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# Investigation of Vortex Bursting at a Low Reynolds Number Using a Schlieren Visualization Scheme

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It has been demonstrated that leading edge vortices (LEVs) formed by airflow past an elevated delta wing, or vortex generator, have the ability to erode granular materials such as snow or sand on the leeward side of the wing (Lang and Blaisdell, 1998; Lang and Blaisdell, 1999). The LEVs generated by the delta wing do not dissipate rapidly, providing effective, sustained erosion. However, the well-known phenomenon of vortex bursting, characterized by a sudden enlargement of the vortex core, may significantly reduce the ability of a vortex to move particulate matter. It is commonly believed that the delta wing's angle of attack strongly influences vortex bursting. Systematic study of airflow past a delta wing, to determine the conditions surrounding vortex bursting, requires a visualization technique, for which there are few choices. This work was aimed at identifying a wing configuration that minimizes the occurrence of vortex bursting by employing an effective visualization technique for airflow past the wing. A Schlieren optical system was employed. Using the density gradient above a heated delta wing we were able to witness and measure LEVs at low Reynolds numbers. With this approach, it was determined that an angle of attack of approximately 15° minimized vortex bursting.

## 1. INTRODUCTION

The delta wing has many applications, most notably as a lift generator for aircraft and re-usable space vehicles (e.g., space shuttle). Of particular interest in cold regions is the ability of the delta wing to remove snow by generating low-speed vortices (patent number 6,053,479). The wing, harnessing the power of natural winds, has the potential under the right conditions to entrain particulate matter in the vortex flow field and to relocate the grains (Lang and Blaisdell, 1998; Lang and Blaisdell, 1999). This is achieved when air flows past a delta wing oriented into the flow at some angle of attack, $\alpha$, by vortices that are formed over the leading edges of the wing (Figure 1). Typically, the vortices extend some distance from the trailing edge of the wing. One phenomenon associated with this system is vortex bursting. Bursting is known to occur over the wing when the angle of attack is too high, or may occur downstream of the trailing edge when the angle of attack is less than some critical angle. Vortex bursting over the wing significantly reduces its ability to entrain particulate matter in the flow. Initial conditions play a crucial role in the formation and subsequent bursting of vortices. It has been determined by experimental observation that the burst point does depend on the resultant angle between the direction of airflow and the leading edge of the wing (McCormick, 1995; McCormick, 1991; Roos and Kegelman, 1990). A combined numerical and empirical approach is discussed in detail in McCormick (1991). Most studies have focused on determining lift coefficients for high-speed airflows ($Re > 3 \times 10^6$) (e.g., Lambourne and Bryer, 1962; Wentz and Kohlman, 1969). To date, very little research has been performed in the area of low-speed vortex generation over a delta wing to directly test the relationship between the angle of attack and vortex bursting (Earnshaw and Lawford, 1966). The objective of this study was to establish a method for observation of low-speed flow and to obtain preliminary data that would define an optimum angle of attack to minimize vortex bursting. After many failed attempts utilizing various types and sizes of smoke generators, a Schlieren optical system was employed. An enhanced understanding of the nature of vortex bursting is important to determine the limitations and suitability of delta wing vortex generation for passive snow removal.

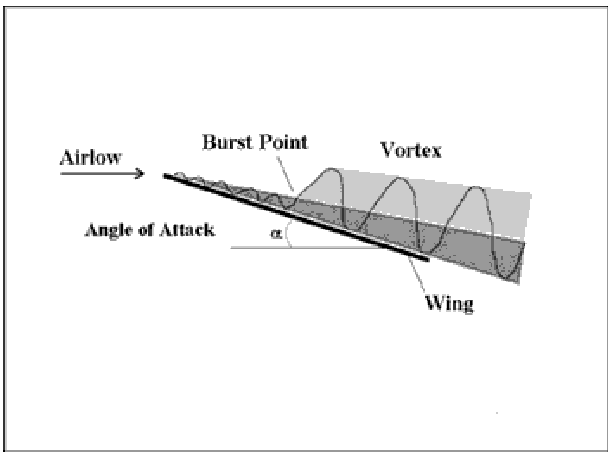


Figure 1. Representation of vortex bursting over a delta wing.

