Are eVTOL Aircraft inherently more susceptible to the Vortex Ring State than Conventional Helicopters?

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Source: IEEE Spectrum magazine

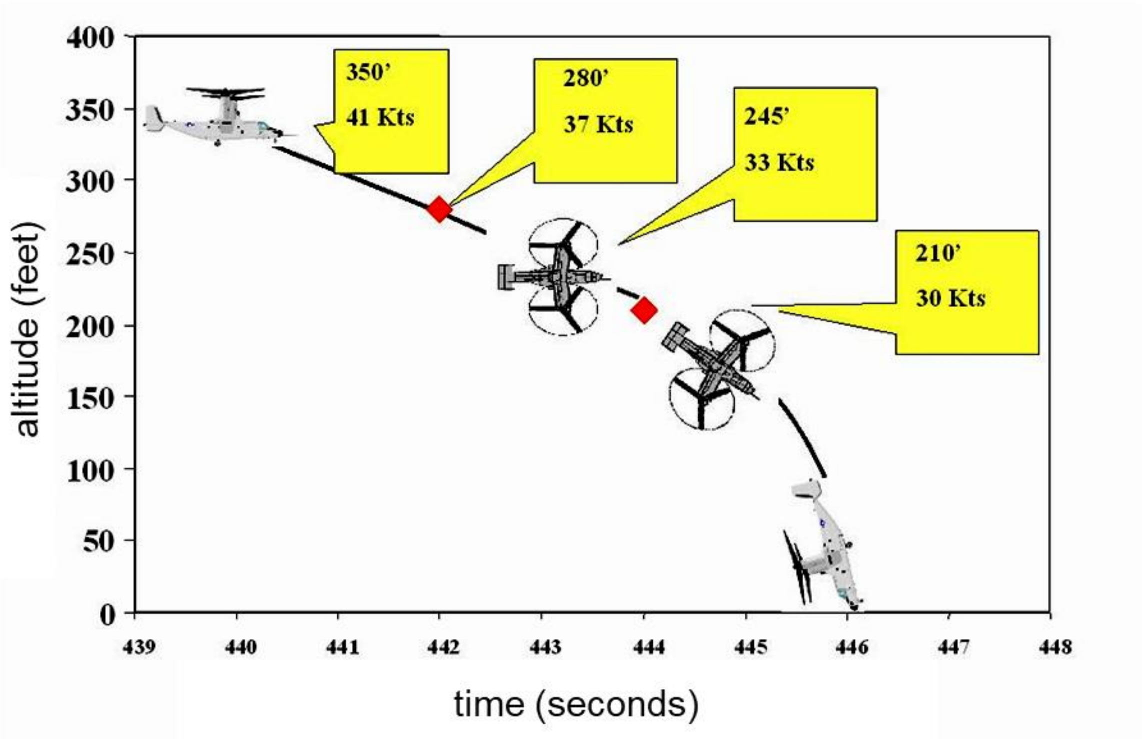
Re-emergence of an “old” problem

U.S. Marines MV-22 Osprey

Marana, Arizona

18 April 2000

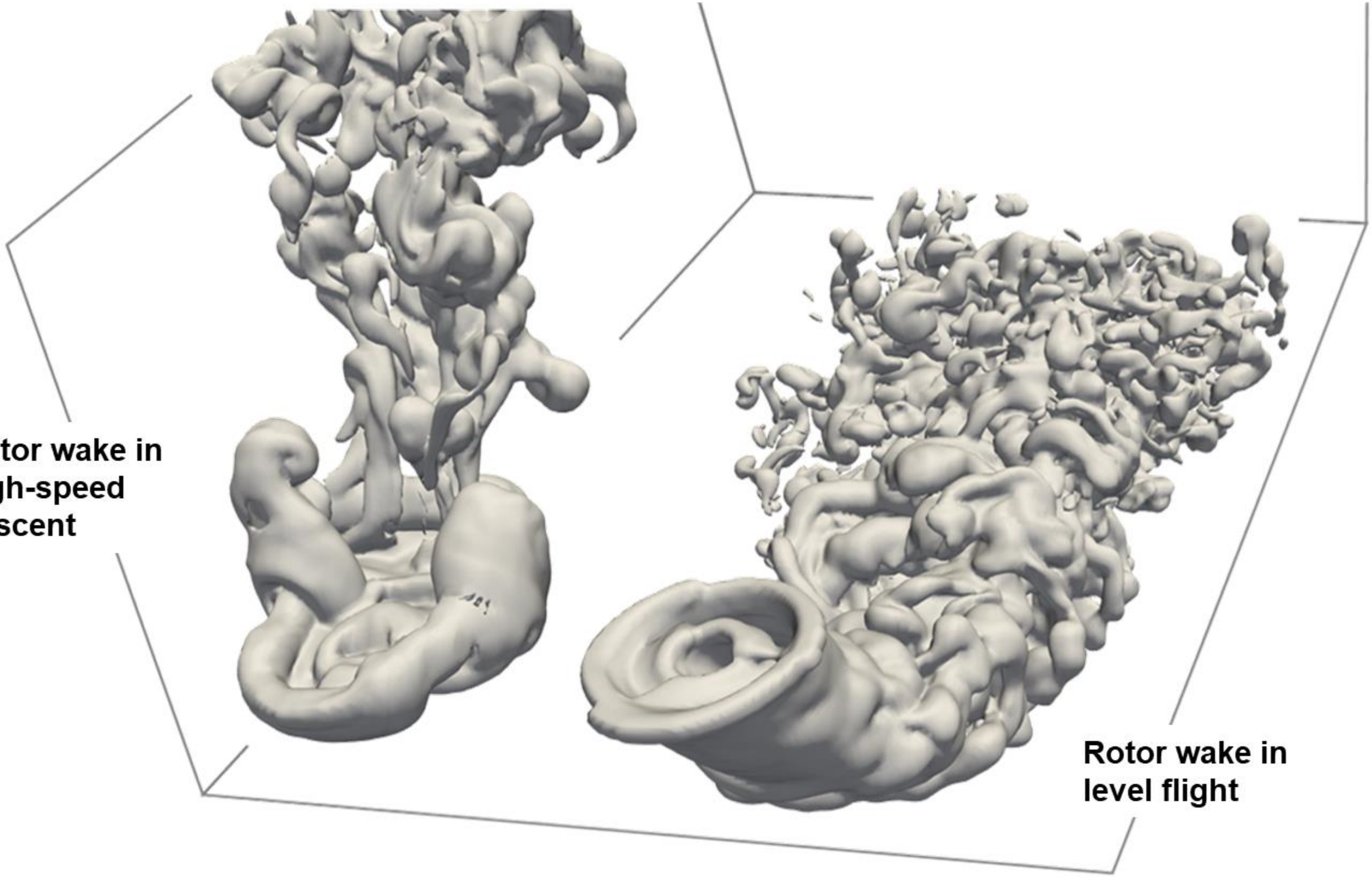
19 deaths



Last 6 seconds of flight

Formation flying, at night with NVG

What is the Vortex Ring State?



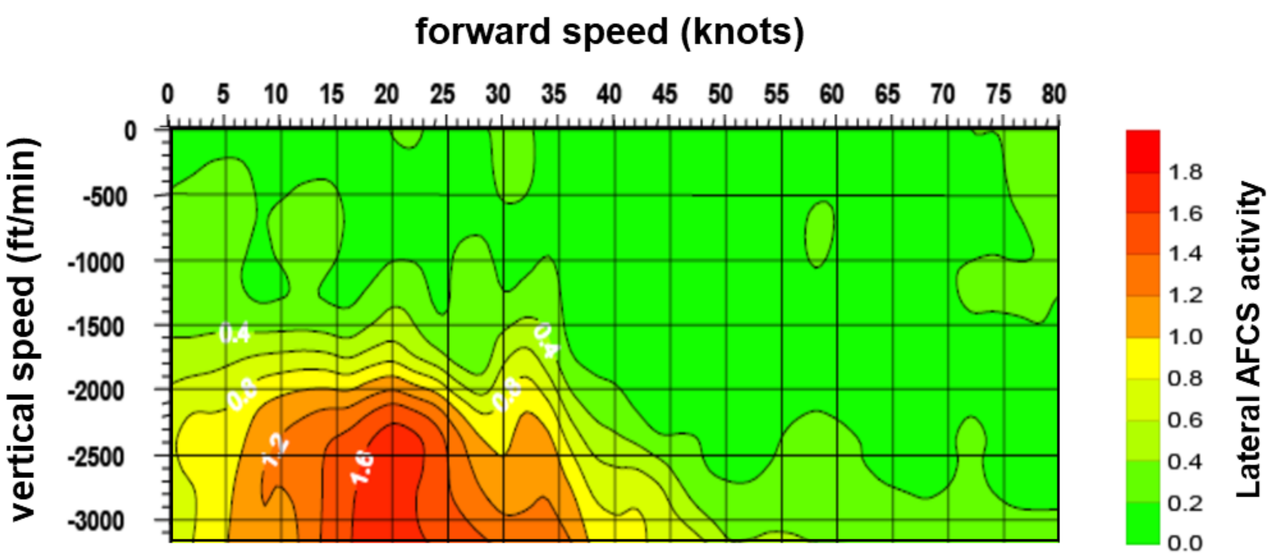
Rotor wake in high-speed descent

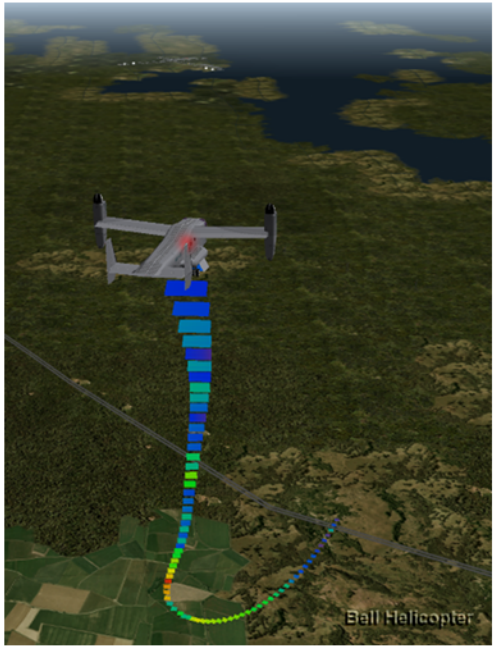
Rotor wake in level flight

What is the Vortex Ring State?

Over a range of forward speeds and descent rates

- thrust and power fluctuations
- reversal of control derivatives (e.g. thrust vs. collective pitch)
- etc…

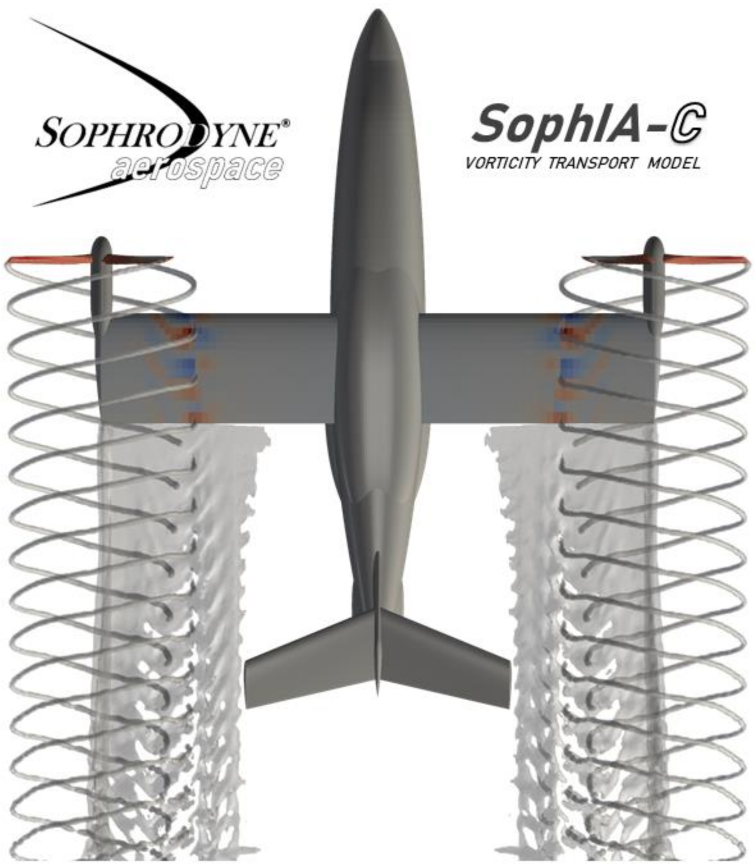




Source: Brand, Kisor, Blyth, Mason, Host, "V-22 High Rate of Descent (HROD) Test Procedures and Long Record Analysis," American Helicopter Society Annual National Forum 2004

Computational methodology

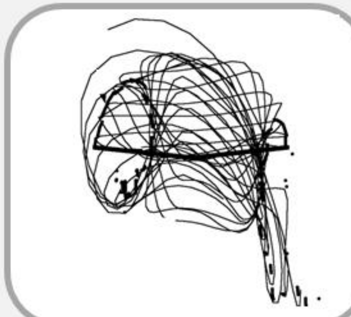
Using the appropriate computational methodology is essential…



"Free wake"

- Lagrangian approach quickly accumulates integration error

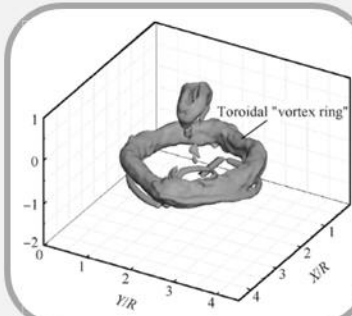
➡ Chaotic evolution of vortex filaments



"Conventional" CFD

- Vorticity not conserved

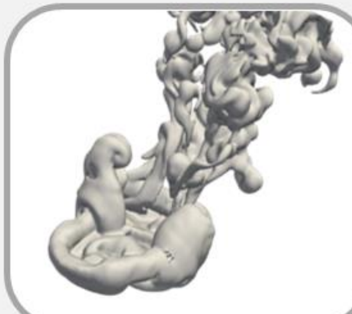
➡ Wake dynamics mis-represented



Vorticity Transport CFD

- Vorticity properly tracked
- Proper control of accuracy

➡ **Wake dynamics accurately represented**



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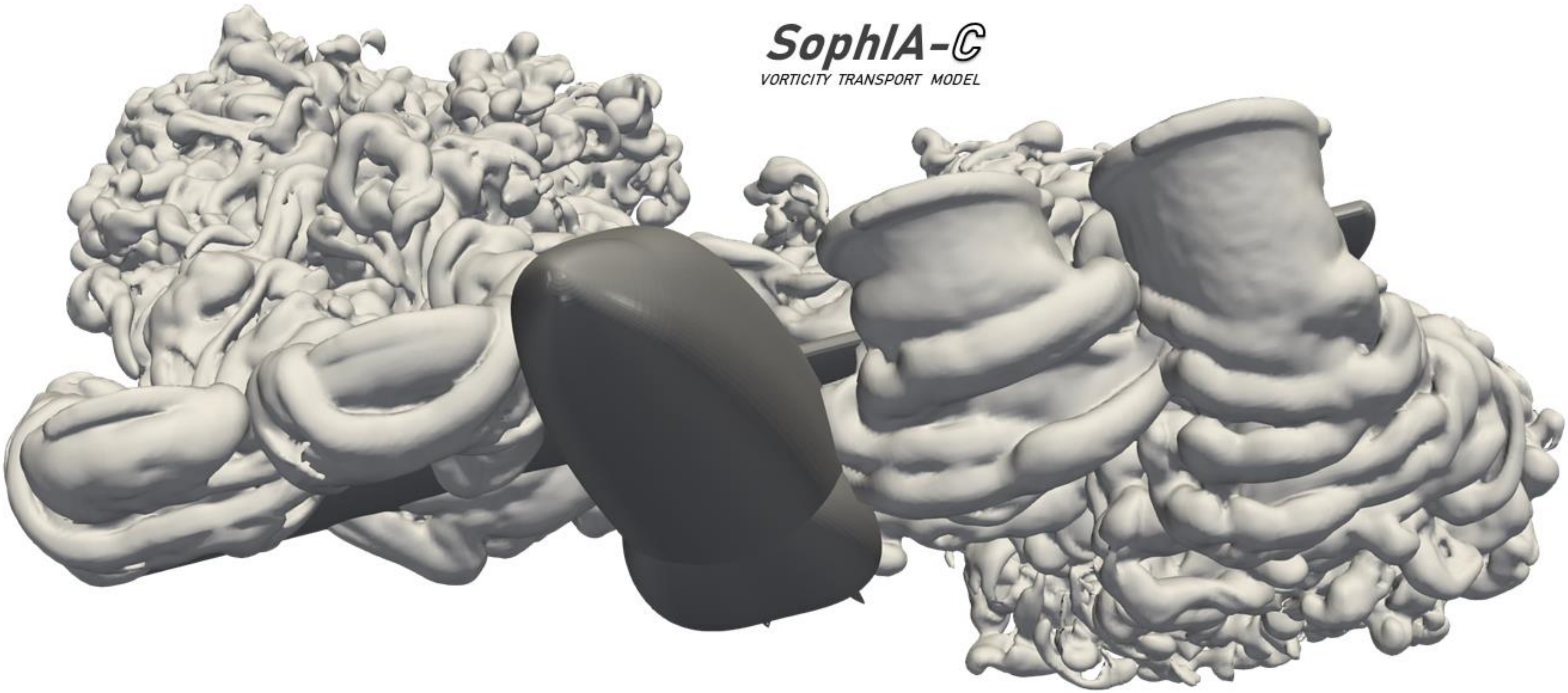
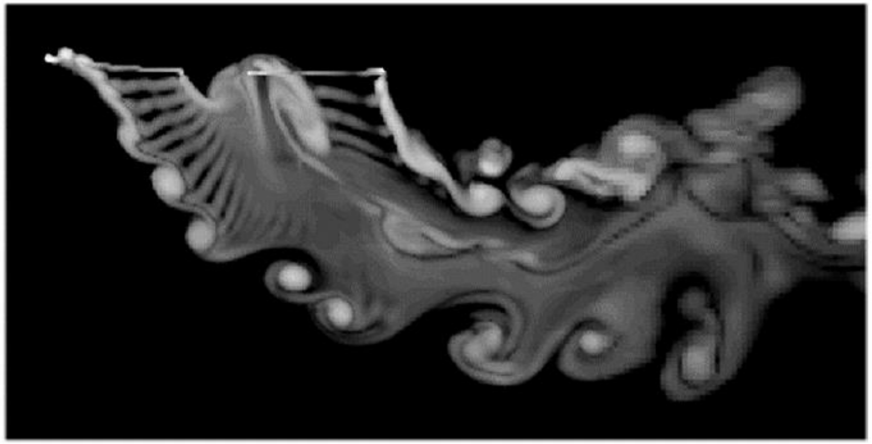
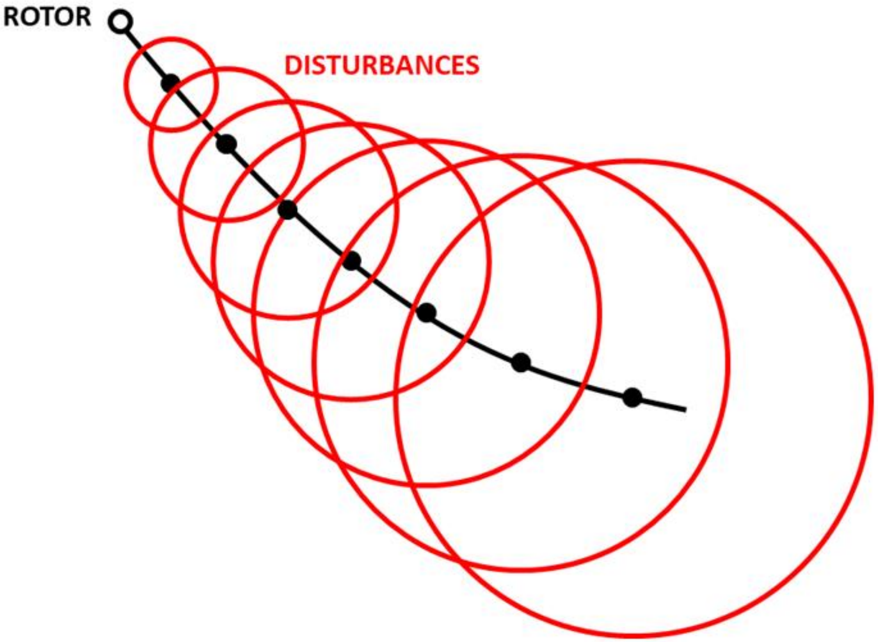


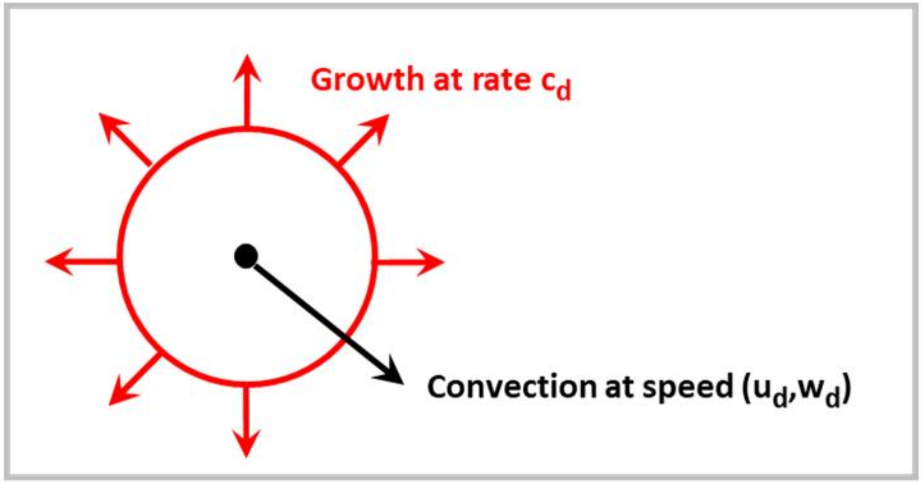
Hex-rotor eVTOL in asymmetric Vortex Ring State

A physical hypothesis (different to the 'usual' explanation)

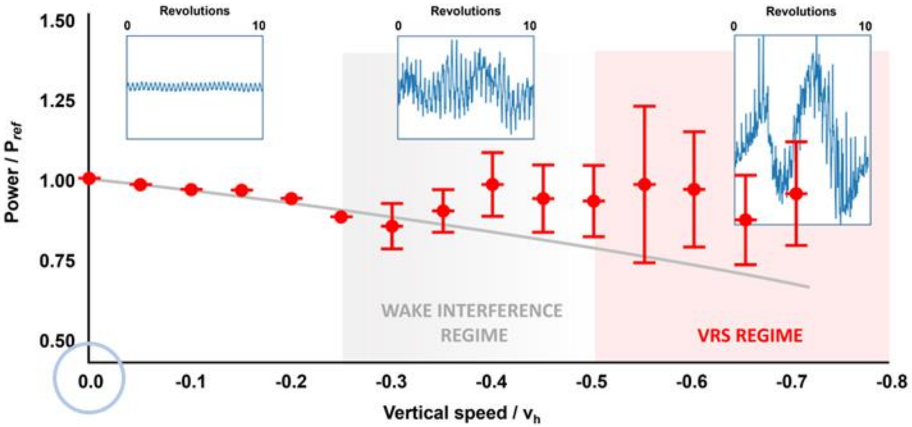
… *wake instability* is the primary physical mechanism that is responsible for the onset of the VRS.

