Experiments on the Unsteadiness Associated with a Ground Vortex

J. M. Cimbala,* M. L. Billet,† D. P. Gaublomme,‡ and J. C. Oefelein§
Pennsylvania State University, University Park, Pennsylvania 16802

The ground vortex formed by a jet impinging on the ground in the presence of a crossflow has been studied experimentally. High speed motion pictures and spectral measurements were obtained to study the unsteady features of this flowfield. A very low-frequency pulsation or "puffing" instability was observed. Since this unsteadiness could not be correlated with any other oscillations in the flowfield, the low-frequency oscillations must come from the gross features of the ground vortex itself. Namely, jet fluid accumulates in the ground vortex until the vortex is so large that the flowfield breaks up, the ground vortex is swept away, a new smaller vortex forms, and the process repeats itself. Measurements of the frequency of these oscillations are presented for the first time, and data on the vertical extent (height) of the ground vortex are also shown.

Nomenclature

D_j = inner diameter of jet
f = frequency
h = distance from nozzle exit to ground plane
h_v = ground vortex height (from ground to top of ground vortex)
h_{vc} = ground vortex center height (from ground to center of ground vortex)
p_0 = maximum pressure (at impingement point on ground)
p_∞ = static pressure of the freestream
r = radial dimension from centerline of jet
St = Stouhal number, $=fD_j/V_\infty$
V = velocity
V_0 = reference velocity, $= [2(p_0-p_\infty)/\rho]^{1/2}$
V_j = velocity of jet at nozzle exit
V_∞ = wind tunnel (crossflow) velocity
x = distance along ground plane, in direction upstream of jet centerline
x_i = jet impingement point
x_{mp} = maximum upstream penetration point of ground vortex
x_s = ground vortex separation point
x_v = ground vortex center point
y = distance normal to the ground plane
ρ = density
λ^* = reference jet-to-crossflow velocity ratio, $= V_0/V_\infty$

Introduction

A GROUND vortex is formed when a vertical jet impinges on the ground in the presence of a crossflow. When an air jet strikes the ground, it tends to flow radially outward from the point of impingement. With crossflow present, which may be due to either horizontal movement of the aircraft or a crosswind, the jet flow along the ground in the opposite direction of the relative crossflow is rolled back onto inself. The formation of a horseshoe-shaped ground vortex is the result, as sketched in Fig. 1. Summaries of recent research can be found in NASA Ames Ground Vortex Workshops held in 1985[1] and 1987,[2] in the Society of Automotive Engineers (SAE) Powered Lift Conference in 1987,[3] and in the 1989 SAE Aerotech Conference.[4]

The location of this ground vortex and its induced effects on the nearby lifting surfaces are of importance in predicting the performance of the aircraft. Also, to avoid the ingestion of hot gas or dirt and debris, the engine inlet should be ahead of or above the flowfield associated with the ground vortex. Several investigations have been conducted to determine the forward projection of the ground vortex. However, the height of the ground vortex flowfield has received very little attention. Results of a recent ground vortex study conducted at Penn State are given in Refs. 5 and 6. The structure of the ground vortex was determined for several flow conditions in tests in the Applied Research Laboratory (ARL) Penn State 48-in. wind tunnel. The flowfield was produced by a 76.2-mm (3 in.) diam round jet with jet velocity $V_j = 45.7$ m/s (150 ft/s) impinging on a ground board in the wind tunnel. The crossflow velocity V_∞ was varied from 4.6 to 18.3 m/s (15 to 60 ft/s), whereas the nondimensional height (h/D_j) between the jet exit and the ground plane was varied between 1 and 6.

Results showed that the vortex separation point location did not agree with the theory or measurements of Colin and Olivari[7] but agreed fairly well with the empirical relationship suggested by Abbott.[8] Time-averaged laser velocimetry surveys indicated that the ground vortex was elliptical in shape and did not have a velocity field describable by a classical free vortex. Flow visualization of the flowfield utilizing the smoke-wire technique showed large scale unsteadiness of the ground vortex, particularly at the smaller values of V_∞/V_j. This is illustrated in Fig. 2, which shows two photographs of the flowfield at $h/D_j = 3$ and at $V_\infty/V_j = 0.1$. Although the jet and wind tunnel conditions were identical for the two cases, the flow patterns are remarkably different! The photograph in Fig. 2a shows a relatively smooth interface between the freestream and ground vortex, whereas the photograph in Fig. 2b shows a highly three-dimensional nearly chaotic flow—almost a complete breakup of the flowfield. To date, the exact source and nature of this unsteadiness were not known.

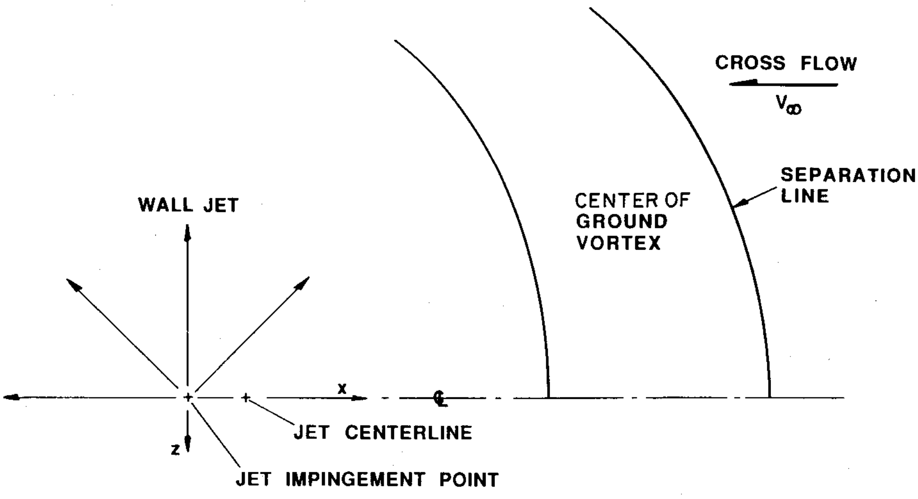
The goal of the present investigation was to identify and quantify the source and nature of the unsteadiness of the flowfield associated with a ground vortex. High speed movies utilizing the smoke-wire flow visualization technique, hot-wire anemometer measurements, and laser velocimeter (LV) measurements were performed to investigate this unsteady flowfield.

