Real-time Simulation of Wake Vortices

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Overview

- CFD methods to produce wake vortices
- Organisation and compression of vortex data
- Real-time access to vortex data
- Integration of the vortex model in a flight simulator
- Conclusions

Background

- Threat from wake vortex encounters
- Trends: larger aircraft, free flight, increasing traffic density
- Simple models of vortices used in flight training – simple rotational airflows
- Dynamic and longitudinal elements are not modelled – instabilities in the flow field

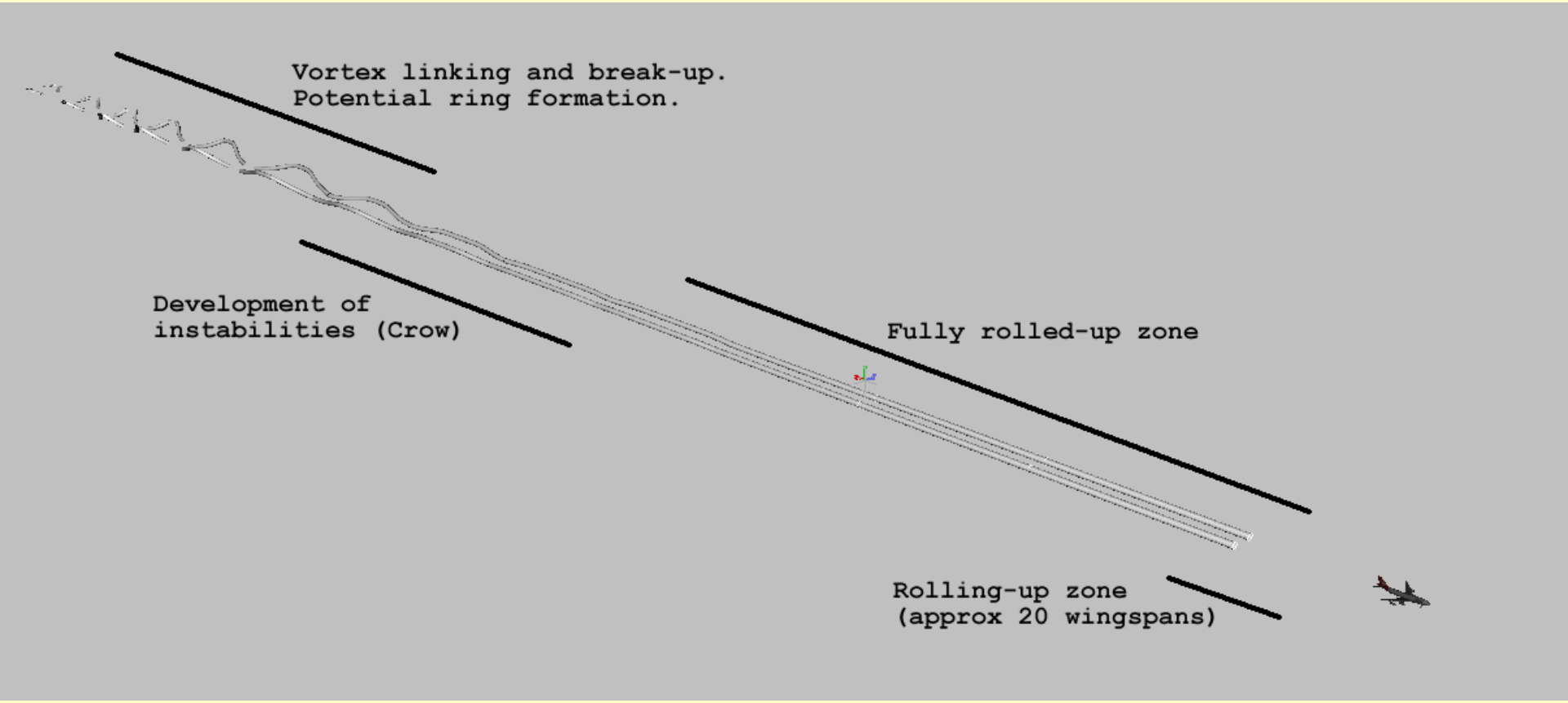
CFD Methods

- Several non real-time CFD models of vortices have been developed including wake decay and instabilities
- Large Eddy Simulations (LES) are computationally intensive – 2 weeks on a 30 processor cluster
- Data – 20 GB for 200 s of vortex data to represent 3D flow fields
- Flow data is specific to the aircraft generating the vortex and the prevailing atmospheric conditions

The Problem

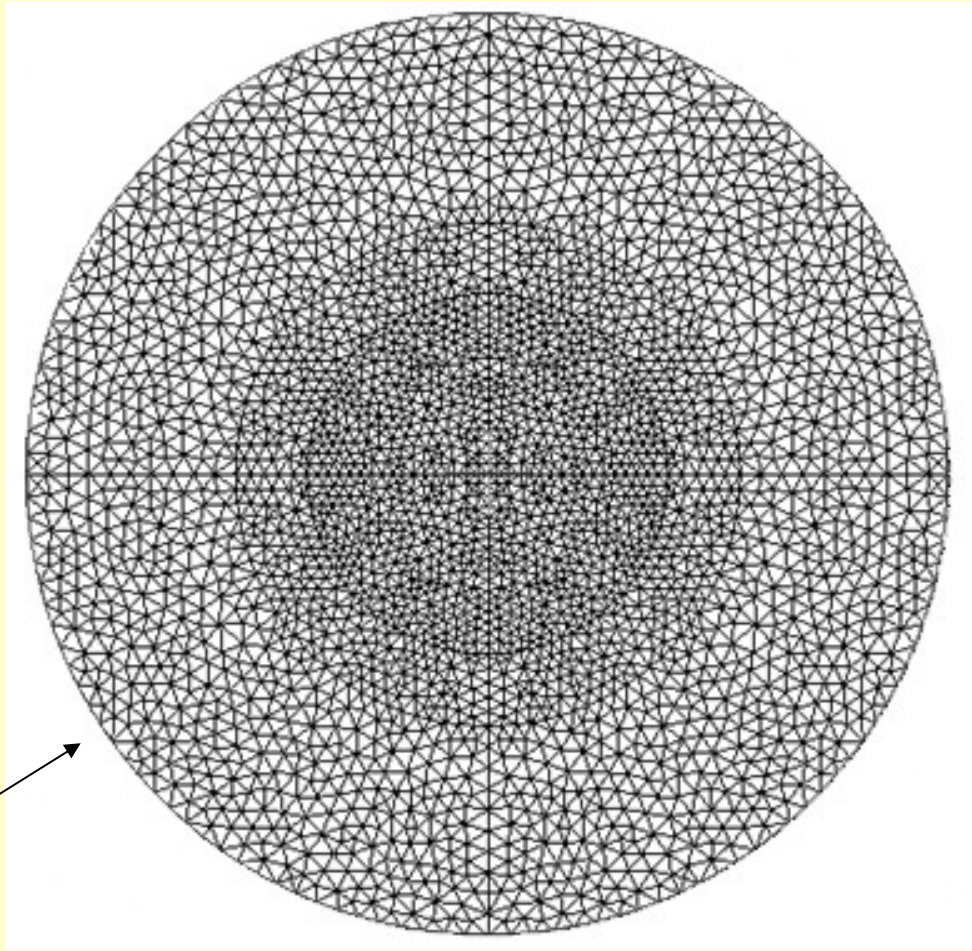
- Generate wake vortex data from an off-line CFD model
- Access the CFD data in real-time
- Compute the interaction between the vortex and the aircraft
- Validate the model?
- Render the vortex in the visual scene
- Compute and visualise the airframe structural loading

Wake Vortex Structure



CFD Data

Property	
Period of wake decay	200s
Tetrahedra per file	1871728
Total solution size	>20 GB



2D slice through the 3D mesh

CFD Data

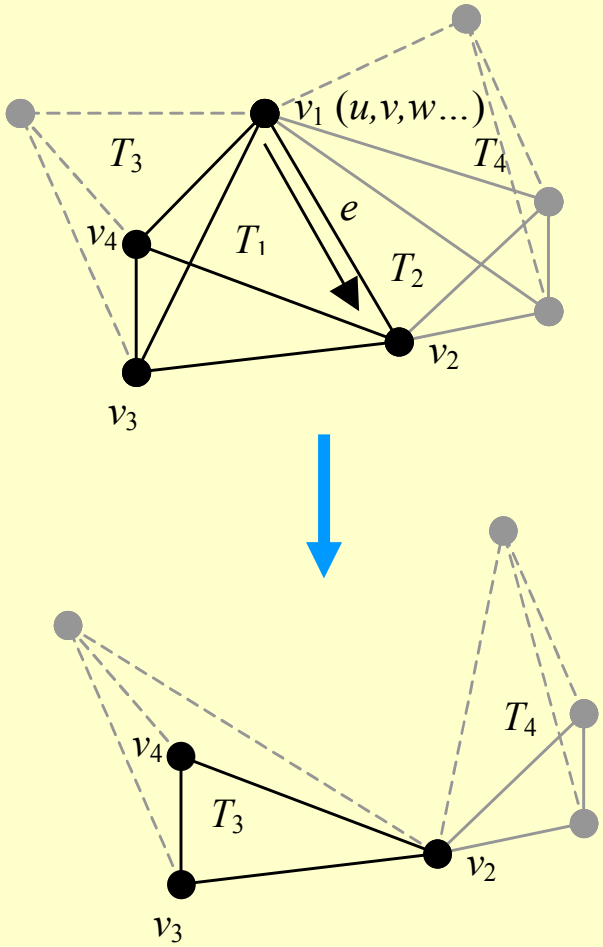
- Aim – to capture evolving short and long wave instabilities (e.g. Crow instability)
- LES methods require high resolution meshes to reproduce vortex decay (spatial and temporal)
- Meshes are defined as unstructured grids, discretised according to the flow characteristics forming tetrahedral, pyramidal and hexahedral cells

