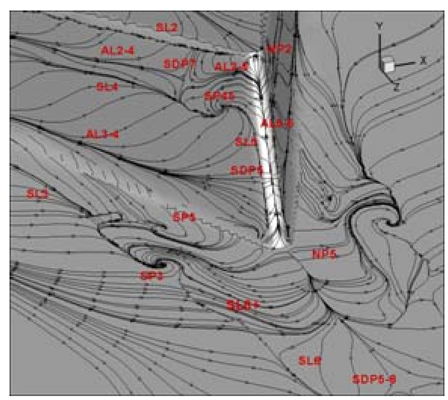


Figure 5. Numerical visualization showing singularities around MVG trailing edge; AL = attachment line, SDP = saddle, SL = separation line, SP = spiral.[43]

Figure 7 shows another possible vortex filament emanating from the top rear of the MVG. However, the flow feature seen at the top may be a combination of a secondary vortex shed from the top slant edge of the MVG plus the vortex filament.[b] This feature is likely not an expansion fan, which would be revealed in schlieren imaging but not always clearly seen in seeded flows, that also exists at the top of the MVG trailing edge.

Based on these observations, Lu et al.[41] proposed a detailed flowfield topology, Fig. 9. Most of the previously reported topological features remain.[25] But, vortex filaments associated with surface spiral points are included to complete the flow topology.

The complex flow around the MVG is also evident in the near wake. Time-averaged data, either through RANS[32,35] or PIV/LDV[25,31] reveal a streamwise momentum defect around the centerline of the wake and regions of higher

[b]Note that these vortex filaments were identified previously as secondary vortices although, strictly speaking, the former terminology is the correct one.

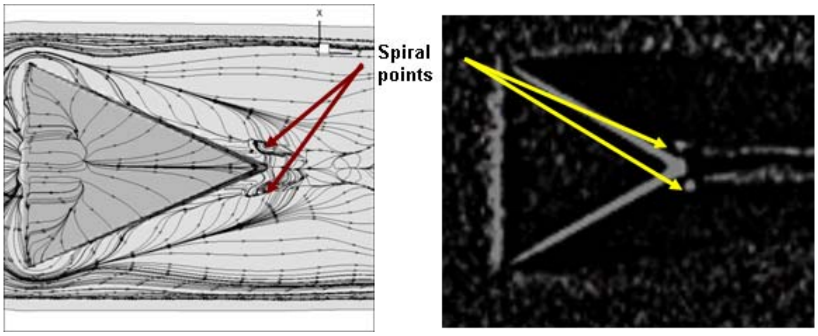


Figure 6. LES and experimental visualizations showing a pair of spiral points on the flat plate at the MVG trailing edge.[43]

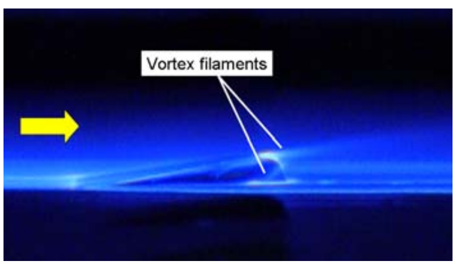


Figure 7. Panoramic visualization showing vortex filaments.[43]

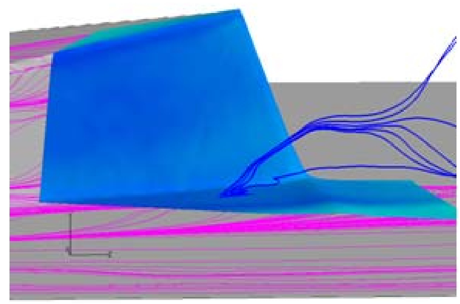
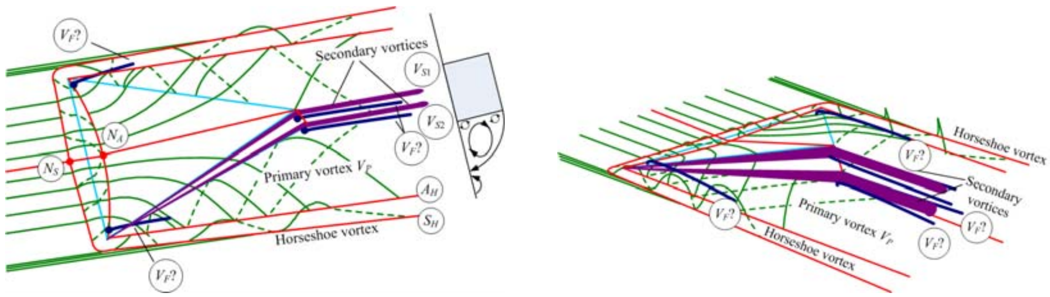


