Flight-simulator study of airplane encounters with perturbed trailing vortices

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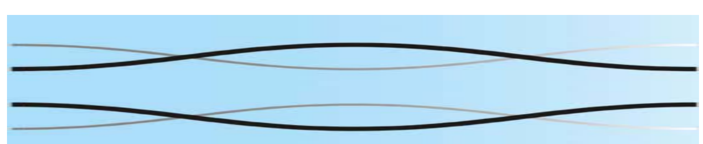
June 2010

(Reference: R.E. Loucel and J.D. Crouch, AIAA Paper No. 2004-1074)



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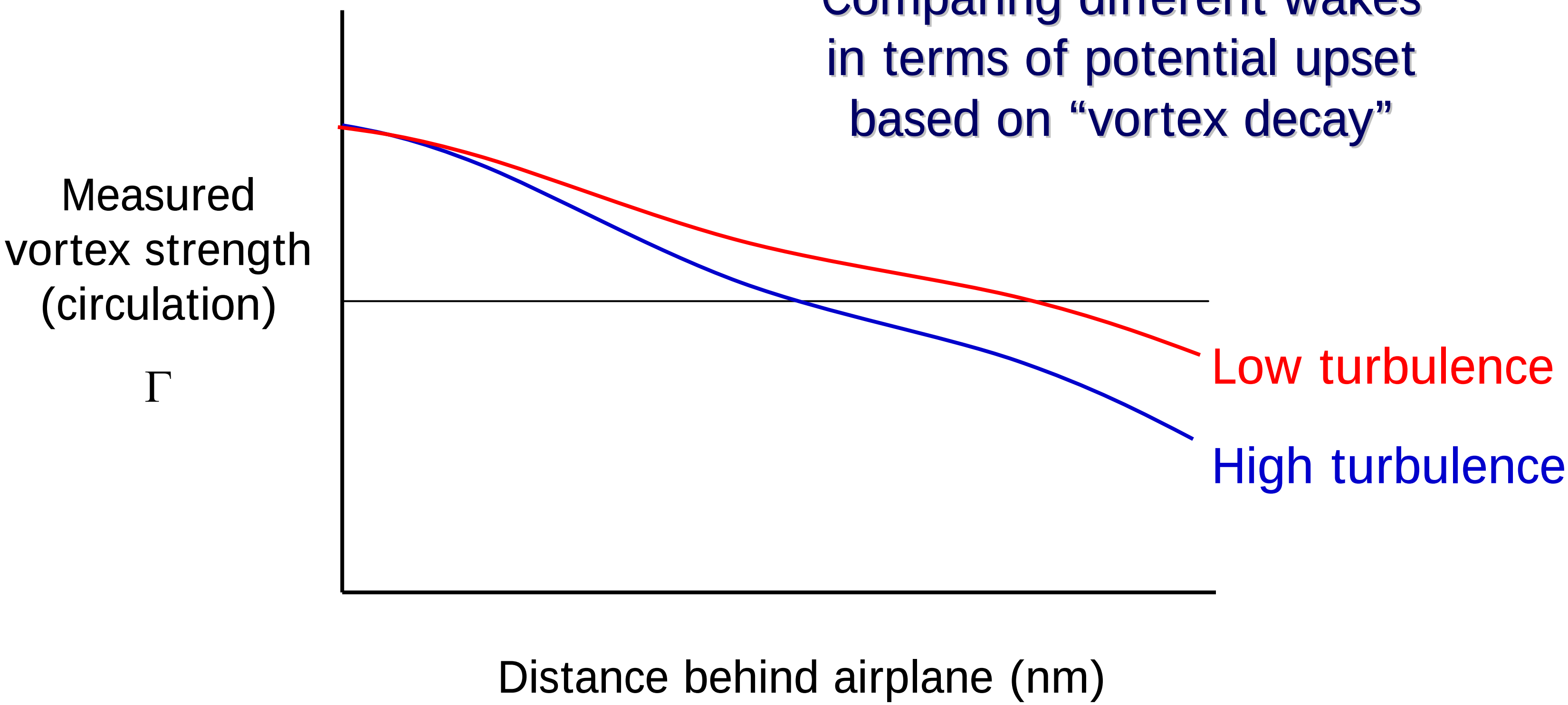
Overview

- Motivation
  - Role of vortex strength -vs- distortion
- Flight-simulator modeling
  - Vortex model – velocity flow fields
  - Airplane and autopilot
- Vortex-encounter results
  - Straight vortices – need for fast-time simulation
  - Effects of vortex distortion
  - Simple measures for “wake severity”?
- Conclusions

Motivation for Study –

Encounter upset depends on vortex strength

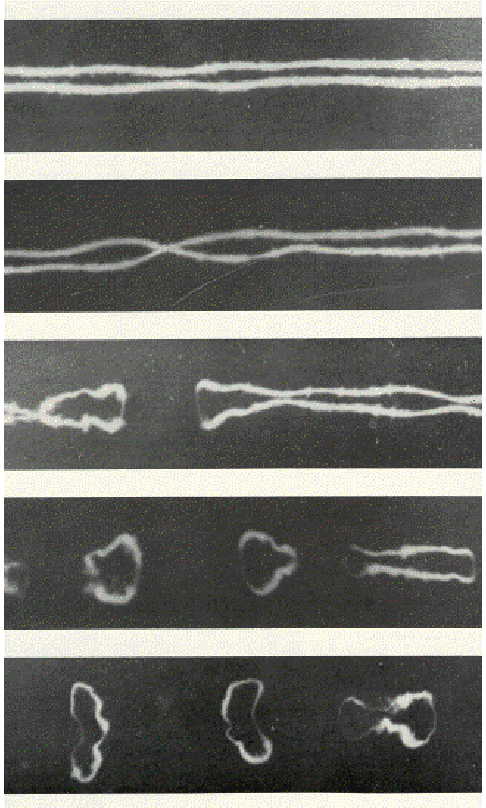
Comparing different wakes
in terms of potential upset
based on “vortex decay”