## 2. THEORY

The geometry of the delta wing, when oriented into the wind, creates the conditions necessary for vortex formation. The sweepback angle, $\Lambda$, is defined as the angle between the vertical plane perpendicular to the wind and the leading edge of the wing (Figure 2). From Roos and Kegelman (1990), the compound angle, $\lambda$, is defined in terms of the sweepback angle and the angle of attack, $\alpha$, as

$$\lambda = \cos^{-1}(\sin \Lambda \cos \alpha).$$

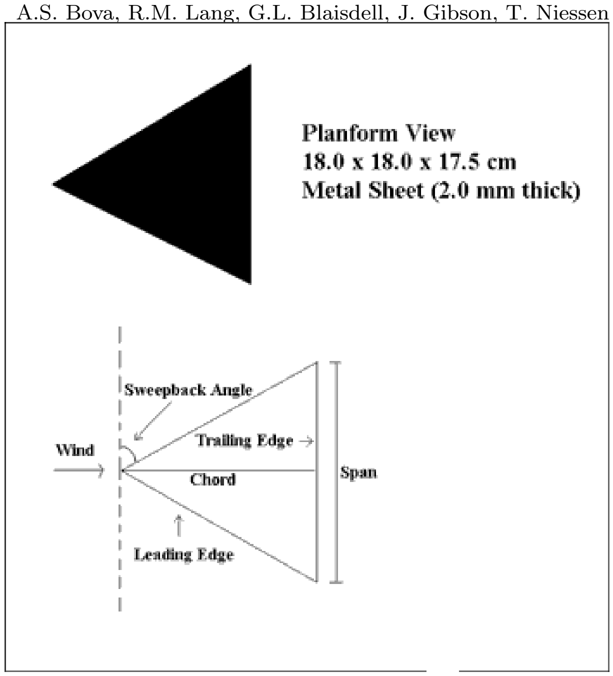


Figure 2. Planform view and wing specifications.

From fluid dynamics theory (e.g., Lamb, 1945), the flow circulation of a vortex is

$$\Gamma(r) = 2\pi r V_t(r) = \text{constant},$$

where $\Gamma(r)$ is the circulation at the core radius, $r$ , and $V_t(r)$ is the tangential velocity at that radius. The strength of the vortex can be represented by the swirl angle,

$$\xi = \tan^{-1}(\frac{V_t}{V}),$$

where $V$ is the ambient wind velocity. When the swirl angle, and hence the vortex strength, is sufficiently high the vortices become unstable and bursting occurs. The burst point is the location of the instability. Vortex bursting is characterized by a reduction in $V_t$, and by the sudden significant increase in the size of the core (Figure 1). It has been hypothesized that the burst point indicates a standing wave in which momentum is conserved while the energy decreases (McCormick, 1995; McCormick, 1991).

## 3. EXPERIMENTAL METHOD

The initial objective of our study was to determine an appropriate method for visualizing very low speed airflow in the presence of a delta wing. A simple Schlieren optical system was adapted for our purposes (Geisert, 1984). Schlieren images are obtained by blocking portions of light that have been refracted through a fluid density gradient. The resulting variations in image brightness around the subject allow the gradient to be discerned.

The customary Schlieren setup employs a bright light source, a knife edge and two concave mirrors that reflect the light through a subject gradient in a “Z” pattern (Merzkirch, 1974).

A simplified system was adopted for these experiments which consists of a diffuse light source (a mercury lamp or low-watt frosted light bulb), two Ronchi rulings with the same line density, a spherical mirror and a plane mirror (adapted from Geisert, 1984; Figure 3). The Ronchi rulings were created by using a computer graphics program to generate an image of parallel black lines, equal in width to the spaces between them, at a density of 11 lines per cm. These images were then printed onto transparencies. Disturbances to the air density in the region between the mirror and the rulings (such as heat) will result in Schlieren images when the source light is observed as it exits from the ruling. The Schlieren images that are presented here were captured from a video recording of the light traveling through the Ronchi rulings and a wind tunnel (Figures 3 and 4).

