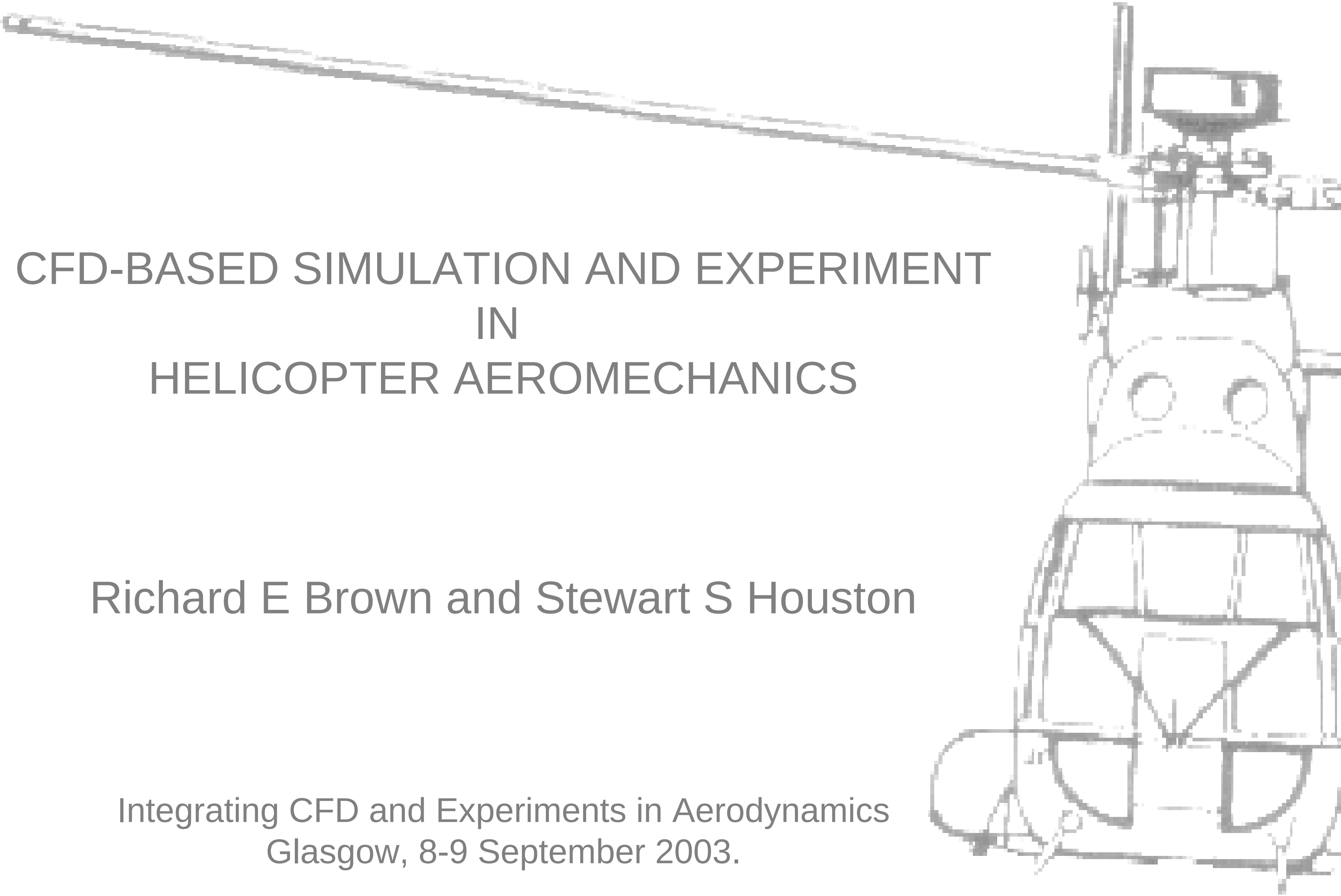

CFD-BASED SIMULATION AND EXPERIMENT IN HELICOPTER AEROMECHANICS

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Integrating CFD and Experiments in Aerodynamics
Glasgow, 8-9 September 2003.

Imperial College
London

UNIVERSITY
of
GLASGOW

Helicopter Aeromechanics:

A difficult simulation problem

multiple rotors (with multiple blades) attached to a manoeuvring fuselage

Aerodynamic environment:

- dominated by the rotor wakes
- highly unsteady

Structural dynamics

- large deflections
- aeroelasticity

'Interdisciplinary' effects

- pilot behaviour
- engine dynamic behaviour
- control systems

A highly simplified schematic of the helicopter wake

- **strong aerodynamic coupling between well-separated components (e.g main rotor and tail rotor)**
- **strong coupling between dynamics and aerodynamics**

Model Fidelity:

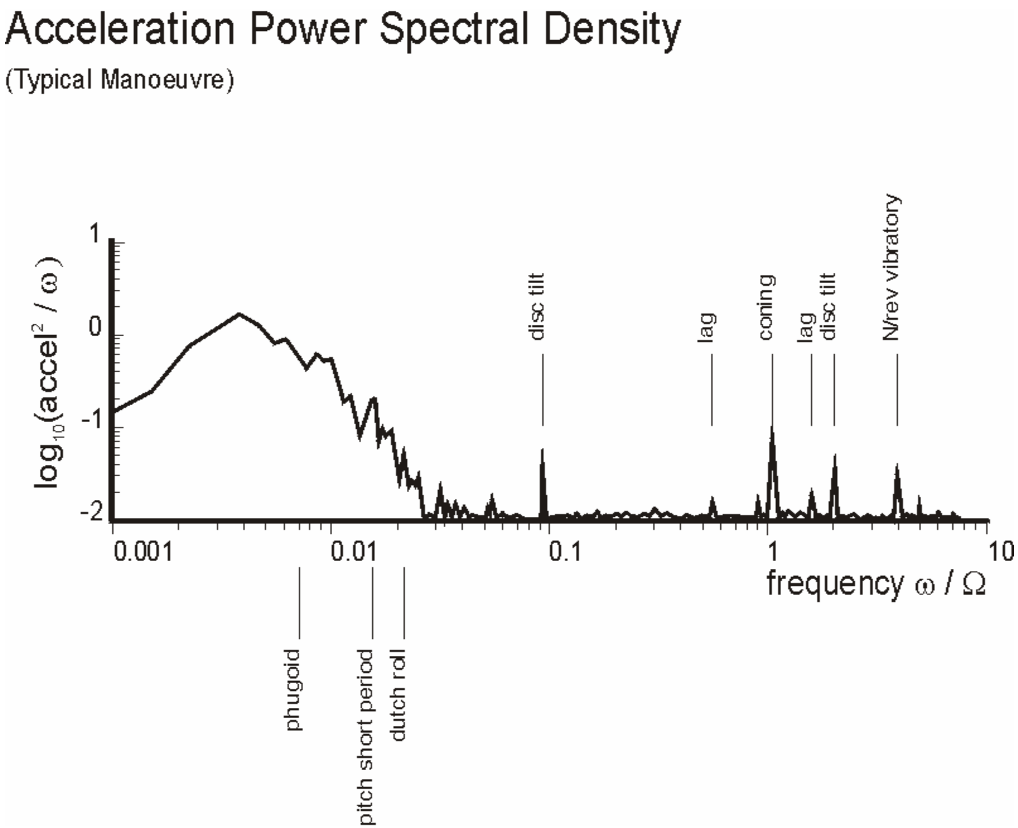
Wide range of relevant timescales

Fidelity defined in terms of bandwidth over which simulated and real transfer functions agree to within acceptable bounds

A Rational Approach to Fidelity Enhancement?

Padfield's (1988) hierarchy of models

- **Step-by-step approach**
- **Sequential enhancements to individual constituent physical models**



Flight dynamic modes (to be simulated)

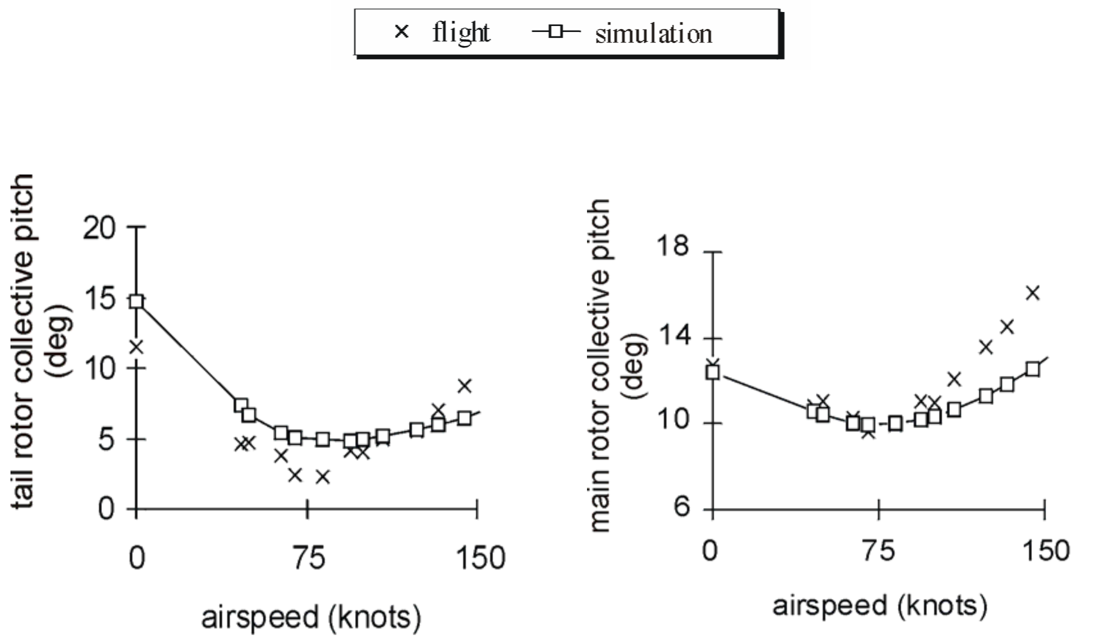
Rotor dynamic modes (that drive flight dynamics)

Two orders of magnitude range in timescales

Model Fidelity:

Typical Simulation Results

- Poor correlation with flight test
- Why?



Typical correlations between 1990s-vintage flight dynamic simulation and flight test data from DERA Puma

Model Fidelity:

An explanation?

- Poor modelling of the wake?
- Simplified dynamic models used to represent delays in development of the inflow through the rotors.