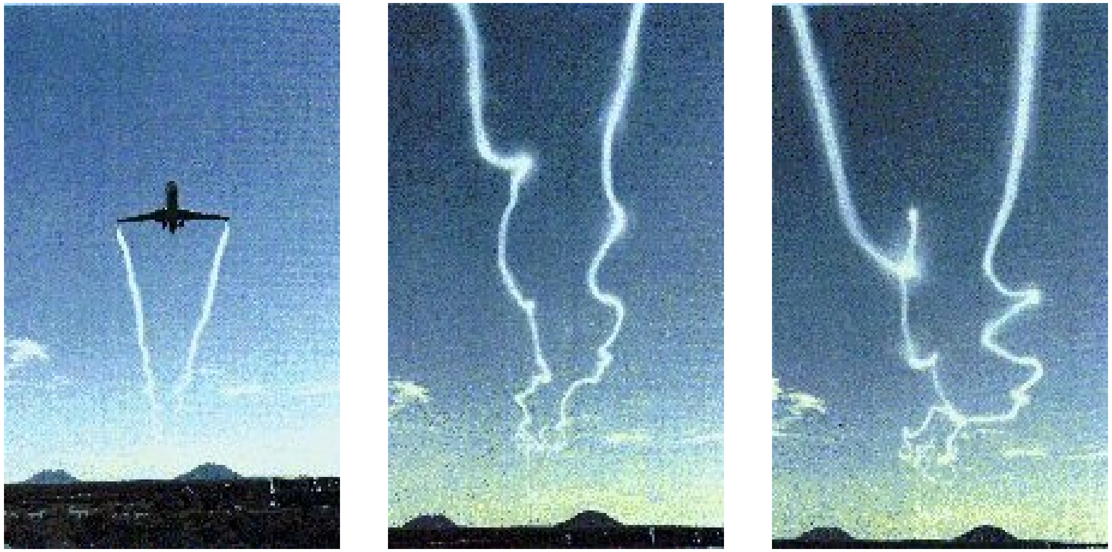
How much better is the high-turbulence case?
How to compare vortices?

Motivation for Study –
Background turbulence also leads to distortion and breakup

"Low turbulence"
Breakup via Crow instability
excited by turbulence



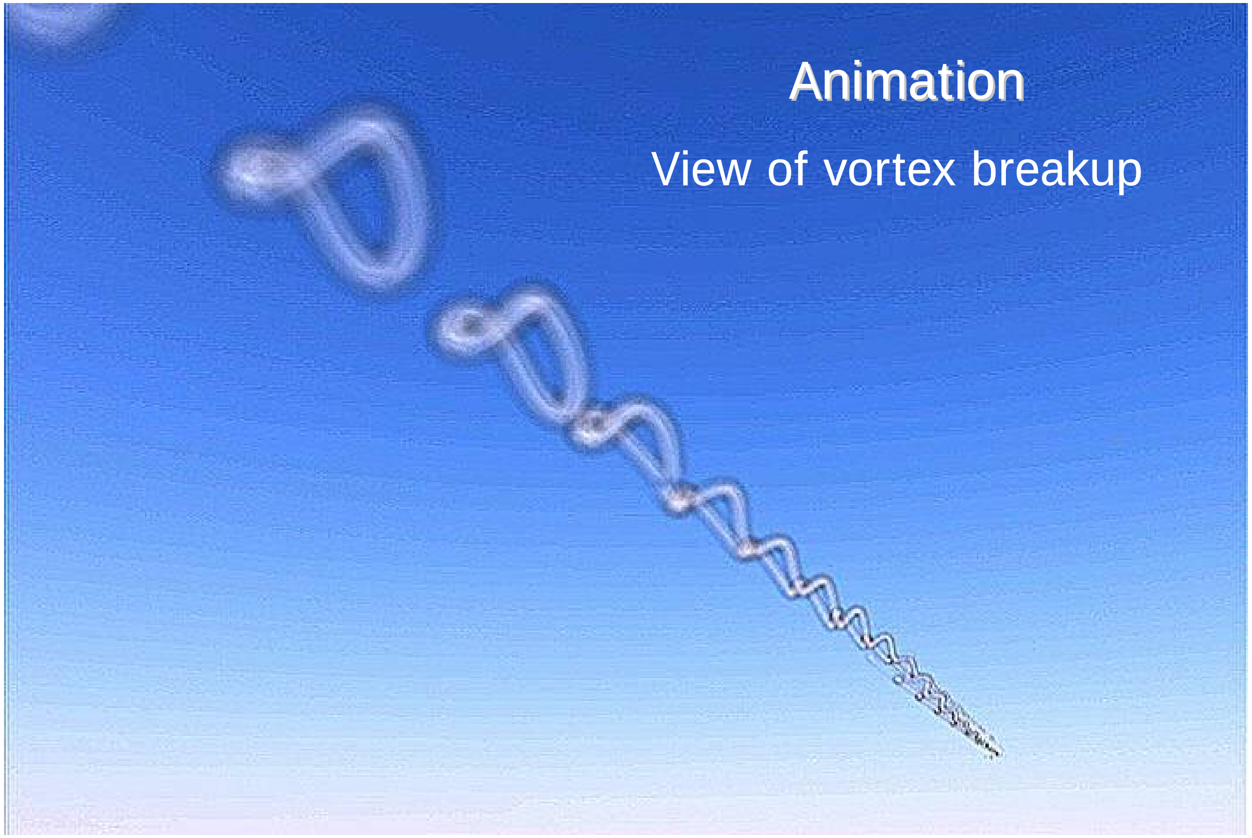
"High turbulence"
727 wake at INEEL Test Range
Images from NOAA (1990)



0 8 sec 16 sec

Role of background turbulence in encounters?
Decay? Distortion? Breakup?