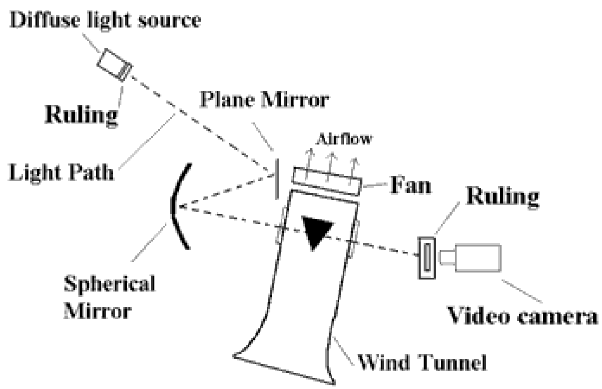


Figure 3. Schlieren optical arrangement. The source light was 2.3 m from the plane mirror, the plane mirror was 0.7 m from the spherical mirror. The distance from the spherical mirror to the camera's objective was its focal length, 3 m. The angle between the source light and the normal to the plane mirror surface was 20 degrees

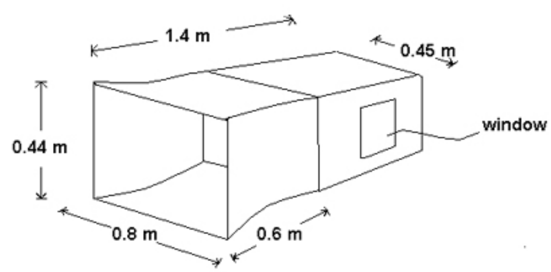


Figure 4. Sketch of the wind tunnel.

A mercury lamp with a translucent screen was placed behind an 11 line/cm Ronchi ruling. A 20 cm square plane mirror with a silvered surface was placed 2.3 m from the light source and angled to direct the light toward a 30 cm diameter spherical mirror with a 3.1 m focal radius placed 0.74 m away (Fiigure 3). (This departure from the "V" pattern suggested by Geisert (Geisert, 1984) is to ensure that the source light is not directed through the heated outflow of the wind tunnel we used to simulate wind passing over a scale-model vortex generator.) The spherical mirror was then adjusted to direct the collimated light through a simplified wind tunnel (Figure 3) to a Ronchi ruling and video camera set 3.1 m distant. The exact angles of the light path between the source light, plane mirror and spherical mirror are not critical, but should be kept as shallow as possible ($< 30°$) to avoid distortion of the source light image. This configuration is very forgiving and may be made to accommodate spherical mirrors of different focal lengths without affecting image quality.

As expected, at low airspeeds the natural ambient density gradient around the delta wing was not sufficient to generate a useful image. However, even small temperature variations created clear visual effects. This suggested a unique approach to visualizing the flow. A scale-model metal delta wing was heated to a temperature of 100°C with a heat gun, and placed in the flow field. Room temperature air passing over the heated wing created dramatic images of the airflow (Figure 5).

Figure 5. Smooth vortices at 20° angle of attack.

A 0.40 m diameter high-speed household fan (mounted on a separate table to isolate mechanical vibration) was used to draw air through a simplified wind tunnel past the delta wing. Preliminary test results and the images presented here were achieved at a flow speed of 0.50 m/s, yielding a Reynolds number of 5200, with the characteristic length as the chord length of the wing. The uniformity of the flow field was not established. A small but relatively sensitive cup anemometer (with an error of $\pm 0.5\%$) was used to record the air speed. Angles of attack from 10° to 23° inclusive were investigated at one-degree increments. The error in the angle of attack was $\pm 0.5°$ degrees.

The 2.0 mm thick steel delta wing (Figure 2) was constructed with 18 cm leading edges, a 17.5 cm wingspan, and mounted on a wooden base to an elevation of 18 cm. The sweepback angle was $60.5^{c}irc$, giving the wing an aspect ratio $(4/\tan\lambda)$ of 2.26. Machine screws were inserted 5.1 cm apart along the midchord, perpendicular to the plane of the wing, to provide a clear distance scale (Figure 6). The screws were used in all of the experiments in which burst point measurements were made (i.e., all of the experiments used to provide the graphed data). The wing was fitted with a pivot to allow for an easily adjustable angle of attack, and mounted on a $25 \times 25 \times 2$ cm$^3$ square plywood stand.

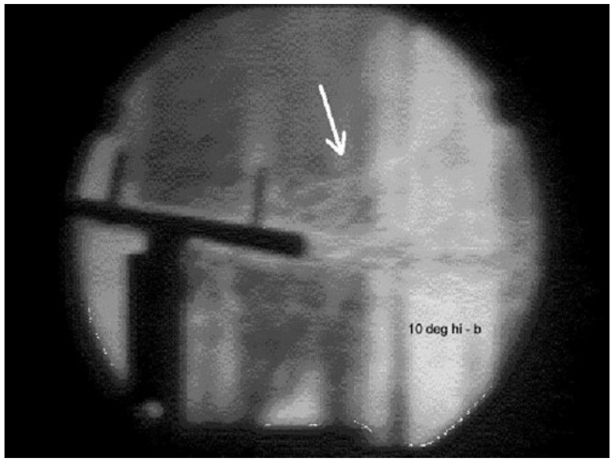


Figure 6. Spiral breakdown and vortex bursting at 10° angle of attack. The screws perpendicular to the plane of the wing are 5.1 cm apart. Arrow indicates location of burst point.