Figure 8. Streamlines emanating from SP5.[43]

momentum further outboard on either side of the MVG as well as nearest to the surface, beneath the low momentum region, Fig. 10. It is suggested that this momentum redistribution is due to entrainment of high momentum fluid from the freestream into the boundary layer by the trailing primary vortices. Interestingly, the laser lightsheet visualizations by Bur et al.[48] of counter-rotating micro-vane vortex generators (Fig. 1(b)) show two dark trailing spots which they identify as trailing vortices. Whether these are high momentum regions as in the above discussion is not known.

In an attempt to further understand the MVG wake, Blinde et al.[26] interpreted their detailed stereo PIV maps to produce a conceptual sketch as shown in Fig. 11. The figure shows high-speed regions outboard of each MVG that serve to channel an array of hairpin vortices directly downstream of an MVG. Blinde et al. stated that no trailing vortices were apparent in instantaneous snapshots. Instead, large structures in the form of pairs of counter-rotating vortices are convected in the boundary layer. These authors further remarked that their observations are consistent with observations in the wake of protuberances at low speeds, experimentally and also computationally using DNS.[49–51] Note that while Blinde et al. identified outboard high-speed (or high momentum) regions, they suggested a different vortex structure for entraining freestream fluid. This sub-boundary-layer vortex shedding mechanism with its unsteadiness has also recently been studied in low-speed flows.[52–55] Specifically, Angele and Grewe[52] suggested that the unsteadiness contributes to maximum Reynolds stresses around the mean vortex centers which should not be the case if the vortices were steady. Li and Liu[39] noted that the mean velocity profile downstream of the MVG exhibits



(a) (b)

Figure 9. Postulated mean flowfield topology past an MVG (dashed lines indicate surface flow).[41]

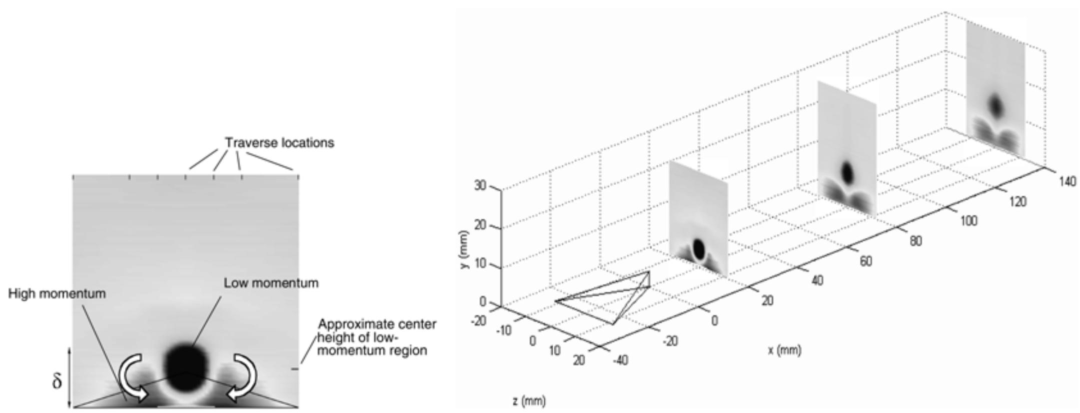


Figure 10. Streamwise momentum deficit and surplus in the wake of an MVG.[25]

an "inflection surface" that is unstable, thereby causing a Kelvin–Helmholtz (KH) instability to occur.[56] There has been previous suggestions that such a mechanism is the cause of turbulent vortex rings.[57]

Evidence of such ring vortices is provided by high-order LES.[39] Figure 12 displays the iso-surface of a small negative value of λ_2, commonly used for numerical visualization of vortices.[58] These ring vortices were identified as hairpin vortices by Blinde et al. Moreover, the instantaneous numerical schlieren of Fig. 13 shows large, intermittent density structures. Time-averaging of these structures will give the impression of a thickened boundary layer.