Motivation for Study –
Vortex distortion critical to upset assessment

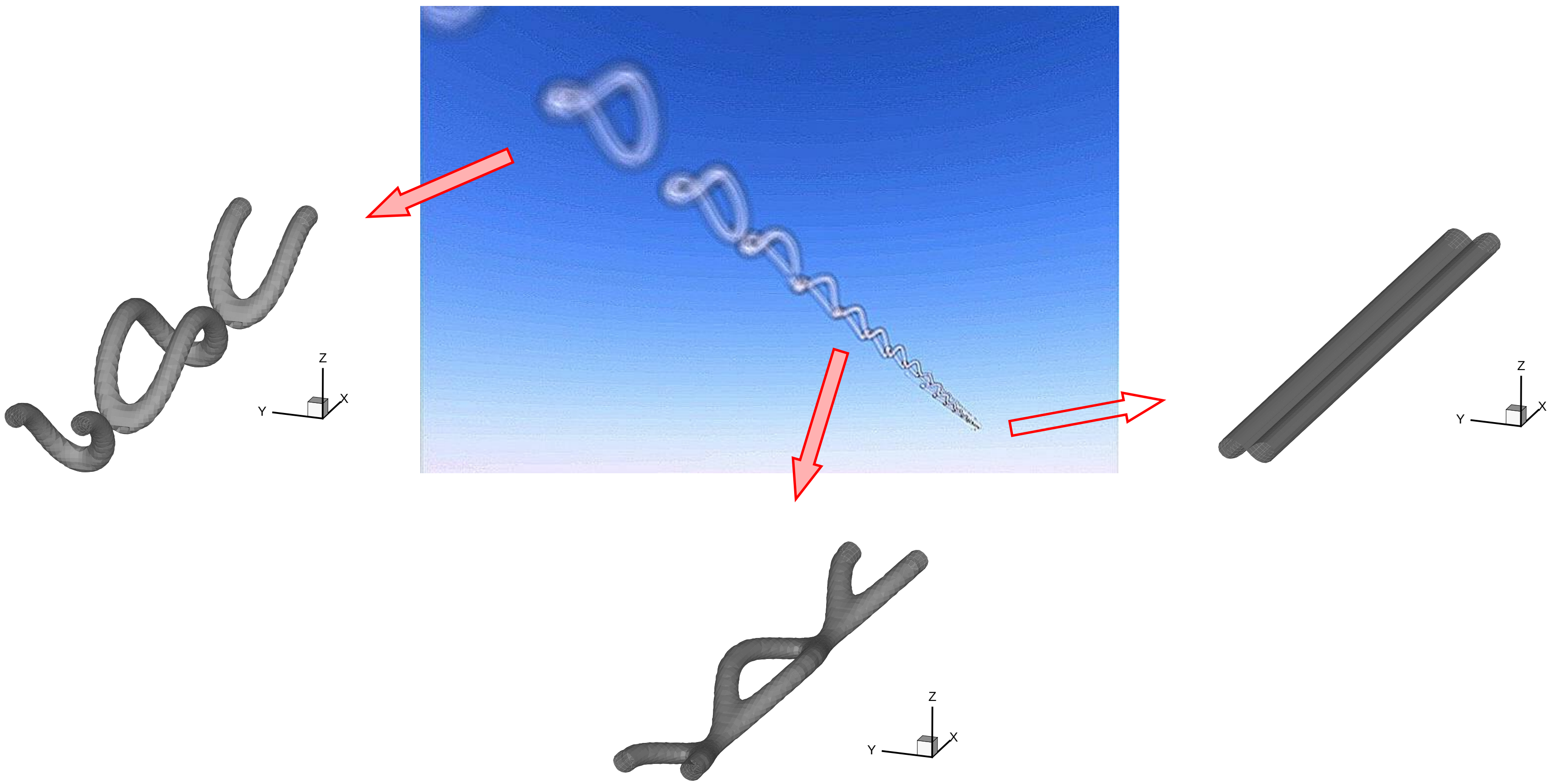


At what stage is an encounter benign?
Similar levels of upset?

Vortex Model – for Fast-Time Simulation

- Vortex filaments “frozen” in space and time

Airplane at fixed following distance



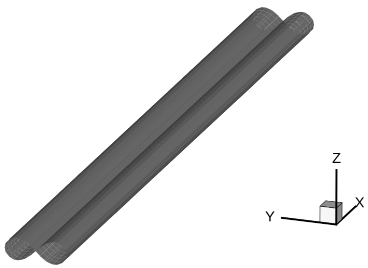
Vortex Model – for Fast-Time Simulation

- Straight vortices: analytical solution for velocities
- Wavy vortices: numerical integration for velocities
  - Integrate over 3 wavelengths w/ analytical far-field model
  - Waviness based on stability theory
  - Straight-filament approximation inside the core
- Ring vortices: numerical integration for velocities
  - Integrate over 3 rings w/ analytical far-field model
  - Ring shape based on experimental observation
  - Straight-filament approximation inside the core

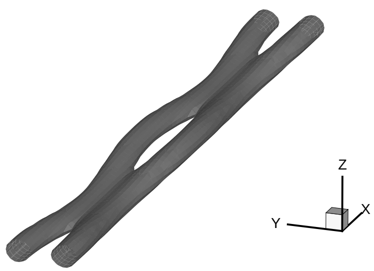
(Extending integration over 5 wavelengths results in < 1% change in local velocity)