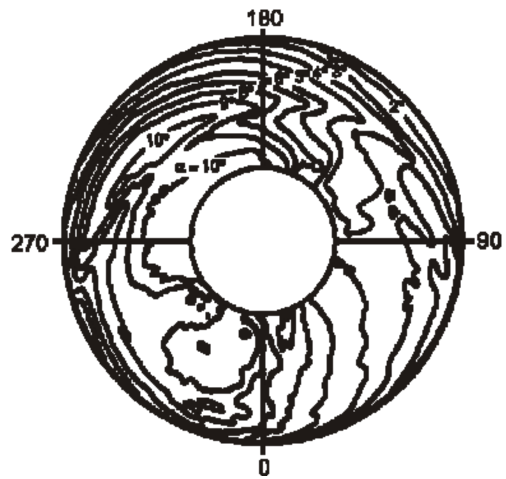
Was 'accepted' within the field that a more realistic representation would be

- 'computationally expensive'

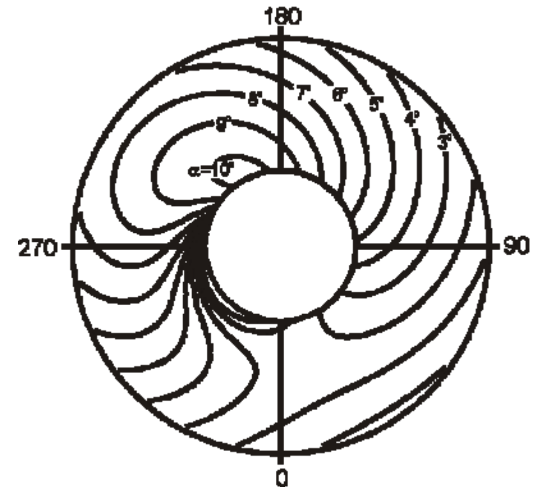
and that

- 'small-scale (high frequency) effects not relevant to flight dynamics'

Azimuthal variation of angle of attack experienced by a single rotor blade:



Test data from DERA Puma main rotor



Typical 1990s flight dynamic simulation of Puma main rotor

Simulation *misses* 'real world' flow features such as

- **blade-vortex interactions**
- **tail-rotor interference**

Model Fidelity:

An Examination

Hypothesis: **(Houston)**

Poor representation of the wake (in terms of its structure and its dynamics) is the reason for poor simulation fidelity.

Approach:

Examine impact of wake fidelity:

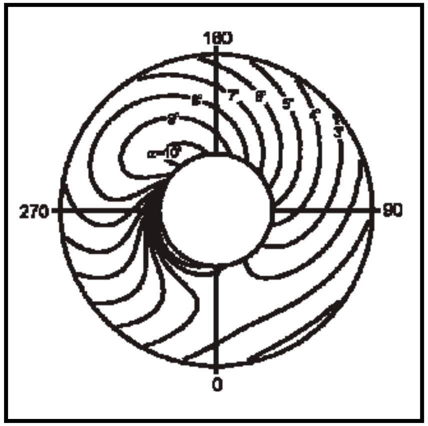
- **construct a version of Glasgow's RASCAL flight dynamic simulation in which fidelity of wake modelling could be varied:**
  - **simplified model based on dynamic inflow theory (glorified momentum theory)**
  - **CFD based model (would be required to incorporate 'real' effects (Brown))**
- **validate simulations (against flight measured data from DERA Puma.)**

RASCAL Model:
Wake Evolution

Simplified model

- represents the delay in the development of the inflow through the rotor.

- dynamically too simple to represent ‘real world’ effects
  - no convection so
    - no blade-vortex interactions
    - poor representation of manoeuvre-induced effects (e.g. from wake distortion)
  - no rotor/rotor interactions



Pitt-Peters Dynamic Inflow Model:

inflow:

$$v(t) = \mathrm{a}(t) \cdot \mathrm{V}$$

dynamic equation:

$$[\tau(\mathrm{a}, \dot{\mathrm{x}}_{rotor})]\dot{\mathrm{a}} + \mathrm{a} = [\mathrm{L}(\mathrm{a}, \dot{\mathrm{x}}_{rotor})]\mathrm{F}$$

Typically

$$\mathrm{a} = (a_0, a_{1s}, a_{1c})$$

$$v(t) = a_0(t) + a_{1s}(t)\frac{r}{R}\sin\Psi + a_{1c}(t)\frac{r}{R}\cos\Psi$$

representing uniform component as well as longitudinal and lateral gradients of inflow across the rotor disc.

RASCAL Model: Wake Evolution

CFD-based model

Structured-grid solution of the incompressible, inviscid Vorticity Transport Equation

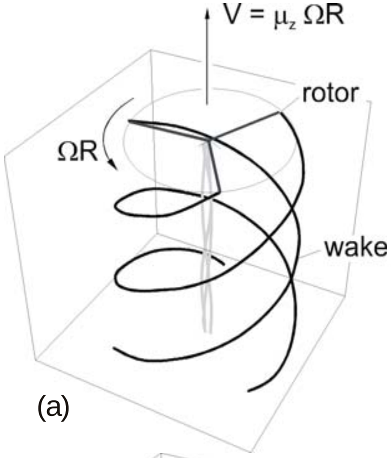
$$\frac{\partial}{\partial t}\omega + v \cdot \nabla \omega - \omega \cdot \nabla v = S$$

$$\nabla^2 v = -\nabla \times \omega$$

using a variant of the Weighted-Average Flux TVD scheme

together with a lifting-line model for the blade aerodynamics:

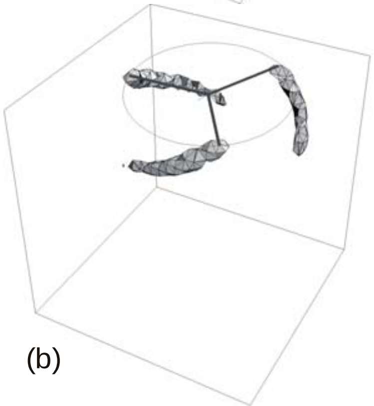
$$S = -\frac{\partial}{\partial t}\omega_b + (v_b - v) \cdot \nabla \omega_b$$