Mesh Compression

- Lossy compression technique developed
- Tetrahedral mesh compression
  - Edges removed which minimise error in the mesh
  - As edges are removed, a tetrahedron becomes a triangle
- Cartesian mesh converted to a tetrahedral mesh
- Trade-off between file size and compression errors

Mesh Simplification

- *Edge collapsing*
- v_1 collapses to v_2
- T_1 and T_2 degenerate
- Underlying scalar field altered
- Mesh consistency retained



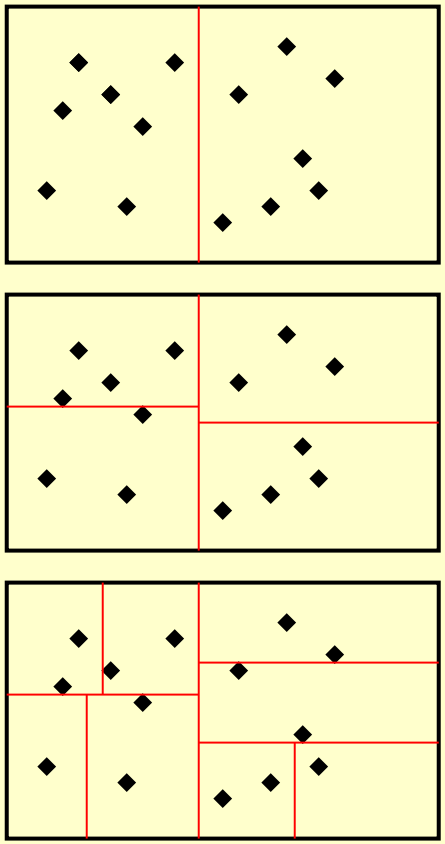
Mesh Simplification

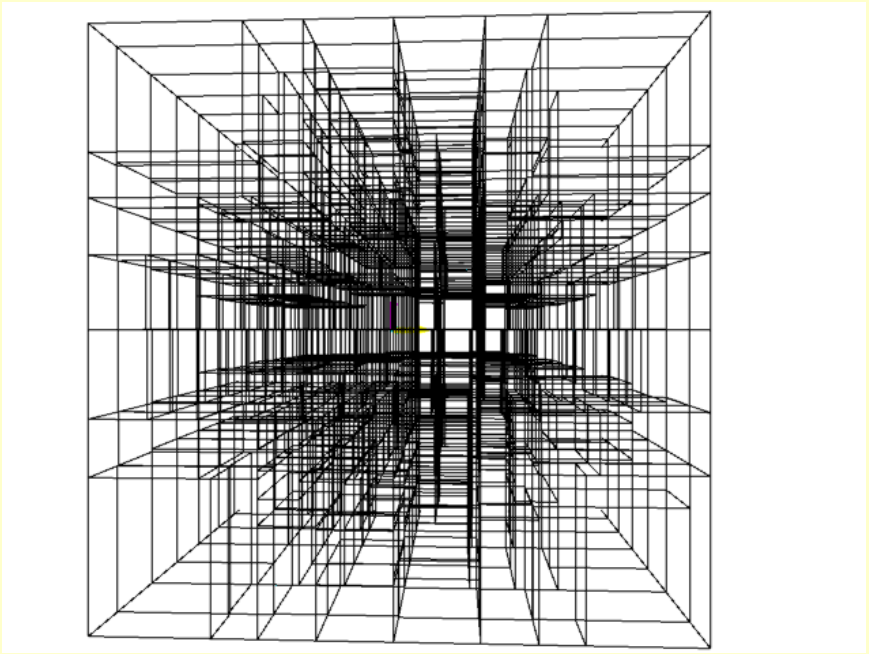
Error (m/s)	Tetrahedra	Edges collapsed	File size (bytes)
0.0	1,871,728	0	7,631,932
0.001	1,548,411	56,523	6,275,380
0.01	879,902	169,108	3,573,340
0.05	473,663	237,014	1,943,596
0.1	387,141	252,896	1,562,428
0.5	311,125	266,060	1,246,492
1.0	299,930	267,927	1,201,684
5.0	297,237	268,361	1,191,268

Real-time Access

- Linear search through 200,000 points is impractical for real-time applications (20 ms frame)
- Spatial data structures offer logN traversal time
- Kd-tree adopted
- Data set reduction from 20 GB to just over 20 MB.

Kd-tree

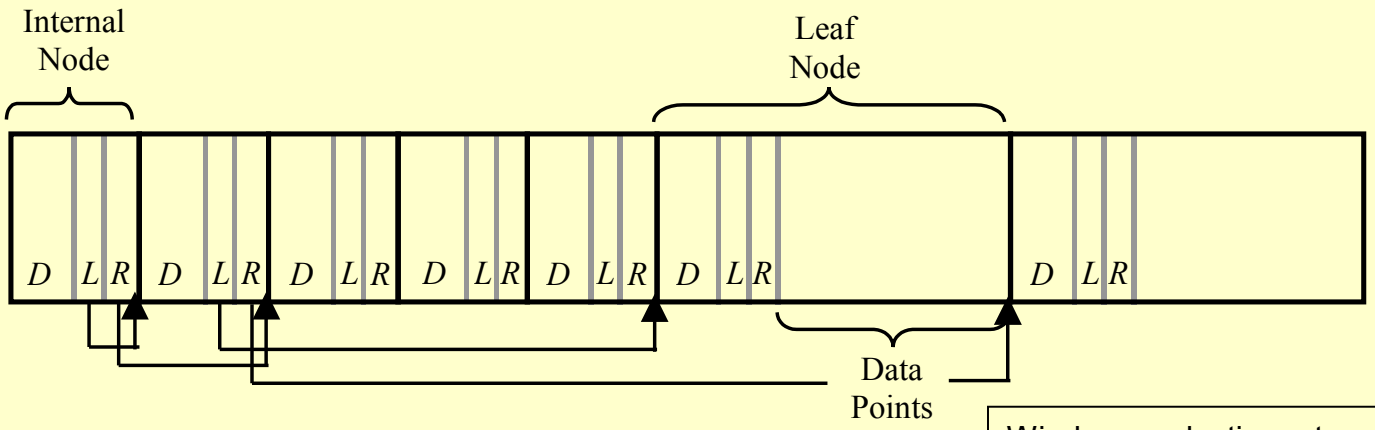




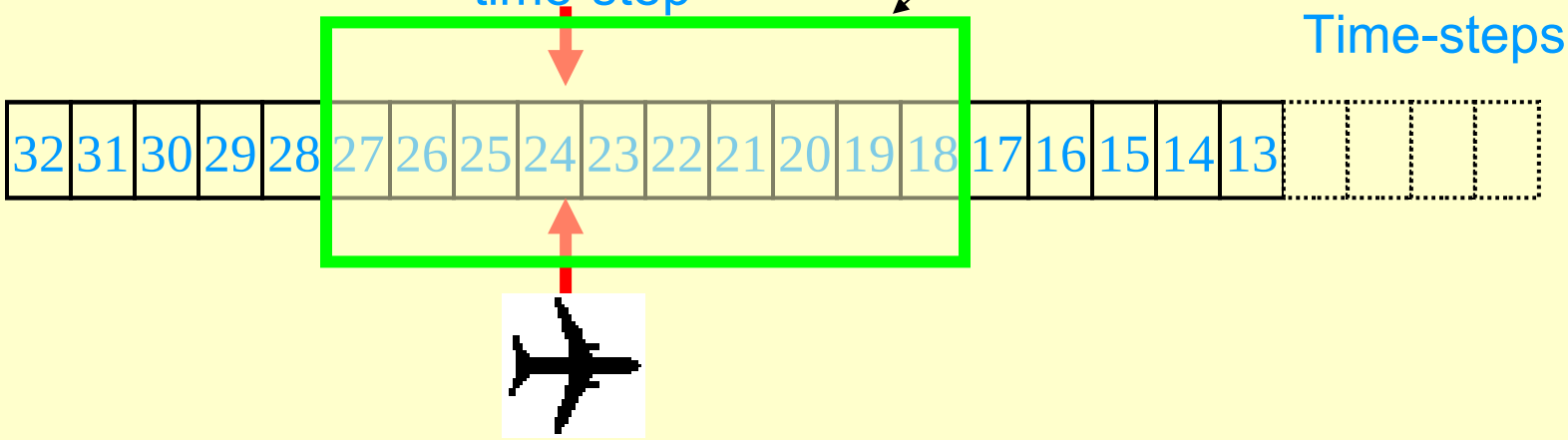
Paging

- The compressed data is still unlikely to fit in RAM
- Virtual memory organisation can interfere with access to the dataset
- Kd-tree is stored on disk with pre-fetching of tree nodes to RAM – controlled by the application
- A secondary thread performs speculative prefetching loading a time step before it is required and avoiding delay to the application