The numerical visualizations are supported by experiment.[59] Figure 14(a) shows a global lightsheet visualization where the freestream flow is seeded with fine calcium carbonate particles. In this seeding technique, the MVG wake is devoid of scattering particles and thus appears dark. The ragged interface between the wake and the freestream appears similar to the numerical schlieren of Fig. 13. A local lightsheet technique with acetone fog injected from an upstream pressure tap shows large billowing structures, Fig. 14(b), complementing the global lightsheet visualization. These structures are attributed to the MVG since they are not present in lightsheet visualization of the boundary-layer flow past the flat plate, Fig. 14(c).

In summary, the flowfield around an MVG is extremely complex due to the three-dimensional nature. The horseshoe vortex that wraps around the MVG is not a major feature. Instead, a pair of primary vortices trails from the sides of the MVG with associated secondary vortices and vortex filaments. A momentum

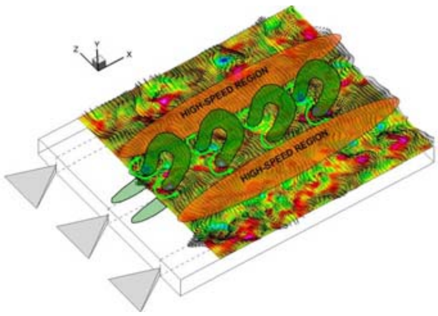


Figure 11. Postulated hairpin vortex train in the wake of an MVG.[26]

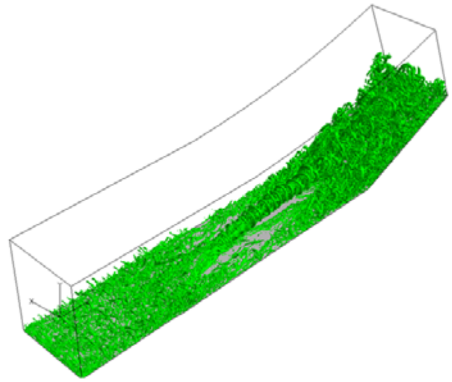


Figure 12. Vortex rings shown by λ_2 isosurface. Figure also shows vortex ring breakdown as the vortex train interacts with the leading shock.

deficit region is observed behind the MVG that is circular in shape. A circular velocity inflection is observed which is thought initiate a Kelvin–Helmholtz instability mechanism. This instability is likely aggravated by symmetry breaking as the two primary vortices impinge on one another. This unsteady, instability mechanism leads to the formation of a train of vortex rings. These rings draw in energetic, freestream fluid and distributes it to the sides. These rings convect over a long distance downstream.

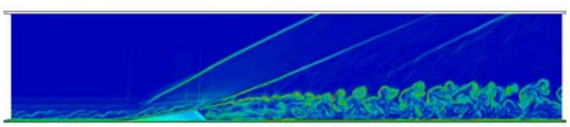
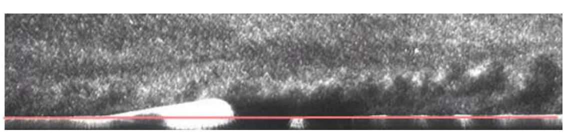
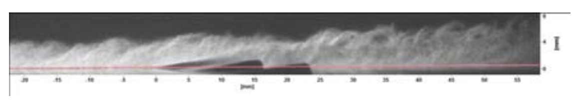


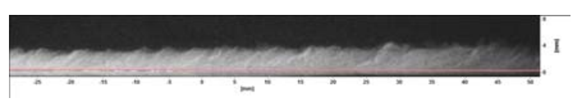
Figure 13. Instantaneous numerical schlieren of centerplane showing large flow structures.



(a) Global lightsheet visualization with lightsheet aligned along MVG axis.



(b) With MVG.



(c) Flat plate, without MVG.

Figure 14. Lightsheet visualizations.

III. Effect of MVGs on SBLI

Only a selective survey is provided here. The interest generally is to reduce the adverse effects of shock-induced, boundary-layer separation. Reducing the size of the separation zone may by itself be a sufficient metric but more specific metrics may include improving pressure recovery, reduced unsteadiness and reduced drag. At this stage, however, it appears that studies are still unearthing the physics of the phenomena and any discussion of performance gains may be premature. These studies tend to use simple geometries for inducing the shock.