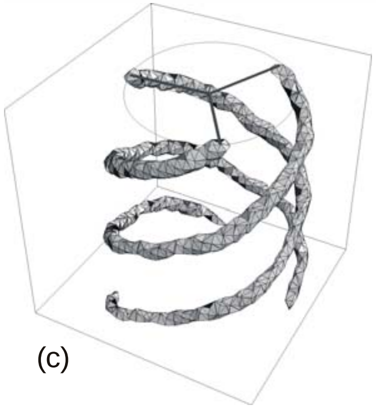
(a)

Example Physical System:

Rotor in vertical ascent


(b)

Highly diffusive behaviour of most conventional CFD-based approaches


(c)

Non-diffusive behaviour of vorticity transport approach.

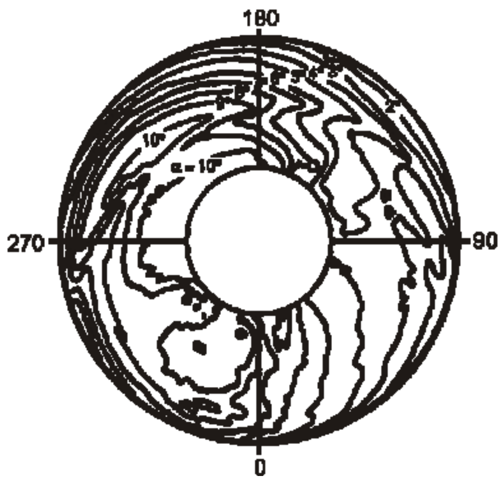
RASCAL Model :

Initial Results:

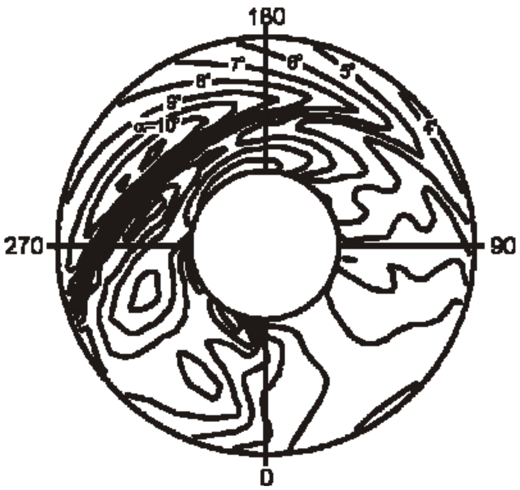
- Representation of wake effects using the vorticity transport approach looked promising

- What would the impact be on flight dynamic predictions?

Azimuthal variation of angle of attack experienced by a single rotor blade:



Test data from DERA Puma main rotor



RASCAL simulation with Vorticity Transport representation of wake

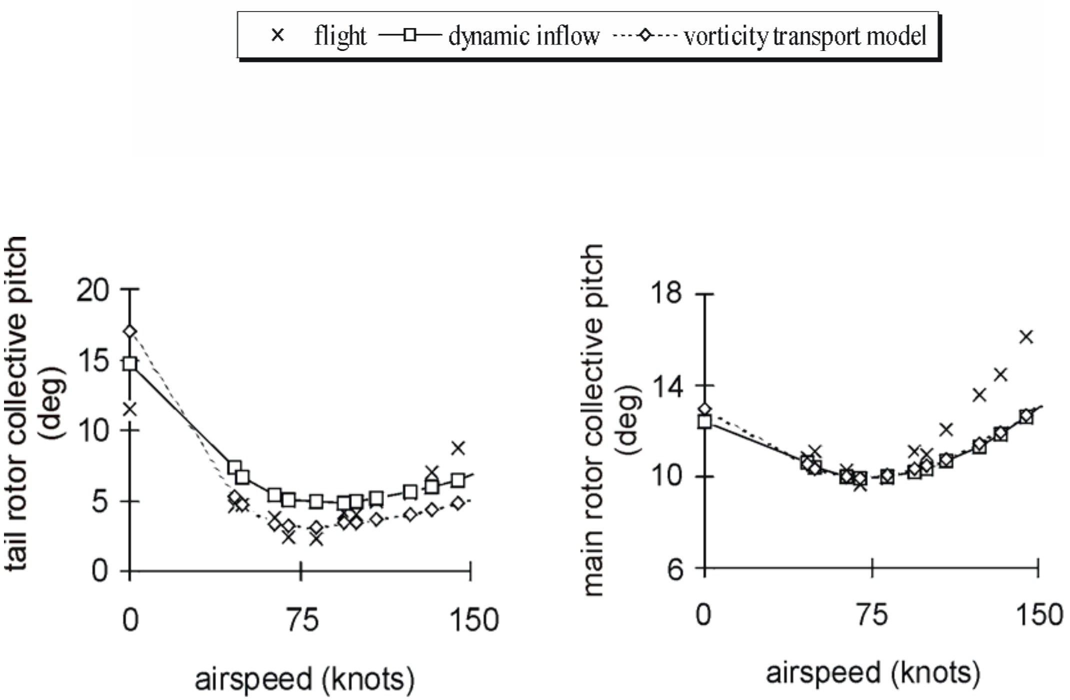
Simulation *captures* 'real world' flow features such as

- **blade-vortex interactions**
- **tail-rotor interference**

RASCAL Model :

Flight Dynamic Simulations:

- Disappointing correlation with DERA Puma flight test data.
  - Some improvement where interactions known to dominate (e.g. tail-rotor collective)
  - Many cases where wake model had no effect at all
  - Inconsistent (non-uniform) correlation across speed range
- Explanation?
  - Fuselage drag model?
  - Other physical deficiency?