Memory Management



Window marks time-steps residing in RAM. Here, biased towards earlier time-steps (catching up with generating aircraft)

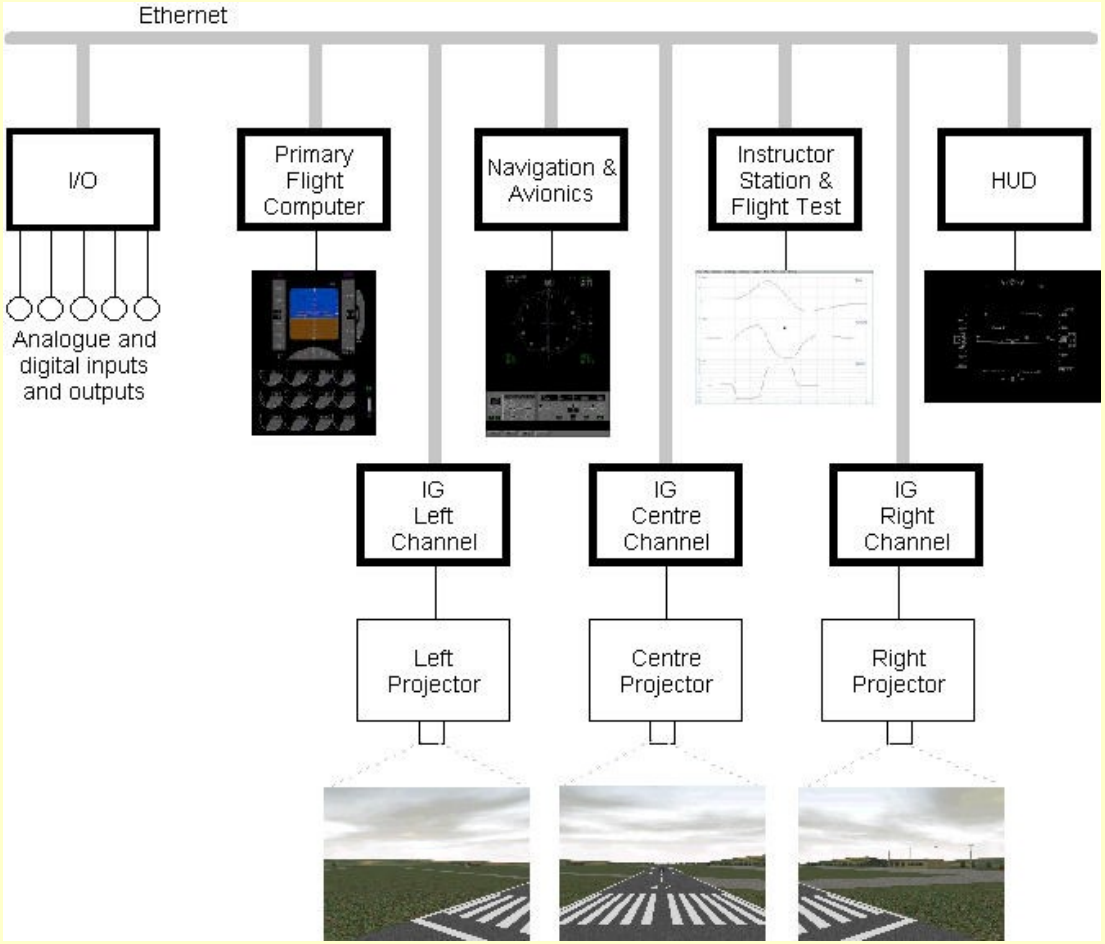


Flight Simulator Integration

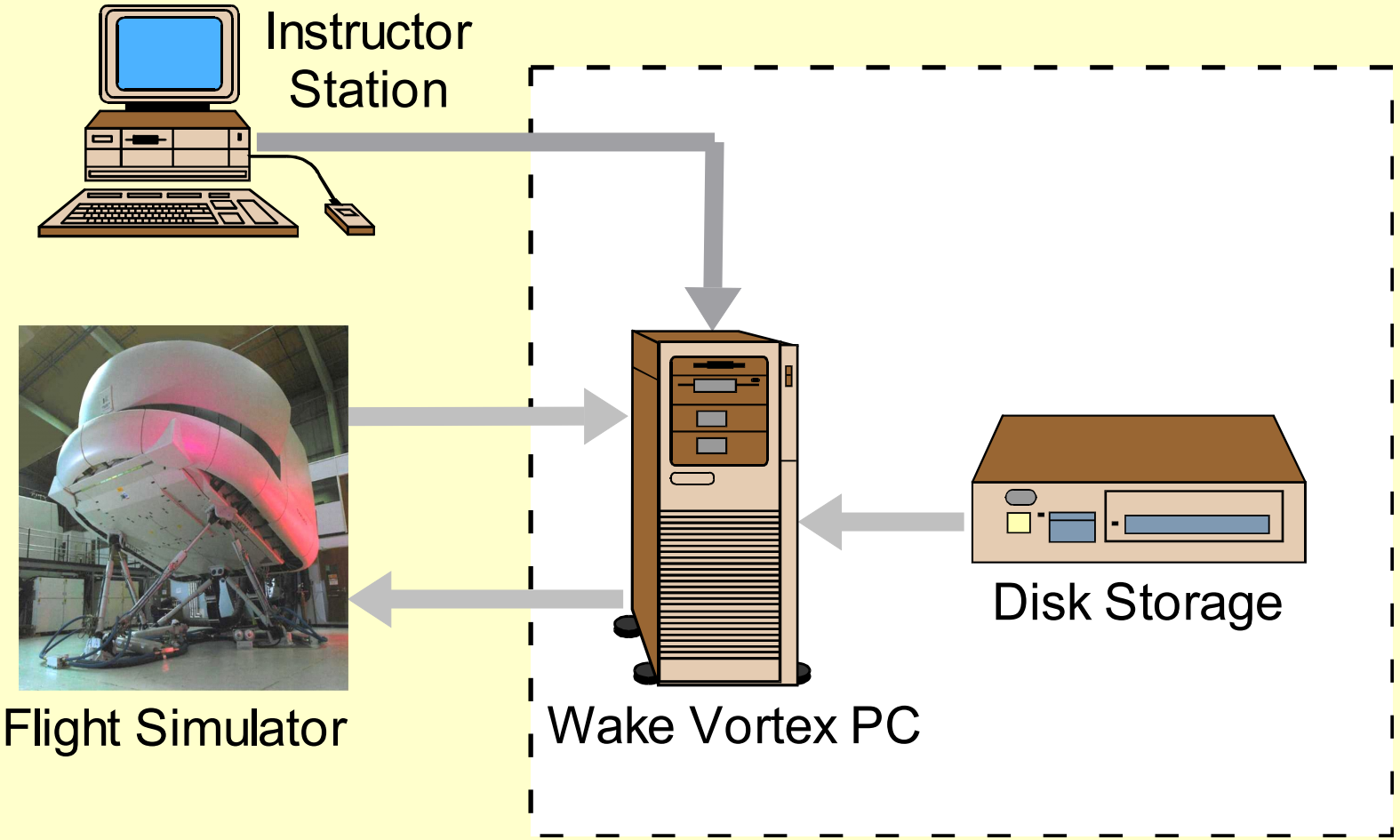
- Modular design
- 8 PCs connected with Ethernet
- Real-time (50 Hz) nonlinear simulation
- Range of flight models
- Engineering flight simulator