Vortex Flow Fields

Contours of velocity magnitude

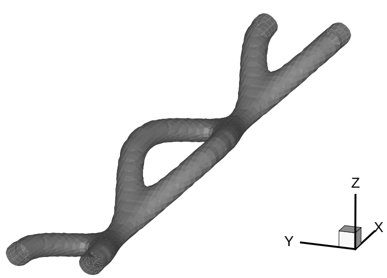


Straight



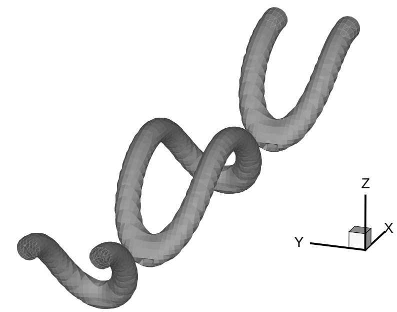
Wavy

$A_v = 0.1$



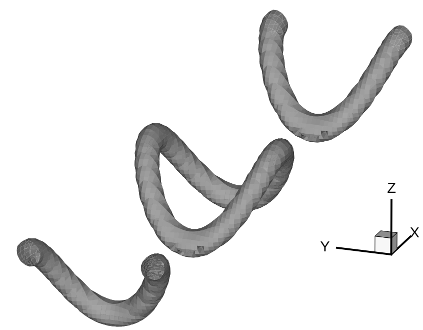
Wavy

$A_v = 0.4$



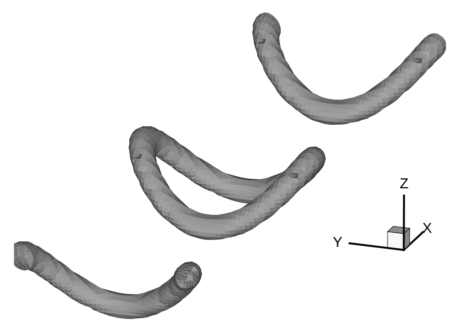
Rings

$T_v = 0.2$



Rings

$T_v = 0.5$



Rings

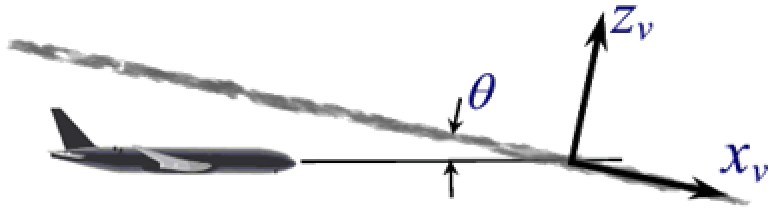
$T_v = 0.8$

Flight-Simulator Model

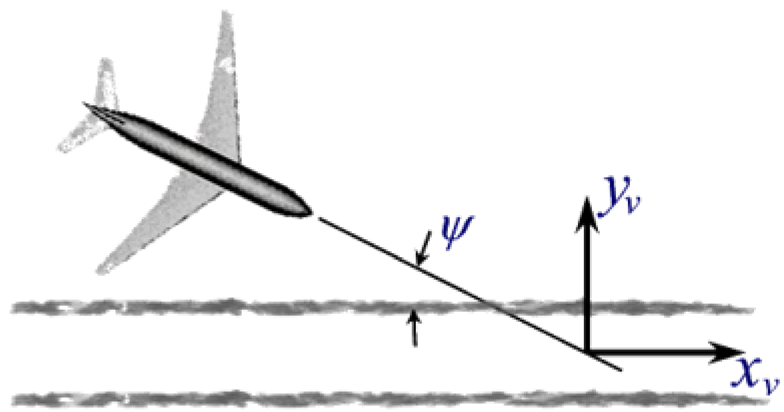
- 737-300 six degree-of-freedom simulation
- Vortex effects modeled using strip theory
  - Wings, horizontal tail, vertical tail
  - Δ velocity from vortices calculated on each strip
  - Δ lift calculated from uniform-flow database
  - Final sectional-lift increment adjusted by spanload function
- Standard 737-300/400/500 autopilot
  - Roll mode: heading select with a 15º bank-angle limit
  - Pitch mode: altitude hold with autothrottle and speed select

Vortex Encounter Parameters

Airplane in level flight



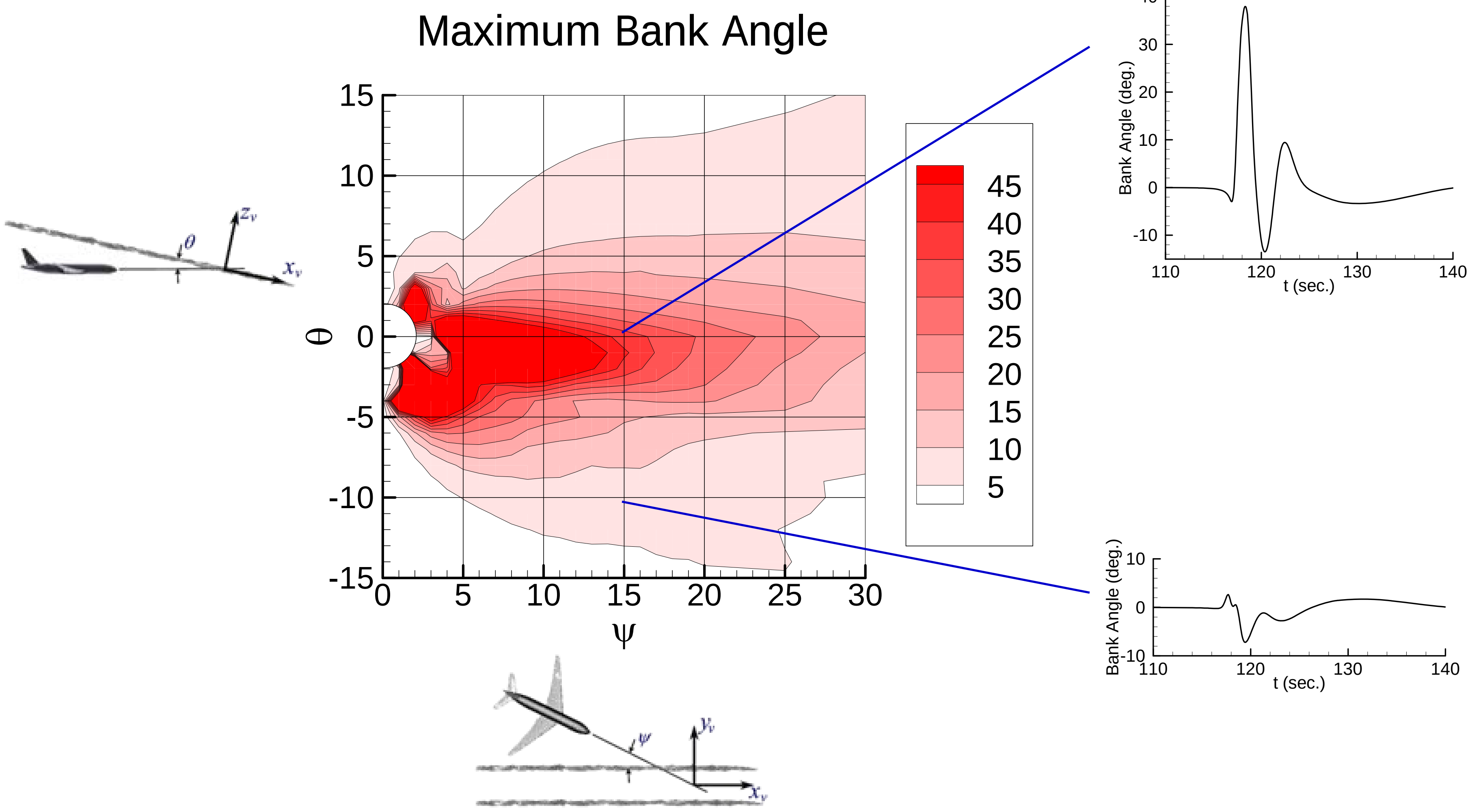
Wake Pitch Angle



Wake Grazing Angle

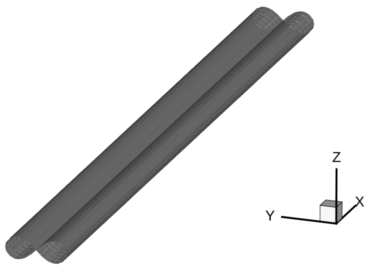
Vortex Encounters with Straight Vortices

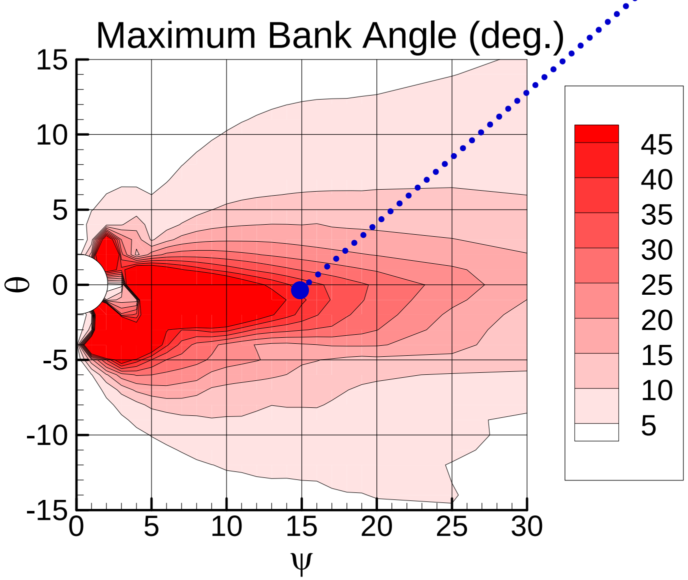
Wake corresponds roughly to a 767-sized airplane