Typical correlations between RASCAL flight dynamic simulation and flight test data from DERA Puma

Validation Issues:

Flight Dynamic Simulations:

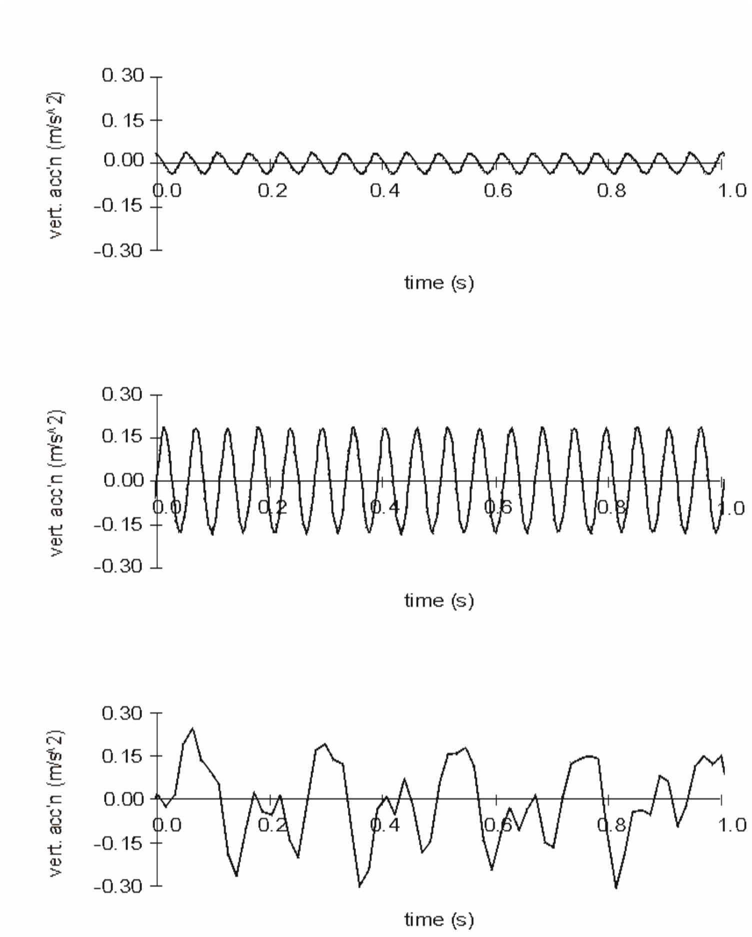
- Flight test data too opaque to provide proper environment for validation.
  - Physics too complicated to allow discrimination between possible causes for poor correlation.
  - Unmodelled physical effects? (simulations driven towards maximum complexity)
  - Undocumented defects in system? (possible example at right)

Scientifically **we are on shaky ground, but there are *engineering* needs.**

dynamic inflow:

vorticity transport model:

flight:

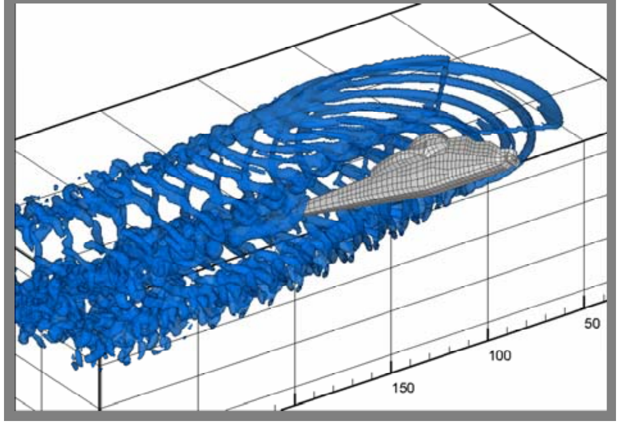


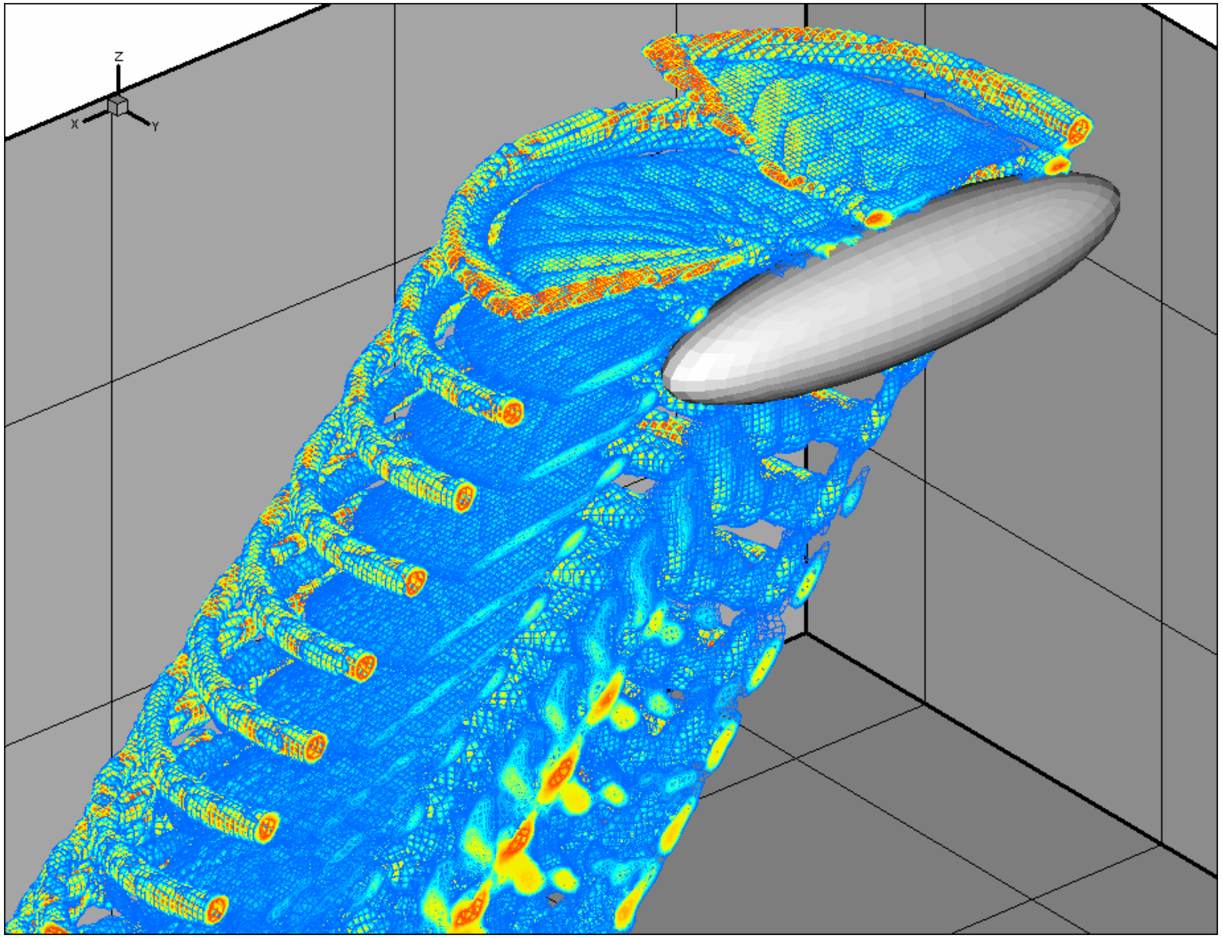
Correlations between RASCAL flight dynamic simulation of fuselage vibration levels and flight test data from DERA Puma

VTM Model :

Essentially the RASCAL model without the flight dynamics

- What happens if we validate this model in a simplified environment?
  - laboratory-type experiments on isolated rotors
  - physical effects well isolated compared to flight test





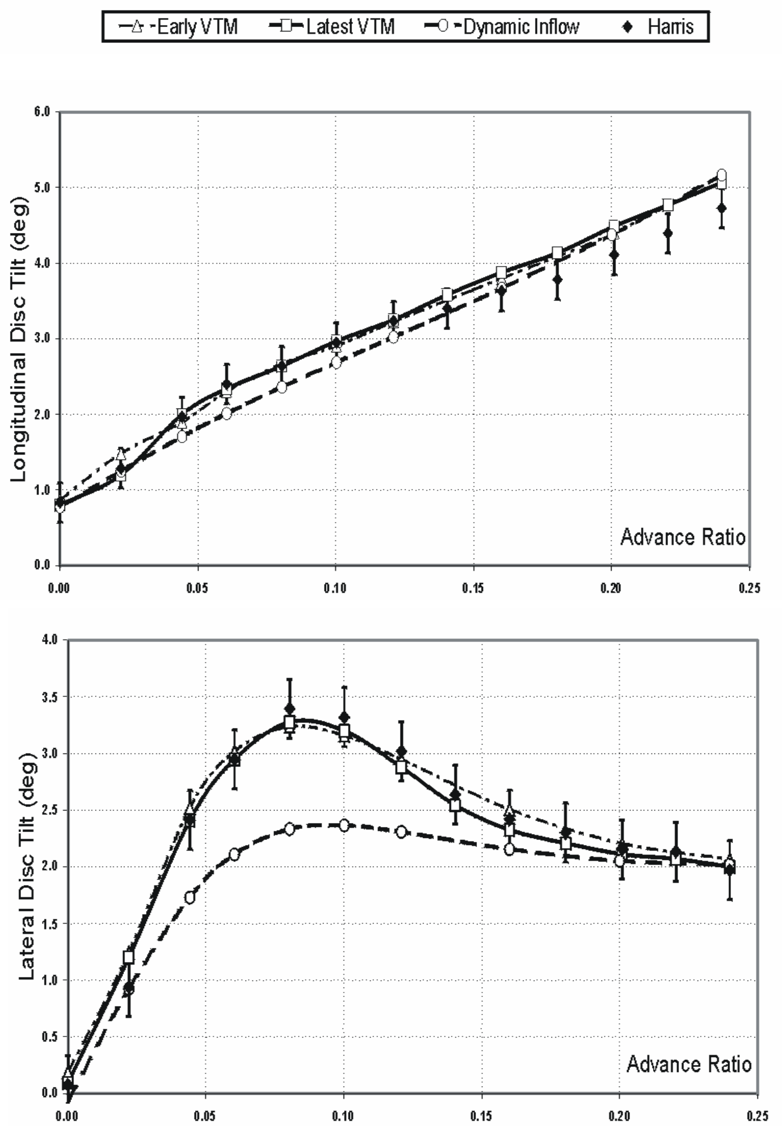
Typical VTM simulation:
Interaction between a rotor and a simplified fuselage in ascending flight

VTM Model :

Isolated Rotor Performance:

- Harris' 1972 data for rotor flapping as a function of forward speed
  - VTM captures distortion of wake downstream of rotor and hence lateral flapping variation.
  - Deficiency in blade aero model leads to systematic error in longitudinal flapping variation.
  - More subtle contamination by boundary conditions eliminated in latest 'boundary free' VTM.