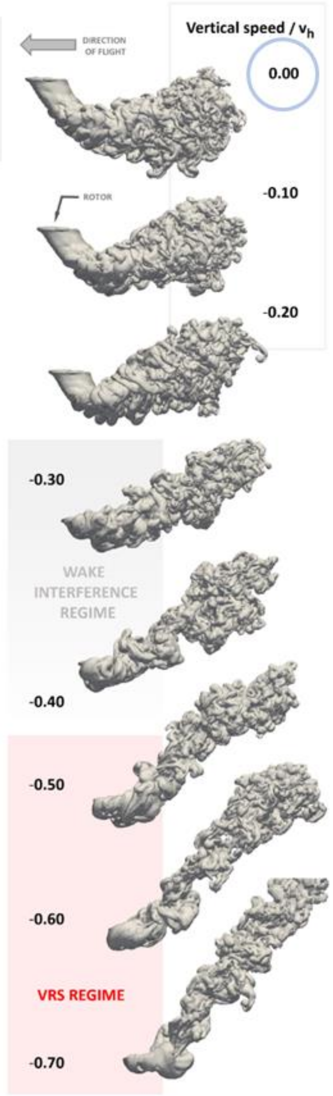


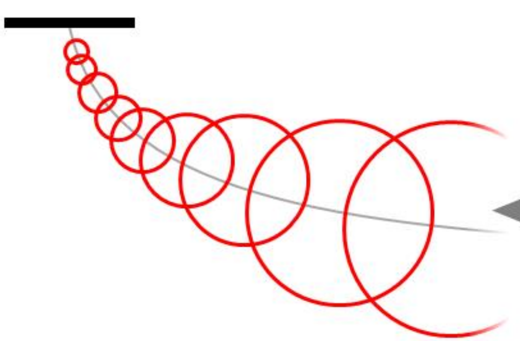


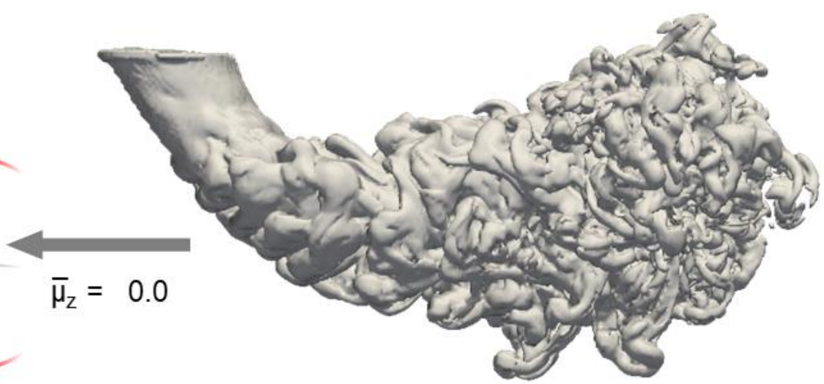


SophIA-C simulations for an isolated, single rotor









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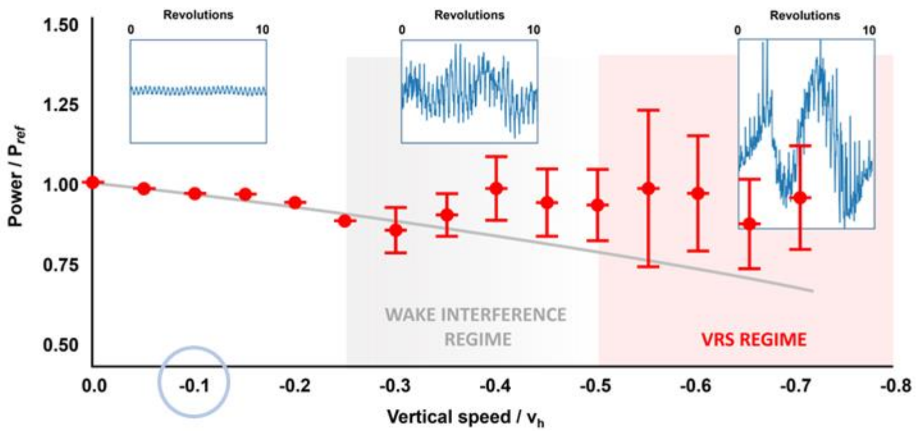

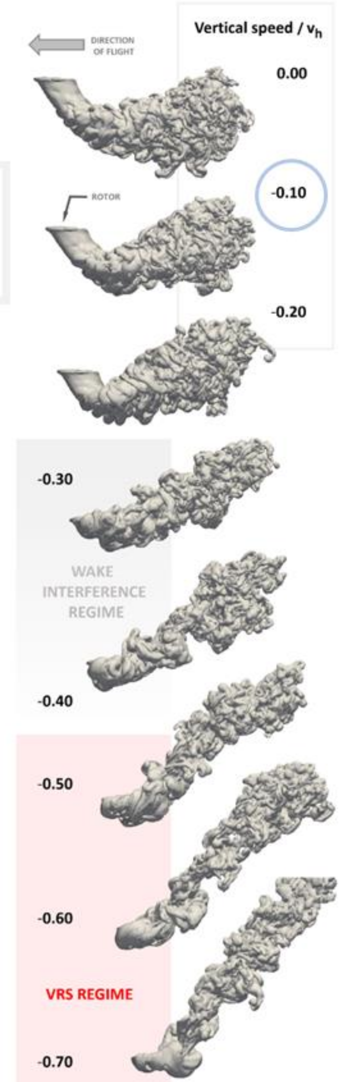

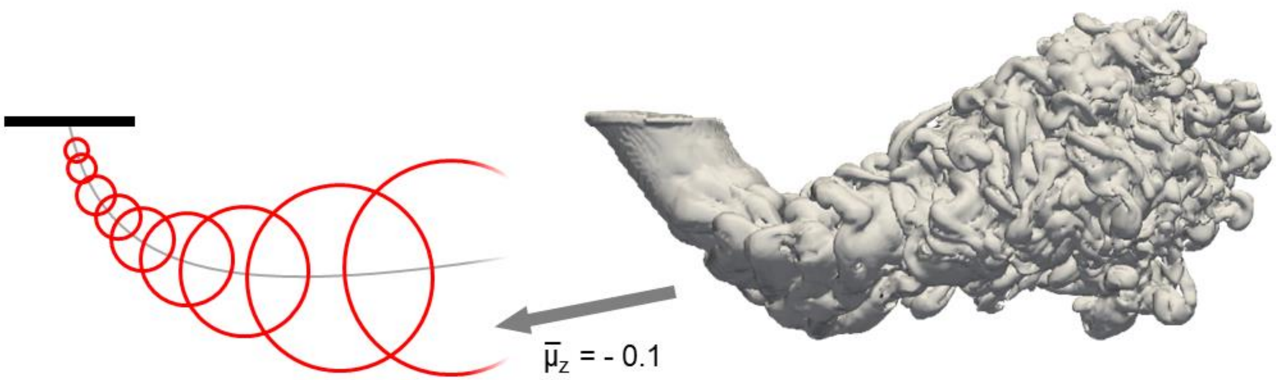

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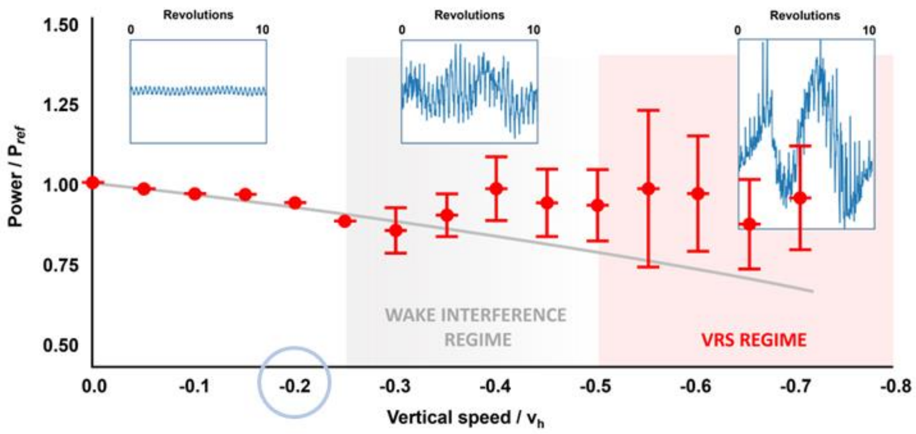

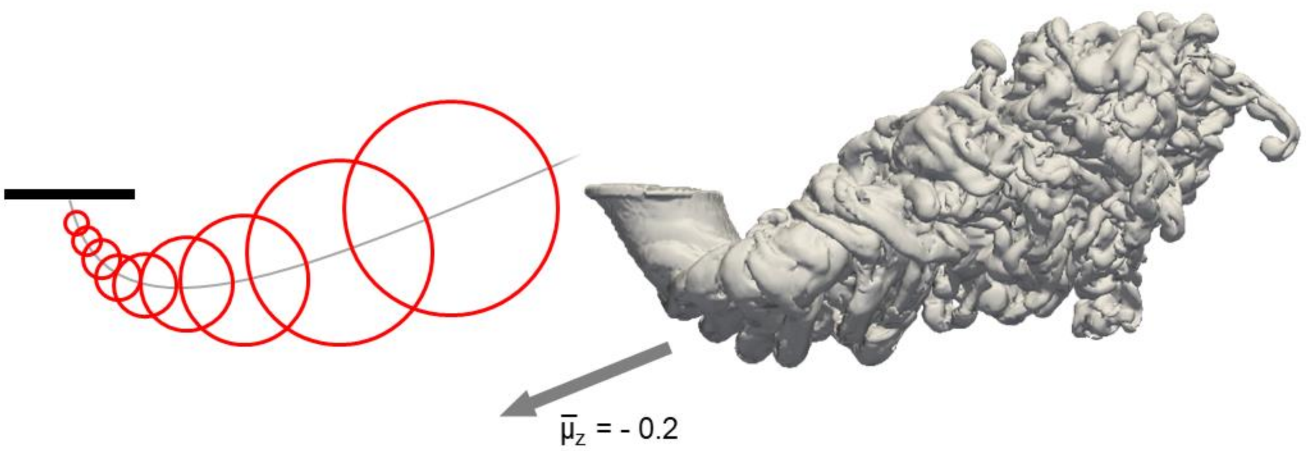

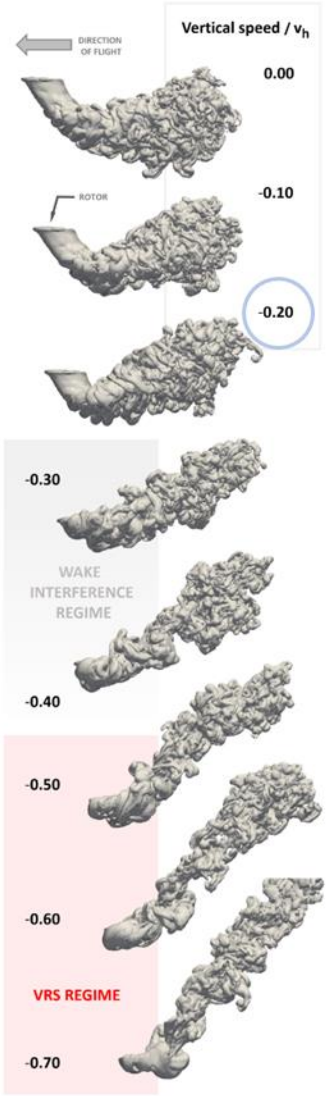

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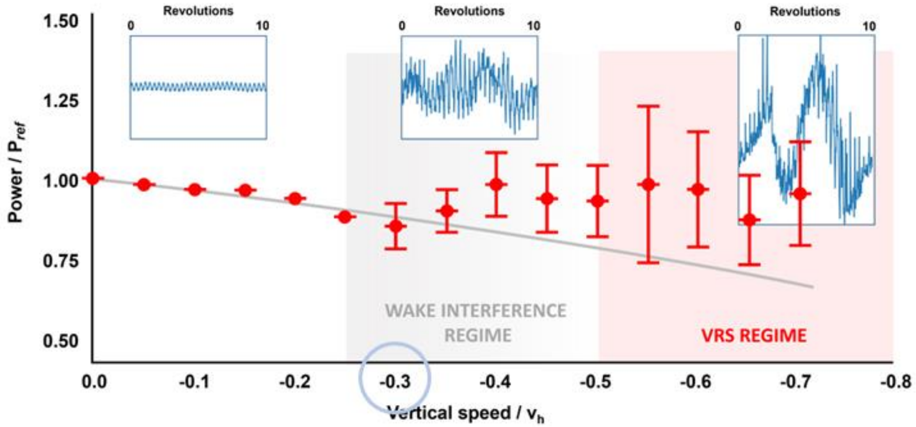

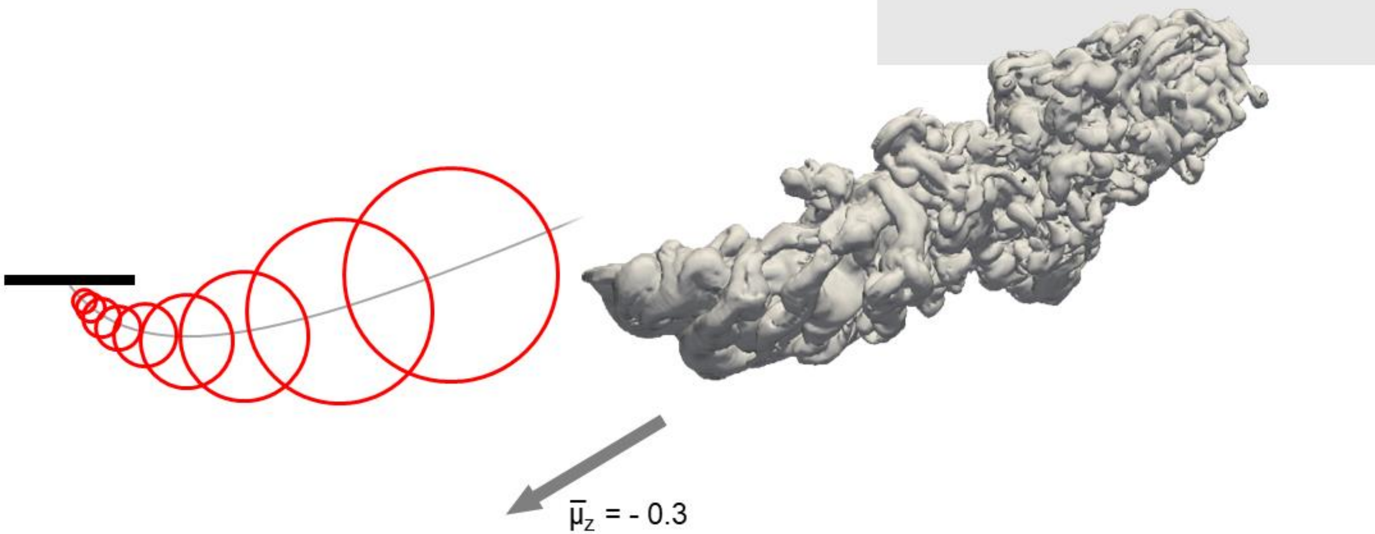

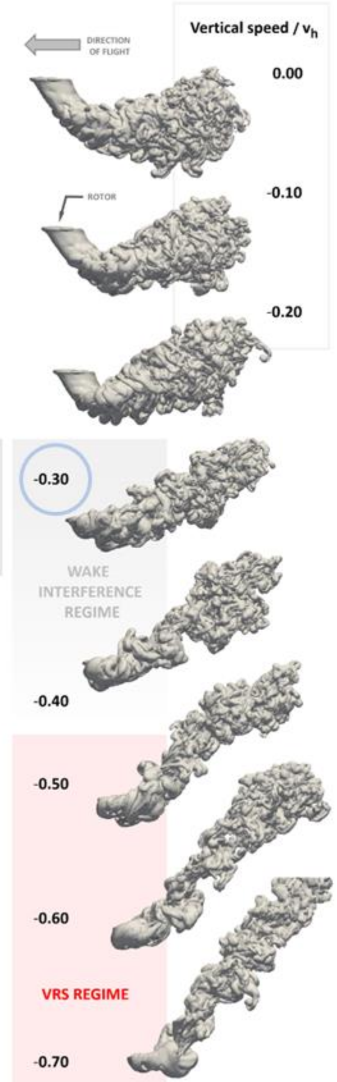

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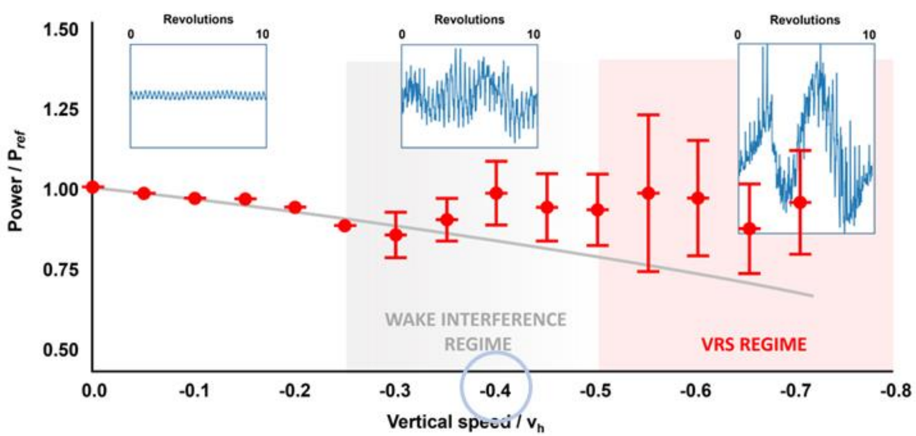