http://fltsim.group.shef.ac.uk/

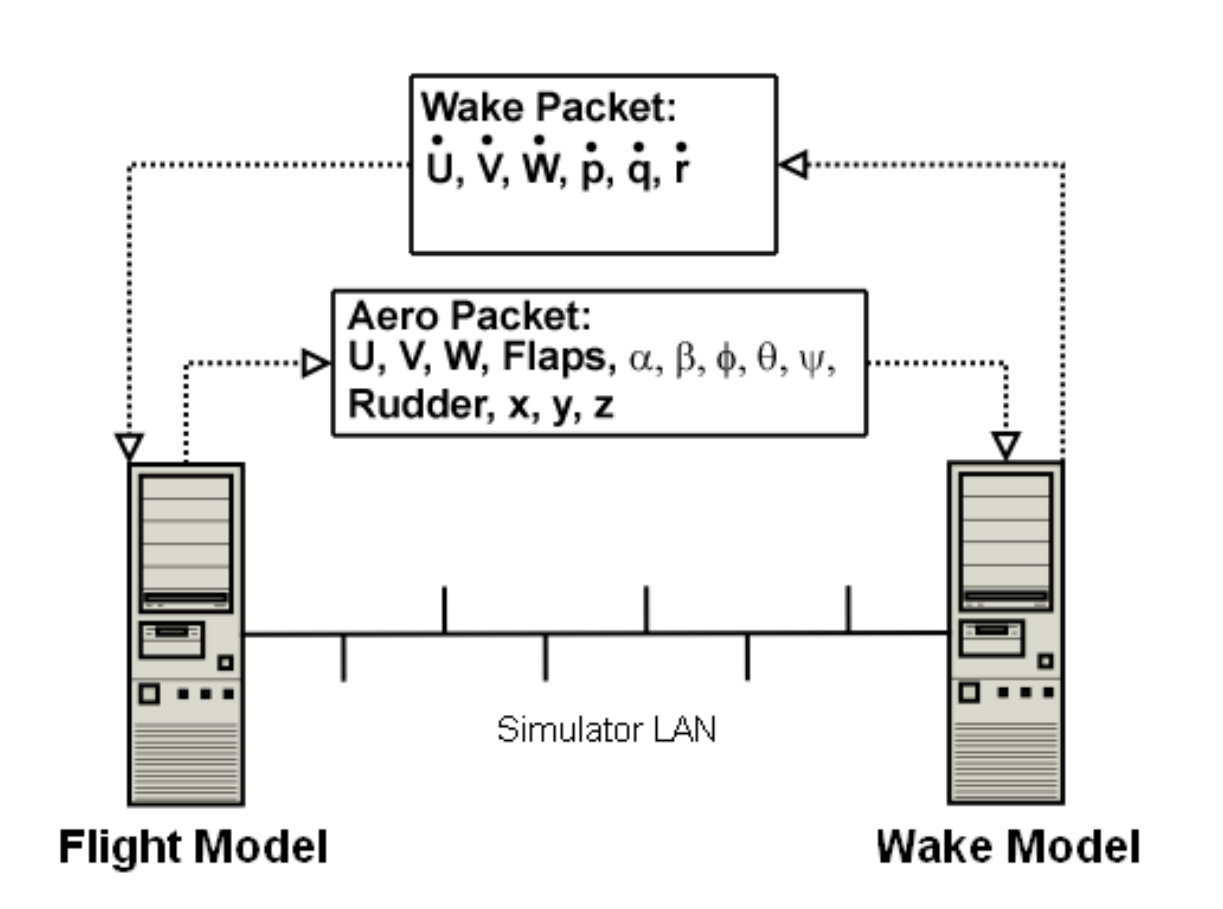
Flight Simulator Integration



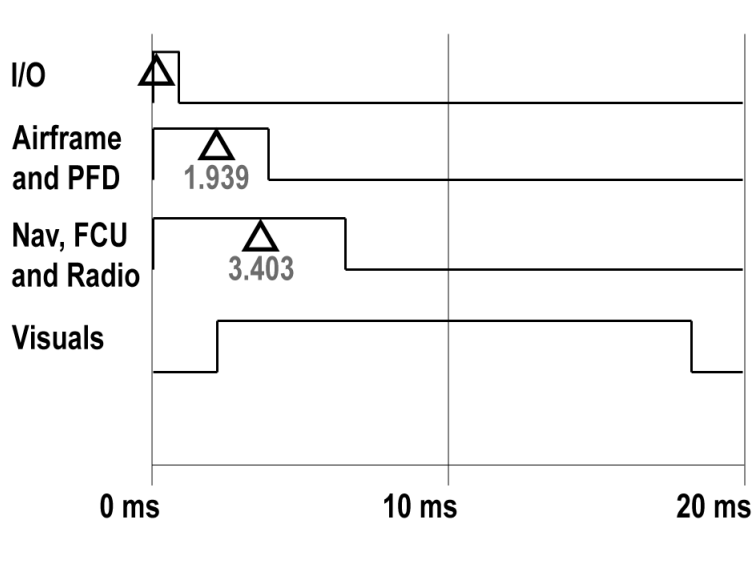
Flight Simulator Integration



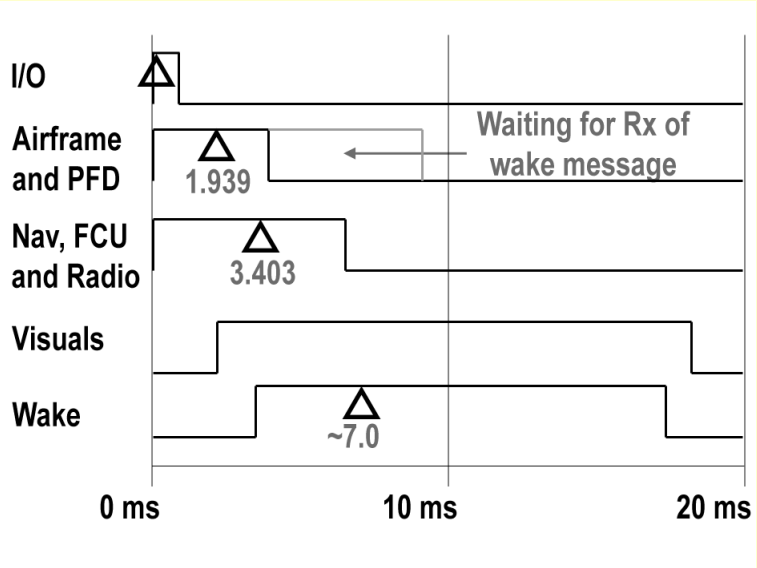
Flight Simulator Integration



Real-time Performance

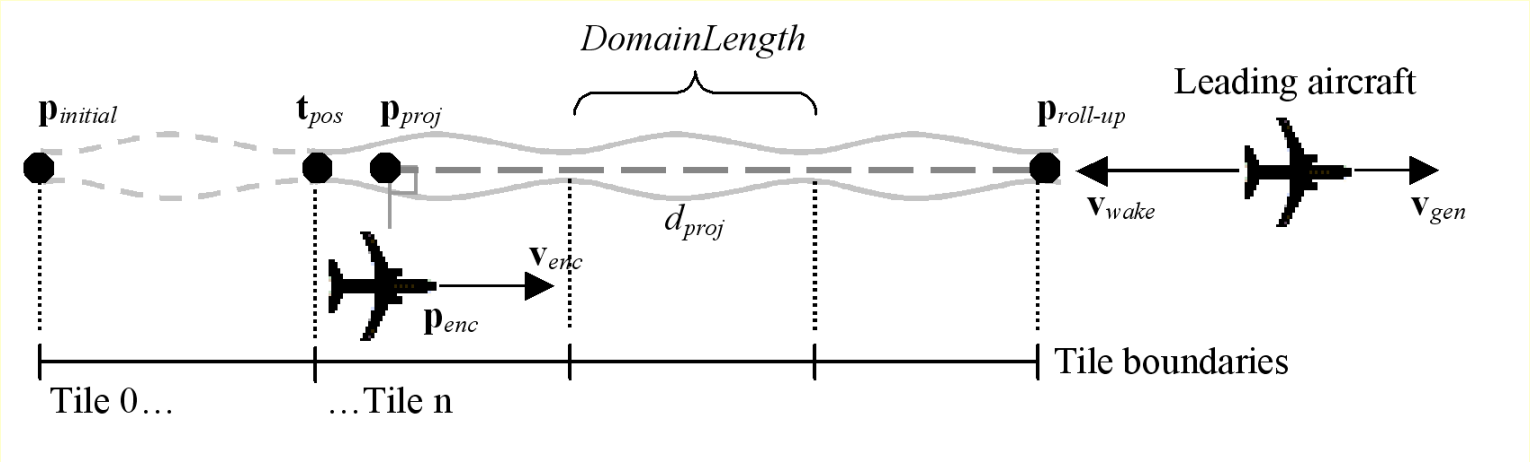


baseline



wake vortex

Tiling



- 3D data blocks orientated in the world coordinate system
- LES data occupies several hundred meters (longitudinal)
- Tiles are cached and provide seamless interaction with the vortex as the trailing aircraft closes on or falls back from the leading aircraft