Facility and Equipment

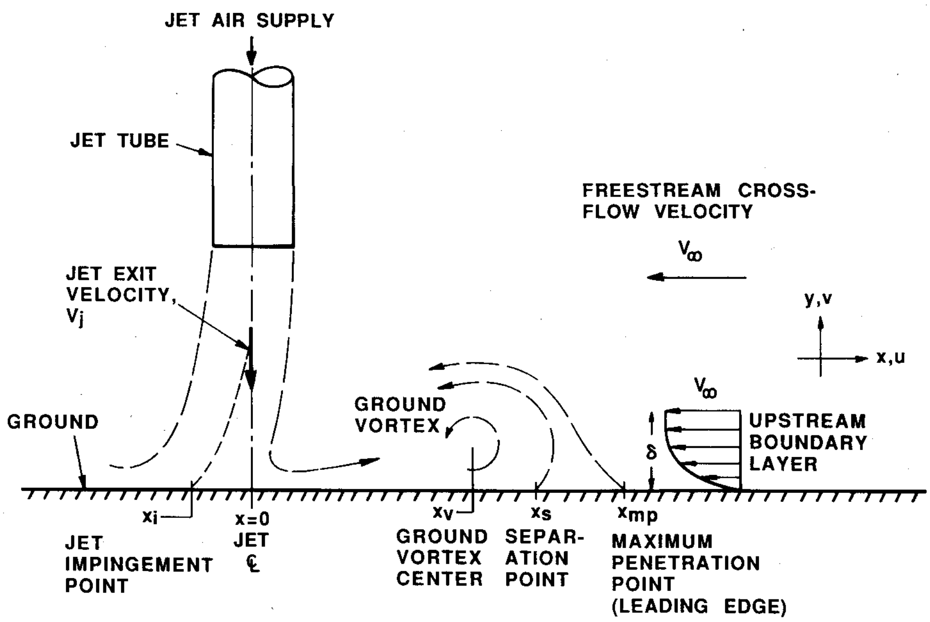
The ground vortex tests were conducted in the subsonic 48-in. wind tunnel of ARL Penn State, described in Ref. (9). This facility is a closed-circuit wind tunnel with an octagonal test section that is 1.22 m (4 ft) across flats and 4.88 m (16.0 ft) long. The manner in which the jet was installed in the wind tunnel for the ground vortex tests is shown in Fig. 3. For these tests the jet ingested air from the wind tunnel through a port

Received Feb. 21, 1990; revision received July 11, 1990; accepted for publication Aug. 26, 1990.

*Associate Professor, Mechanical Engineering. Member AIAA.
†Senior Scientist, Applied Research Laboratory.
‡Graduate Assistant, Aerospace Engineering; currently Engineer, Naval Air Test Center, Patuxent River, MD 20670.
§Research Assistant, Applied Research Laboratory.

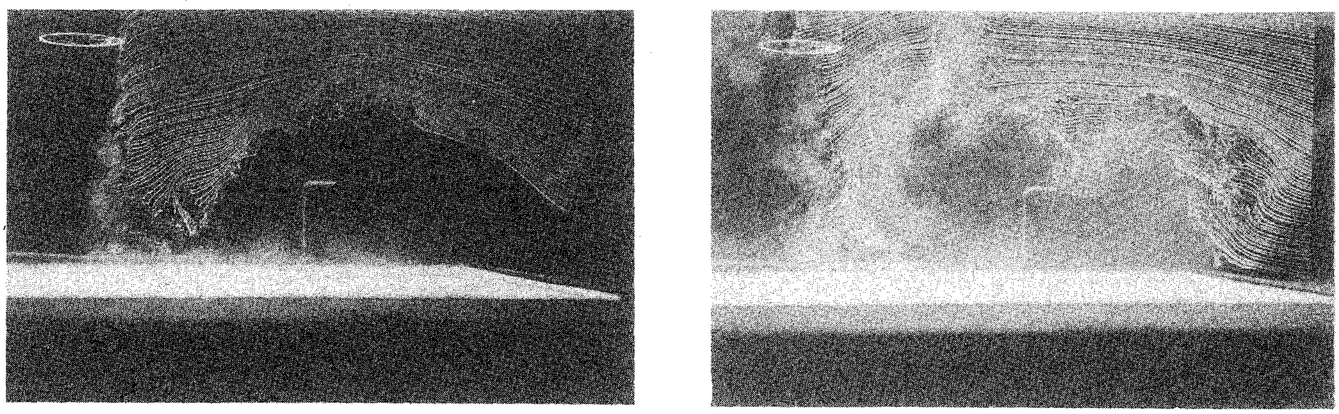


a) Top view



b) Edge view

Fig. 1 Ground vortex formed by a jet impinging normal to the ground in a crossflow.



a) b)

Fig. 2 Smoke-wire still photographs of ground vortex for the large jet at $h/D_j = 3$ and $V_\infty/V_j = 0.1$. Photos a) and b) are for identical conditions, but different times, which illustrates the unsteadiness of the flowfield.