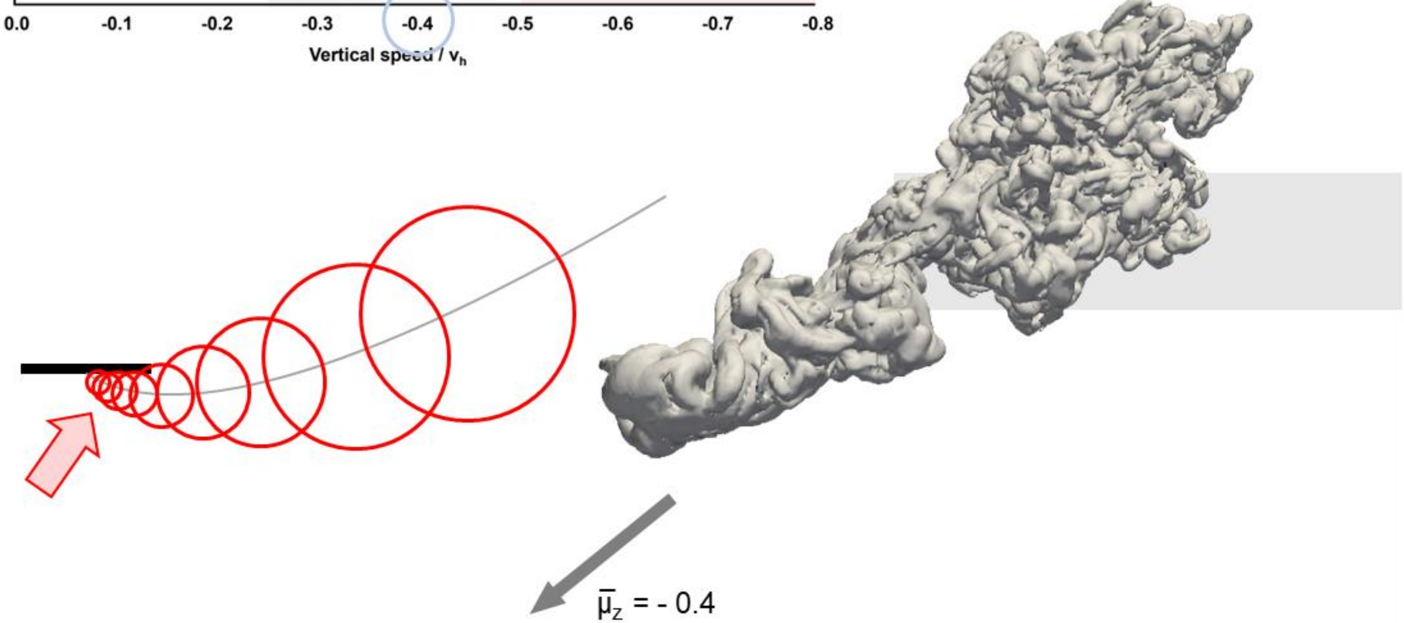

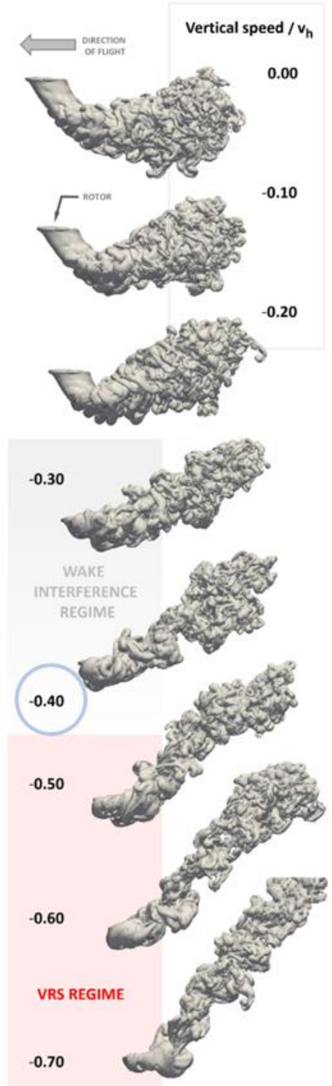

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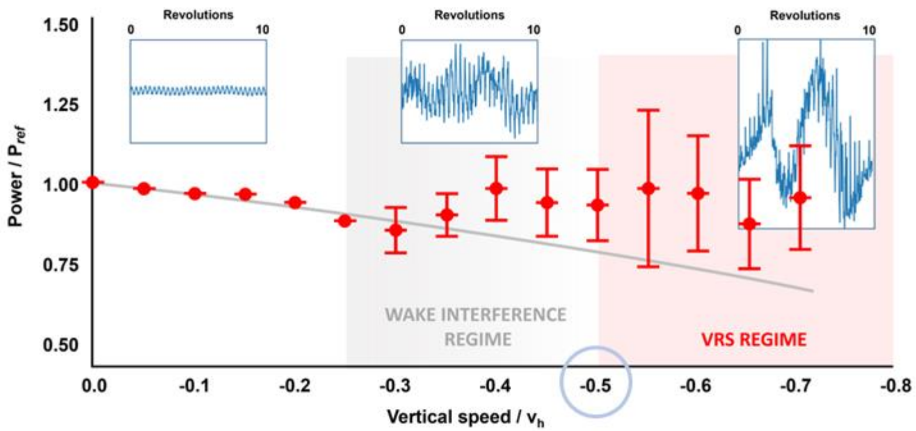

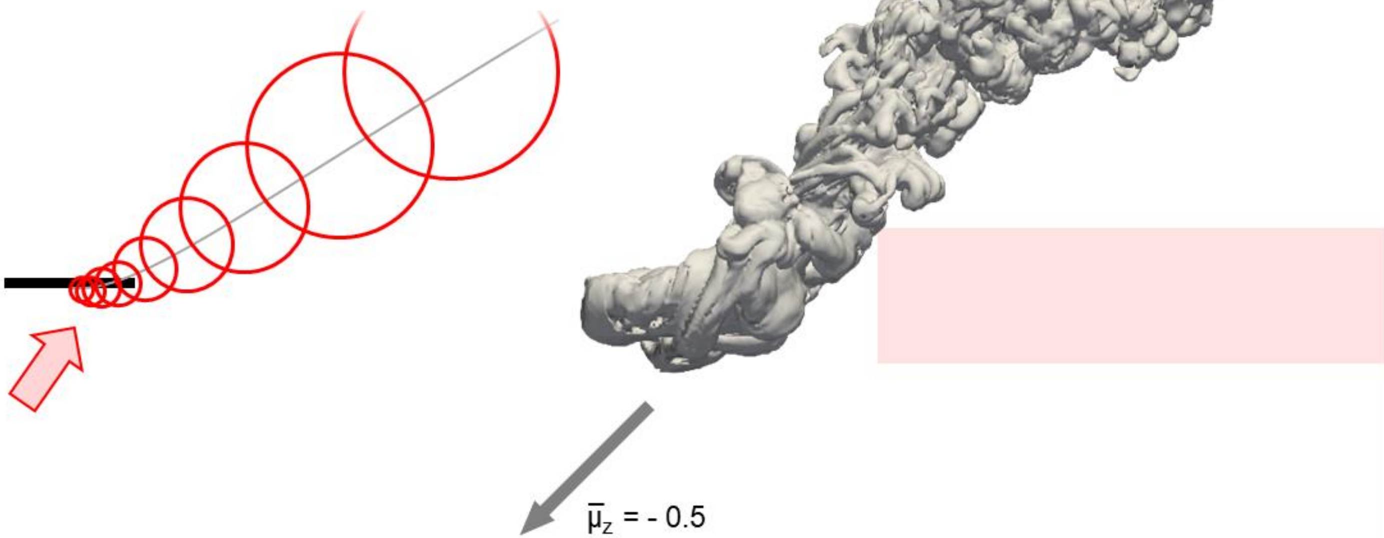

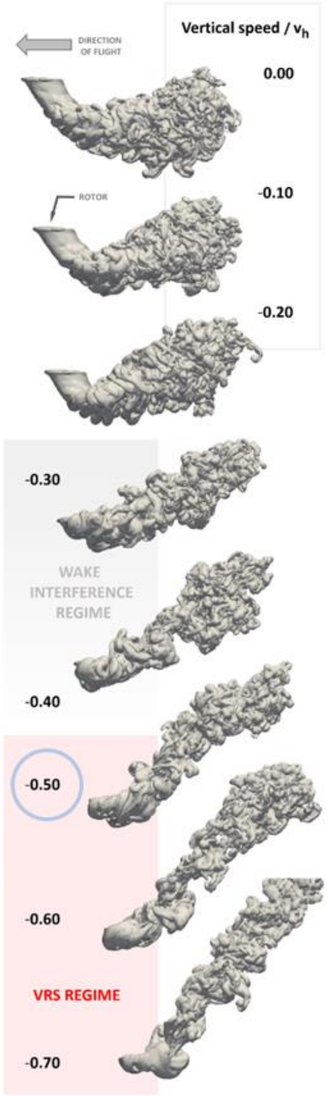

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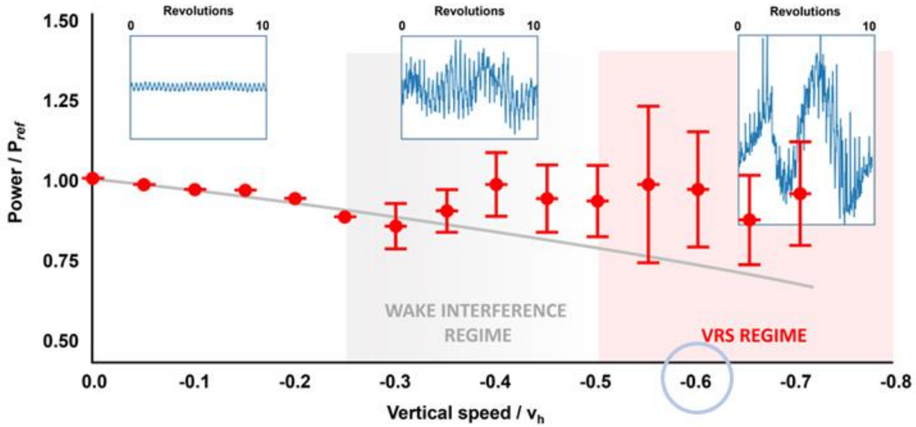

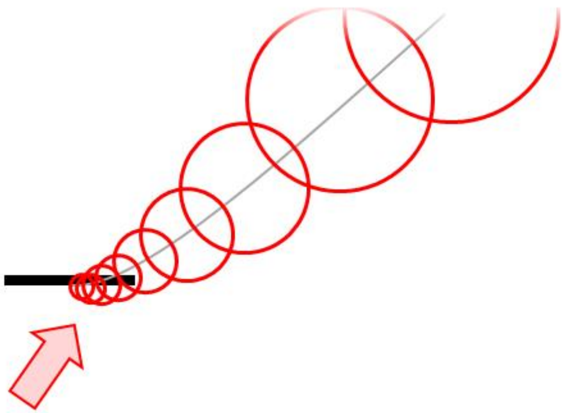

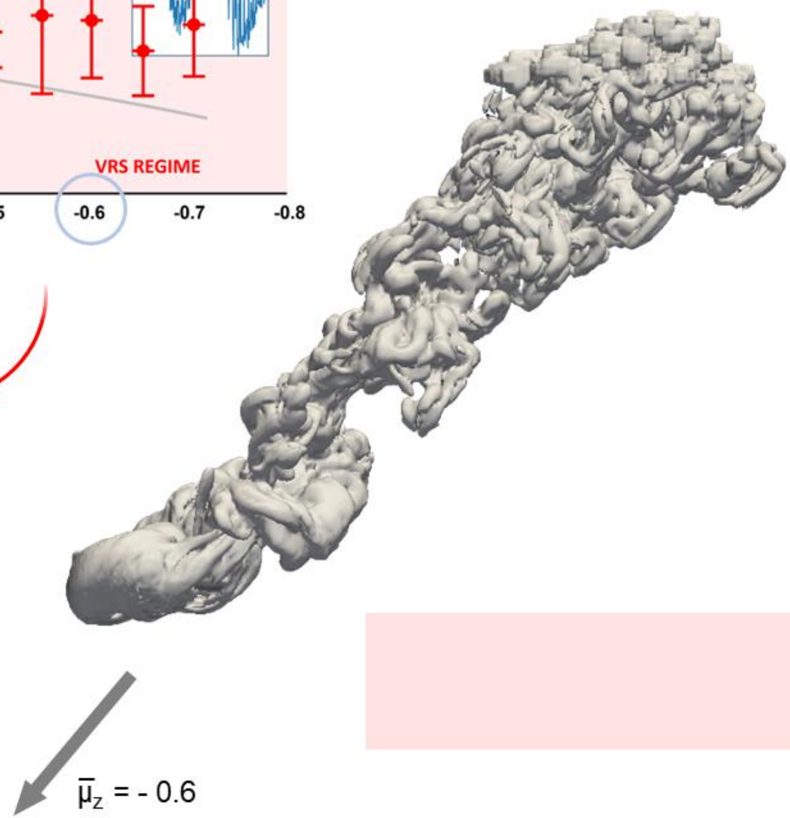

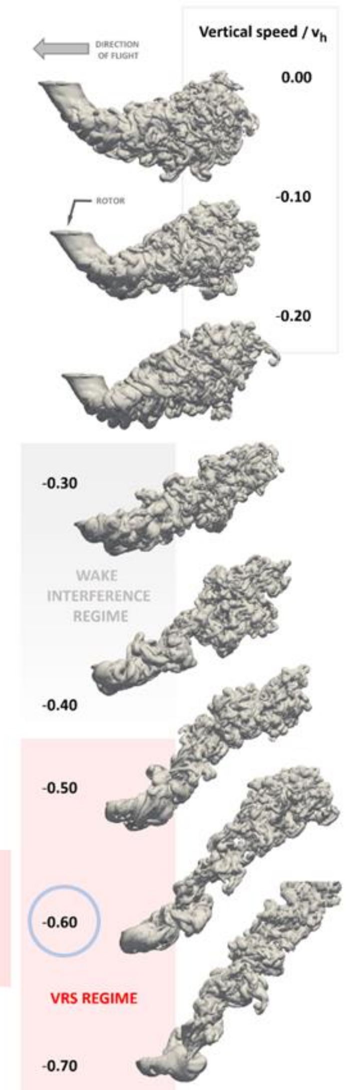

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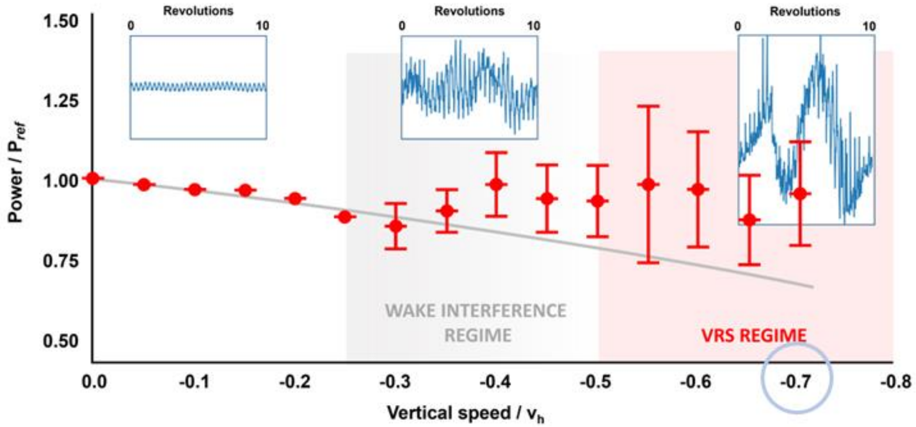
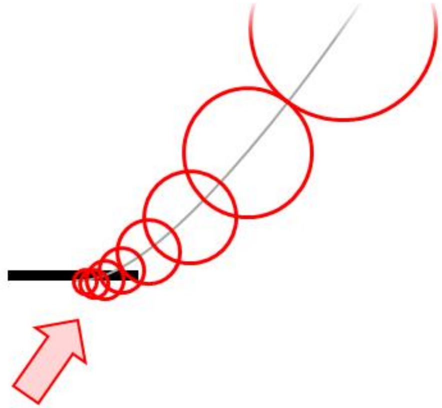
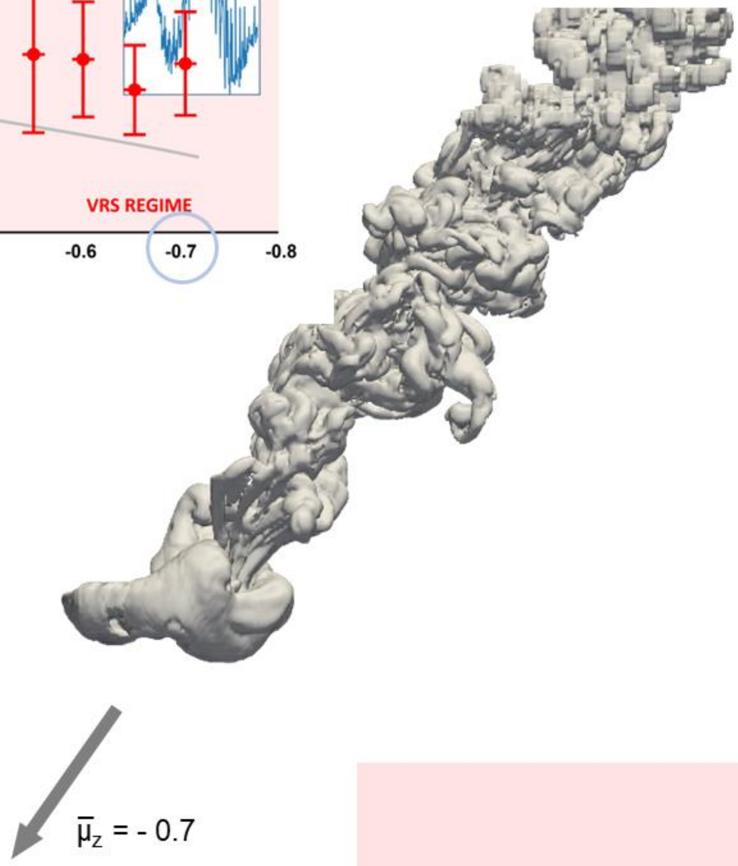
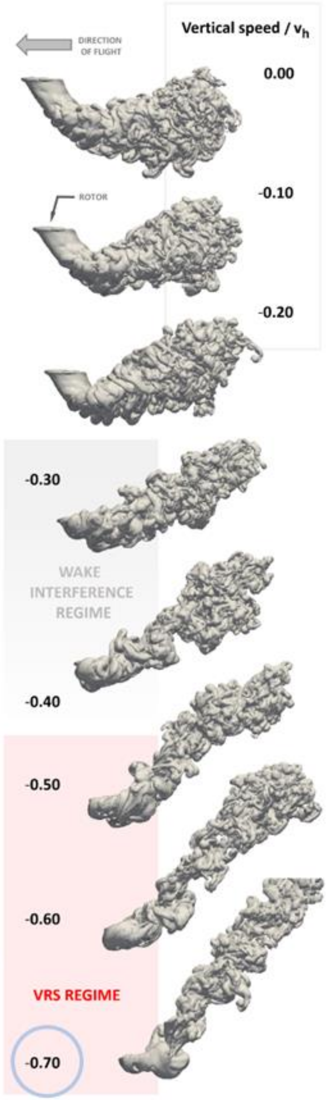
SophIA-C simulations for an isolated, single rotor