## 4. RESULTS

Initial investigations were made into the relationship between the angle of attack and vortex bursting.**Movie 1** provides a good example of laminar flow around the vortex generator. In changing the angle of attack, we discovered that vortex bursting is an intermittent phenomenon, but not clearly periodic. Thus, we had to sift through the video records to capture the burst events. Bursting events (shown clearly in **Movie 2**) sometimes lasted for a few seconds, but at other times they appeared for less than one second. As the angle of attack increased, bursting events moved toward the vortex generator apex and seemed to become more common and longer lasting.

Of 67 burst event images captured from video recordings of the experiment, 28 were used to obtain burst point measurements. The remaining images were discarded because of poor image quality (e.g., blurring). The burst points were measured relative to the midchord of the wing, and have an estimated error of ±1.0 cm (±6.4% of the 15.7 cm midchord length).

Figure 7 plots the burst point against the angle of attack. Although the data show some scattering, there is a general trend of burst points moving toward the apex of the delta wing as the angle of attack increases, confirming our impression from watching the complete video record. Burst points near and beyond the trailing edge of the wing, as suggested by the regression line, will occur at angles of attack of less than 10°.

Data plotted against the compound angle (Figure 8) are compressed into a band between 30° and 40°. A similar plot in Wentz and Kohlman (1969) indicates that the band should extend into the 40° to 50° range as burst points occur near the vortex generator apex.

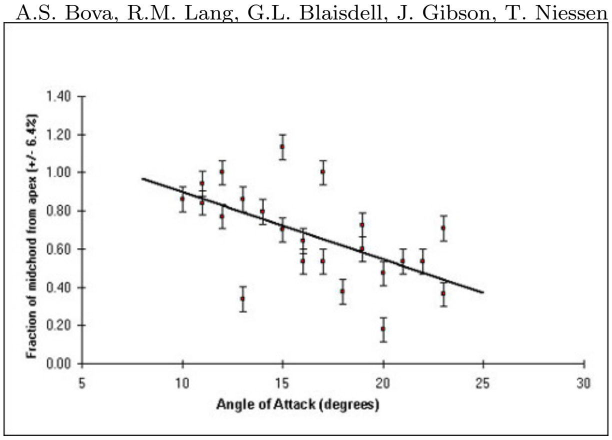


Figure 7. Burst point as a function of angle of attack.

However, our particular generator configuration ($\simeq 60^\circ$ sweepback) was not tested at angles of attack high enough ($30^\circ$ to $35^\circ$) to cause bursting very near the apex, so this departure from the Wentz data (Wentz and Kohlman, 1969) should not be surprising.

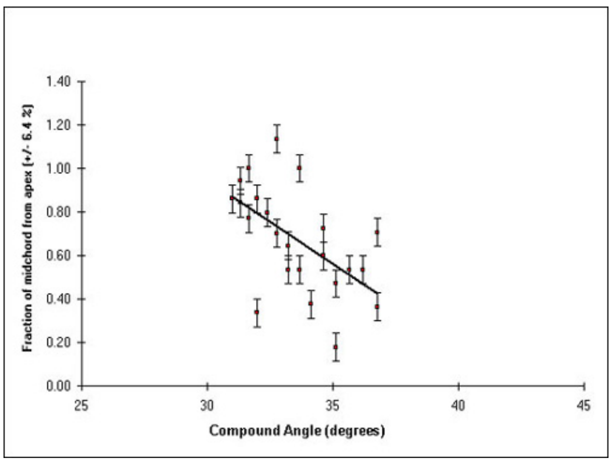


Figure 8. Burst point as a function of compound angle.

## 5. DISCUSSION AND CONCLUSIONS

It is known that airflow at low velocities vacillates between stable and unstable states on a short time scale. This is caused by the many influences that can affect fluid flow in the environment, where small perturbations from the equilibrium flow can induce turbulent flow. The classification for any fluid flow regime, including a vortex, is simply to determine if the flow is inherently stable or inherently unstable.

