Development of the VIPER Fast-Time Wake Vortex Model
(Development, Assumptions, Examples, and Plans)

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Acknowledgements

- VIPER is being developed for the U.S. Federal Aviation Administration
  - Will be used to predict the evolution of aircraft-generated wake vortices under a variety of atmospheric conditions and aircraft flight regimes for evaluating new, proposed operational procedures
- Steve Barnes at AFS-440 is the Program Manager
- Wayne Bryant is also involved
- The support of both Steve and Wayne is gratefully acknowledged
What Is VIPER?

- A new fast-time wake vortex model
- VIPER stands for Vortex algorithm Including Parameterized Entrainment Results
- Self-consistent model based on control-volume analyses and the fluid laws for conservation of mass, momentum, and angular momentum
Why a New Fast-Time Wake Model?

- Want consistent treatment of stratification and entrainment/detrainment of fluid from the wake oval
  - Use recent advances in our understanding from lab experiments, LES simulations, and field observations
- Example: Nearly all models assume the wake cell density is constant with time
  - But, we know this is not true
Many Models Assume Constant Wake Cell Density

$$\rho_c = \rho(z_0)$$

$$\rho(z)$$
Many Models Use Circulation to Get $V$

- $V = \frac{\Gamma}{2\pi b}$ \quad \therefore \quad \Gamma \to 0 \text{ as } V \to 0$
- Not consistent with buoyancy

**Diagram:**

- $\rho(z) \quad \rho_c = \rho(z_0)$
- $\rho_c \quad V_0 \quad \rho_c$
- Buoyant deceleration implies reduction in $\Gamma$ as wake oval descends
- Rebounding requires a negative $\Gamma$
NWRA Lab Experiments Demonstrate Importance of Entrainment and Detrainment

(Laminar Vortex Ring
Re=3,000)

(Turbulent Vortex Ring
Re=12,000)

(Delisi and Pierce 2011, Circulation Measurements of Merging Vortex Rings, AIAA 2011-3033)
Our Current Picture of the Turbulent Vortex Cell

Look at movies of a laminar vortex ring and a turbulent vortex ring

Detrainment

Laminar cores

Turbulent detrained wake

Entrainment

Turbulent cell
Entrainment-Based Modeling Approach (What We Did)

- Introduced an entrainment model to detrain wake momentum and buoyancy from the wake vortex cell with turbulent vortices
- Self-consistent treatment of mass, momentum, and angular-momentum conservation laws
- Self-consistent treatment of ambient meteorological data (HW, CW, stratification, and turbulence)
- Allows $V=0$ at finite $\Gamma$
- Obtained model constants from aircraft landing data
The Model

Includes: Entrainment/detraiement from trailing edge of wake oval, stratification, headwind, crosswind and crosswind shear gradients
Model Assumptions (1 of 5)

- The wake oval density, $\rho_c$, varies with time as ambient fluid is entrained into and wake cell fluid is detrained out of the wake oval.

- The wake oval density is rapidly mixed and is, therefore, taken to be spatially uniform throughout the wake cell.
  - We know this is wrong since the cores and cell detrain at different rates. This will be modified in the next version.
Model Assumptions (2 of 5)

- Wake oval cross sectional area, $A$, is approximately constant during the wake cell evolution
  - Found from NWRA lab experiments; also seen in LES simulations
  - Also implies $b$ does not change with time (see next slide)
Average b vs. T from Lab, Field Data, and Numerical Simulations

Normalized Vortex Separation vs T

- NWRA Laboratory
- B47 contrails in Van Dyke
- Fred Proctor numerical, EPS * = 0.01, N* = 0
- Fred Proctor numerical, EPS * = 0.07, N* = 0
- Fred Proctor numerical, EPS * = 0.15, N* = 0
- Fred Proctor numerical, EPS * = 0.23, N* = 0
Model Assumptions (3 of 5)

- Entrainment and detrainment occur at the trailing edge of the propagating wake cell
  - Inferred from the movie earlier

- Entrainment and detrainment can be quantified in terms of an entrainment velocity, $u_e$, which is proportional to the shear velocity, $\Delta U$, at the edge of the wake cell ($u_e = c_e \Delta U$)
Model Assumptions (4 of 5)

- Entrainment rates for mass, momentum, and angular momentum are allowed to be different from each other.
- Variations in the atmospheric wind profile are gradual compared to the size of the wake cell.
- Shown to be justified from NWRA lab experiments with vortices in crosswind shear.
NWRA Lab Experiments on Vortex Tilting in a Shear Flow
(Delisi and Robins, 2006, Effects of Crosswind Shear on Trailing Vortex Evolution, AIAA 2006-1075)

Laboratory measurements of the velocity profile

Angle of tilt of the vortex cores

Tilt of vortex cores begins when the vortex cell first enters the region where the shear gradient is non-zero, and returns to zero when the vortex cell leaves the region where the shear gradient is non-zero. Thus, the shear gradient acts on the entire vortex cell, not just the vortex cores, and small perturbations not important.
Model Assumptions (5 of 5)

- The aircraft glide slope angle is $3^\circ$
  - $3^\circ$ is a typical glide slope angle
- The direction of propagation of the vortex pair is perpendicular to their separation
- The vortex pair is completely rolled up by the time we model it
  - Does not include detailed vortex rollup
Example #1: Low Shear Gradient, High Stratification, Low EDR
Example #2: Shear Gradient, Moderate Stratification, Moderate EDR
Development of an IGE Model

- The APA model is not a physics-based IGE model
  - In the APA-series of numerical models, the IGE region is modeled with a series of point vortices. These vortices are numerically efficient, but are not physically realistic, since they do not decay unless a user-defined circulation decay is prescribed. These vortices also ignore the effects of stratification and EDR.

- A physics-based IGE numerical model is currently being developed to combine with the OGE model
Future Plans (1 of 2)

- Continue IGE development
- Improve OGE model:
  - Include Magnus effect for spinning objects in mean wind
  - Why? Differing descent rates for vortices with identical circulation magnitudes are observed in the field data
Future Plans (2 of 2)

- Model vortex cores separately from their wake half-cell
  - Why? We know from NWRA lab experiments that entrainment rates, and therefore densities, differ for vortex cores and the wake oval
  - (Delisi and Lai, 2011, Detrainment from a Vortex Pair in a Nonstratified Fluid, Recent Progress in Fluid Dynamics Research, American Institute of Physics Press)
Questions for This Workshop

- What are the important aspects of OGE to model that are not being modeled?
- What are the important aspects of IGE to model?
- How much can we use field data and/or LES simulations as “truth”? 
Questions?