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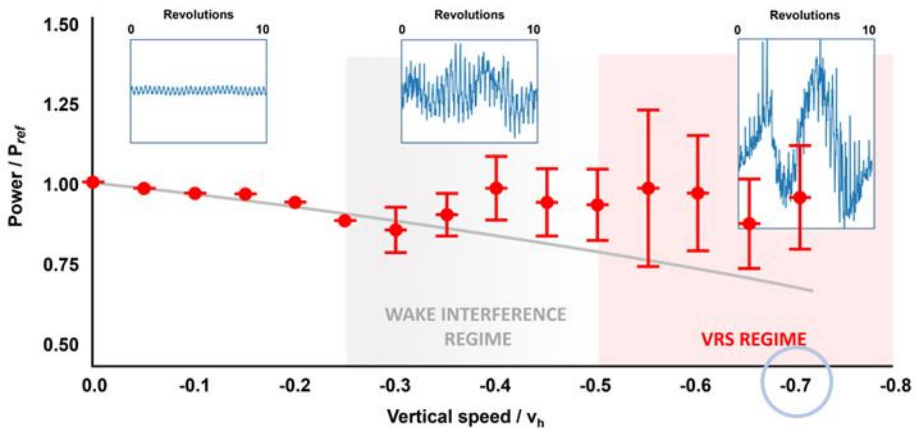
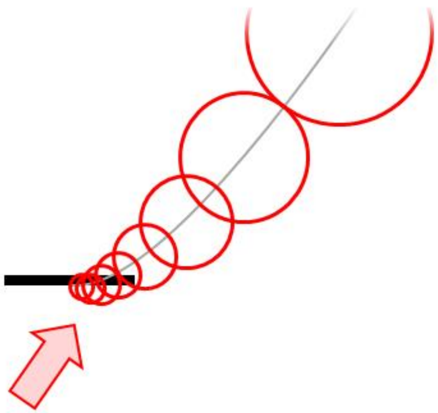
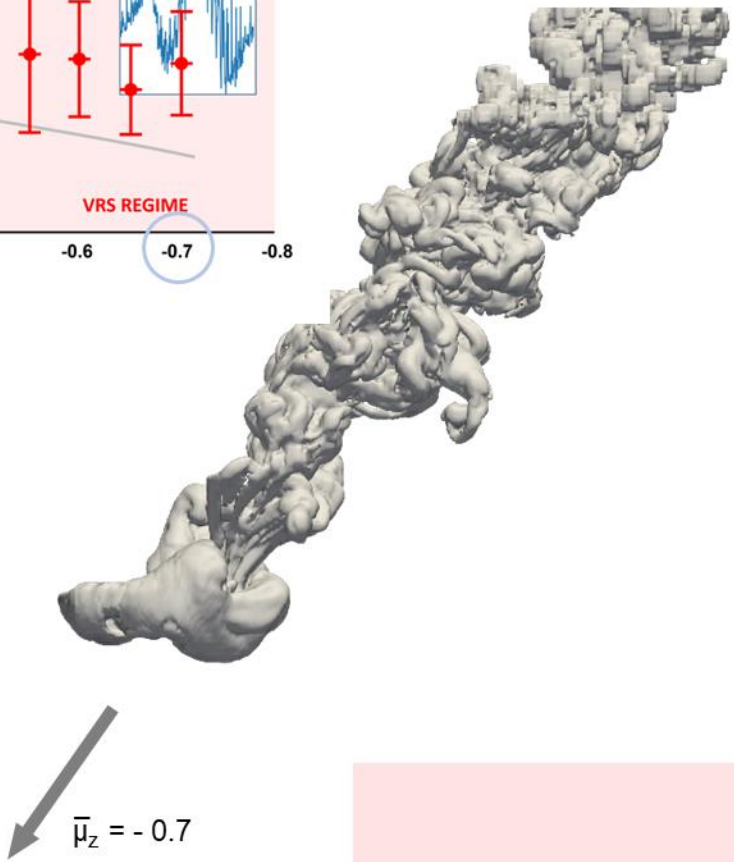
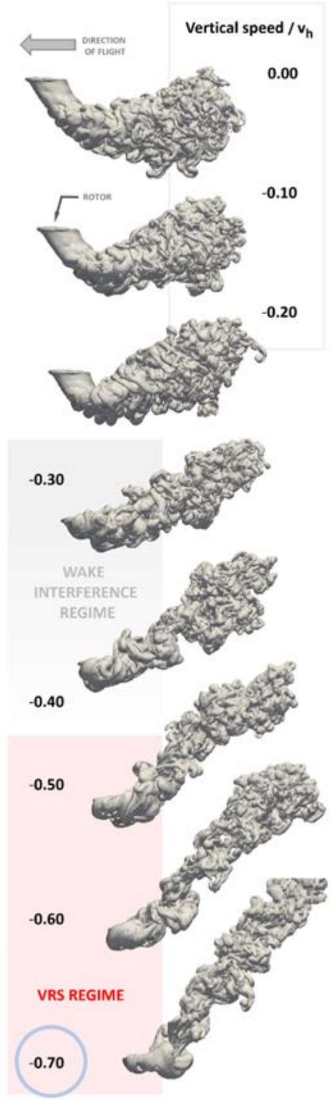




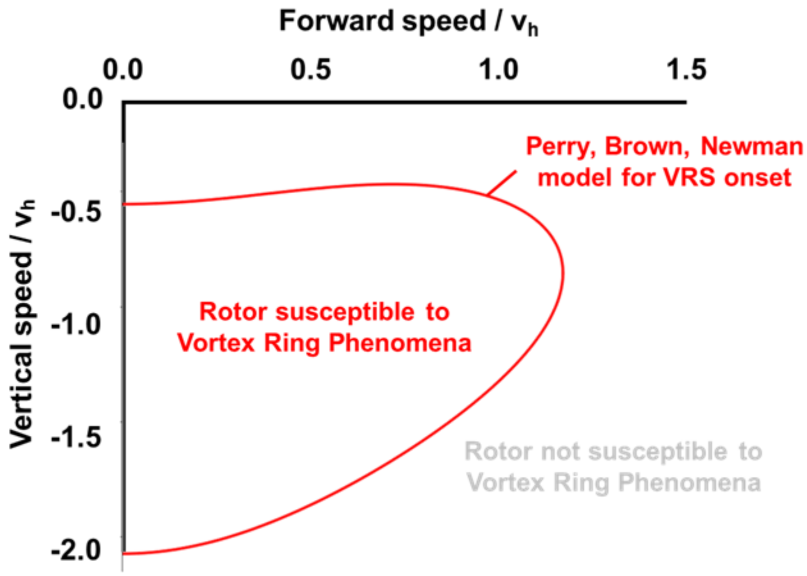




An analytic model for VRS onset

Original Perry Model (2003) $$\bar{\mu}_W^2 = (k\bar{\mu}_x)^2 + (\bar{\mu}_z + \bar{\lambda}_i)^2$$

Enhanced model (2005) $$(\mu_x - u_d)^2 + (\mu_z - w_d)^2 = c_d^2$$



Disturbance propagation rates :

$$u_d = (1-k)\mu_x$$

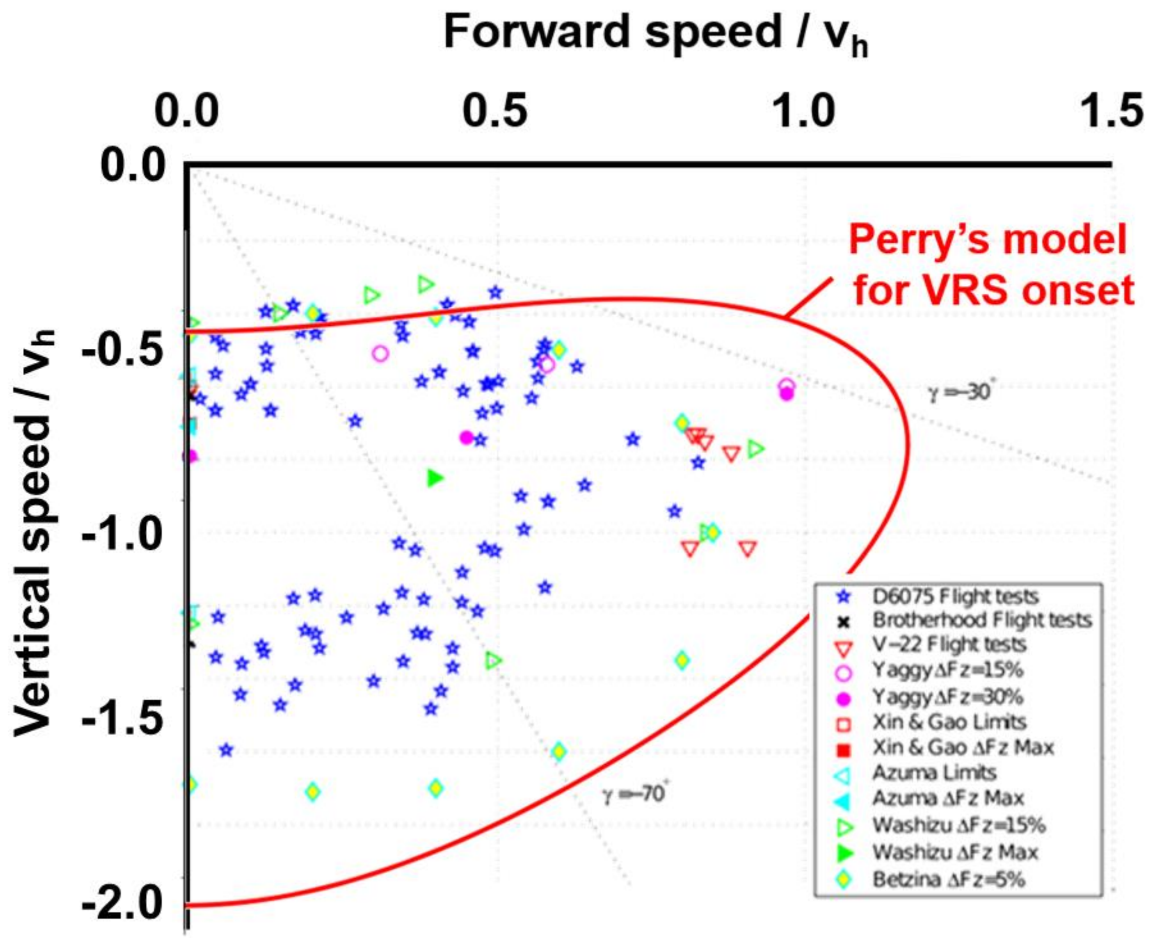
$$w_d = -\lambda_i$$

Disturbance growth rate :

$$c_d = \bar{\mu}_W \sqrt{C_T/2}$$

(Thrust coefficient C_T ~ Disc Loading!)

An analytic model for VRS onset



This presentation :

- Vortex Ring State is a real threat to the helicopter community, as borne out by accident statistics :

  NTSB CAROL accident database :

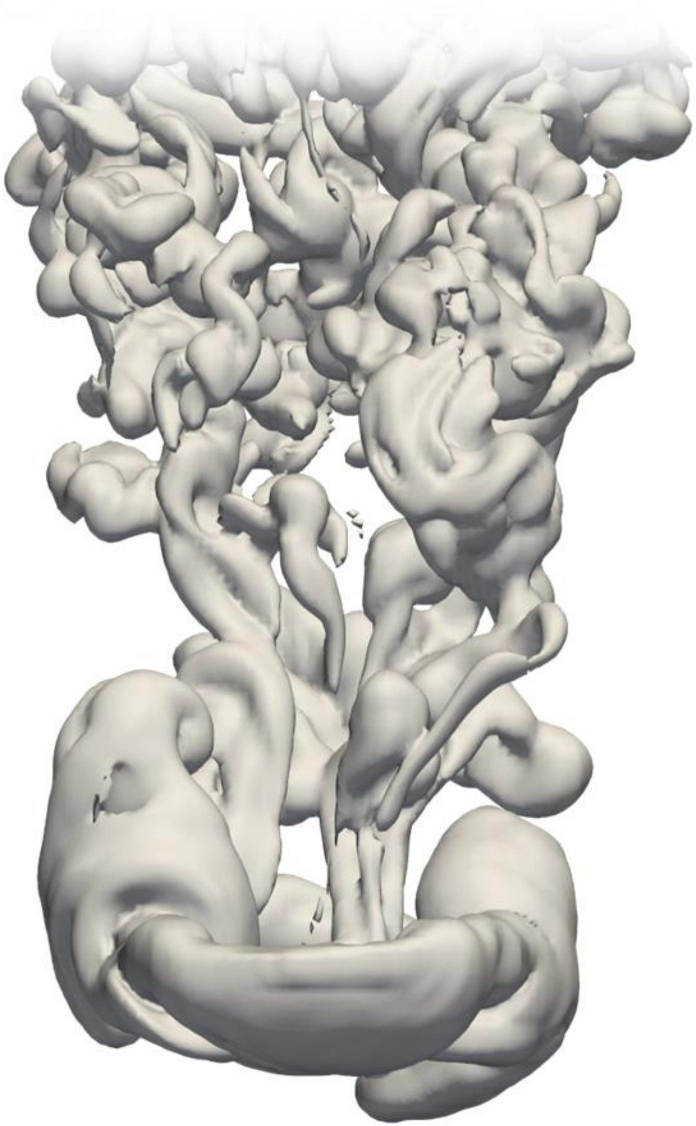
  79 results for "settling with power"
  17 for "Vortex Ring State"

- Proper attention to the phenomenon is presently obscured by confusion over terminology and lack of understanding of the physics.

Is the eVTOL community going to make the same mistake?

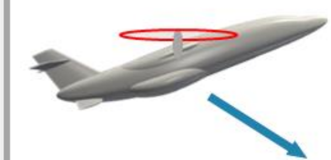
How can regulators *help*?

Structure of presentation



Trajectory

- How the trajectory followed by the aircraft may influence its susceptibility to the VRS.



Manoeuvres

- How rigid-body manoeuvres may conspire with certain elements of the aircraft's configuration to influence its susceptibility to the VRS.

The Urban Environment

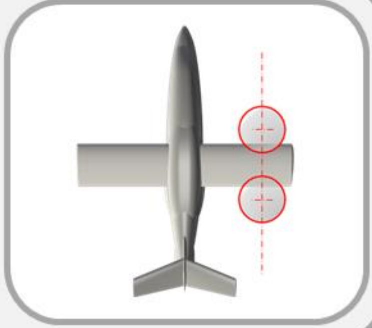
How does operation in the urban environment influence susceptibility to the VRS ?

- Gusts
- Vertiport Design.

Structure of presentation

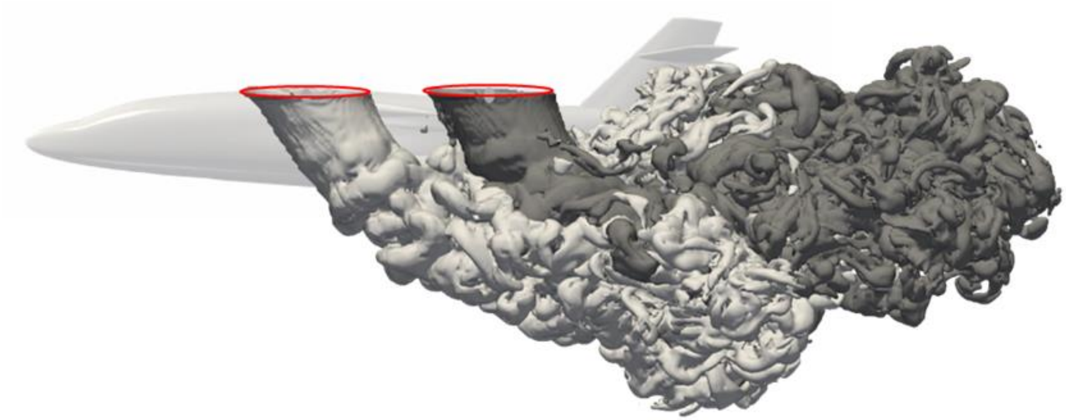
Aerodynamic Interactions

- How "second-order" aerodynamic effects may play an important role in promoting VRS in aircraft with certain configurational features.



Please go to Sophrodyne's website:

https://sophrodyne-aerospace.com/resources



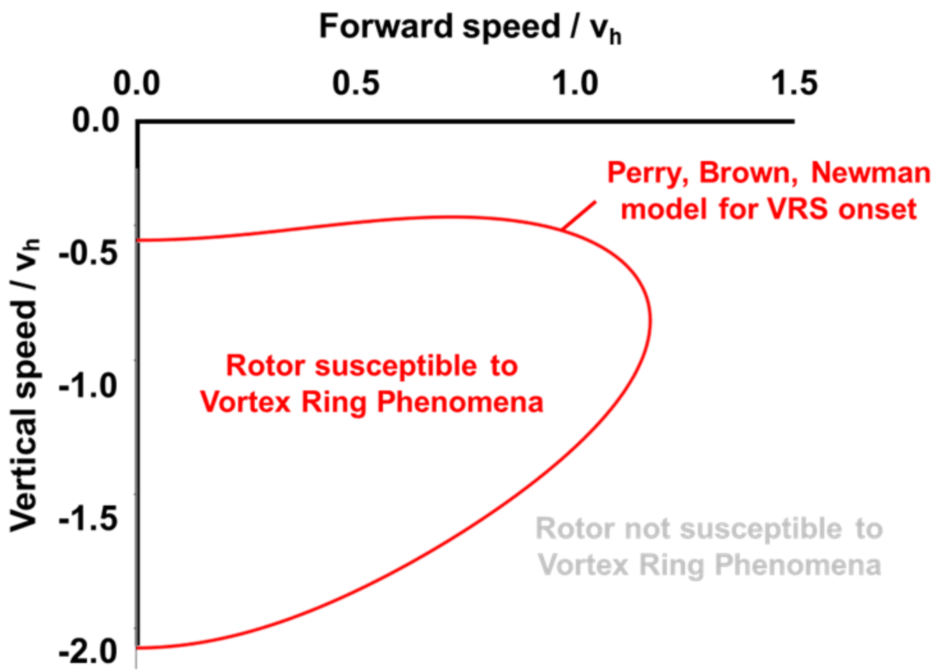
A model for VRS onset

Original Perry Model (2003) :

$$\overline{\mu}_W^2 = (k\overline{\mu}_x)^2 + (\overline{\mu}_z + \overline{\lambda}_i)^2$$

$\overline{\mu}_W$: "critical wake transport velocity"

k : "effectiveness of lateral wake transport"