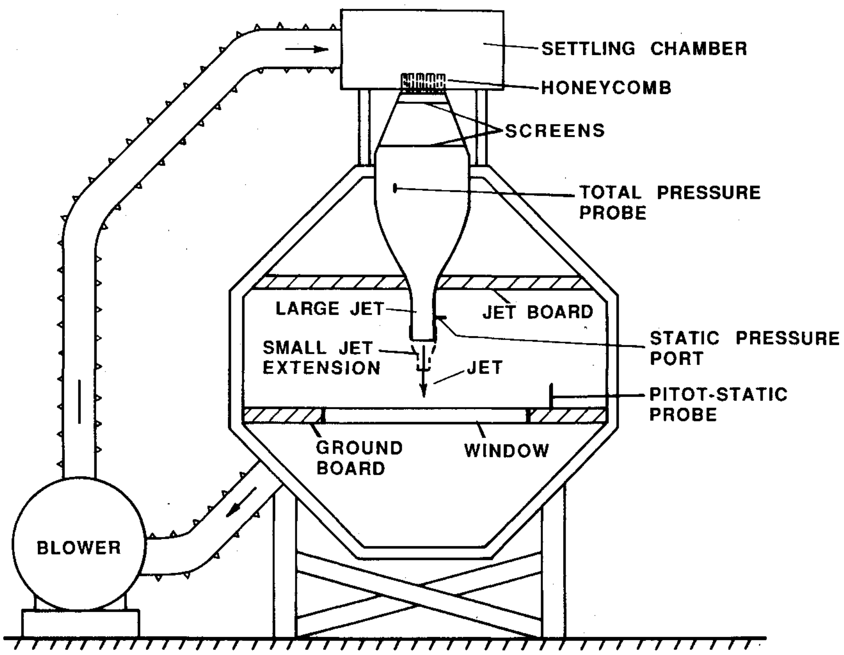


Fig. 3 Jet installation in 48-in. wind tunnel.

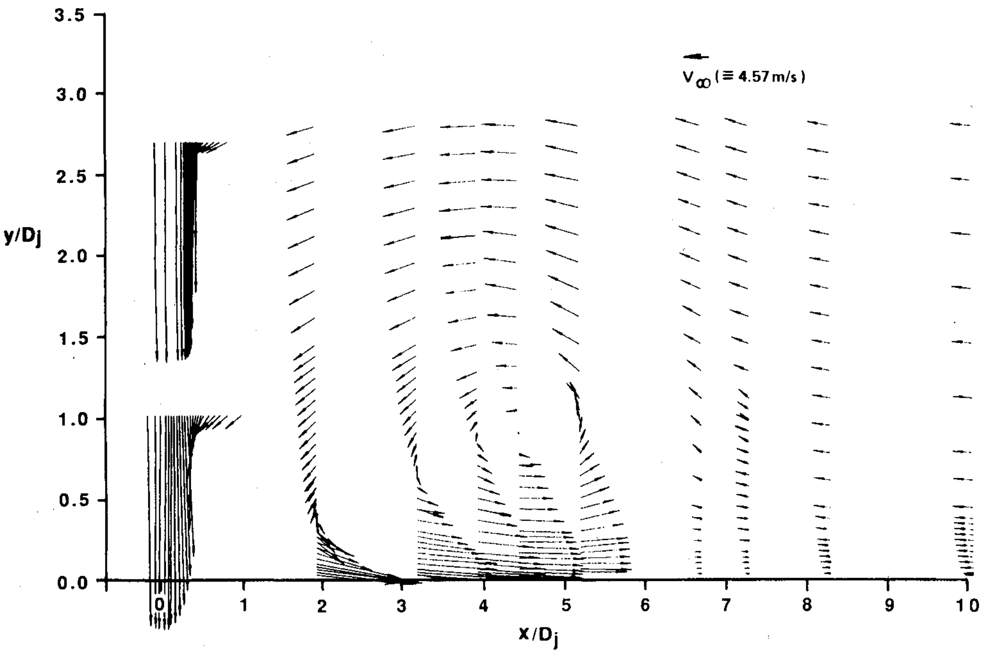


Fig. 4 Mean velocity vector plot of ground vortex; large jet at $h/D_j = 3$, $V_\infty/V_j = 0.1$.

far downstream from the test chamber. Details of the configuration and instrumentation can be found in Refs. 5 and 6.

Two different jet sizes were used in the study. The first jet was 76.2 mm (3 in.) in diameter; approximately 300 mm (12 in.) of the constant diameter jet tube protruded down from the jet board (see Fig. 3). This jet was used in all of the authors' previous ground vortex work. Stewart[10] pointed out, however, that this jet may have been too confined for the size of the wind tunnel. A Plexiglas extension was therefore constructed that fit over the jet tube and smoothly contracted the jet to an inner diameter of 38.1 mm (1.5 in.). Many of the previous measurements were repeated with this smaller jet, which was also used for most of the high speed motion pictures.

The unsteady flowfield was studied both qualitatively and quantitatively. High speed movies were taken with a Redlake Model 41-0004 Hycam camera using both Kodak 4-X black and white and Kodak Echtachrome color 16-mm film. A pair of Sylvania FF-33 floodflash flashbulbs located behind the wind tunnel provided illumination for several seconds. Later, a pair of 2400-W lights (Photographic Analysis Company) replaced the flashbulbs. Circuitry was built such that up to four smoke wires could be operated sequentially over a period of about 2 s. The smoke wires were located along the centerplane and far upstream of the ground vortex. Framing rates up to 2000 frames per second were possible with this setup.