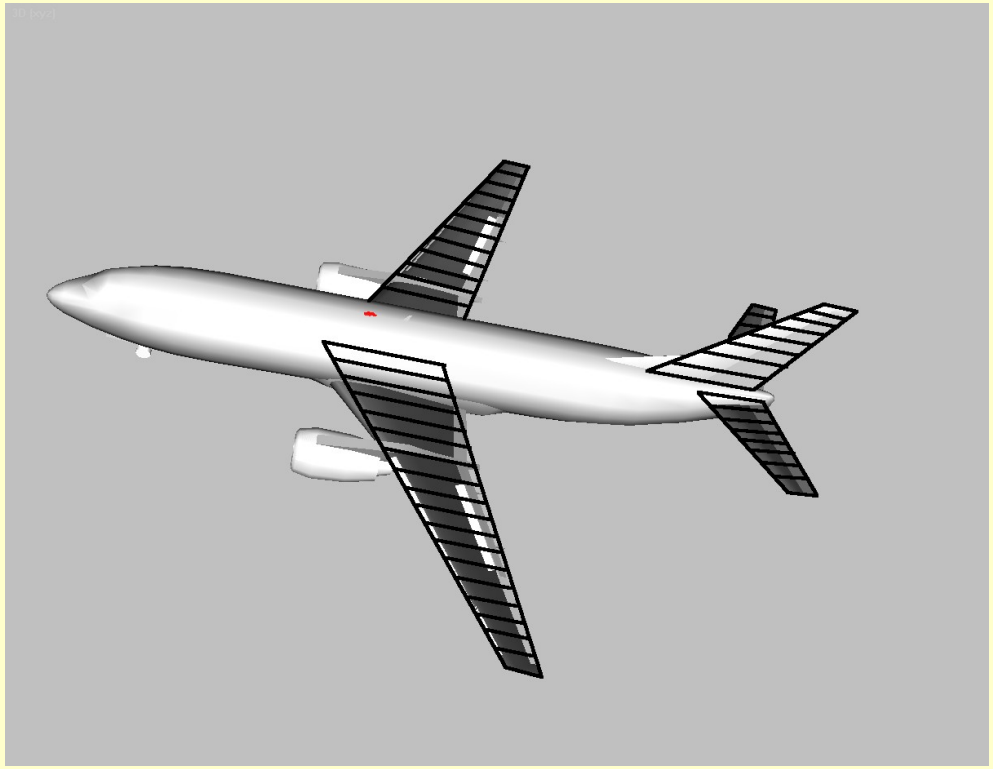
Visualisation

Aircraft-Vortex Interaction

- Accelerations computed from the vortex model are applied to the aircraft dynamic model in real-time
- A strip model of the aircraft is used to compute the forces and moments on the aircraft
- Structural loading terms are also computed, including pilot inputs in response to the disturbance

Strip Method

- Straight-forward and fast
- 60 strips used for wings and tail surfaces
- Number of strips is limited by Kd tree search speed
- Loads displayed in real-time visualisation



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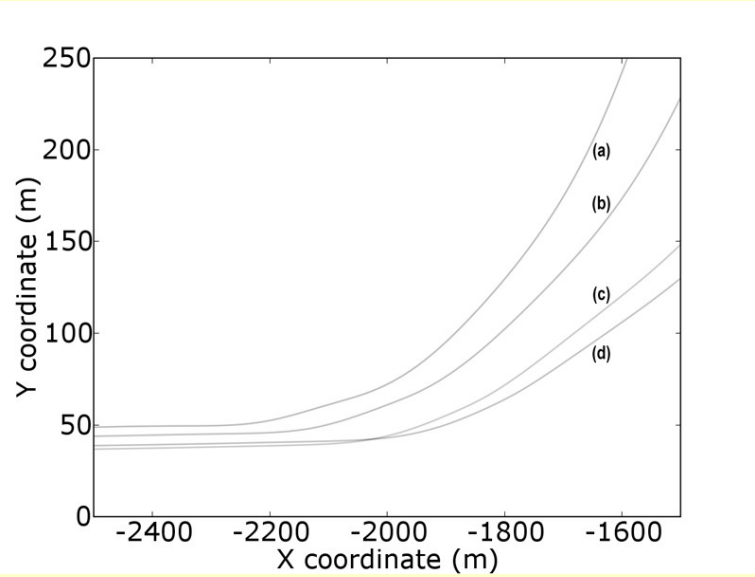
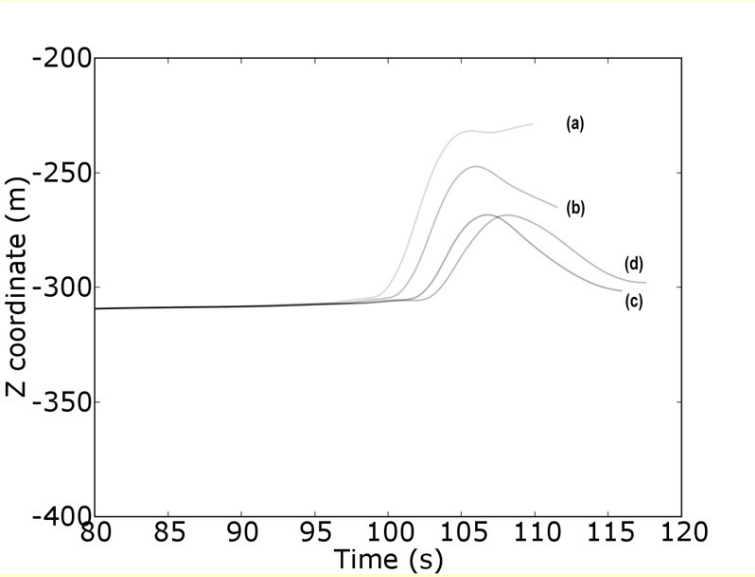
Results - Disturbance