There appears to be two classes of interactions that have been studied thus far. The first is of transonic interactions. The second is mostly of incident oblique shocks except for the numerical study by Li and Liu[39] which is of a ramp-induced shock interaction. While not so important in numerical studies, experimental studies of incident shocks have been found to suffer from serious, wind tunnel sidewall interference, even with large wind tunnels.[60–62] Another observation is that numerical studies are of interaction with a single MVG while experiments involve an array of them. As will be evident, the MVG array produces features that are not seen when only a single MVG is placed ahead of a separated SBLI.

All the studies thus far involve configurations that produce two-dimensional SBLIs, despite well-known experimental difficulties such as the aforementioned sidewall interference. All these studies remark on how the shock/boundary-layer interactions take on a three-dimensional nature as to be expected when MVGs are placed ahead of them, Fig. 15. However, many open questions remain unanswered as to how such three-dimensionality is introduced and how the adverse characteristics of separation are mitigated. There is general consensus that vortices are involved. Now, at low speeds, as reviewed by Lin,[7] regardless of whether the MVG produces a pair of counter-rotating trailing vortices or a train of vortex rings, these vortices introduce high-momentum fluid into the separated zone downstream. As is clearly evident, the high-momentum fluid is able to reduce the separated zone, in some cases, by a substantial amount. However, in separated SBLIs, the vortices encounter the leading shock of a lambda-foot shock structure, producing a shock/vortex interaction. Such interactions have been studied in many contexts and one possible outcome is "vortex bursting".[63–67] In the following subsections, a number of studies in the transonic and supersonic regime are reviewed; see Table 1 for a listing.

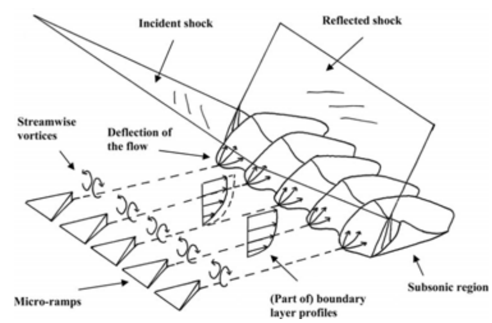


Figure 15. Conceptual sketch of two-dimensional, separated SBLI modified by wake from MVG array.[26]

A. Transonic Mach Numbers (Normal Shock)

Vane,[21,48] ramp[21,31] and a contoured bump[68] MVGs were studied. In these studies, a normal or nearly normal shock impinges the turbulent boundary layer. Note that the vane configuration of Ref. [21] is similar to the third figure in the right of Fig. 1(b), with the apex pointing downstream. In Ref. [48], the vanes have their apex pointed upstream. Except for the contoured bump, the MVGs were placed ahead of the shock impingment location. In the case of the contoured bump, the shock impinged on the bump.

The presence of the MVG array appears to create a "global distortion" of the separated flowfield, as revealed by surface oil flow visualization.[21,48] Except for a region near the center of the interaction, the surface streamlines turn inward in the outboard regions. The distortions appear to be more serious in [48]. perhaps because of its unusual MVG configuration. This distortion is also revealed in surface pressure distributions.

Bur et al. concluded that the spanwise spacing of MVGs and their distance ahead of the shock impingement location are important. For the former, a closer spacing allows the vortices to merge to reduce separation. For the latter, sufficient distance must be provided to allow entrainment of the high-momentum freestream fluid; see also Ref. [17]. In terms of potential benefits, Holden and Babinsky[21] suggested that the vane-type MVG causes a lower wave drag rise while Bur et al. suggested that the MVG height should be less than the sonic line of the incoming boundary layer. Holden and Babinsky observed that vortices from vane-type MVGs do not lift off as fast as ramp-type MVGs and are more effective in energizing the boundary layer. These investigators also observed that the MVGs successfully eliminated shock-induced separation.

Ogawa et al.[68] are interested in the effects of a contoured bump on the performance of a transonic airfoil. The larger contoured hump is different from the usual MVG element but its height is still less than the boundary-layer thickness. Thus the fall into the MVG category. The study places the hump under the shock. The intention is to reduce wave drag and not to exploit the vortices produced downstream.