Unsteady measurements such as frequency spectra and coherence properties were obtained with two hot wires mounted at various locations in the flowfield. Their signals were first linearized, then processed by a two-channel Spectral Dynamics SD375 Dynamic Analyzer. Mean velocity surveys were obtained with a two-component backscattering LV system. The LV data rate was typically between 100 and 200 samples per s, and 500 data samples were collected and averaged at each survey position. Smoke was introduced from four small holes along the ground plane to provide seeding. Further details about the LV equipment and measurements can be found in the report of Cimbala et al.[5]

Results

Detailed Measurements with the Larger Jet

The ground vortex tests consisted of surveying the mean velocity flowfield in detail, visualizing the flowfield on film, finding the frequency composition at various locations in the flow, and obtaining correlation and coherence information between pairs of points. Parameters varied in the study included jet diameter D_j, height h between the jet exit plane and the ground, jet velocity V_j, and freestream velocity V_∞. Most of the detailed measurements were obtained with the 76.2 mm (3 in.) jet at $V_j = 45.7$ m/s (150 ft/s), $h/D_j = 3$, and $V_\infty = 4.57$ m/s (15 ft/s). The Reynolds number of this jet was therefore approximately 2.3×10^6.

The results of the LV flow measurements are presented in Fig. 4, which is a vector plot of the vortex velocity field. The vortex center is approximately 336 mm (13.2 in.) ($x_v/D_j = 4.4$) upstream of the jet centerline. The vertical survey through the vortex center revealed a maximum velocity of 7.7 m/s (25.2 ft/s) in the direction of the freestream and a maximum wall jet velocity (opposite in direction to that of the freestream) of 15.2 m/s (50 ft/s). These two extrema were measured at $y = 185$ and 9.5 mm (7.28 and 0.375 in.), respectively. The boundary layer on the ground plane upstream of the vortex at $x = 762$ mm (30 in.) was measured to be approximately 20 mm (0.8 in.) thick.

A mean velocity vector plot such as shown in Fig. 4 is misleading because the flowfield is in reality extremely unsteady. In order to visualize the flow and to study how the characteristics of the ground vortex change with time, several high-speed movies of the flowfield were taken. The smoke-wire technique was used to visualize the flow, while a high-speed camera recorded the action on film. In all cases, the smoke wires were placed along the centerplane of the flowfield. Upon viewing the films, the severe unsteadiness of the flowfield was confirmed. Several specific aspects of the unsteadiness will now be discussed.

As in the previous still photographs of the ground vortex (see Ref. 5 and also Fig. 2a), shear layer vortices are sometimes visible in the high speed films. These vortical structures are shed from the upstream lip of the jet and are observed to amalgamate with each other as they travel along the edge of the jet and as they are turned upstream by the ground plane. It is difficult to follow individual vortices in the films, but it appears that they amalgamate further as they convect into the ground vortex. They appear to join with the large ground vortex and lead to the turbulent appearance of the ground vortex. Occasionally some of these vortices continue to convect around the circumference of the ground vortex.

As was noted previously,[5] the ground vortex itself is quite unsteady, both in size and shape, and also in location. The films reveal a large-scale low-frequency pulsating behavior, which will be referred to as puffing of the ground vortex. The sequence of this puffing behavior is as follows. First the ground vortex is very small, but growing. The shear layer vortices, which convect with the wall jet, seem to merge one by one into the growing ground vortex. As the ground vortex continues to grow, it eventually becomes too large for the flowfield to sustain. At this point the entire flowfield breaks up violently, and the large ground vortex is swept downstream. Immediately, a new small ground vortex begins to grow upstream, and the cyclic process repeats itself. In some of the films, two ground vortices or separation bubbles seem to be present at the same time. Apparently a new small vortex sometimes forms before the larger one has completely broken up. The entire process is extremely unsteady, and the above sequence describes only the gross features of the flow. The smaller scale randomness associated with turbulence makes observation difficult.

Although great care was taken to mount the smoke wire(s) as close as possible to the centerline of the flowfield, the smoke did not always remain in the plane of the centerline. This implies that the ground vortex is not only unsteady, but highly three-dimensional. (This can also be observed in the still photograph of Fig. 2b.)

Hot-wire anemometry measurements were taken to obtain more quantitative information about the unsteadiness of the flowfield. Two hot wires were utilized during the testing. The first (referred to as hot wire A) was kept at a fixed distance of 1.08 jet diameters from the jet exit plane just beyond the shear layer, while the second (hot wire B) was moved to various positions to explore the rest of the flowfield. The three major characteristics of the flowfield that were investigated were the frequency spectra, the correlation between the two hot-wire signals, and the coherence of the two signals. These detailed dual-probe tests were performed only for the larger jet at $h/D_j = 3$ and $V_\infty/V_j = 0.1$.