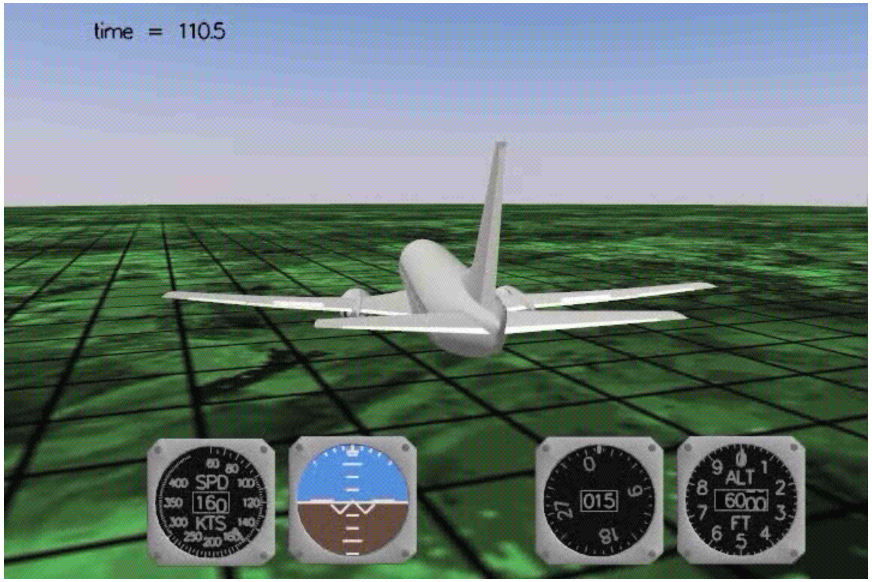


Vortex Encounters with Straight Vortices

Wake corresponds roughly to a 767-sized airplane



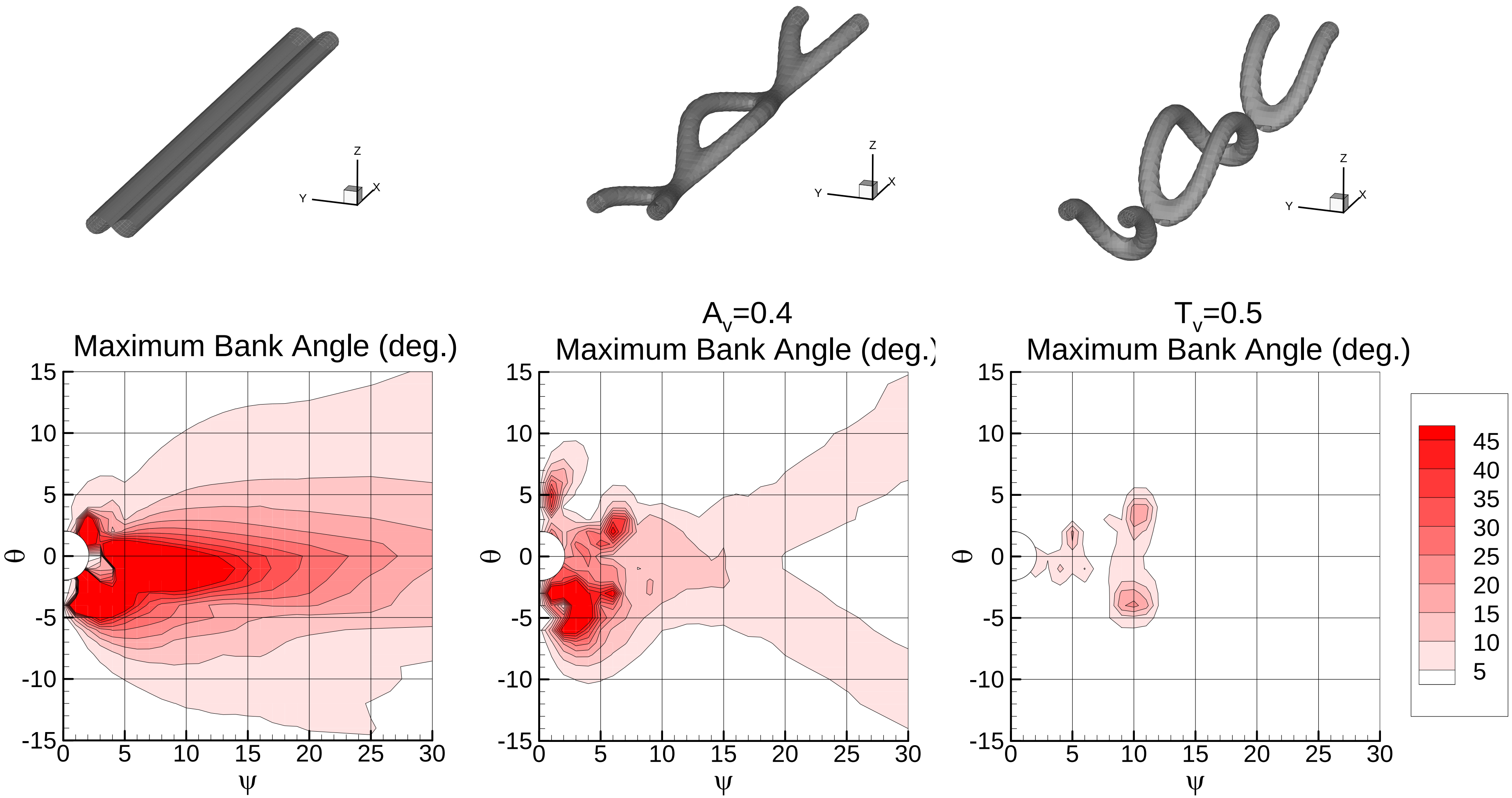




High variability with grazing angle
Need fast-time simulations to capture worst case

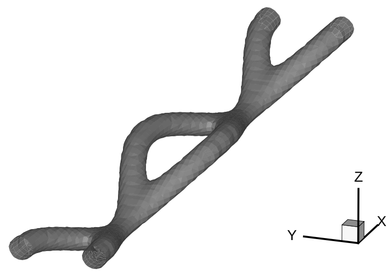
Vortex Encounters with Distorted Vortices