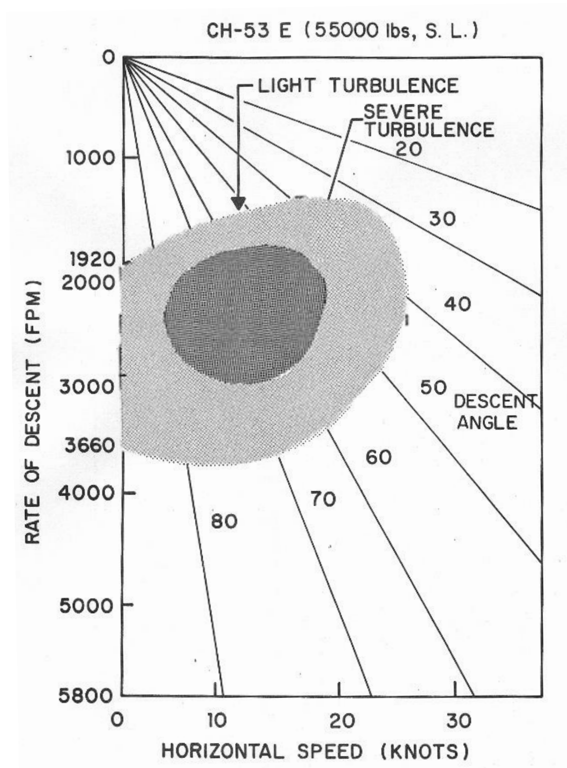
v_h = induced velocity in hover

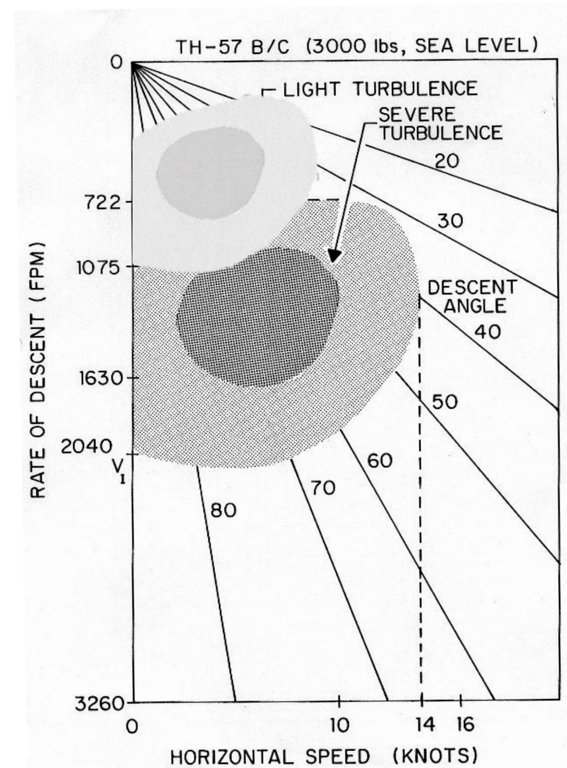
as modelled using momentum theory

so

v_h = (disc loading / 2ρ)$^{1/2}$

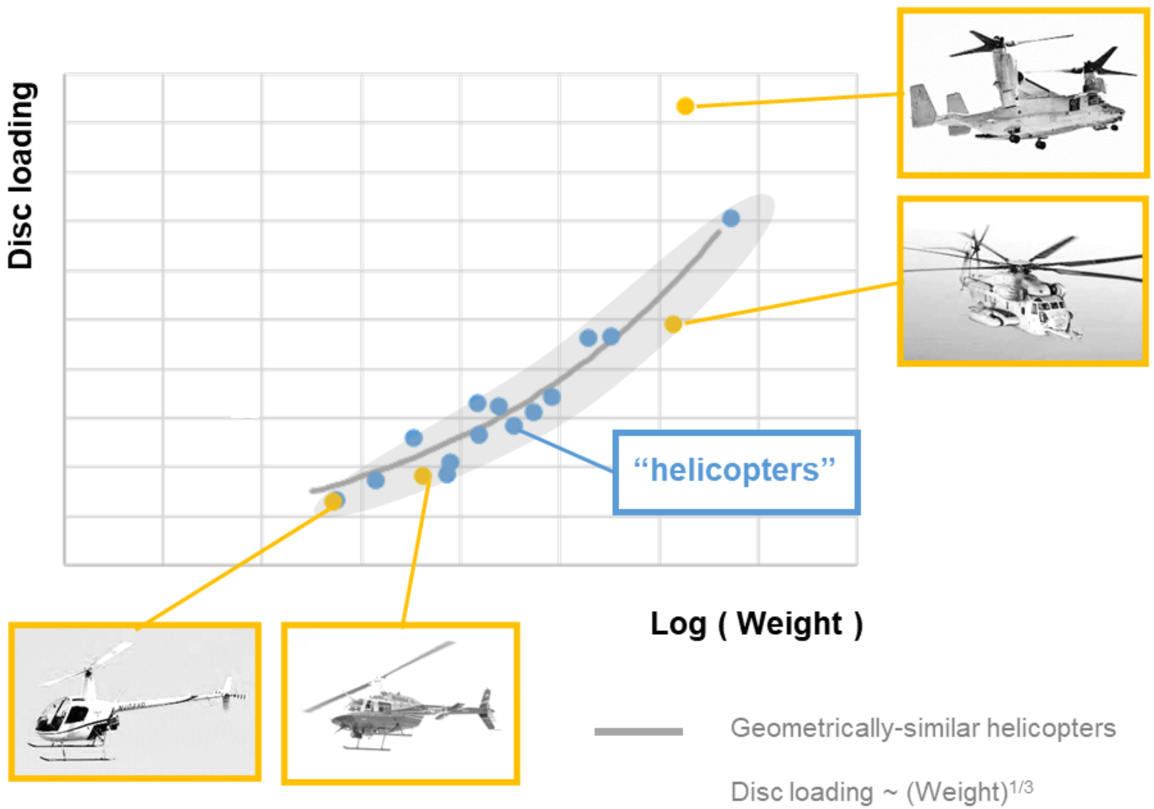
Dependence on Disc Loading





Disc loading = $\dfrac{\text{Weight}}{\text{rotor area}}$

Dependence on Disc Loading



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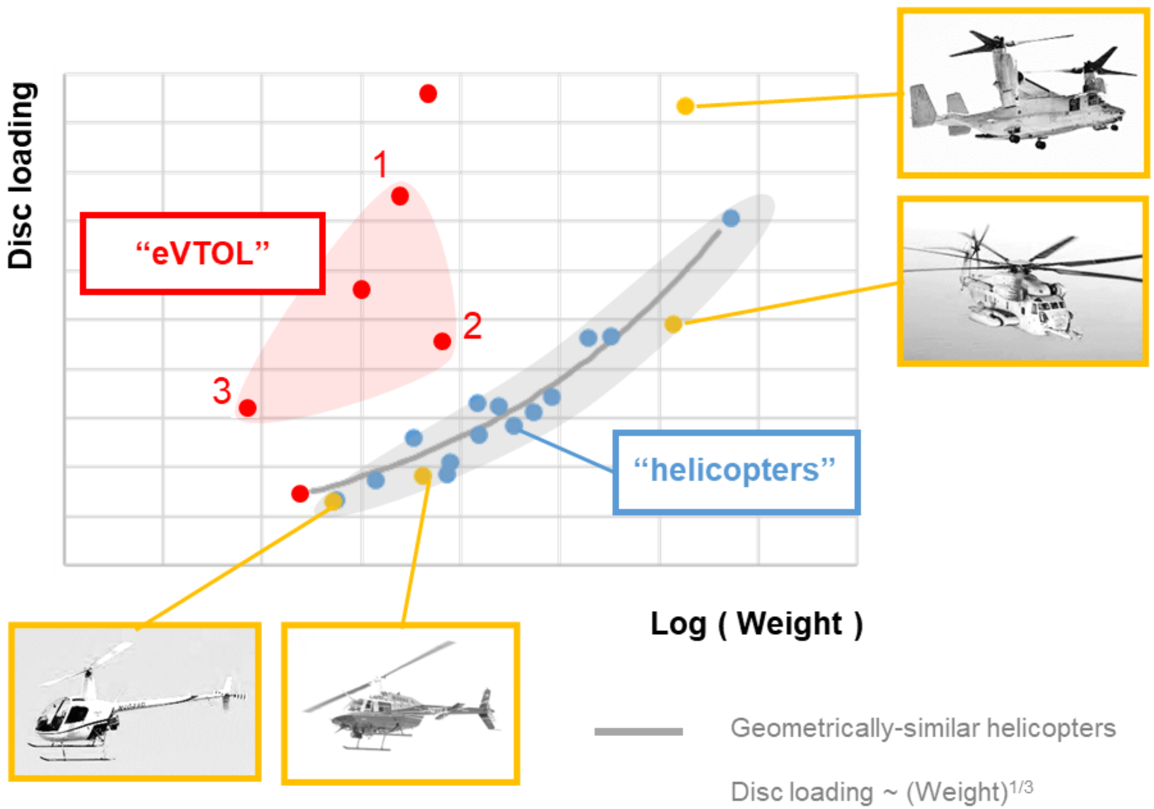
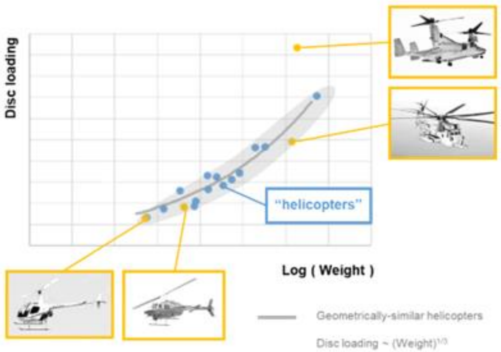
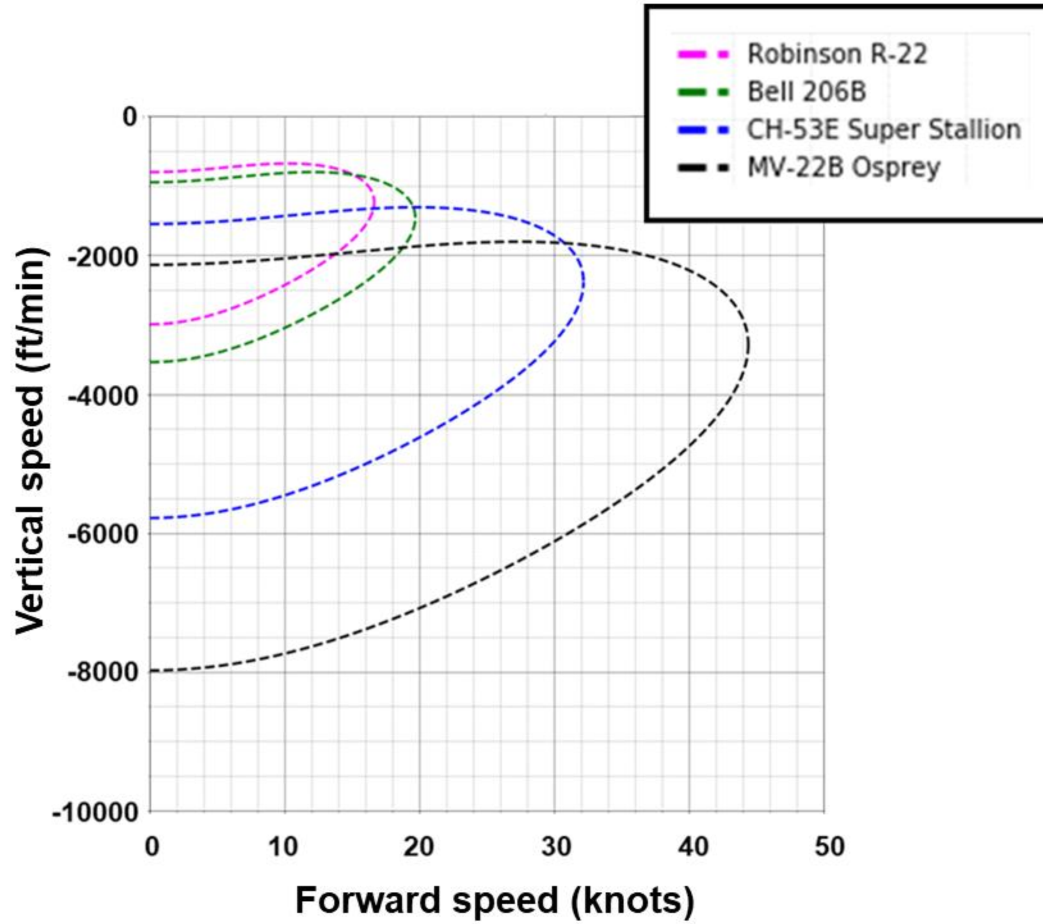


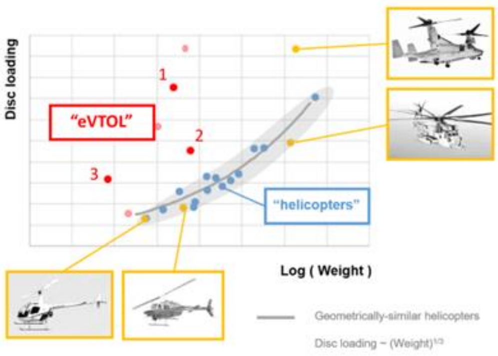
$$\text{Disc loading} = \frac{\text{Weight}}{\text{rotor area}}$$

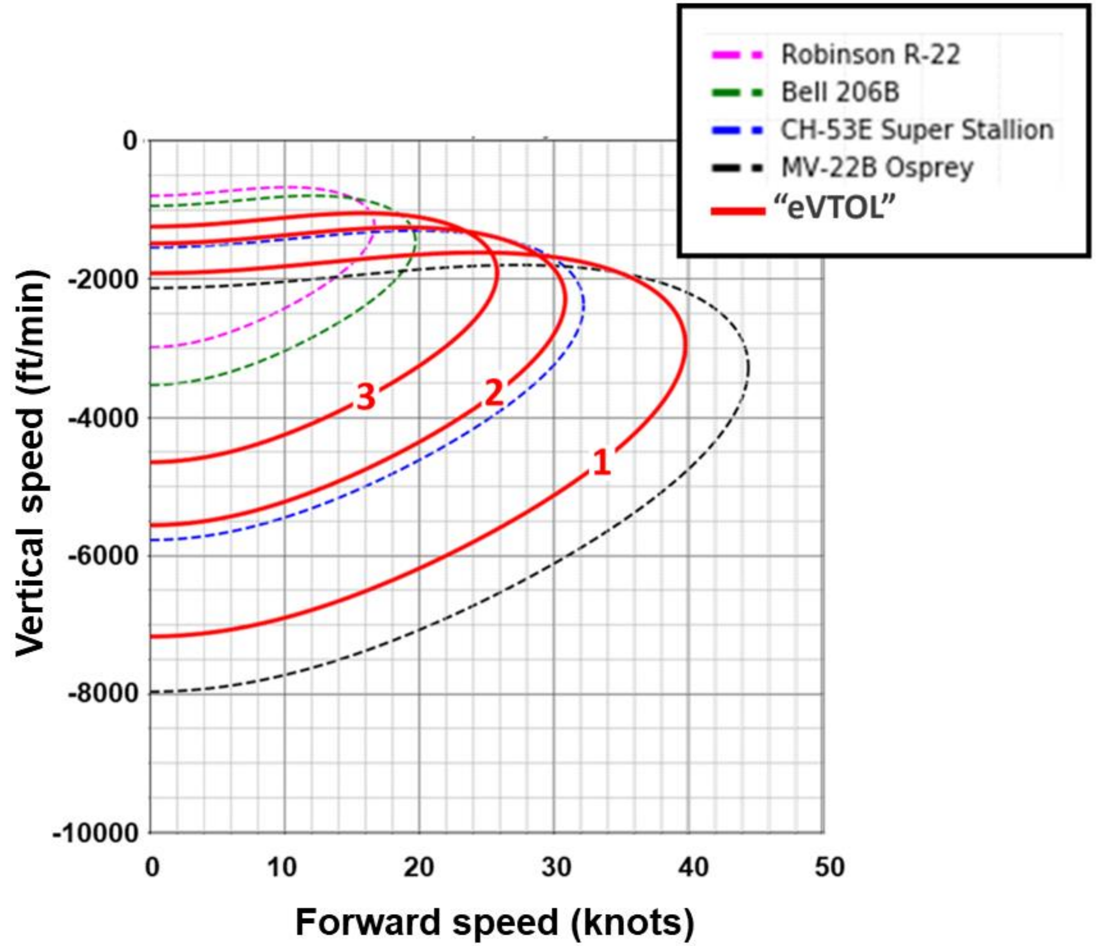
VRS regime for Conventional Helicopters



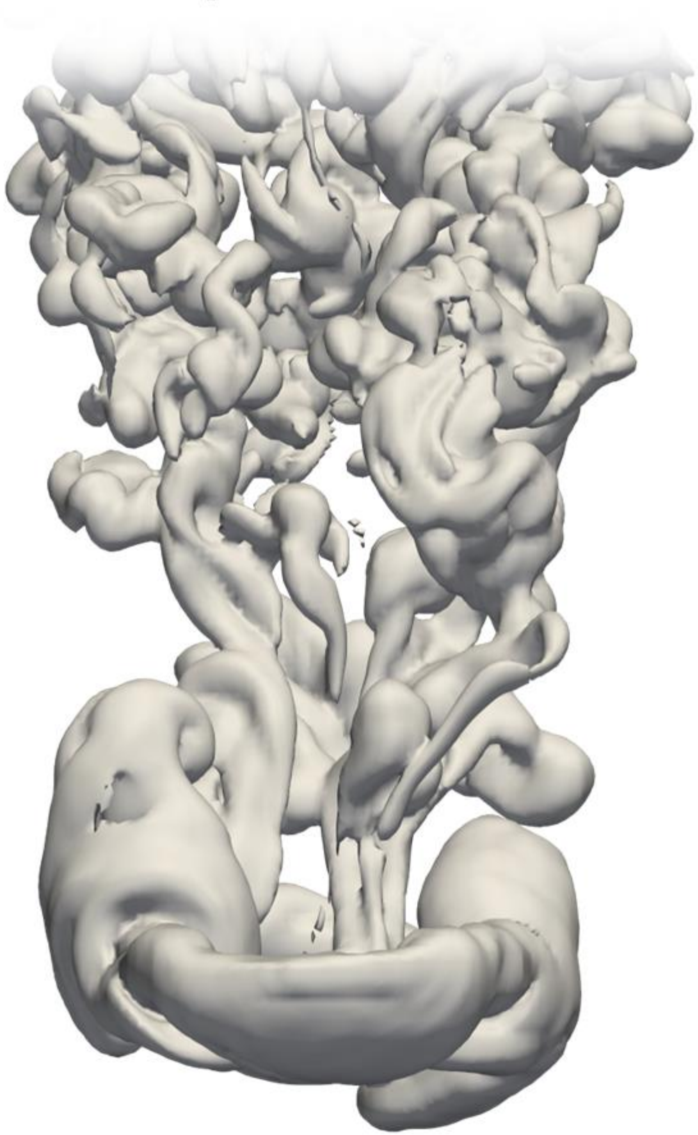


VRS regime for eVTOL Aircraft





Structure of presentation



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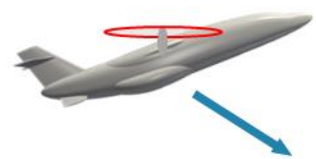

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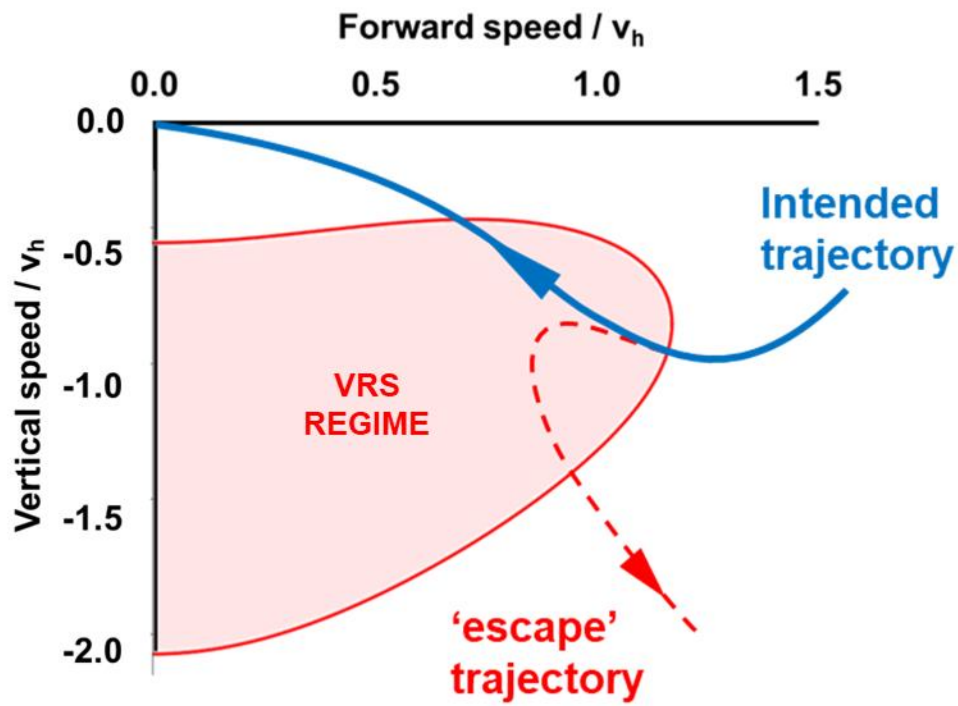
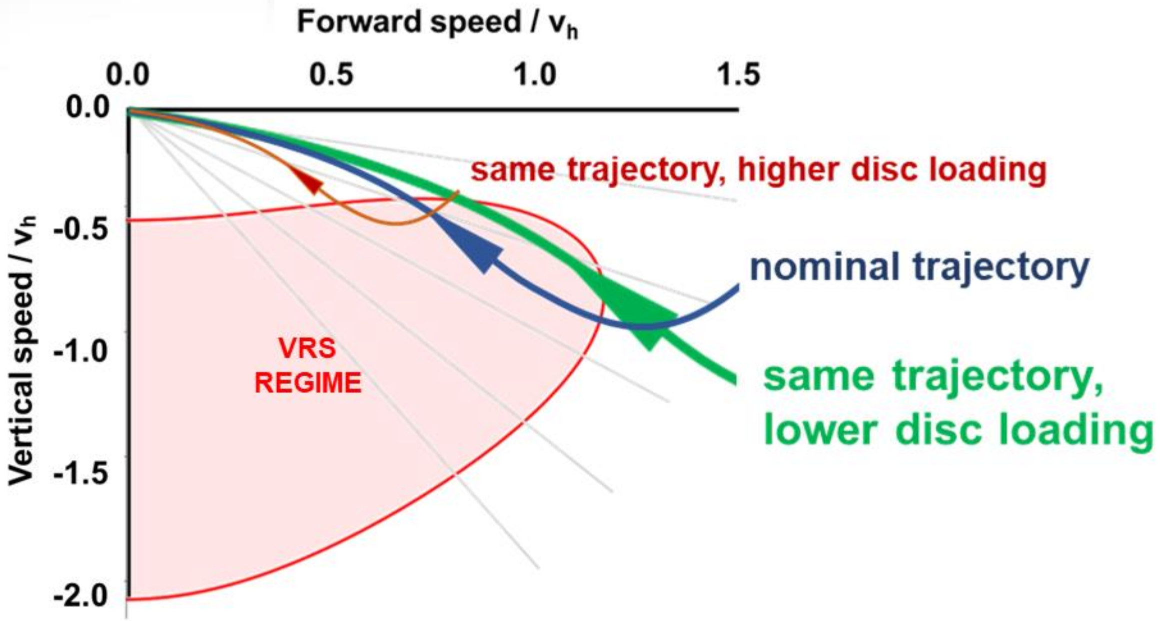
Aircraft trajectory and the VRS regime



Aircraft trajectory and the VRS regime

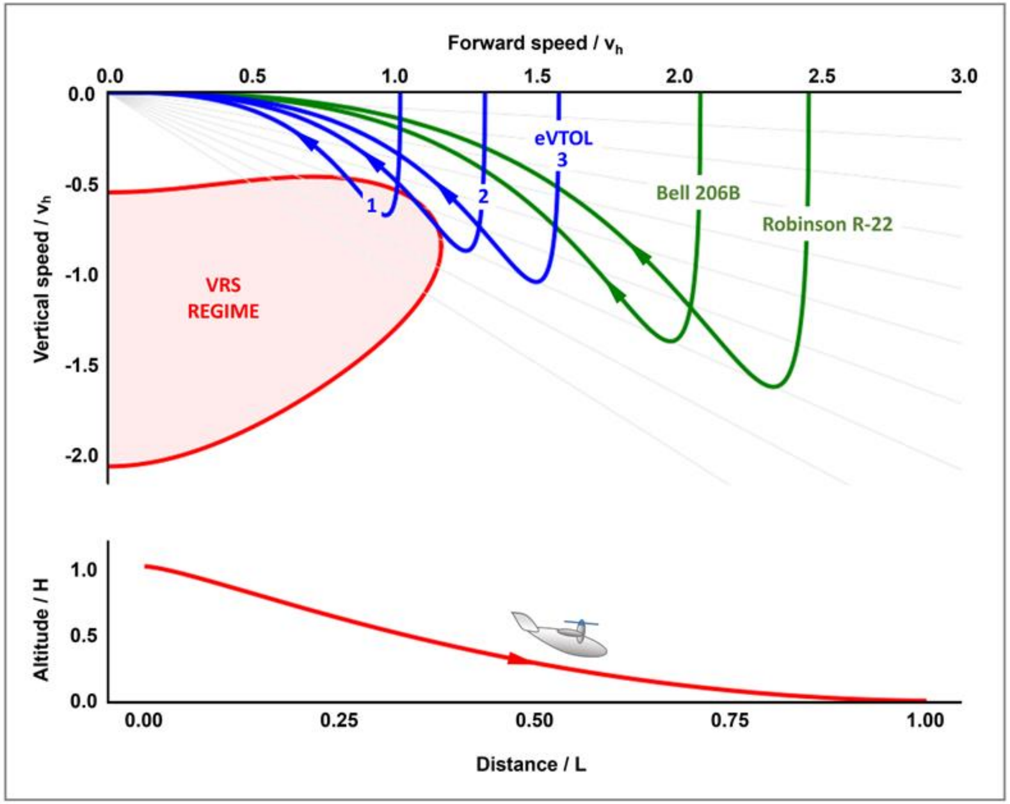
On non-dimensional axes :

- The VRS boundary remains fixed
- The *same* trajectory scales with disc loading by *shrinking or expanding* around the origin.