Many of the frequency spectra revealed broadband humps indicating concentrations of unsteady turbulent energy. Figure 5 shows an example; this spectrum was obtained with hot wire B located near the streamwise vortex center, but close to the ground. The center frequency of the broadband hump in this case is at approximately 4 Hz. Figure 6 shows the center frequency of the spectral humps at various other positions in the flowfield. At the position of hot wire A, the central frequency is 460 Hz, which is the local passage frequency of shear layer vortices shed from the lip of the jet. These vortices amalgamate, as seen in Fig. 6, where the center frequency decreases steadily as hot wire B is moved along the path of the shear layer vortices. This decrease of frequency continues until about $x/D_j = 4$ along the ground plane, where a center frequency of approximately 4 Hz is observed. From that point on, in the region of the ground vortex and along the predicted path of the vortices, the measured frequencies remain relatively low, and difficult to discern, but with a broad hump between approximately 2 and 10 Hz, similar to that shown in Fig. 5. Even when the second probe was placed further away from the ground plane and moved around to various points in the flowfield, the broad hump remained in this low frequency range.

Once this low frequency unsteadiness was identified, attention was focused on its source. Some possible sources include the jet itself, the upstream boundary layer along the ground board, the crossflow, and the periodic shedding in the wake of the jet protrusion. These were each investigated separately.

With a hot-wire probe positioned just inside the jet near the exit plane, frequency spectra were obtained with the crossflow off and with the crossflow on. For the case with no crossflow, no low frequency humps were observed in the spectra. When

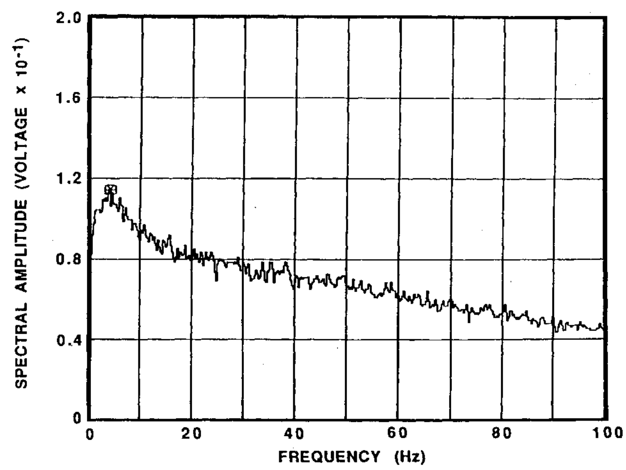


Fig. 5 Sample frequency spectrum; large jet at $h/D_j = 3$, $V_\infty/V_j = 0.1$. The hot-wire location was $x/D_j = 4.13$, $y/D_j = 0.17$; this is an example of the low frequency broadband hump.

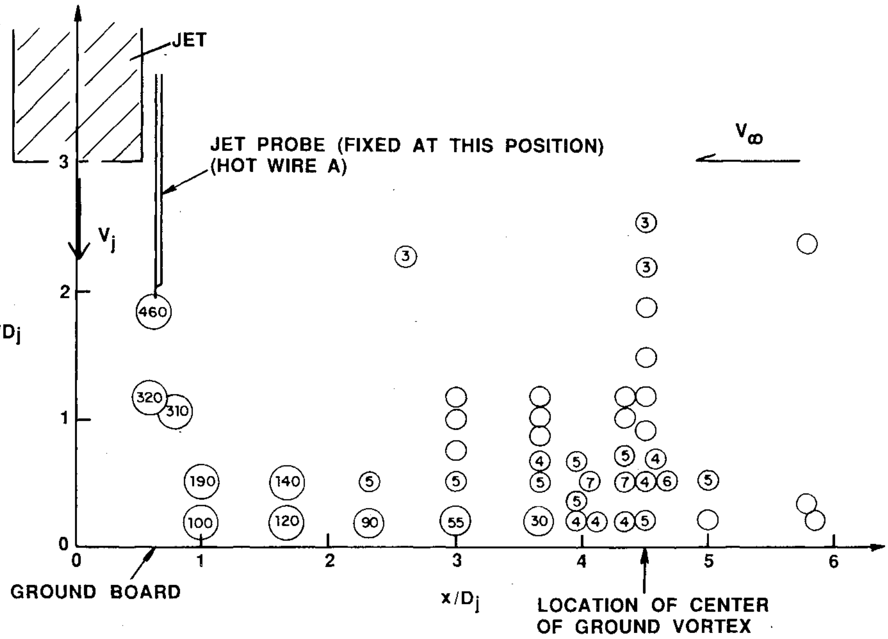


Fig. 6 Approximate central frequencies of broadband spectral humps at several spatial locations (values shown in Hz); large jet at $h/D_j = 3$, $V_\infty/V_j = 0.1$; open circles represent locations where measurements were made but no identifiable spectral humps were found.

the crossflow was turned on, the spectral amplitude at all frequencies increased, but no clearly defined humps were observed. This suggests that the observed unsteadiness of the ground vortex cannot come directly from oscillations in the jet. Furthermore, the signals from hot wires A and B did not correlate at all when hot wire B was placed near the ground vortex. This suggests that the shear layer vortices shed from the lip of the jet, while contributing to some of the higher frequency turbulent fluctuations, are not directly responsible for the low frequency oscillations of the ground vortex. Experiments were also performed with a roughened jet exit in an attempt to study the significance of the vortices shed from the lip of the jet. A 3.18-mm (0.125-in.) diam brass tube was inserted into the inner wall of the jet exit to disrupt the shear layer vortices shed from the jet. Frequency spectra were obtained for several locations. The approximate central frequencies corresponding to the spectral humps were compared to those corresponding to the standard case with a smooth jet exit (see Fig. 6). No significant difference was detected. This also indicates that the vortices in the jet shear layer do not significantly affect the low-frequency puffing unsteadiness of the ground vortex.