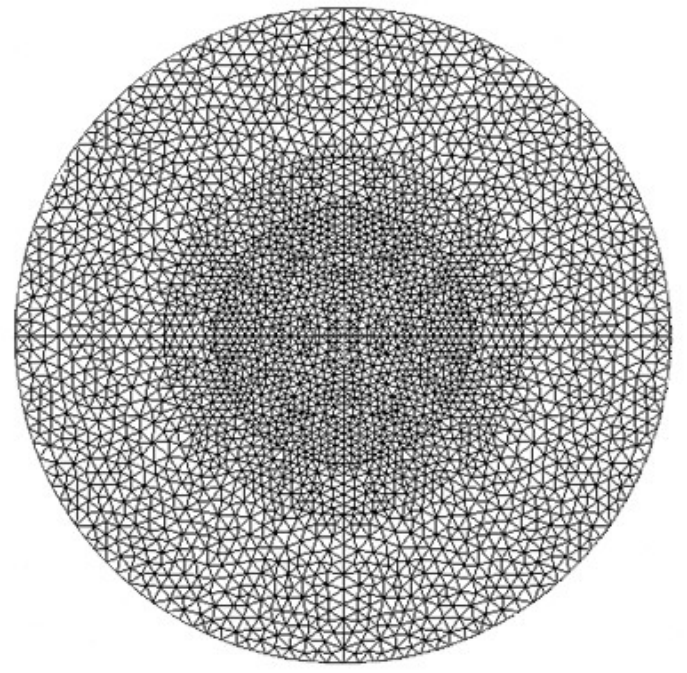


Lateral perturbation

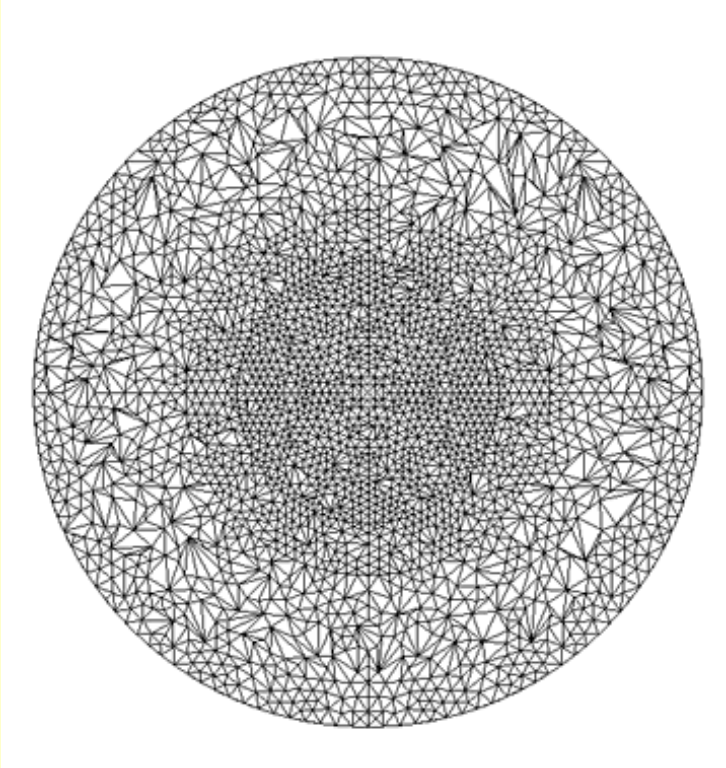
Vertical perturbation

(a) 0 offset (b) 66m offset (c) 132m offset (d) 198m offset

Results - Compression

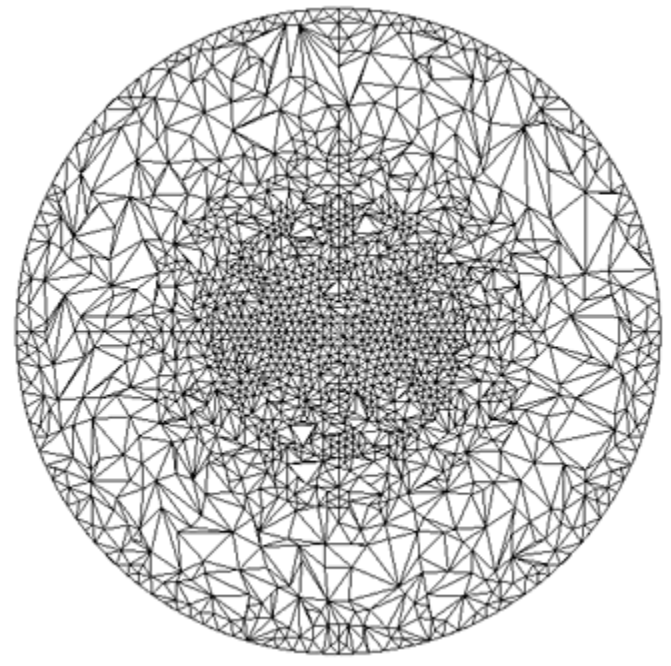


0.0 m/s field error
1,871,728 tetrahedra
7,631,932 bytes

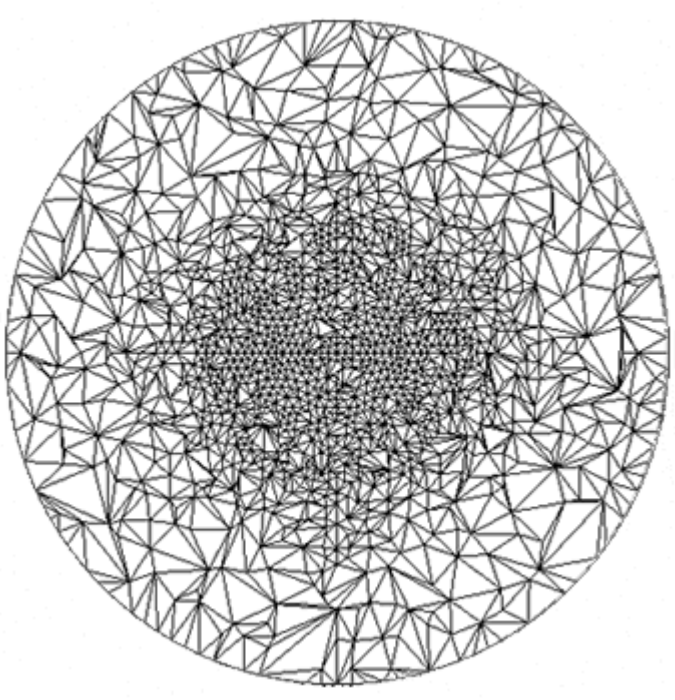


0.001 m/s field error
1,548,411 tetrahedra
6,275,380 bytes

Results - Compression



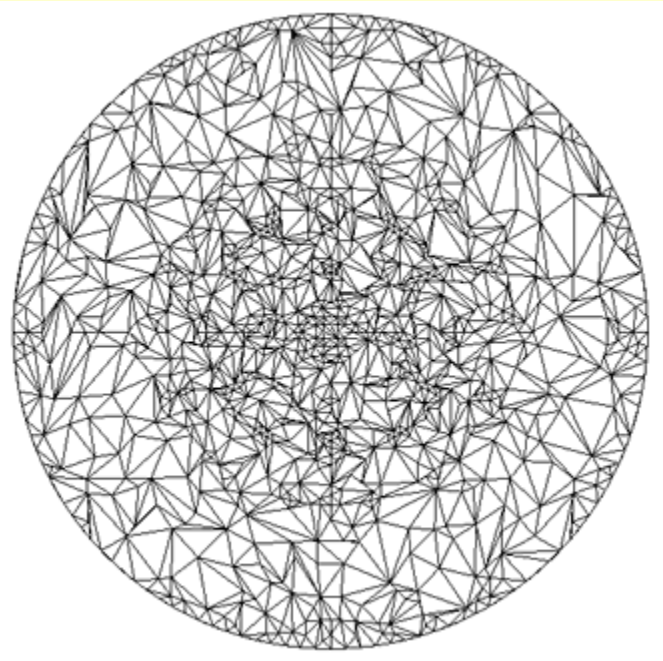
0.01 m/s field error
879,902 tetrahedra
3,573,340 bytes



0.1 m/s field error
387,141 tetrahedra
1,562,428 bytes

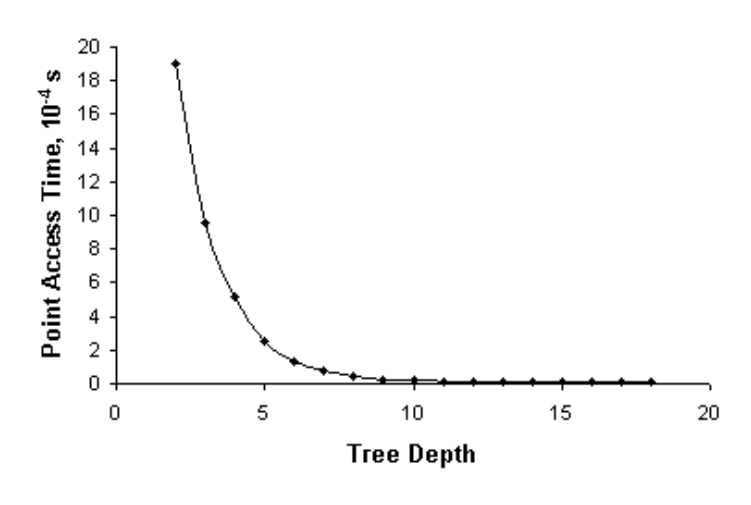
Results - Compression

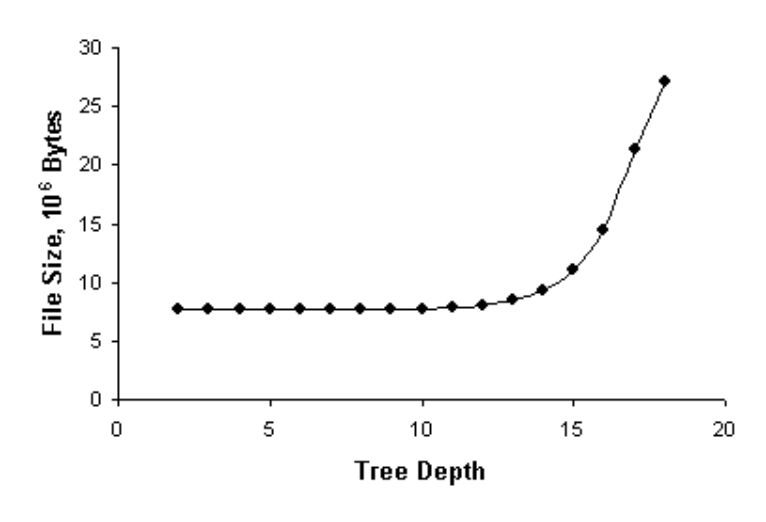
- Threshold >= 1.0 m/s, lose information near vortices
- Only small reduction in storage
- Can seriously distort underlying scalar fields