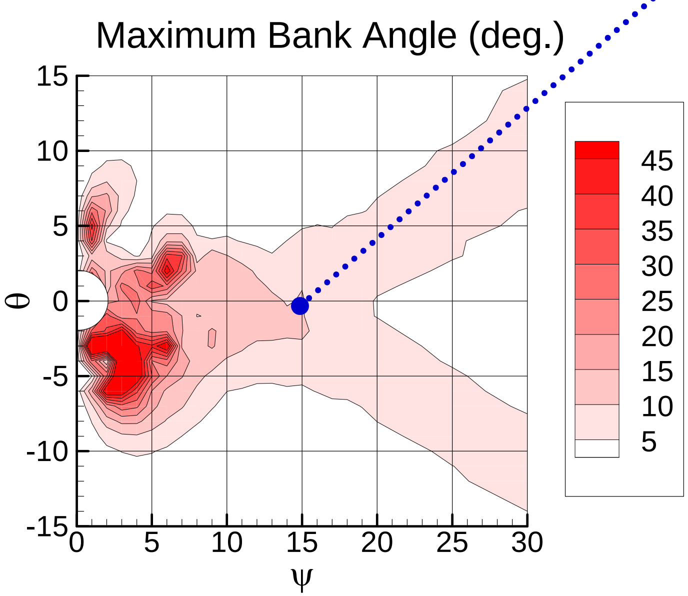
Wake corresponds roughly to a 767-sized airplane

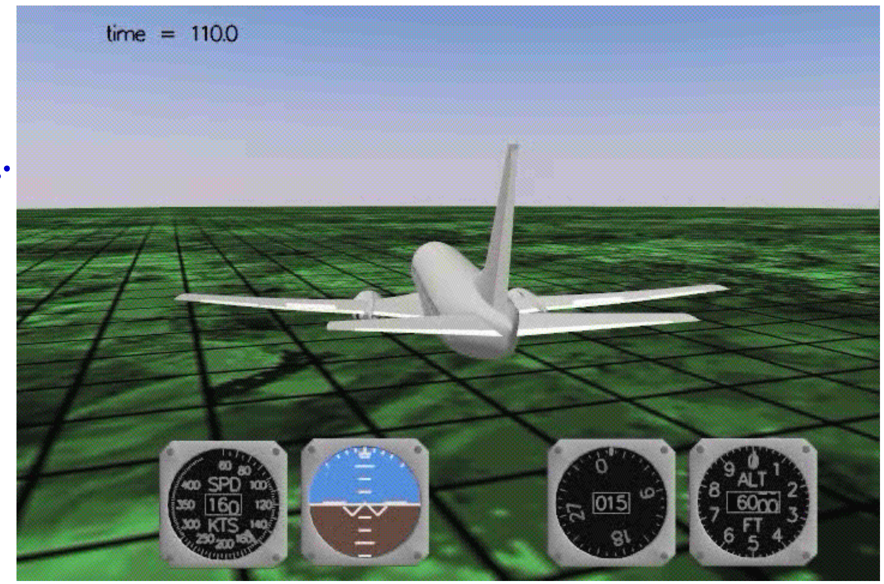


Vortex Encounters with Wavy Vortices

Wake corresponds roughly to a 767-sized airplane



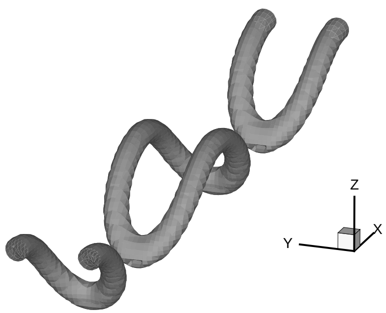


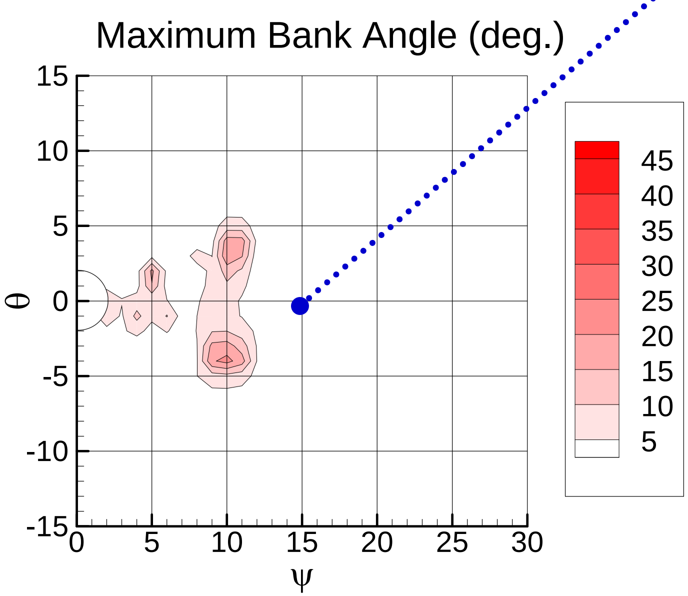


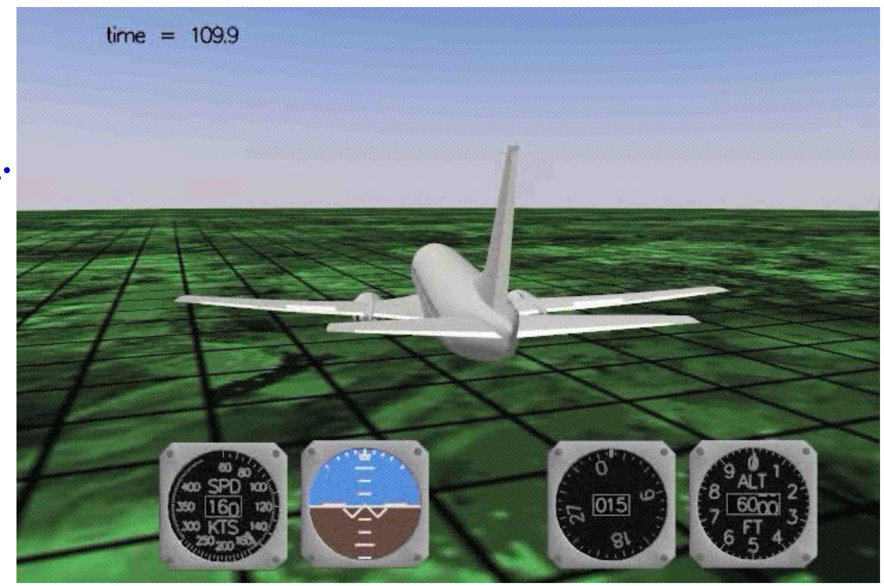
$A_V = 0.4$ (~ 2 nm behind airplane)