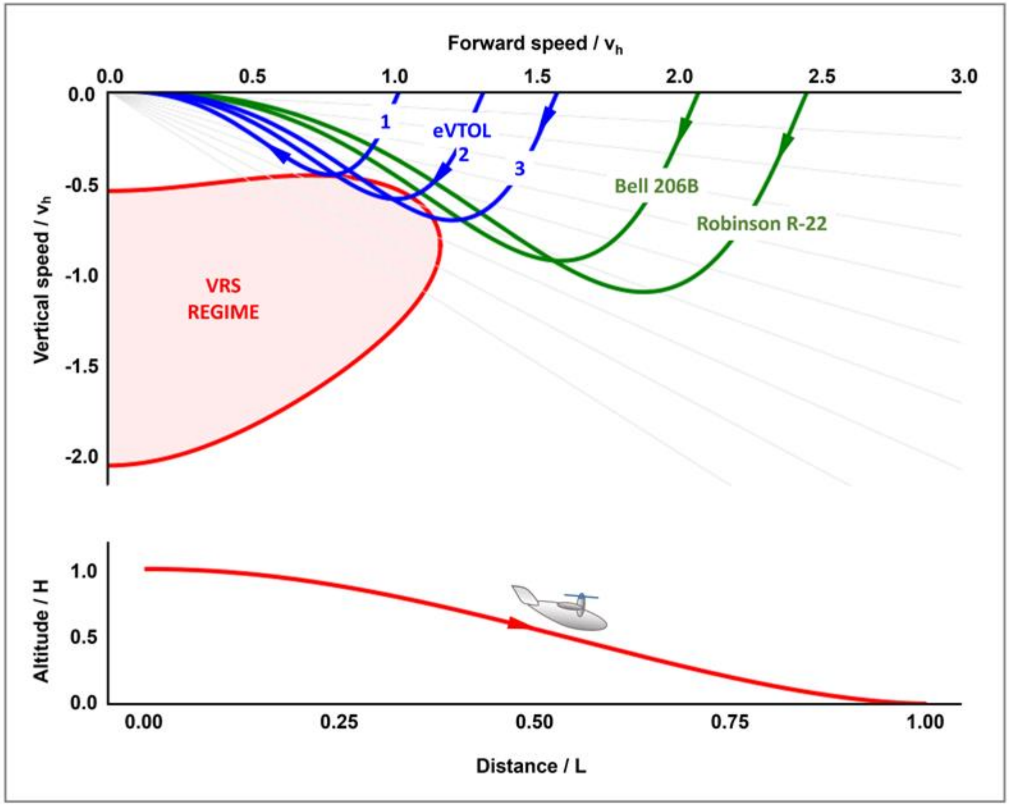
Aircraft trajectory and the VRS regime

(a) "shallow descent"



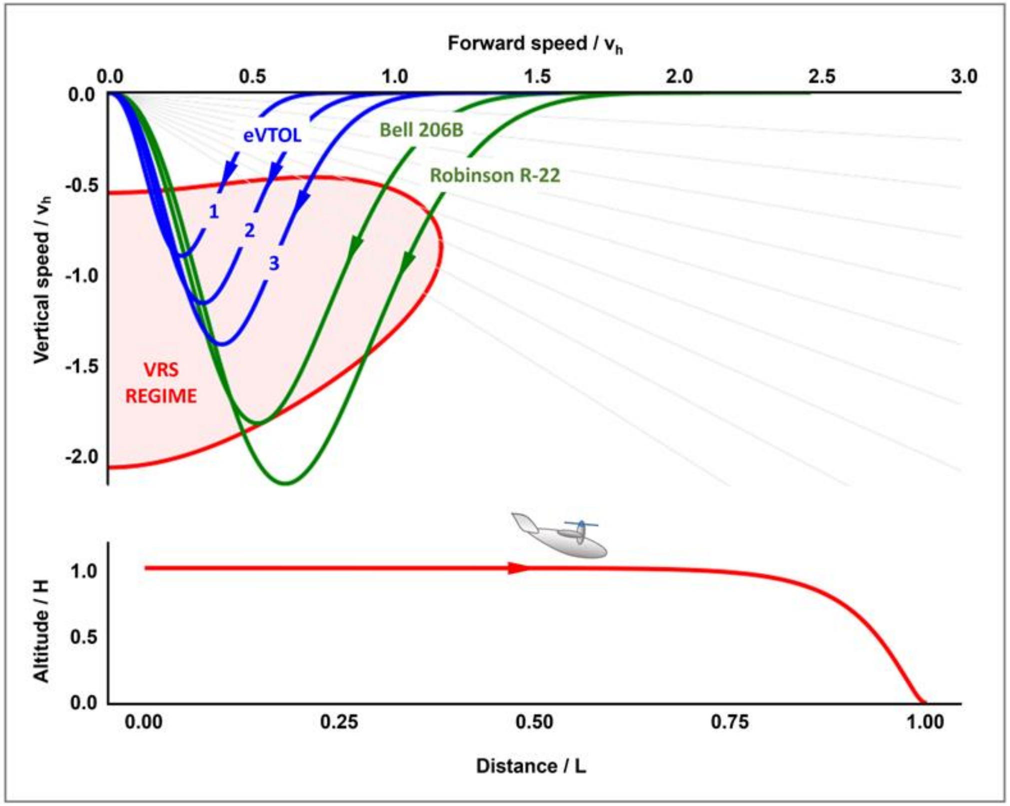
Aircraft trajectory and the VRS regime

(b) "aggressive descent"



Aircraft trajectory and the VRS regime

(c) *"steep descent"*

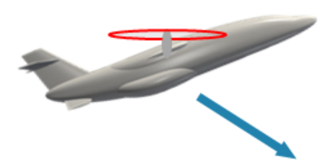


Aircraft trajectory and the VRS regime

Conclusions :

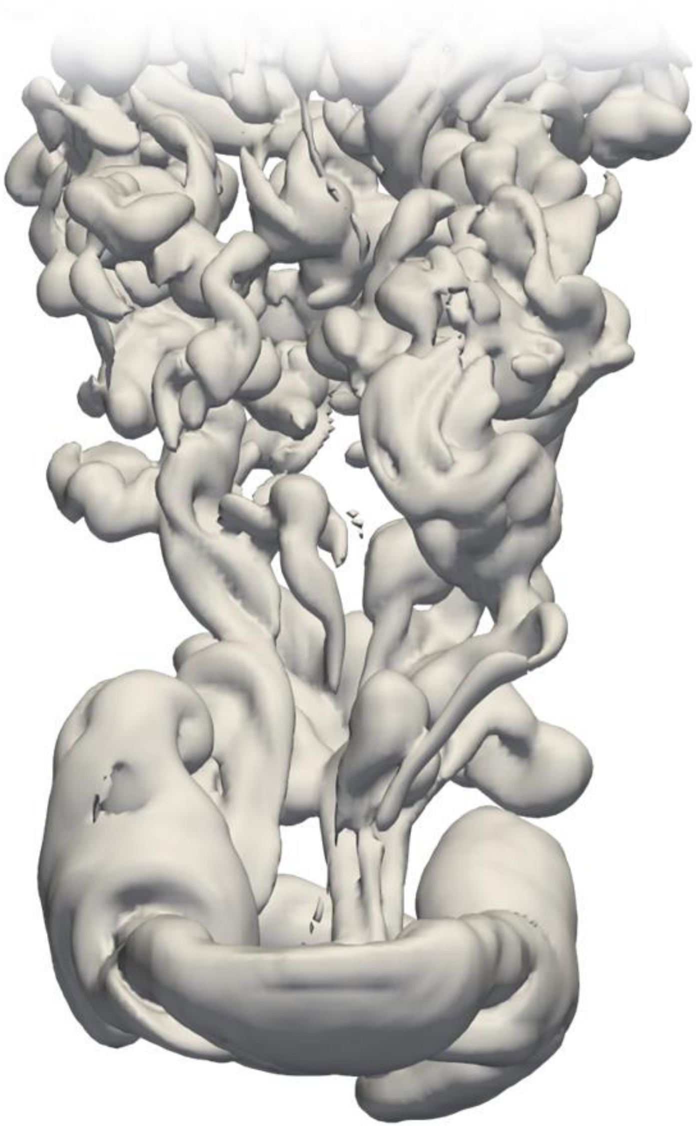
Trajectory

- How the trajectory followed by the aircraft may influence its susceptibility to the VRS.



- eVTOL disc loadings are generally not high enough to exploit a favourable shift in the VRS boundary.
- Trajectories that tend to be "safe" for helicopters tend to be less so for eVTOL.
- Some ideas for eVTOL operation in urban areas and for noise abatement may need to be re-visited in the light of the danger posed by VRS.

Structure of presentation

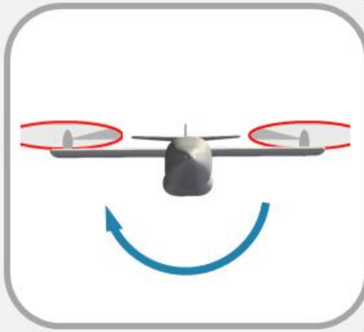


Trajectory

- How the trajectory followed by the aircraft may influence its susceptibility to the VRS.

Manoeuvres

- How rigid-body manoeuvres may conspire with certain elements of the aircraft's configuration to influence its susceptibility to the VRS.



The Urban Environment

How does operation in the urban environment influence susceptibility to the VRS ?

- Gusts
- Vertiport Design.

Aircraft manoeuvres and the VRS regime

Some eVTOL aircraft have configurational features which are known (largely from tiltrotor experience) to be problematic with respect to VRS:

Two examples :

- Side-by side rotors
(during lateral manoeuvres)
- Vectored rotor thrust
(during conversion)

Aircraft manoeuvres and the VRS regime

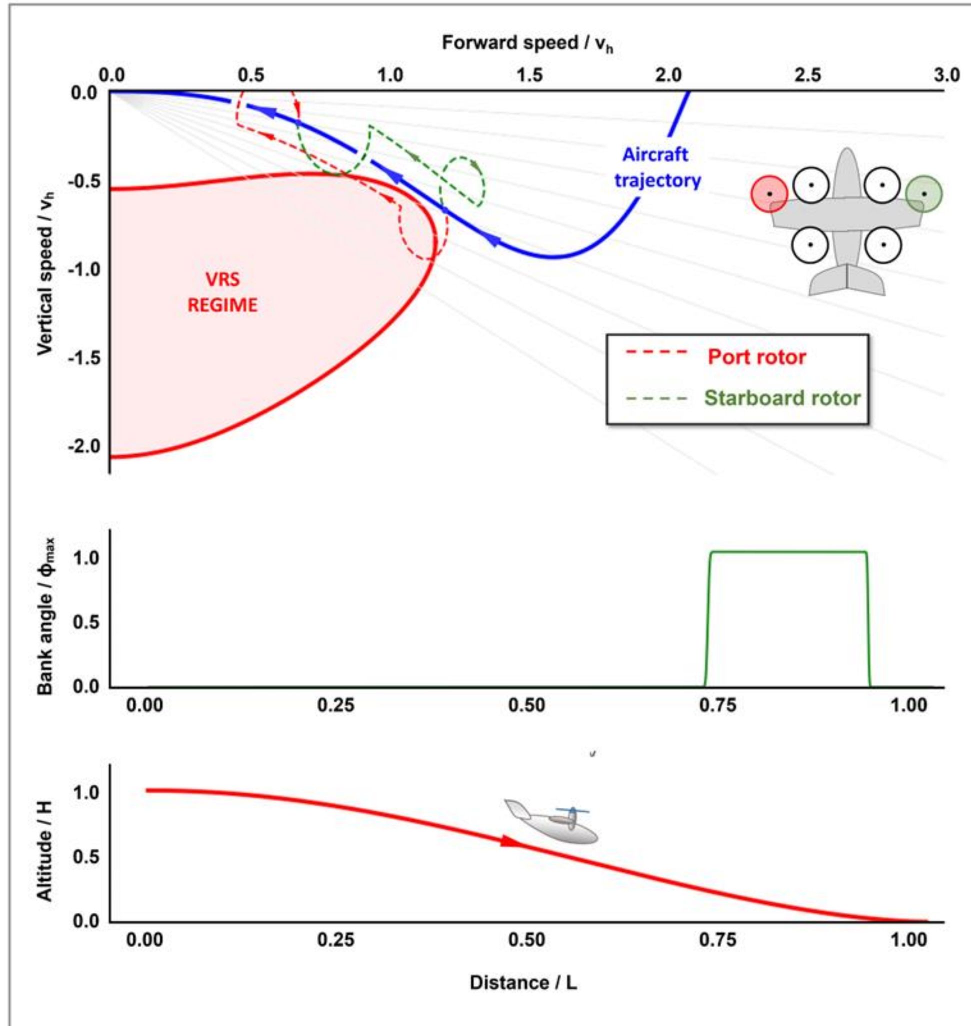
1. Use of differential thrust to instigate a turn.

wake structure (safe descent)

symmetric vortex ring condition

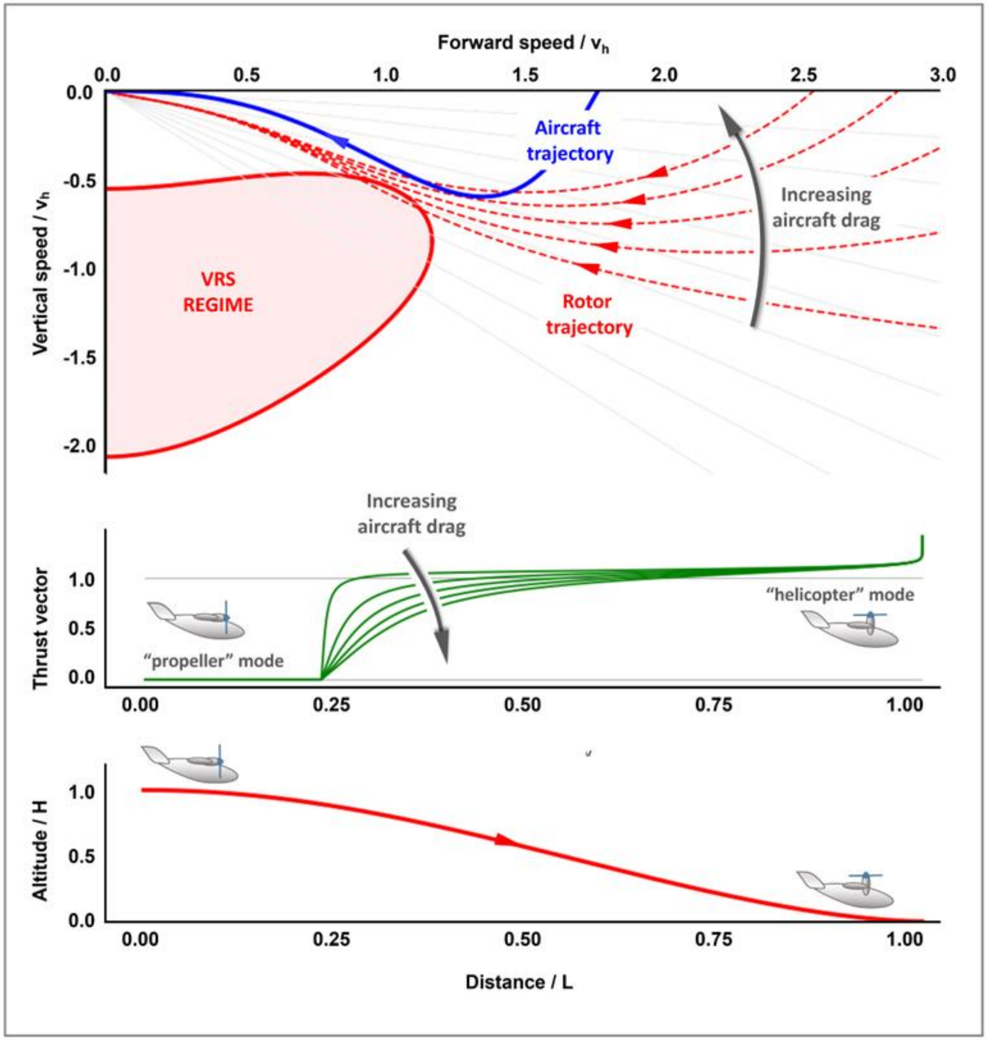
WORST CASE

asymmetric vortex ring condition



Aircraft manoeuvres and the VRS regime

2. Use of thrust vectoring to decelerate the aircraft.



Aircraft manoeuvres and the VRS regime

Conclusions :

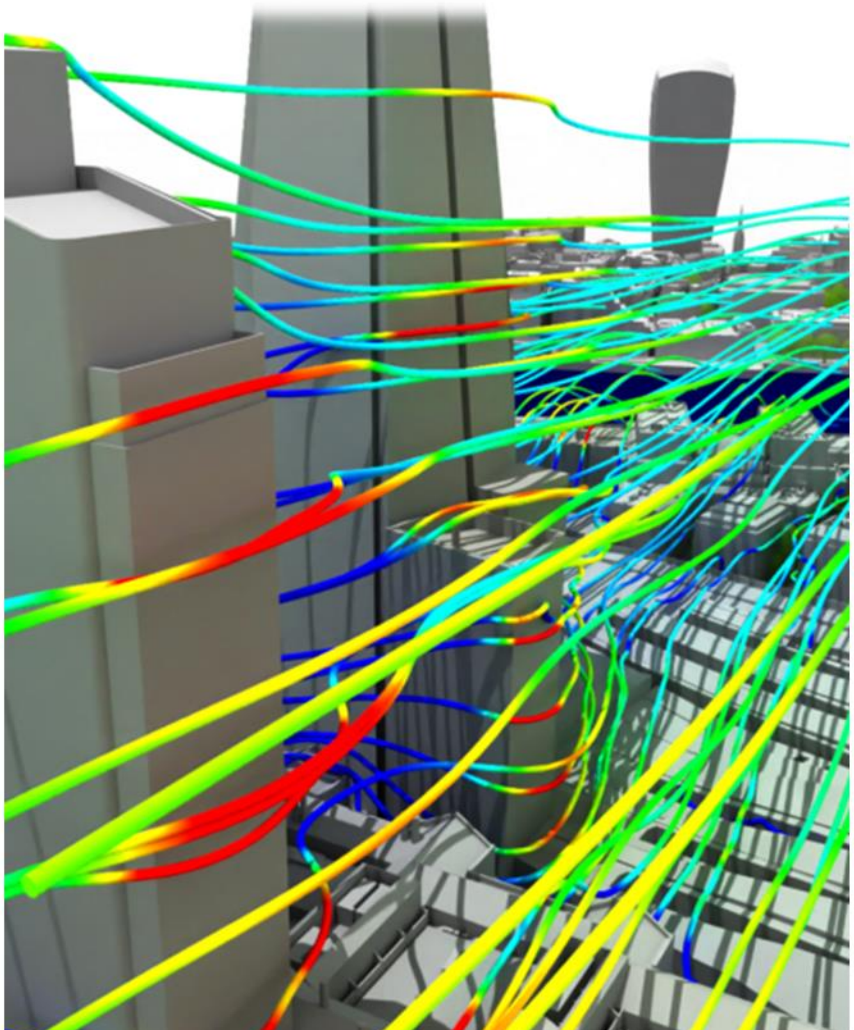
Manoeuvres

- How rigid-body manoeuvres may conspire with certain elements of the aircraft's configuration to influence its susceptibility to the VRS.