Prior tests have shown that, with a specific geometry and configuration of delta wing, we can produce inherently stable vortices that are capable of eroding particulate materials such as snow or sand from the ground surface. An unstable condition called vortex bursting can occur close to the delta wing and significantly degrade the delta wing's erosion potential. Our ultimate goal is to minimize or eliminate vortex bursting upstream from the point where the vortex impinges on the ground, in order to maximize the momentum of the vortex and thus its capacity for erosion. We have seen that brief over-wing bursts occur at nearly all angles of attack, but have not yet determined their overall effect on downstream vortex strength. We completed this study to attempt to determine the best angle of attack to minimize the appearance (number and duration) of bursting events directly over the vortex generator. We achieved this by adapting a visualization scheme that allows detection of air currents.

Though further testing is required, the agreement between the preliminary data and previous independent experiments (McCormick, 1991; Lambourne and Bryer, 1962; Wentz and Kohlman, 1969; Earnshaw and Lawford, 1966) suggests that the heated-wing Schlieren visualization system is a valid method for detecting vortex behavior at low Reynolds number airflow. This agreement also suggests that, for a delta wing (vortex generator) with a $60^\circ$ sweepback angle, an angle of attack of $13^\circ$ to $16^\circ$ (composite angle $\simeq 32.5^\circ$) may be optimal for keeping significant or persistent vortex bursting well away from the wing. This configuration shows the fewest vortex bursts over the wing, and so has a greater potential for moving granular materials on the leeward side. However, the same compound angle may be achieved by other sweepback angles at different angles of attack, which suggests that other configurations should be investigated.

Over the course of our investigation several possible refinements of the experiment became apparent. The images we obtained were somewhat distorted by density variations in the glass walls of the wind tunnel enclosure. Using high-quality optical glass would reduce this effect. The image quality degraded quickly as the wing cooled and the density gradient decreased. A thermostatically controlled heating element integrated with the wing structure would maintain a nearly constant density gradient. Though the scaling screws did not appear to affect the behavior of vortex bursting, there is the possibility that perturbations from the screws may have contributed to airflow instability, especially at lower angles of attack. A less intrusive method of scaling would be preferable. A double-pass Schlieren system should improve the image quality. Finally, high-speed photographic equipment (video or still) would increase the image detail and reduce the margin of error in measurement. Together, it is likely that these modifications would greatly improve the quality of the images and the reliability of measurements.

Development of low-wind-speed delta wing technology should include investigations into vortex strength, longevity, bursting and burst point, wing dimensions, angle of attack, wing elevation above the ground and wind speed. Application to relocating granular materials, such as snow, will benefit from an exploration of the maximum length of the vortices and a more precise relationship between vortex bursting and delta wing geometry, including its angle of attack. This unique heated-wing visualization method will enable the experimenter to investigate vortex generation and bursting, even at very low wind speeds.

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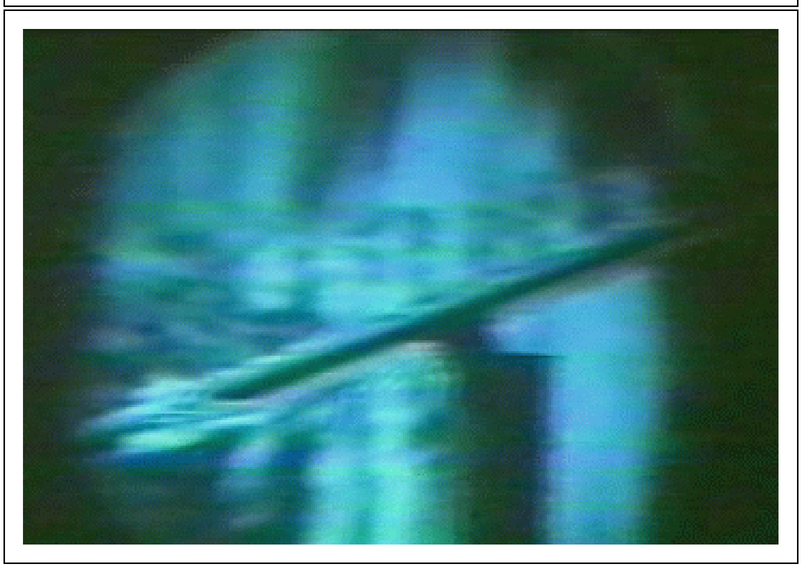

Figure 9. Still from movies 1 and 2.