The nature of the freestream was investigated by placing a hot wire at positions far upstream of the ground vortex. Tests were conducted with the crossflow on and the jet off and then with both the crossflow and the jet on. For the jet-off case, frequency spectra were obtained, whereas for the case with the jet on, coherence data were obtained in addition to the frequency spectra. The same low-frequency broadband hump appeared between about 2 and 10 Hz in the case with the jet on, but no such hump could be found in the freestream when the jet was off. This indicates that the low-frequency energy detected in the ground vortex flowfield is not due to freestream oscillations. In other words, these frequency spectra dismiss the possibility that the unsteadiness of the ground vortex arises from periodicity in the freestream. The correlation and coherence data obtained with both jet and crossflow on possess similar traits to those at positions further downstream. Namely, both the hot wire near the jet exit and the one far upstream detect the same low frequency behavior in the flowfield. This indicates that the effects of the ground vortex oscillations are indeed felt far upstream. In other words, the low-frequency puffing influences the entire flowfield, but the source of this unsteadiness does not originate in the freestream.

The boundary layer was explored by placing a hot wire far upstream and close to the ground plane. Data were acquired for cases with only the crossflow on and for cases with both the jet and crossflow on. No correlation was found between oscillations in the boundary layer and the observed low-frequency puffing oscillations in the ground vortex. Furthermore, a test was conducted with air blown through a slot to energize the boundary layer just upstream of the ground vortex. The momentum of the injected air nearly balanced the momentum defect of the boundary layer so that the boundary layer was practically eliminated. While this caused the entire ground vortex to move significantly downstream, the blowing had little effect on the frequency of the puffing instability. This eliminates fluctuations in the boundary layer as the source of the ground vortex instability.

Finally, a hot wire was placed in the wake of the jet tube which protrudes down from the jet board (which was sketched in Fig. 3). A very well defined frequency appeared in the spectrum due to Kármán vortex shedding. However, this oscillation did not correlate with the puffing instability of the ground vortex.

This evidence suggests that the unsteadiness associated with a ground vortex does not originate with oscillations of the jet, the crossflow, the approaching boundary layer, or the wake of

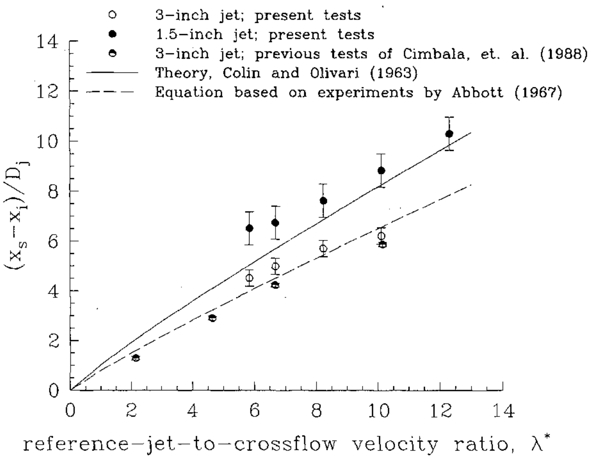


Fig. 7 Location of separation point as a function of reference velocity ratio for both the large and small jets at $h/D_j = 3$.

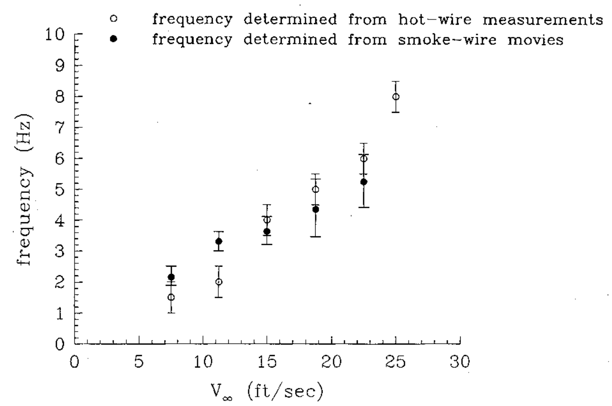


Fig. 8 Puffing frequency as a function of freestream velocity; small jet at $h/D_j = 3$ and $V_j = 45.7$ m/s (150 ft/s) for all cases.

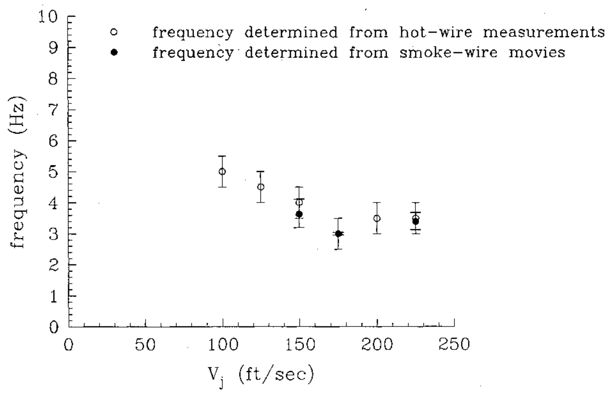


Fig. 9 Puffing frequency as a function of jet velocity; small jet at $h/D_j = 3$ and $V_\infty = 4.57$ m/s (15 ft/s) for all cases.

the jet tube. The source of the observed ground vortex unsteadiness must, therefore, be due to the gross features of the ground vortex flowfield.