- Some elements of eVTOL configurational design may increase the chances of entering VRS during descent and landing as a result of manoeuvring at low forward speed.

- Designers would do well to verify that their aircraft do not contain hidden failure modes in this respect.

Structure of presentation


Source: SimScale promotional material

Trajectory

- How the trajectory followed by the aircraft may influence its susceptibility to the VRS.

Manoeuvres

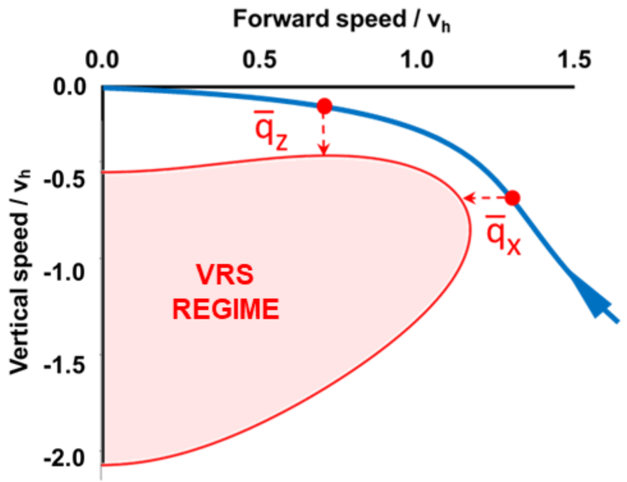
- How rigid-body manoeuvres may conspire with certain elements of the aircraft's configuration to influence its susceptibility to the VRS.

The Urban Environment

How does operation in the urban environment influence susceptibility to the VRS ?

- Gusts
- Vertiport Design.

A VRS-based gust margin



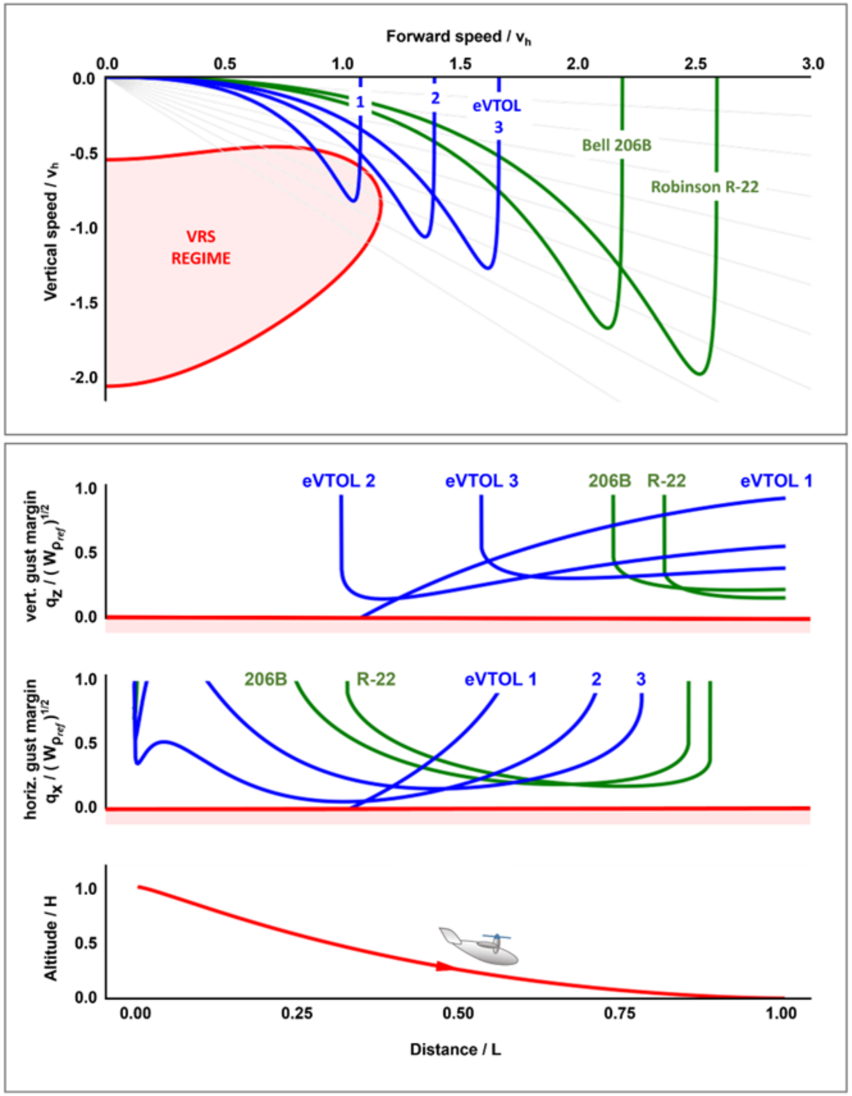
Using the Enhanced VRS model :

Maximum safe horizontal gust :

$$\bar{q}_x = k\bar{\mu}_x - \sqrt{\bar{\mu}_W^2 - (\bar{\mu}_z + \bar{\lambda}_i)^2}$$

Maximum safe vertical gust :

$$\bar{q}_z = (\bar{\mu}_z + \bar{\lambda}_i) - \sqrt{\bar{\mu}_W^2 - (k\bar{\mu}_x)^2}$$



Vertiport design

..with reference to EASA PTS-VPT-DSN

Source: EASA: Vertiport – VTOL Technical Requirements (YouTube)

Vertiport design

..with reference to EASA PTS-VPT-DSN

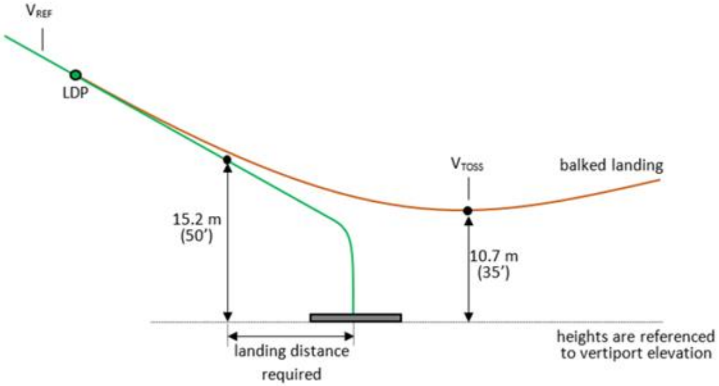


Figure D-28. Landing path

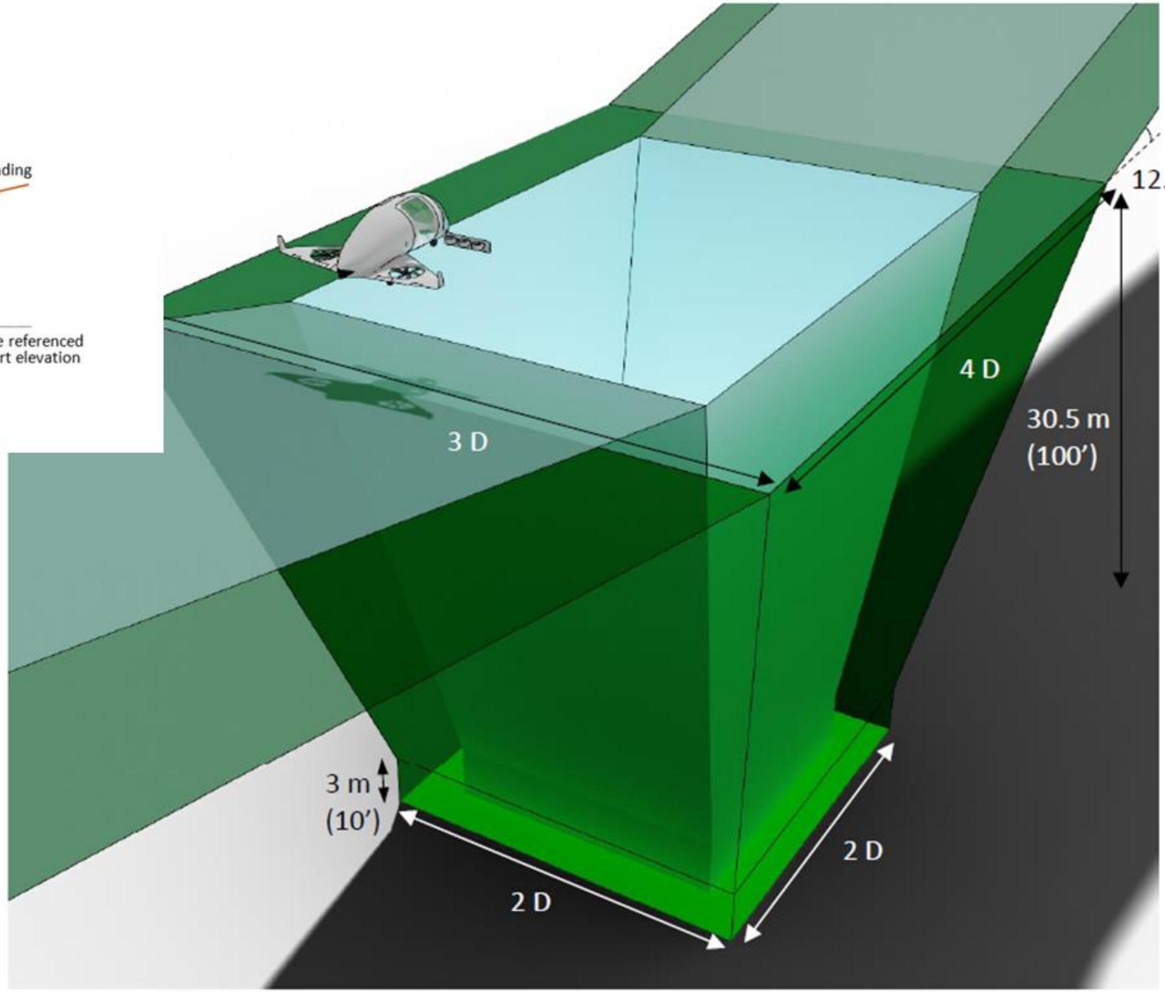
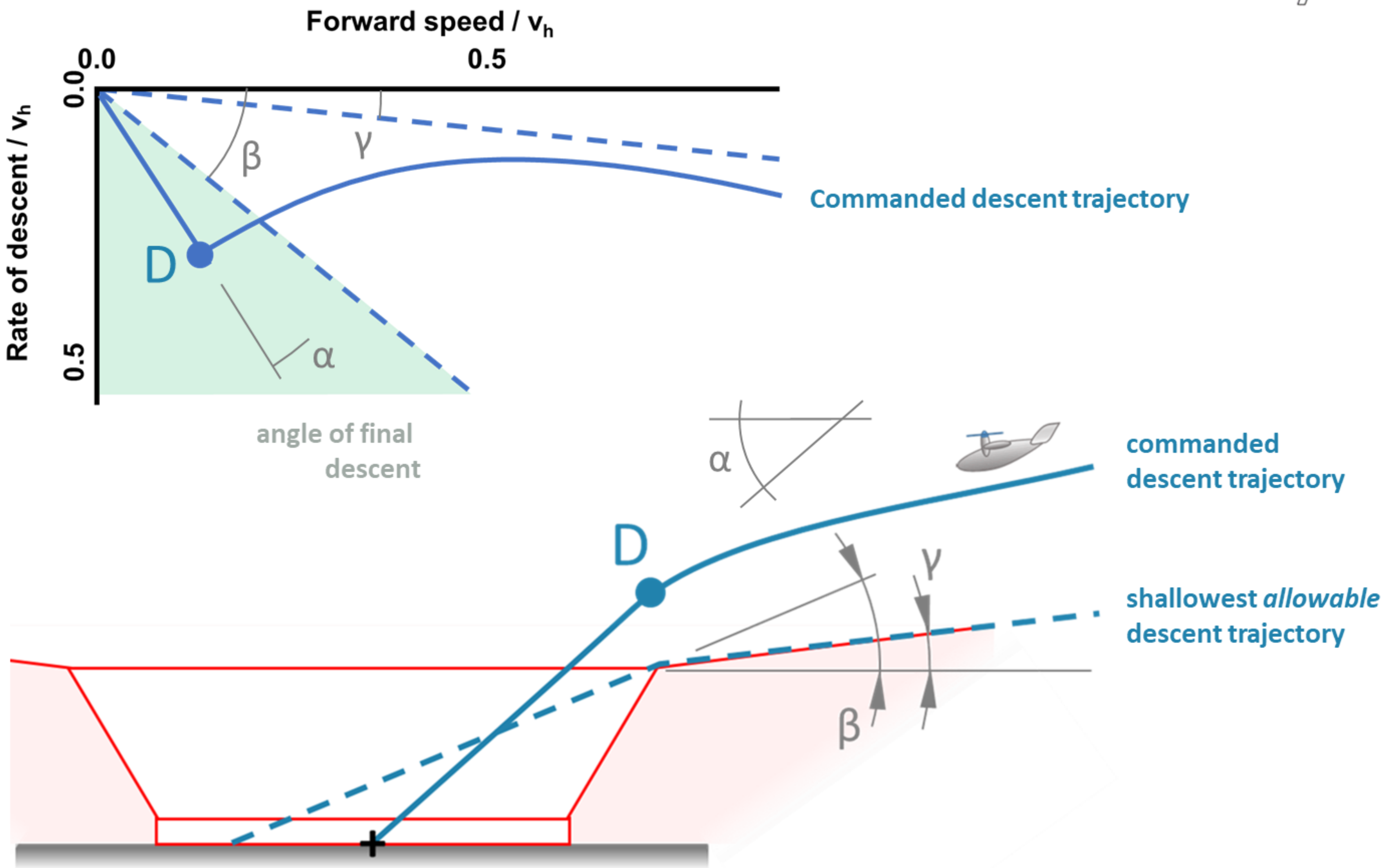
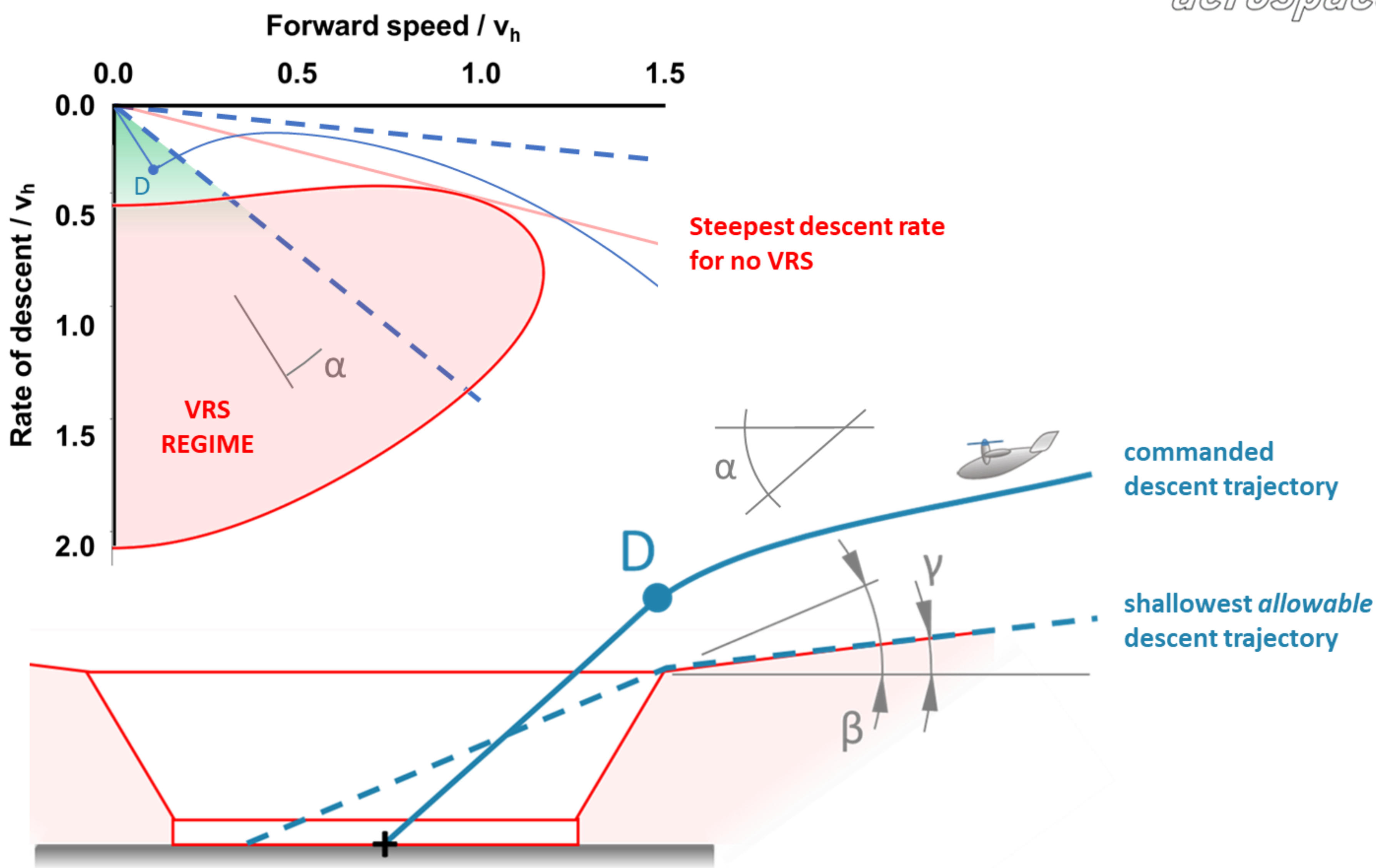
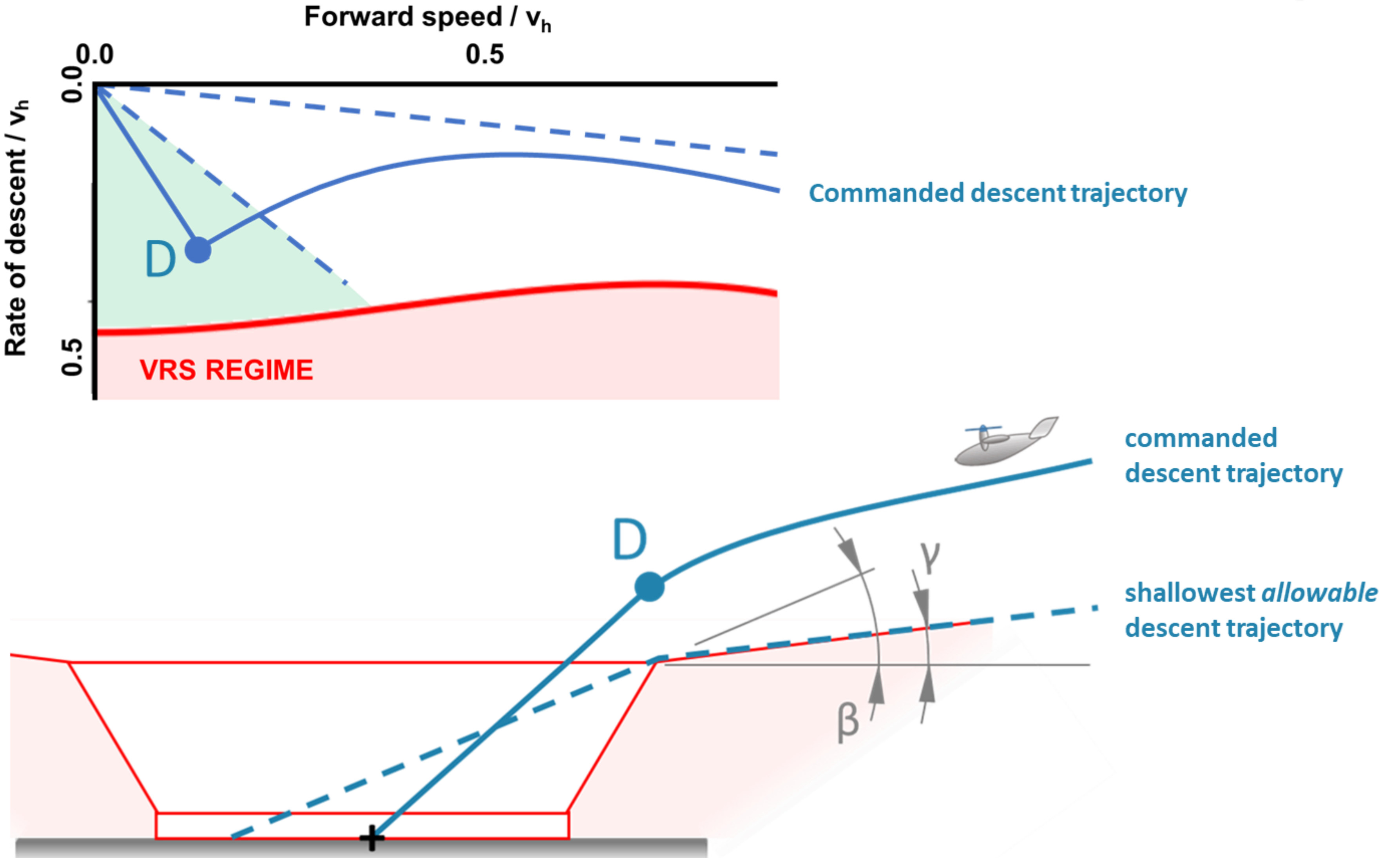