1.0 m/s field error
299,930 tetrahedra
1,201,684 bytes

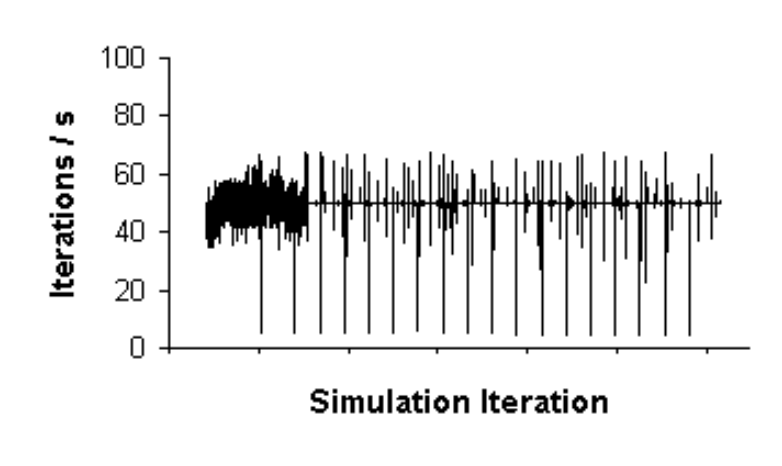
Results – Data Lookup

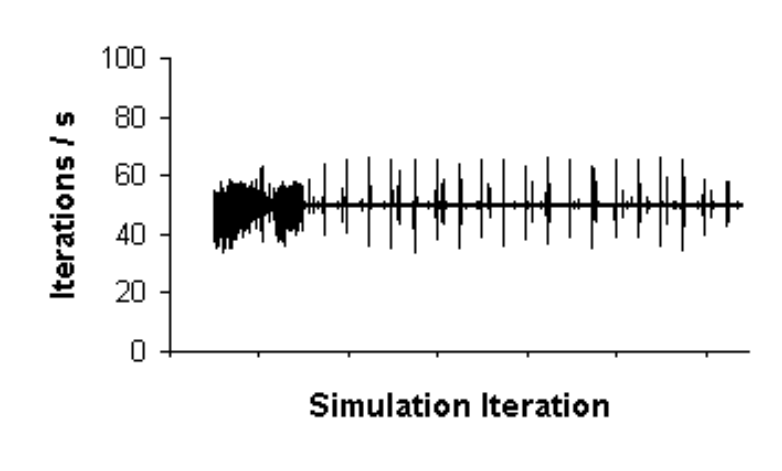




- At a depth of 11, point access time averages 20 μs
- On the current PC hardware, 100 searches take ~2 ms of the 20 ms frame

Results – Application Performance



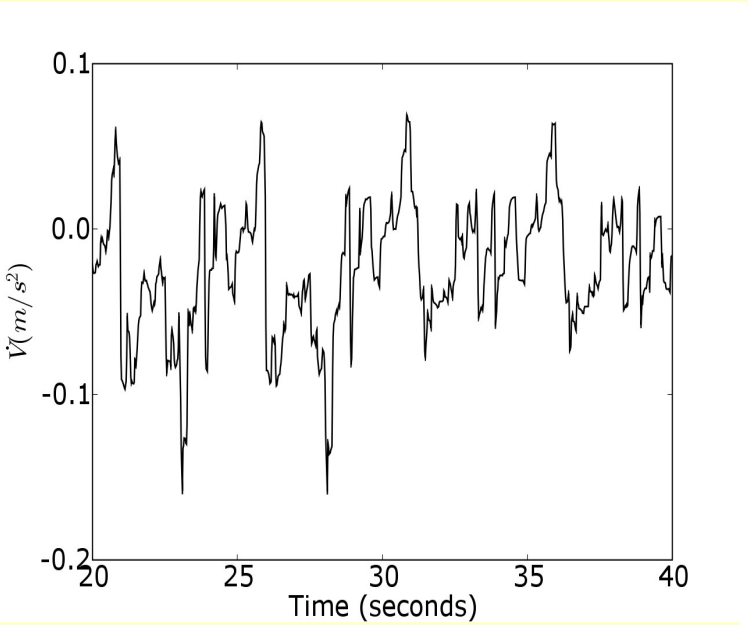


Iteration rate : 49.87 Hz
Variance : 14.38

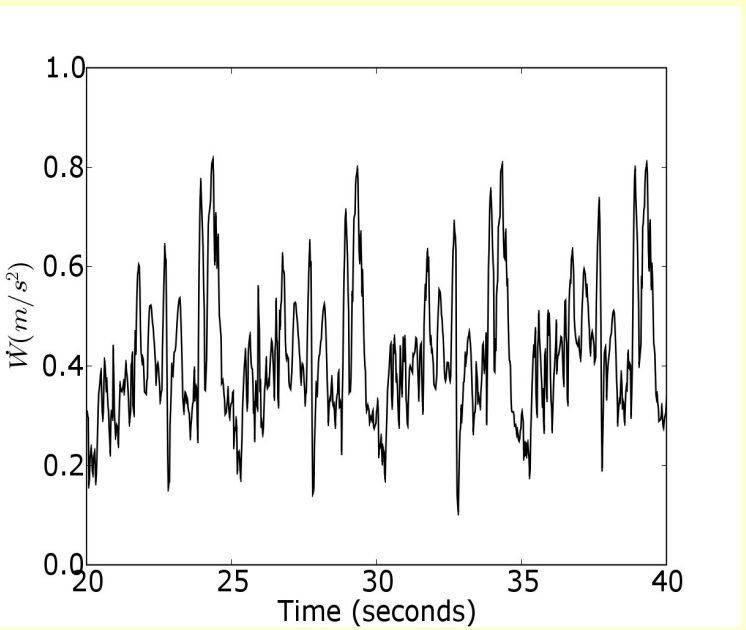
Iteration rate : 49.89 Hz
Variance : 5.47

- Linux (non real-time OS)
- Spikes caused by kernel processes

Results – Application Performance



Lateral velocity

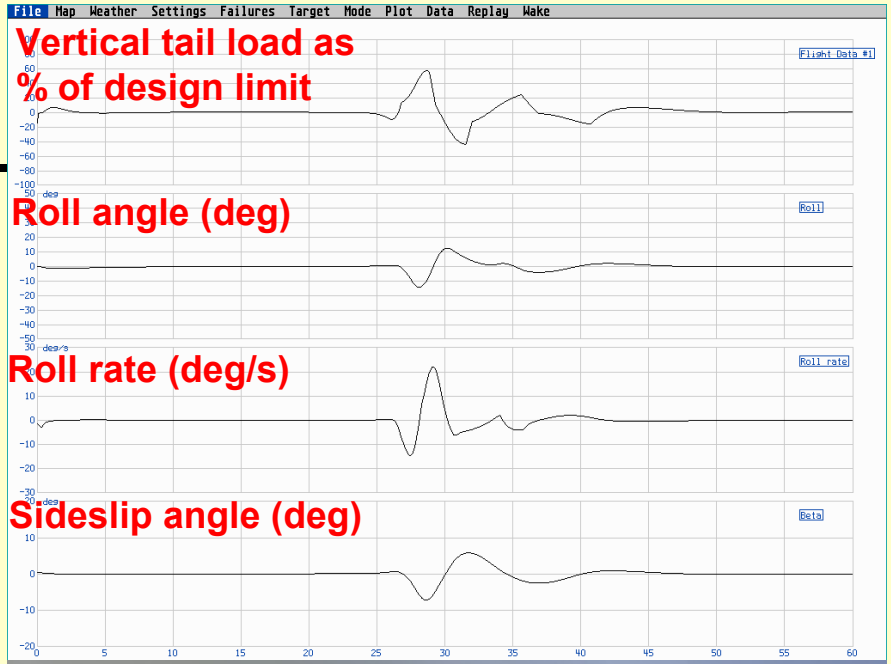


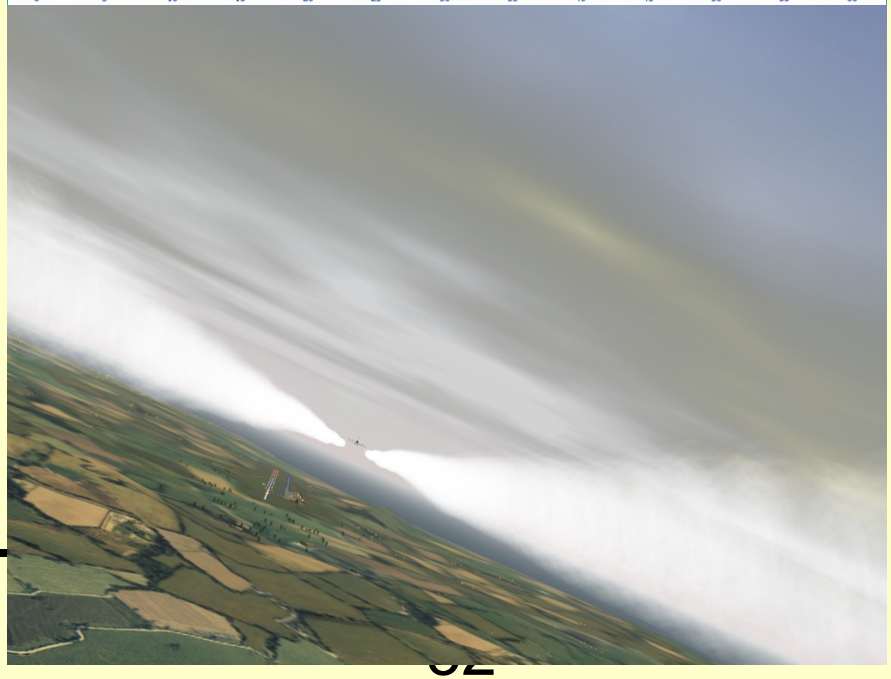
Vertical velocity

Autopilot test – attempting to maintain the flight path

Encounters

- Leading aircraft
  - Boeing 747
  - Encounter distance 2 nm
  - 15° incidence angle
  - Encounter altitude 2000 ft
- Trailing aircraft:
  - Boeing 747 - mass 280,000 kg
  - Speed 180 kt
  - Less than spacing minima