Measurements with the Smaller Jet

As suggested by Stewart,[10] the larger jet used in the preceding experiments caused a large blockage effect in the wind tunnel. While this may have influenced the upstream penetration of the ground vortex, the blockage did not affect the qualitative results concerning the source of the unsteady puffing instability of the ground vortex. This was verified by installing a jet extension in the facility (see Fig. 3), which reduced the jet diameter by a factor of 2 to 38.1 mm (1.5 in.). Static pressure surveys on the ground board were repeated for both jet sizes at $h/D_j = 3$, in exactly the same manner as described in the authors' previous publication.[6] Results are shown in Fig. 7 and compared to the theory and experiments of Colin and Olivari[7] and Abbott.[8] Clearly a blockage effect is present, since the normalized ground vortex separation distance increased significantly for the smaller jet case. In fact, the new data show much better agreement with the theory of Colin and Olivari. The smaller jet was therefore used in the quantitative measurements of vortex height and frequency discussed below.

With h/D_j fixed at 3, the frequency of the ground vortex puffing oscillation was measured as a function of freestream velocity, as shown in Fig. 8. The hot wire was positioned at the streamwise center of the vortex and above the vortex center, where the strongest spectral broadband hump could be found. Smoke-wire movies were taken under identical conditions, but not simultaneously with the hot-wire measurements. The agreement between the frequency inferred from the movies and that measured directly by the hot wire is excellent. This confirms that the low-frequency energy found in the spectra is due to the large scale puffing oscillation of the ground vortex. Furthermore, the frequency increases linearly with V_∞. Note that V_∞ was varied while holding V_j fixed at 45.7 m/s (150 ft/s).

In a separate test, V_j was varied while holding V_∞ fixed at 4.57 m/s (15 ft/s). These data are shown in Fig. 9. Comparison of Figs. 8 and 9 shows that the puffing frequency is much more a function of freestream velocity than of jet velocity. In fact, at the high values of V_j (which correspond to small V_∞/V_j), the observed puffing frequency was nearly independent of jet velocity and asymptoted to a value of approximately 3.5 Hz, which corresponds to a Strouhal number (based on V_∞ and jet diameter) of $St = fD_j/V_\infty = 0.029$.

The vertical extent (height) of the ground vortex, although extremely important when ingestion of hot gases or debris into the engine inlet of a V/STOL aircraft is considered, has not been studied intensively in the past. Figure 10 shows normalized height of the vortex center h_{vc}/D_j as a function of velocity ratio for both jets. The center height was taken here to be the location of minimum turbulence intensity (the "eye of the storm") as measured with a hot wire. The vortex size decreases steadily with V_∞/V_j, as was also observed from the smoke-wire photographs of Ref. 6. At $V_\infty/V_j = 0.1$, $h_{vc}/D_j \approx 0.90$ for the larger jet, which agrees quite well with the center height $h_{vc}/D_j \approx 0.88$ as determined from the LV measurements of Fig. 4.

In Fig. 11, the vortex center height data have been normalized by the distance between ground vortex separation point x_s and jet impingement point x_i along the ground plane. This distance $(x_s - x_i)$ represents a characteristic dimension of the

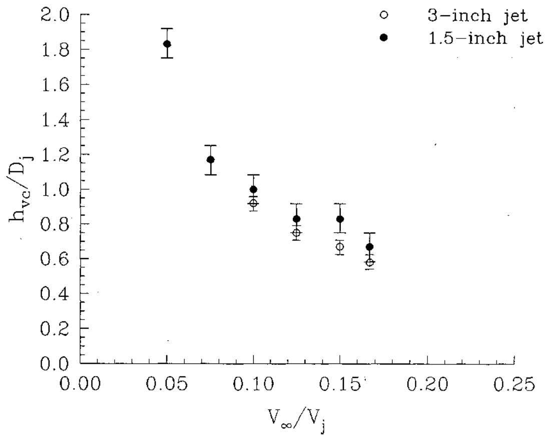


Fig. 10 Vortex center height as a function of velocity ratio for both the large and small jets at $h/D_j = 3$; center height taken as the location of minimum turbulence intensity inside ground vortex.

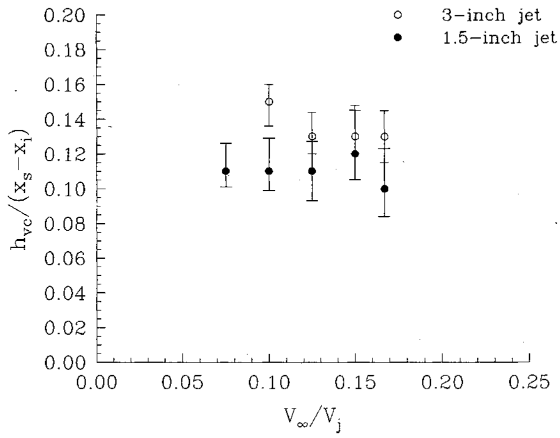


Fig. 11 Normalized vortex center height as a function of velocity ratio for both the large and small jets at $h/D_j = 3$; center height taken as the location of minimum turbulence intensity inside ground vortex.

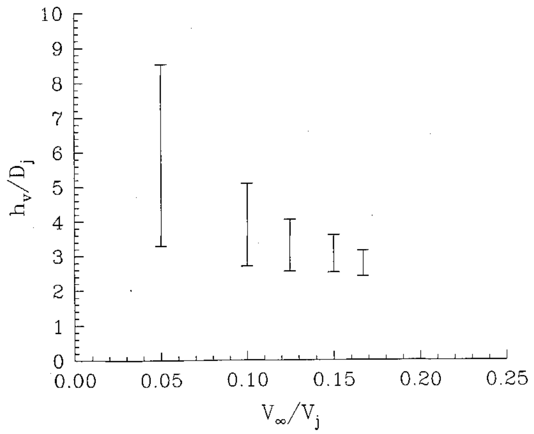


Fig. 12 Range of unsteady vortex height as a function of velocity ratio; small jet at $h/D_j = 3$; error bars represent minimum and maximum height of ground vortex as measured from high-speed motion pictures.

vortex. The normalized height is apparently independent of velocity ratio, with $h_{vc}/(x_s - x_i) \approx 0.11$. The data for the larger jet fall somewhat above this value since, as noted above, wind tunnel blockage forced the ground vortex further downstream.