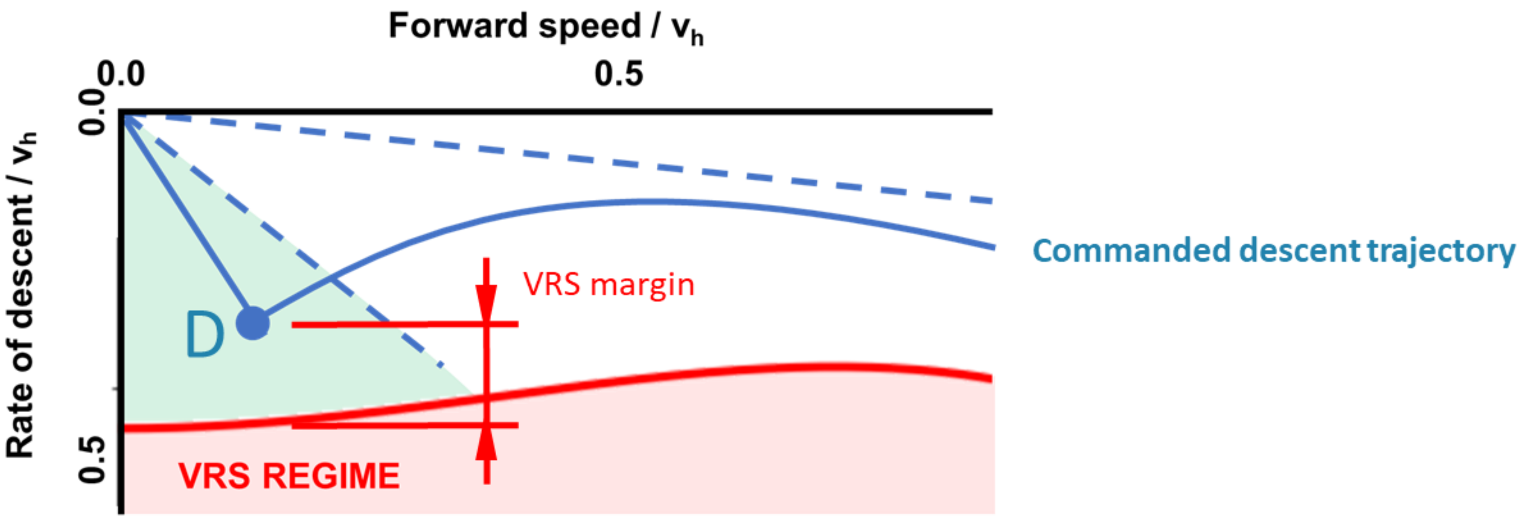
Figure D-21. Reference volume Type 1 dimensions (with the SAs)

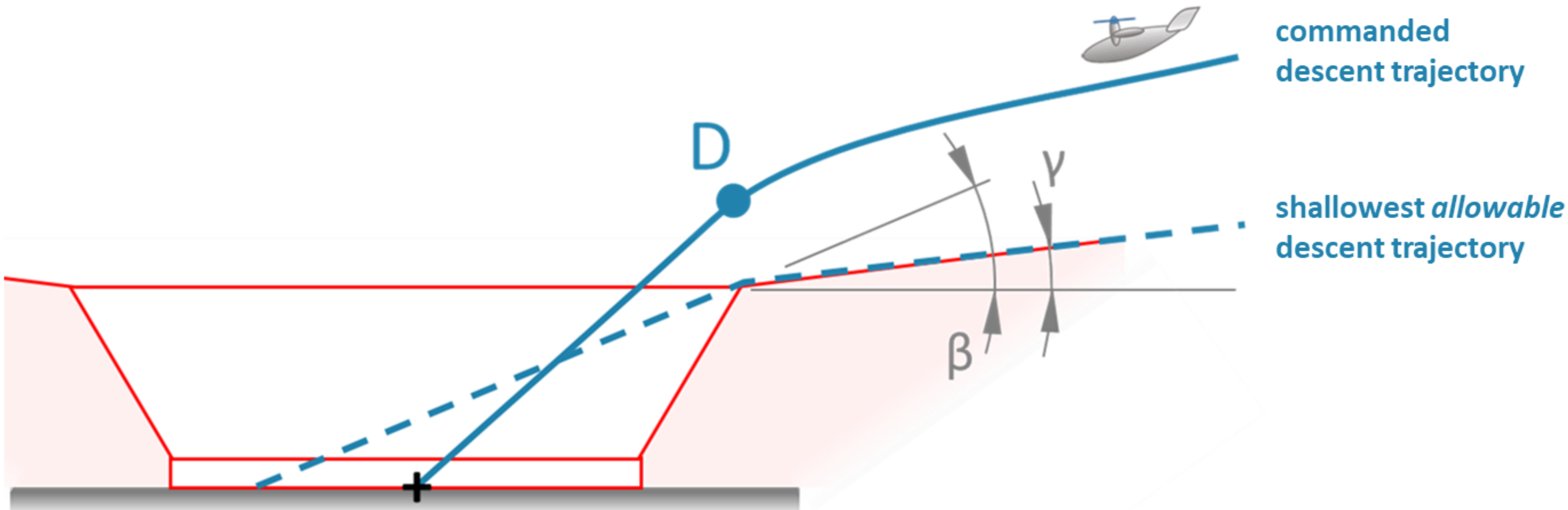


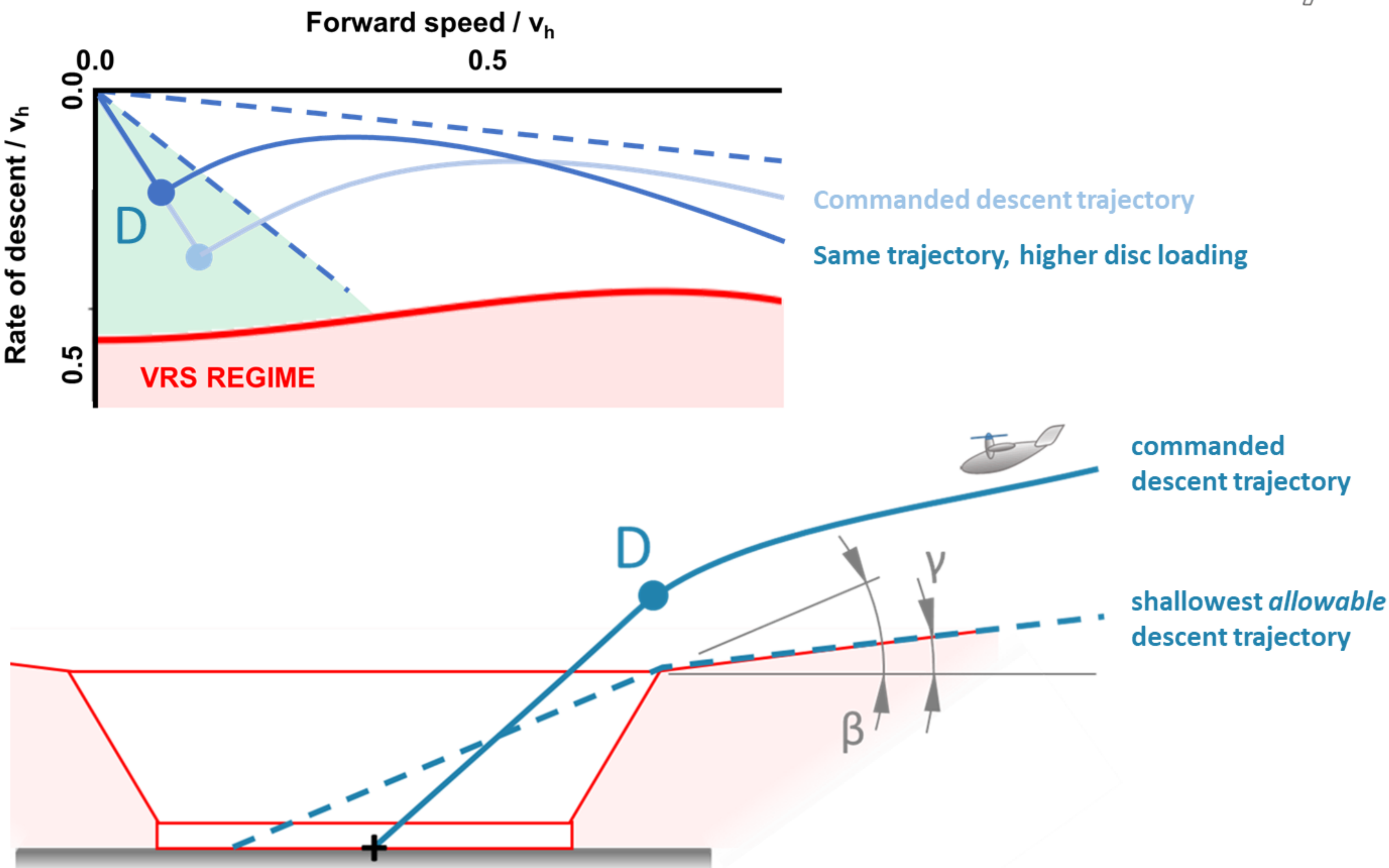
Forward speed / v_h
0.0
0.5
Rate of descent / v_h
0.0
0.5
β
γ
Commanded descent trajectory
D
α
angle of final descent
α
commanded descent trajectory
D
γ
shallowest *allowable* descent trajectory
β


Forward speed / v_h
0.0
0.5
1.0
1.5
Rate of descent / v_h
0.0
0.5
1.0
1.5
2.0
D
α
VRS
REGIME
Steepest descent rate
for no VRS
α
commanded
descent trajectory
D
γ
β
shallowest *allowable*
descent trajectory


Forward speed / v_h
0.0
0.5
Rate of descent / v_h
0.0
0.5
D
VRS REGIME
Commanded descent trajectory
commanded
descent trajectory
D
γ
β
shallowest *allowable*
descent trajectory


Forward speed / v_h
0.0
0.5
0.0
0.5
Rate of descent / v_h
D
VRS margin
VRS REGIME
Commanded descent trajectory

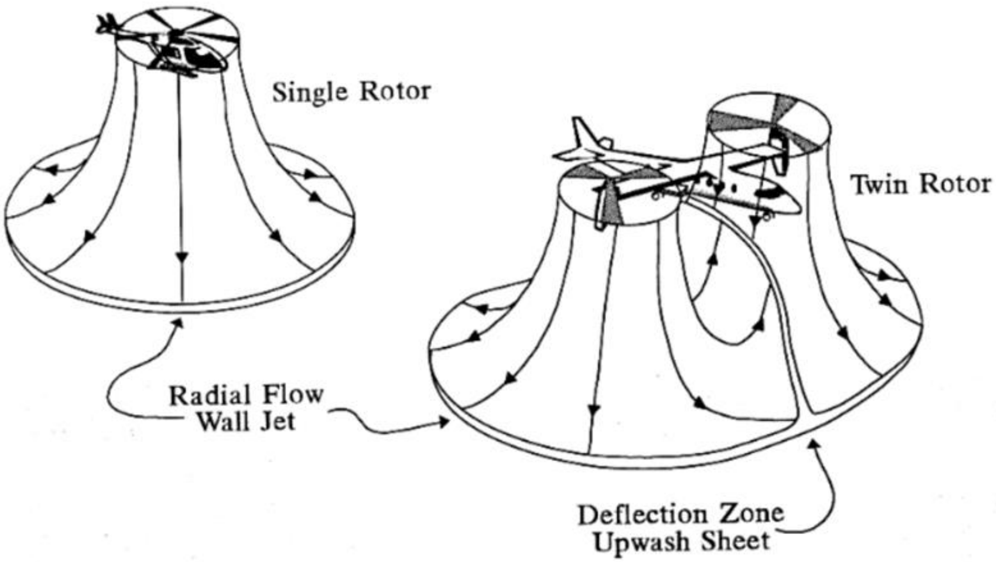

commanded
descent trajectory
D
γ
β
shallowest *allowable*
descent trajectory


Forward speed / v_h
0.0
0.5
Rate of descent / v_h
0.0
0.5
D
VRS REGIME
Commanded descent trajectory
Same trajectory, higher disc loading
commanded
descent trajectory
D
γ
β
shallowest *allowable*
descent trajectory

Vertiport design

..with reference to EASA PTS-VPT-DSN

Outwash effects :



We know that the strength of the wall jet is proportional to disc loading (~ v_h)

Vertiport design

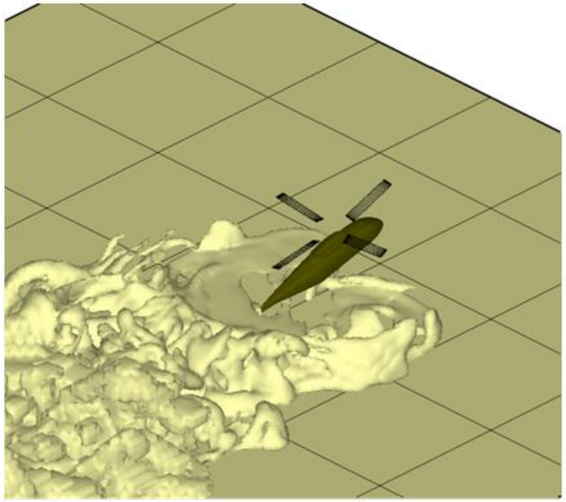
..with reference to EASA PTS-VPT-DSN

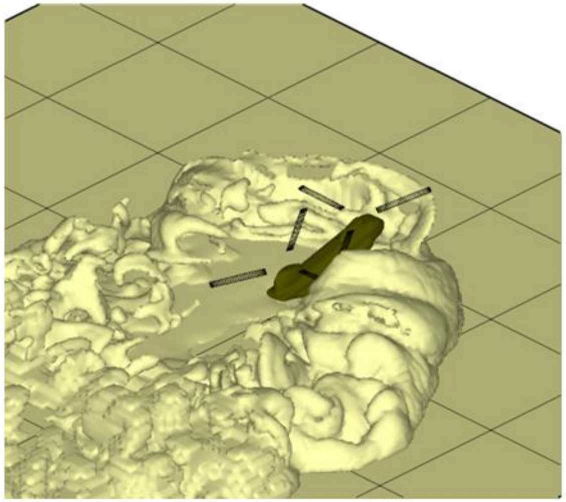
Outwash effects :

We've learned some lessons from our studies of helicopter brownout :

- outwash pattern is complex and configuration dependent

- some simple scaling laws apply





Vertiport design

..with reference to EASA PTS-VPT-DSN

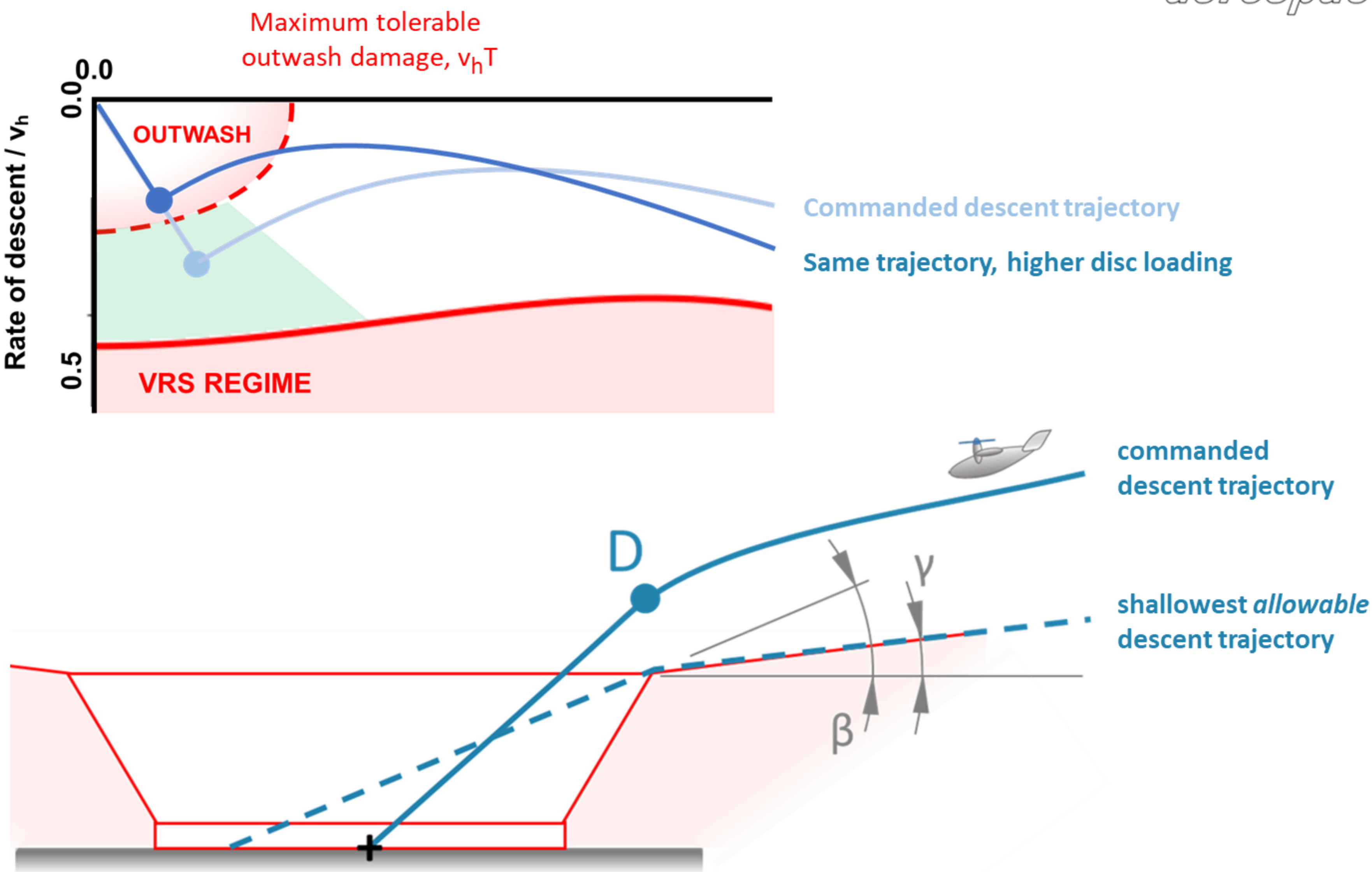
Outwash effects :

We know that the *strength of the wall jet* is proportional to disk loading (~ v_h)

– this gives a limit to the maximum tolerable *disc loading* in an urban setting.

Brownout studies suggest that the *cumulative damage* caused by the outwash scales with $v_h T$ (T : time taken to descend)

– This gives a (lower) limit to the tolerable *rate of descent* into the vertiport



Maximum tolerable outwash damage, v_hT
0.0
Rate of descent / v_h
0.0
0.5
OUTWASH
VRS REGIME
Commanded descent trajectory
Same trajectory, higher disc loading
commanded descent trajectory
D
γ
β
shallowest *allowable* descent trajectory

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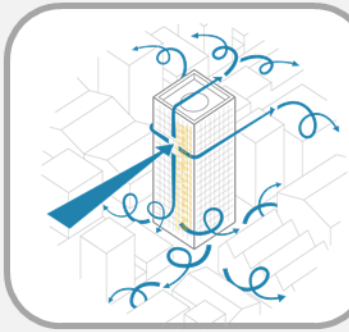
Urban environments and the VRS regime

Conclusions :

The Urban Environment

How does operation in the urban environment influence susceptibility to the VRS ?

- Gusts
- Vertiport Design.



- eVTOL disc loadings may improve gust ride quality but reduce gust margins with respect to VRS.
- Trajectories need to be designed with local atmospheric conditions and appropriate margins against gust-induced entry into VRS in mind.
- Aircraft designers may find themselves pushed into a very tight corner by vertiport design standards that don't take eVTOL aerodynamics into account.

Summary

- There is evidence to suggest that VRS for eVTOL aircraft will be as serious a problem as it is for helicopters.

- The eVTOL community (designers and regulators) can learn from helicopter experience, but additional work is needed to address specific issues with the new technology.

- As eVTOL comes out of its "honeymoon" phase, and flight testing and certification become more pressing issues, we'll need to focus more on detailed, <u>*accurate*</u>, aerodynamic analysis.