New compound types of MVGs known as split-ramps and ramped-vanes were studied by Rybalko et al.[69] These were mounted on the floor of a transonic channel. Flow separation was eliminated in the vicinity of the center but increased sidewall interference was observed compared to the simple vane or ramp geometries. The sidewall interference was labeled as "corner vortices" although these may actually be separation bubbles.

Finally, Herges et al.[31] deployed a comprehensive array of diagnostics and offered modest conclusions. They found that MVGs improved the health of the boundary and could help resist separation in SBLIs. They suggested that MVGs be used to augment or replace bleed for future supersonic inlets.

B. Supersonic Mach Numbers (Oblique Incident Shock or Ramp-Induced Shock)

The primary difference between the transonic studies discussed above and supersonic studies is that the Mach number of the incoming flow is sufficiently past unity and that the flow downstream of the incident shock remains supersonic. Anderson et al.[17] perhaps is the first report of supersonic MVG. MVGs were placed ahead of an incident shock produced by a 10 deg shock generator. These authors provided guidelines on MVG geometries based on a large test matrix.

Experimental studies thus far involve incident shocks.[25,26] The surface flow visualizations of Babinsky et al.[25] show substantial disruptions to nominal two-dimensionality, as to be expected. It is probably appropriate to conclude that there is a disruption instead of a reduction of separation since the latter claim requires further substantiation. These authors suggested that smaller MVGs may be better in having lower wave drag, a conclusion reached separately by Bur et al.[48] Due to their small size, MVGs should be placed closer to the interaction region, a conclusion that was made also at low speeds.[7] Both of these conclusions were also substantiated by Lee et al.[32] who performed MILES of a Mach 3 configuration.

Ghosh et al.[35] simulated Babinsky et al.'s[25] experiments. Unlike most numerical simulations, these authors were able to introduce three MVGs. They found vortical structures forming downstream of the MVGs. The numerical results suggested that the experimental data may be affected by tunnel wall interference, which may be interpreted to be a glancing shock/boundary-layer interaction.[60–62]

Blinde et al.'s study involved detailed stereo particle image velocimetry mapping. An important aspect of their study is determining the size of the reversed flow region, using this to indicate separation. They found that the micro-ramps affected the spanwise distribution of the reversed flow and cause it to be broken up into isolated clumps. They suggest that this is consistent with Babinsky et al.'s[25] findings. Blinde et al. distributed two spanwise rows of MVGs next to one another. They found that two rows are more effective in disrupting the shock-induced separation zone.

Finally, Li and Liu[39] report a high-order LES simulation that showed a train of vortex rings shed from an MVG. The MVG of these authors had a trailing edge inclined at either 45 or 70 deg from the flat plate. The smaller inclination allowed the vortex train to be closer to the wall which is thought to be favorable for flow control. Li and Liu found that the vortex rings interacted with the leading shock to cause serious distortion of the separation bubble. For example, the instantaneous numerical schlieren visualizations of the ramp-induced SBLI in Fig. 16 show that the leading shock has disappeared and large structures billow further outward. Li and Liu also found a reduction of the extent of the separation zone which may be related to the disappearance of the leading shock.

IV. Conclusions and Outlook

A review is presented of the flowfield around an MVG immersed in a supersonic boundary layer and the subsequent interaction downstream with shock-separated flow. The flowfield around an MVG is dominated by a pair of primary vortices that trail from the MVG sides. A complex topology is revealed that includes two pairs of secondary vortices. Two pairs of vortex filaments emanating from the rear of the MVG were also identified and there is the possibility of more of such filaments.

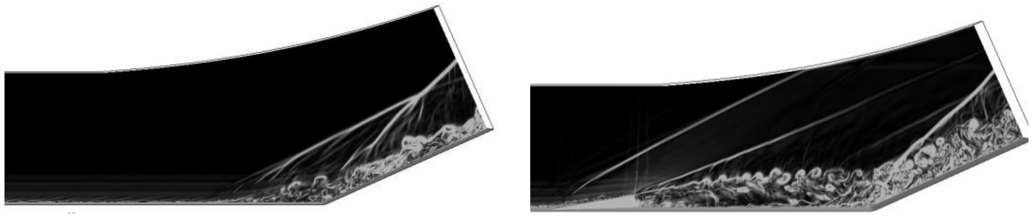
Table 1. Selected MVG studies.