Of more importance to aircraft is the maximum vertical height h_v of the ground vortex, as shown in Fig. 12. These data represent the height of the "edge" of the ground vortex, as visualized with the smoke wire. The very large error bars are a result of the severe unsteadiness of the flowfield and represent measurements of the minimum and maximum vortex height over the entire sequence of the high-speed flow visualization films. The length of the error bars decreases with velocity ratio, which confirms that the unsteadiness of the ground vortex is much more severe at the lower values of V_∞/V_j. Indeed, at $V_\infty/V_j = 0.05$, the edge of the ground vortex can occasionally extend to more than 8 jet diameters above the ground plane!

Conclusions

An investigation was conducted to identify and quantify the source and nature of the unsteady features of the ground vortex. The results are summarized as follows.

1) The ground vortex is highly unsteady and was observed to pulsate by expanding and contracting. This pulsating or puffing action occurs in a very low broadband frequency range and results in a significant unsteady variation in the size of the ground vortex.

2) Shear layer vortices shed from the lip of the jet exit amalgamate into the ground vortex and contribute to its higher frequency unsteadiness, but apparently do not correlate with the low-frequency puffing.

3) The low-frequency puffing phenomenon does not correlate with disturbances either in the crossflow, jet, wake of the jet tube, or the approaching boundary layer. In fact, no correlation could be found with any oscillations in the flowfield.

4) The major source of the low-frequency oscillations must, therefore, come from the gross features of the ground vortex flowfield itself. Namely, jet fluid appears to accumulate in the ground vortex, which grows to an unstable state that interacts with the crossflow. In other words, the ground vortex grows in size until the flowfield can no longer sustain itself. Large portions of the ground vortex then break away, due to the crossflow, a new ground vortex forms, and the process repeats itself. This process is nearly periodic, but the size, shape, and intensity of the breakup process is highly irregular, as observed on the high speed films.

5) The frequency of the puffing oscillation is highly dependent on freestream velocity but is not significantly affected by boundary layer thickness and is nearly independent of jet velocity. Although the location of the ground vortex is influenced by these parameters, the instability is not. This can be explained as follows. The ground vortex forms where the momentum of the upstream flowing wall jet can no longer resist the momentum of the crossflow. Jet velocity, height of the jet from the ground, freestream velocity, and boundary layer thickness will all influence this location. On the other hand, once the vortex is formed, it grows due to accumulation of jet fluid as described above. The rate at which jet fluid enters the ground vortex is expected to be roughly independent of its location once that location has been established. Thus only freestream velocity has significant influence on the frequency of the puffing instability.

6) The unsteadiness of the ground vortex leads to severe fluctuations in the height of the vortex, particularly at low values of V_∞/V_j, where the vortex height occasionally reaches more than 8 jet diameters. This has direct application to the hot-gas ingestion problem of V/STOL aircraft.

Acknowledgments

The authors are grateful for the funding provided by NASA Ames Research Center, Grant NAG 2-484. We would also like to acknowledge David Stinebring, who performed the LV measurements.

References

[1]Mitchell, K. (ed.), *Proceedings of the 1985 NASA Ames Research Center's Ground-Effects Workshop,* NASA Ames Research Center, Moffett Field, CA, NASA CP 2462, Aug. 1985.

[2]Margason, R. (ed.), *1987 Ground Vortex Workshop,* NASA Ames Research Center, Moffett Field, CA, NASA CP 1008, April 1987.

[3]*Proceedings of the International Powered Lift Conference,* Society of Automotive Engineers, Warrendale, PA, SAE P-203, Dec. 1987.

[4]*SAE Aerospace Technology Conference and Exposition*, Society of Automotive Engineers, Warrendale, PA, Sept. 1989.

[5]Cimbala, J. M., Stinebring, D. R., Treaster, A. L., and Billet, M. L., "Experimental Investigation of a Jet Impinging on a Ground Plane in the Presence of a Cross Flow," Naval Air Development Center, Warminster, PA, NADC Rept. 87019-60, March 1987.

[6]Cimbala, J. M., Stinebring, D. R., Treaster, A. L., Billet, M. L., and Walters, M. M., "Experimental Investigation of a Jet Impinging on a Ground Plane in Crossflows," *Journal of Aircraft*, Vol. 25, Oct. 1988, pp. 923–931.

[7]Colin, P. E., and Olivari, D., "The Impingement of a Circular Jet Normal to a Flat Surface with and without a Cross Flow," Von Kármán Institute Final Technical Report, United States Defense Technical Information Center, TR-AD688953, Jan. 1969.

[8]Abbott, W. A., "Studies of Flowfields Created by Vertical and Inclined Jet When Stationary or Moving Over a Horizontal Surface," Aeronautical Research Council, London, ARC CP No. 911, 1967.

[9]Parkin, B. R., and Henderson, R. E., "Garfield Thomas Water Tunnel Test Facilities," Applied Research Lab., Pennsylvania State Univ., University Park, PA, Jan. 1980.

[10]Stewart, V. R., private communication, Columbus, OH, 1988.