Vortex Encounters with Ring Vortices

Wake corresponds roughly to a 767-sized airplane







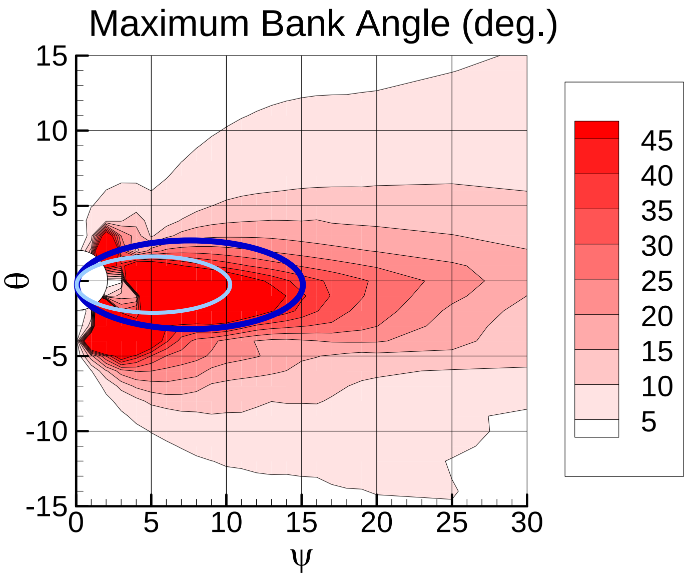
T_V = 0.5 (~ 2.7 nm behind airplane)

A simple assessment of potential severity?

Focus on high-probability grazing angles

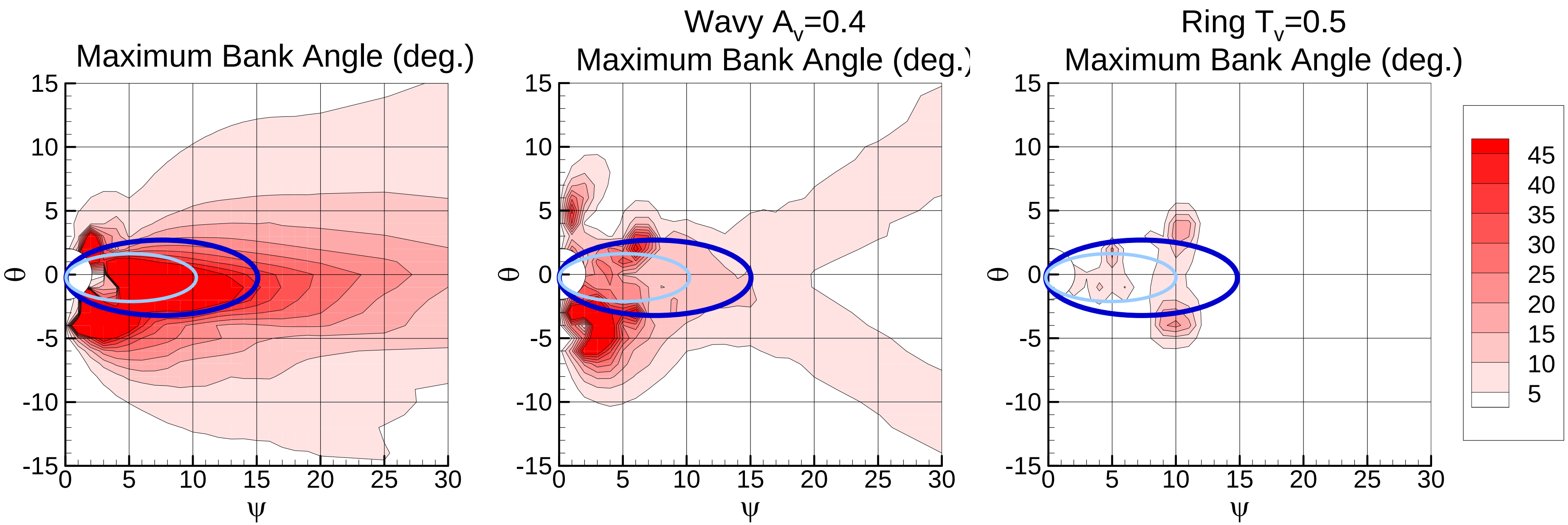
Consider concept of
“tunnel in the sky”

Maximum grazing angle is limited by size of box and wind profile



A simple assessment of potential severity?

Change in upset severity due to vortex distortion and breakup

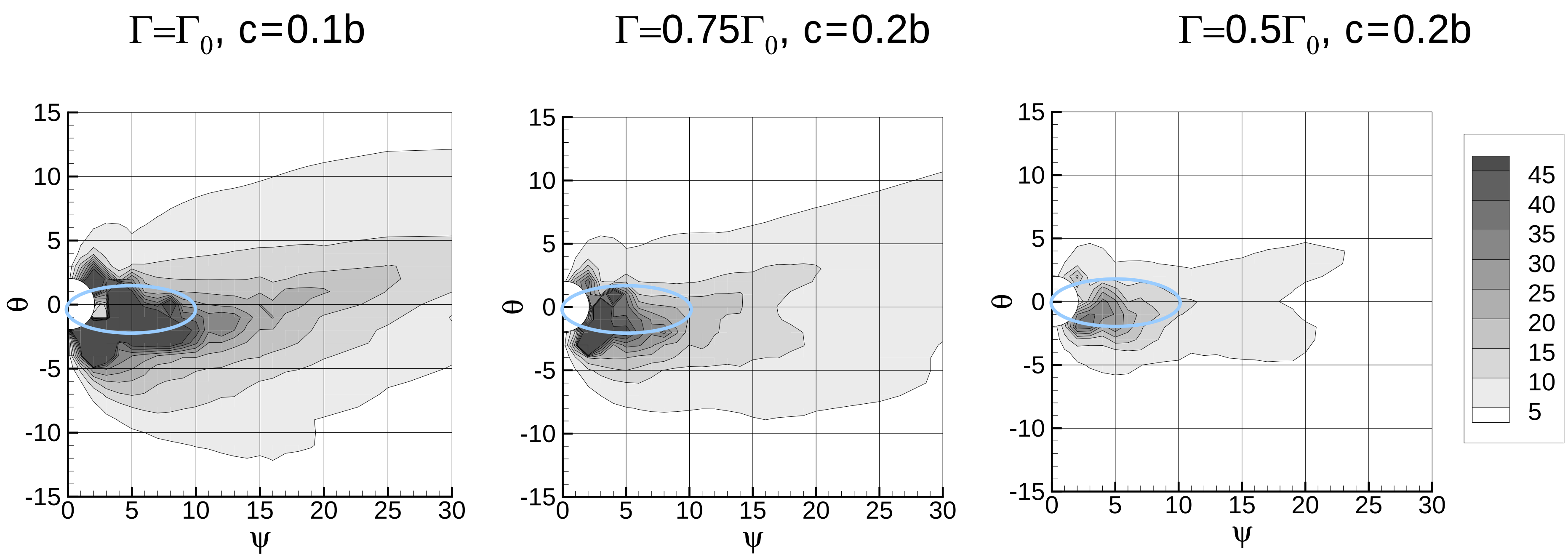


A simple assessment of potential severity?