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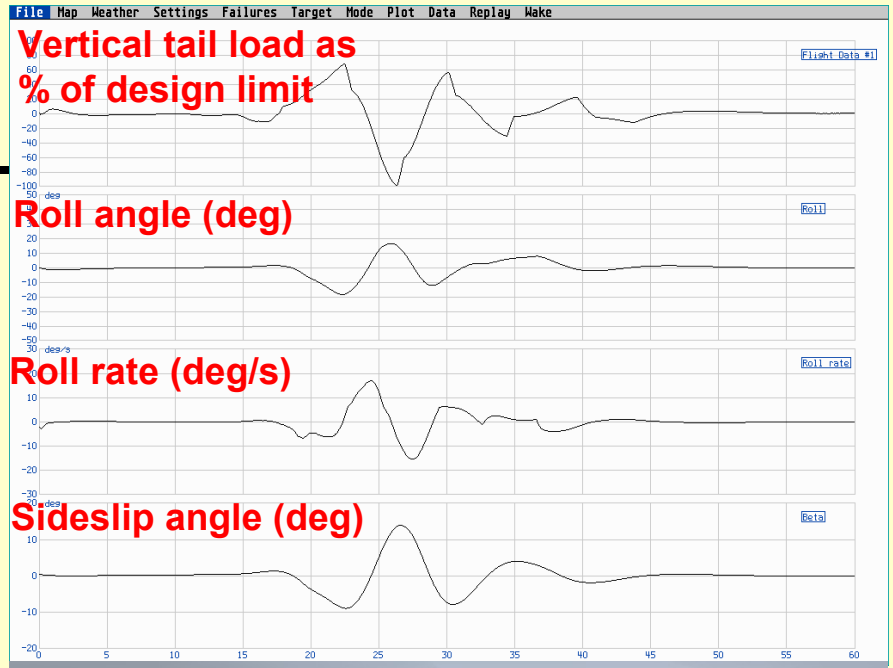
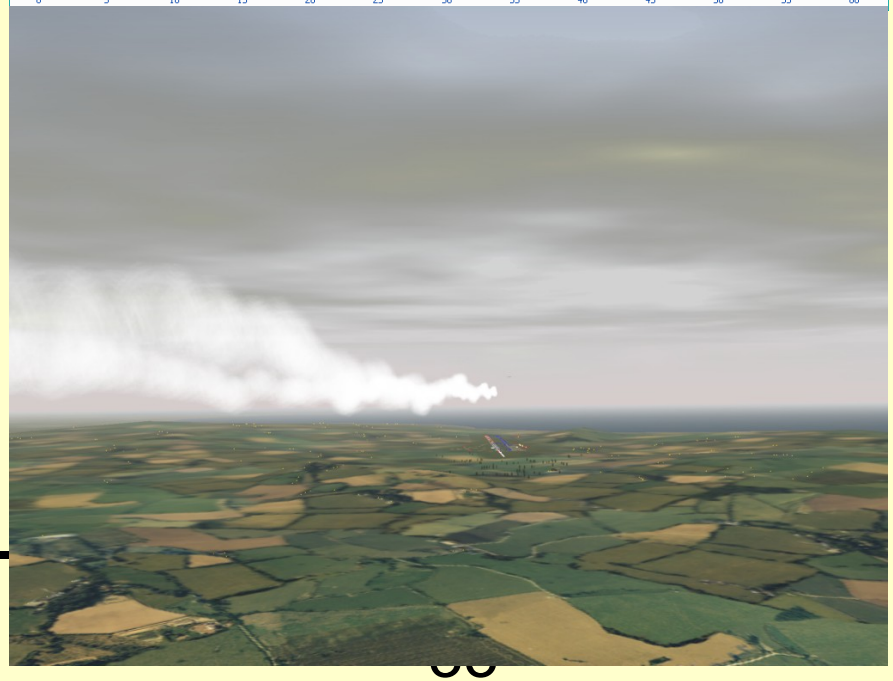
Encounters

- Leading aircraft
  - Boeing 747
  - Encounter distance 4nm
  - 5° incidence angle
  - Encounter altitude 2000 ft
- Trailing aircraft:
  - Boeing 747 - mass 280,000 kg
  - Speed 180 kt
  - At wake spacing minima





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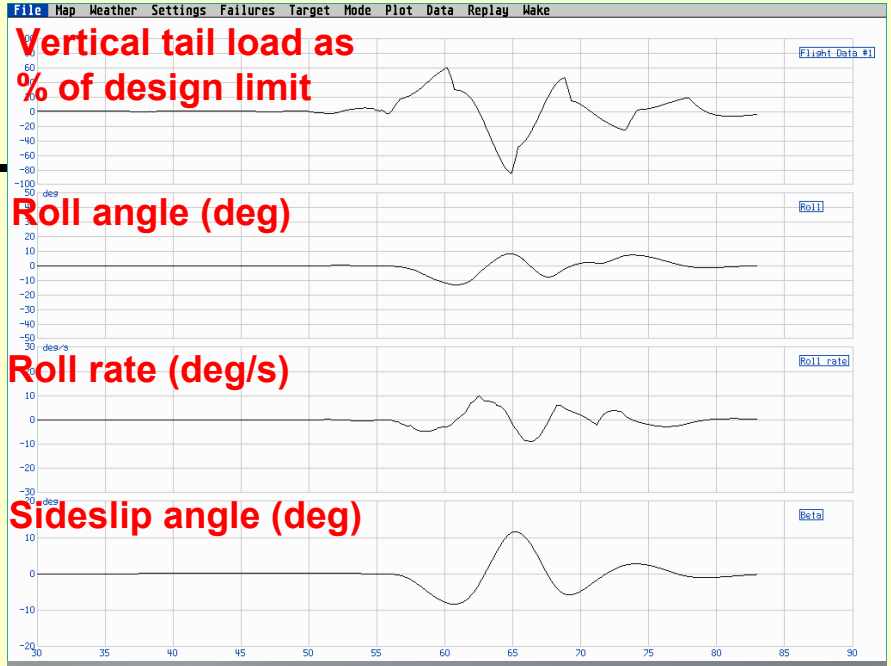
Encounters

- Leading aircraft
  - Boeing 747
  - Encounter distance 6nm
  - 5° incidence angle
  - Encounter altitude 2000 ft
- Trailing aircraft:
  - Boeing 747 - mass 280,000 kg
  - Speed 180 kt
  - Beyond spacing minima



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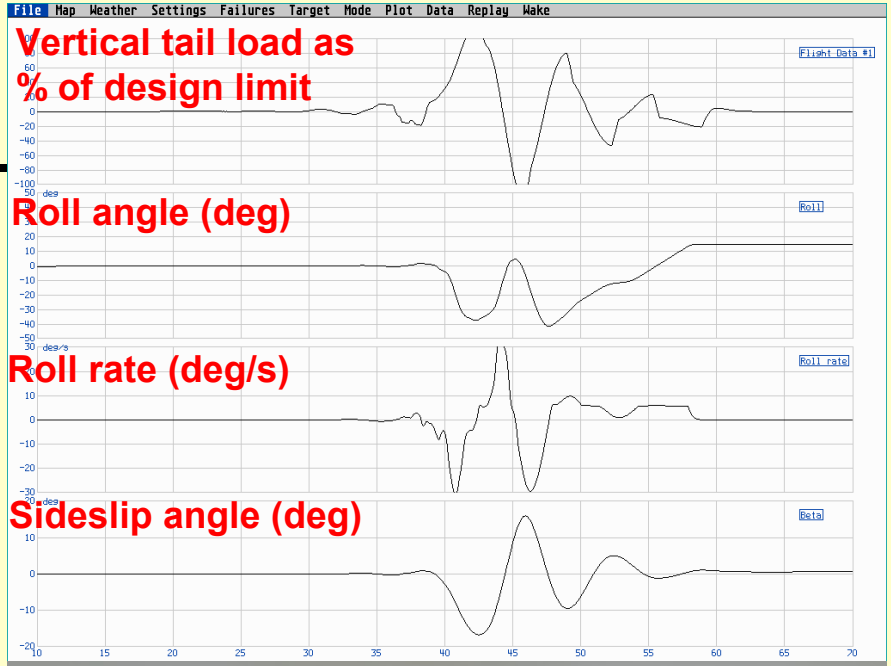
Encounters

- Leading aircraft
  - Boeing 747
  - Encounter distance 5nm
  - 5° incidence angle
  - Encounter altitude 2000 ft
- Trailing aircraft:
  - Medium weight class - mass 58,000 kg
  - Speed 170 kt
  - At wake spacing minima



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Conclusions

- Vortex data generated by CFD LES methods
- Vortex data compressed and reorganised to support real-time access
- Vortex modelled in real-time in a flight simulator
- Straightforward interface to the flight simulator
- Visualisation of the vortex includes airframe loading
- Method is applicable to other types of vortices
- Lack of data for verification
- Demonstration