Good correlation in isolated instance may not imply wider validity of model

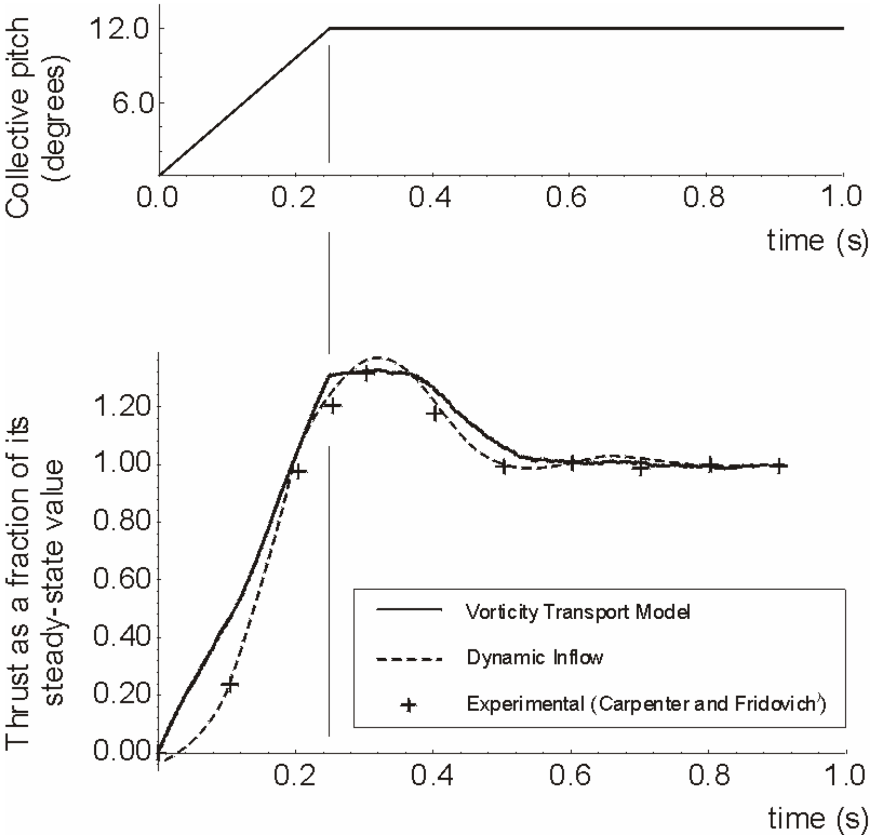


VTM Model :

Rotor Dynamic Response:

- Carpenter and Fridovich's 1953 data for rotor flapping in response to control input
  - Dynamic Inflow model 'designed' around this data
  - 'Odd' qualitative features of VTM seen in other models too!
  - Curious phenomenon of 'accepted' explanation
    - blade torsion
    - no explicit data to support this
- Example where experimental data has been taken out of context

Experiments must be designed specifically to disprove theory (or simulation)



Validation Issues:

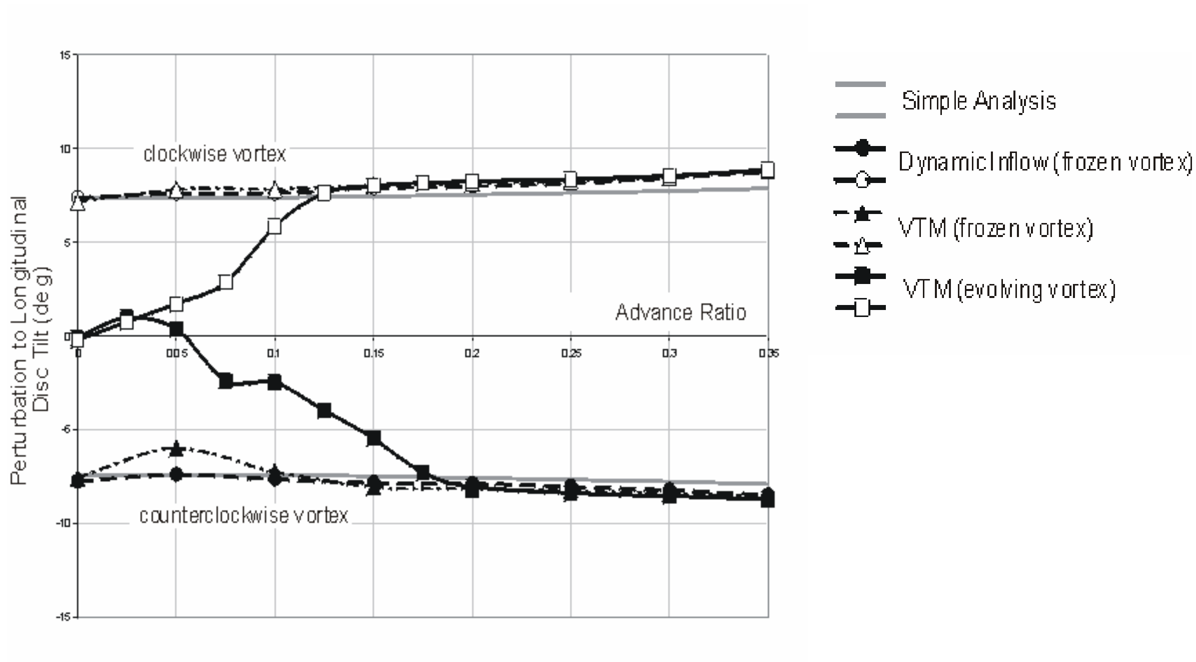
Extrapolation of Validity:

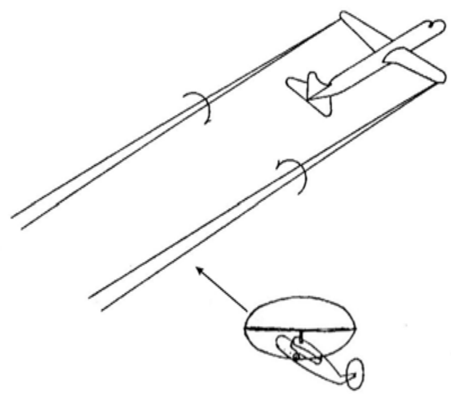
- Good correlation on simplified systems does not translate automatically to valid simulation of more complex systems (e.g. flight test)

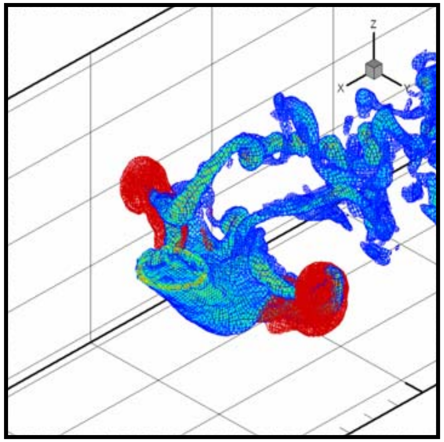
- Example at right shows that validity does not even translate between systems with similar complexity if physics is missing

  - elimination of 'frozen vortex' assumption changes character of predictions

Can observations be condensed into a global understanding of the validation process?







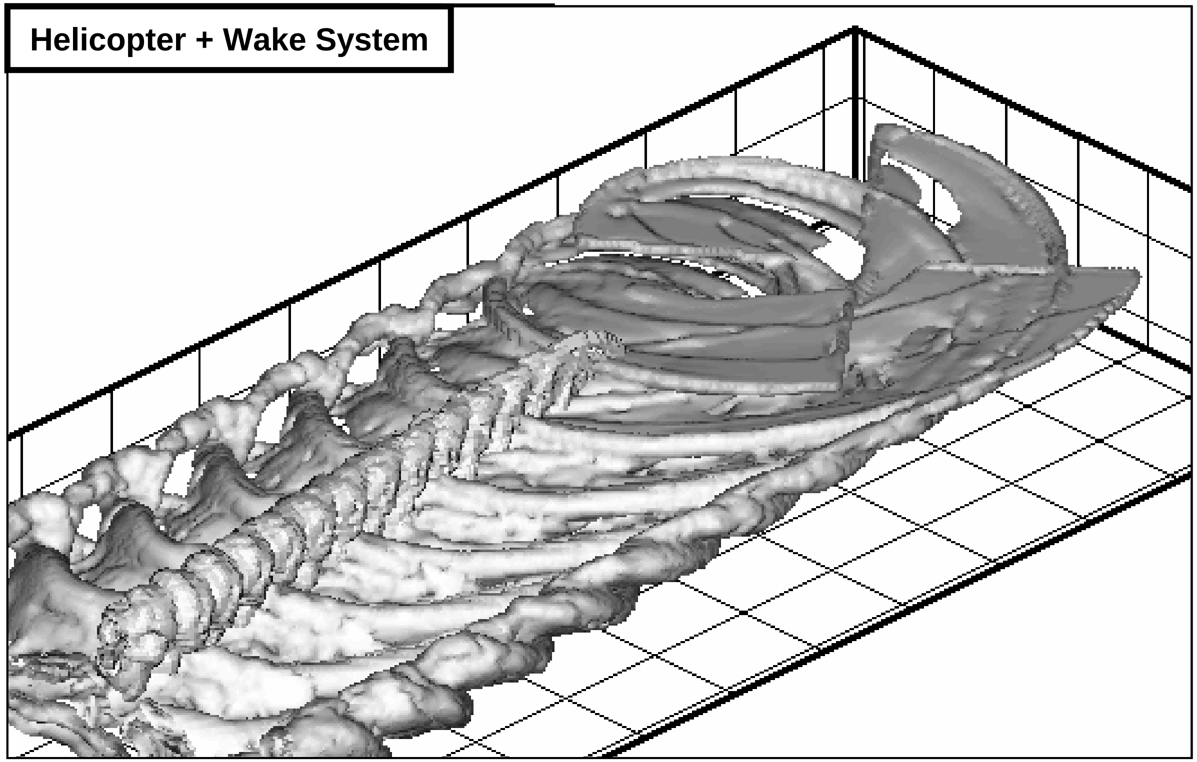
Conclusions:

Is the behaviour of the wake a paradigm for the behaviour of the whole system?

- Interactions become more important as system complexity is increased

- Interactions introduce couplings that cannot be handled by separable physical models

  (hence little hope of incremental fidelity enhancement when simulating a system that is initially too complex)



The challenge for modellers and experimentalists will be to cooperate in designing a range of test cases that bridge the gap between laboratory and flight test, allowing the interactions within the system to be exposed sequentially, then to be captured within simulations.