Change in upset severity due to vortex strength

Assume mildly wavy vortices

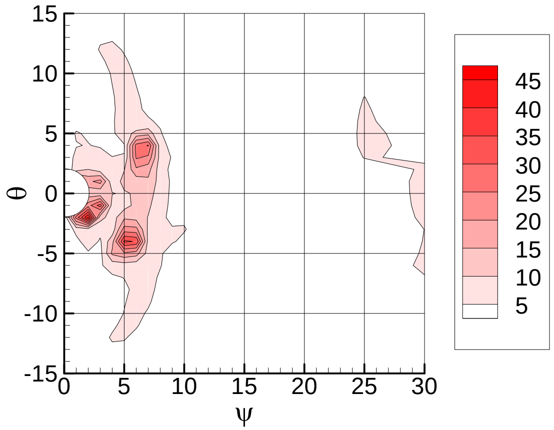
w/ A_v=0.1, Γ_0=372 m^2/s c=0.1b



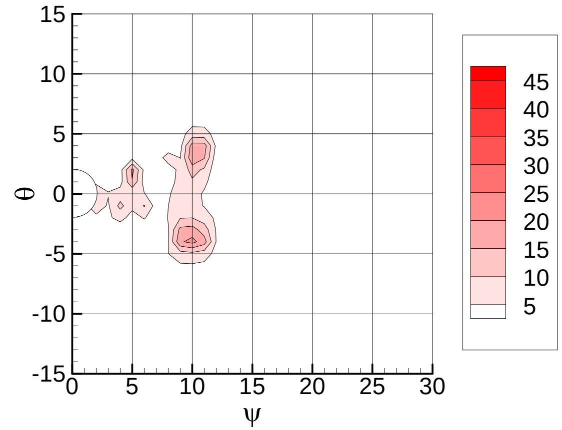
Encounters with Ring Vortices at Different Times in Breakup Process

Wake corresponds roughly to a 767-sized airplane

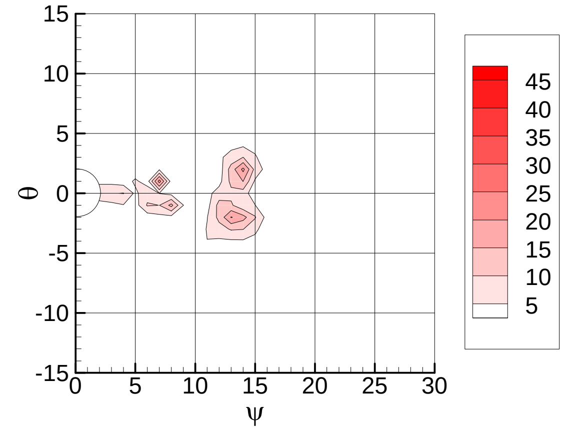
Maximum Bank Angle Contours



$T_V = 0.2$



$T_V = 0.5$

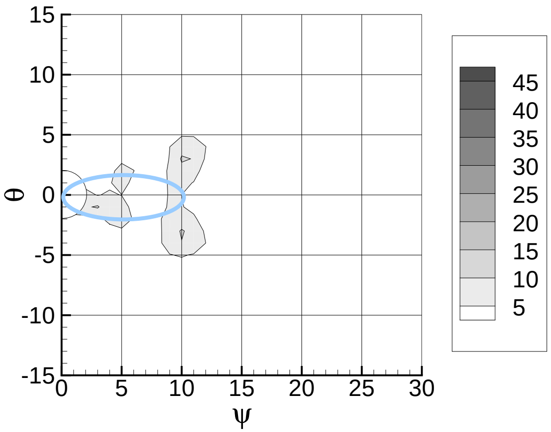


$T_V = 0.8$

Encounters with Ring Vortices for Different Sized Airplanes

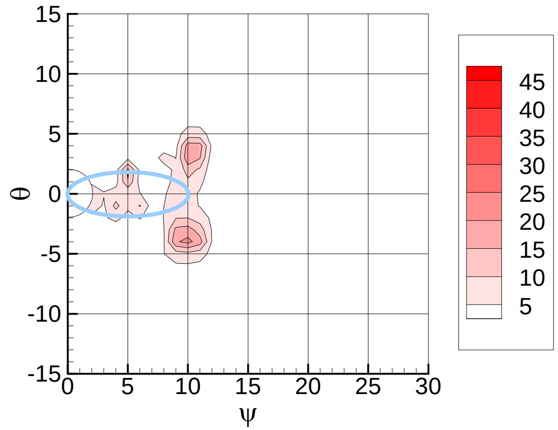
Wakes correspond roughly to 737-, 767-, and 747-sized airplanes

Maximum Bank Angle Contours



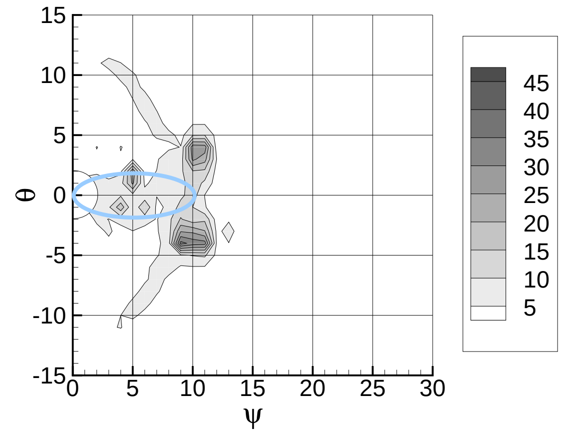
737-sized

$T_V = 0.5$



767-sized

$T_V = 0.5$



747-sized

$T_V = 0.5$

Conclusions from Vortex-Encounter Study

- ⇨ Significant reduction in maximum bank angle, as experienced by an encountering airplane, due to vortex distortion and breakup
- ⇨ Large numbers of simulations required to assess potential upset severity (Fast-time simulations)
- ⇨ Potential upset may be linked to vortex characteristics using a simple measure
  - ⇨ Reduced magnitude
  - ⇨ Reduced likelihood of occurrence