Ref.	Test Conditions			Diagnostics	Remarks
	M_∞	Re/m $\times 10^{-6}$	δ_o, mm		
Transonic					
Ogawa et al. [68]	1.3	–	7.1	S, Pit, SP	TF, diffuser, NS impinging on various single & double contoured bumps, unsteadiness observed
Bur et al. [48]	1.4	14	4	HSS (4000 fps), LLS, SP	TF, channel, NS, counter- & co-rotating vane; large distortions to surface flow, unsteadiness observed
Holden & Babinsky [21]	1.5	$26\,000^a$	5.3	Pit, S, SFV, SP	TF; NS; counter-rotating vane, ramp; shock impinges on MVG and downstream; separation eliminated at centerline; global distortion
Rybalko et al. [69]	1.4	26	5.3	HSS (2000 fps), SFV, SP	TF; diffuser; NS; "split-vane" and "ramped-vane;" separation eliminated at centerline; large global distortion
Herges et al. [31]	1.4	30.4	4.77	HSS (2000 fps), PIV, PSP, SFV, SP	TF; NS; ramp; MVG improves boundary-layer health MVG improves boundary-layer health
Supersonic					
Anderson et al. [17]	2	–	–	(numerical)	optimization of vane- and ramped-types
Babinsky et al. [25]	2.5	40	6	LDV, S, SFV, SP	TF; OS (7); large distortions; smaller MVGs possibly more effective
Ghosh et al. [35]	2.5	40	6	(numerical)	array of 3 MVGs shedding vortical structures
Blinde et al. [26]	1.84	36.6	19	Stereo PIV	TF; OS (10); single & double array ramps
Lee et al. [32]	3	4000^a	6	(numerical)	FP; OS (8); small MVGs closer to the separation zone are more effective than larger MVGs
Li & Liu [33, 39, 43, 56]	2.5	1440^b	–	(numerical)	OS (25 deg ramp); MVG with 45 and 70 deg trailing edges

Notes:

- FP: flat plate; TF: tunnel floor
- HSS: high-speed schlieren; LDV: laser Doppler velocimetry; LLS: laser light-sheet visualization; Pit: pitot survey; PIV: particle image velocimetry; PSP: pressure sensitive paint; S: schlieren; SFV: surface flow visualization; SP: surface pressure
- NS: normal shock; OS: oblique incident shock (number in parenthesis indicates shock generator angle)

[a] based on boundary-layer displacement thickness
[b] based on boundary-layer momentum thickness



(a) No MVG.

(b) MVG upstream.

Figure 16. Instantaneous numerical schlieren.[33]

There is at least two schools of thought regarding the wake of the MVG. First, the MVG wake is thought to be trailing vortices that entrain high momentum, freestream fluid. A nonuniform spanwise region is formed where low momentum fluid exists around the centerline and higher momentum fluid exists further outboard. It is thought the higher momentum energizes the boundary layer to reduce the subsequent separation. Secondly, an instability mechanism is thought to produce a train of either hairpin vortices or vortex rings. The vortex train draws in high momentum, freestream fluid, as in the first model. However, the vortex train interacts differently with the shock. Vortex bursting is thought to cause substantial distortion of the leading shock that may cause it to actually disappear. In addition, it is possible that the interaction creates substantial unsteadiness in the upstream region of the separation zone. This unsteadiness may produce the impression of a reduced separation zone.

In many of the experimental studies, tunnel sidewall interference may make it difficult to properly interpret the results. Thus, it is recommended that attempts be made to avoid such interference. Axisymmetric configurations may be suitable for this purpose. Otherwise, the possibility of using fences to isolate a two-dimensional interaction should be considered. Computationally, it appears that high-order schemes are needed to capture the fine scales present in the flowfield. In addition, a proper identification of the vortical structures and how they interact with the shock-induced separation may be best handled by numerical simulations integrated with experiment.

Finally, performance metrics need to be developed to substantiate the effectiveness of MVGs. For example, the reduction of the separation zone, say, based on surface flow visualization may be quantified by defining an average separation line after the introduction of an MVG array. Further metrics, more for application, will be to properly quantify the performance penalty of MVGs relative to the performance gains.

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