Aircraft Stall-Spin: Measurement and Research

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- Questions

Stall – Spin: Background

BEA air accident report 2010 9 BEA

5. The crew not identifying the approach to stall, their lack of immediate response and the exit from the flight envelope

6. The crew's failure to diagnose the stall situation and consequently a lack of inputs that would have made recovery possible

AAIB Bulletin: 4/2015 G-BNDE EW/C2014/08/03

A number of witnesses near Padbury saw the aircraft descend rapidly, spinning or spiralling until it went out of view. The subsequent impact with the ground destroyed the aircraft and the pilot sustained fatal injuries.

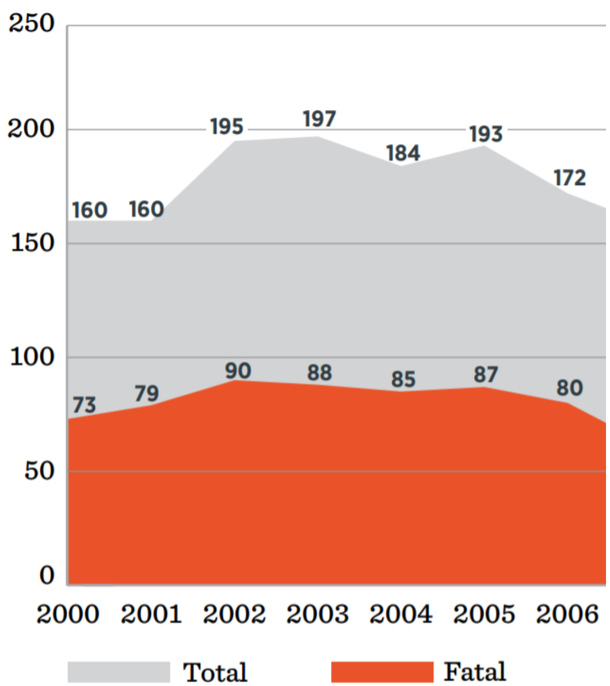
Meteorological information

On the 20 August 2014 the weather conditions for visual flight were good. There was a weak pressure pattern across the United Kingdom with a light north to north-westerly

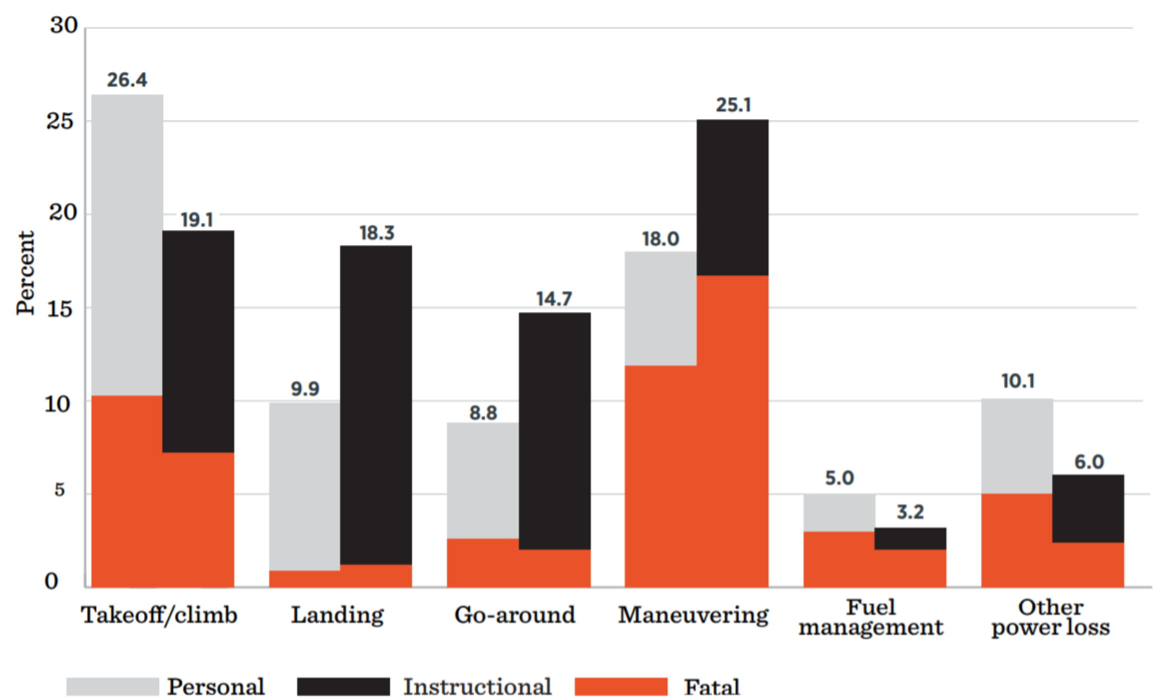
Stall – Spin: Background

- Fixed wing aircraft can stall or spin in any category
- Stall – spin most prevalent in take-off and climb for general aviation
- 30% of all general aviation accidents originate from stall – spin

ANNUAL NUMBER OF STALL ACCIDENTS, 2000-2014



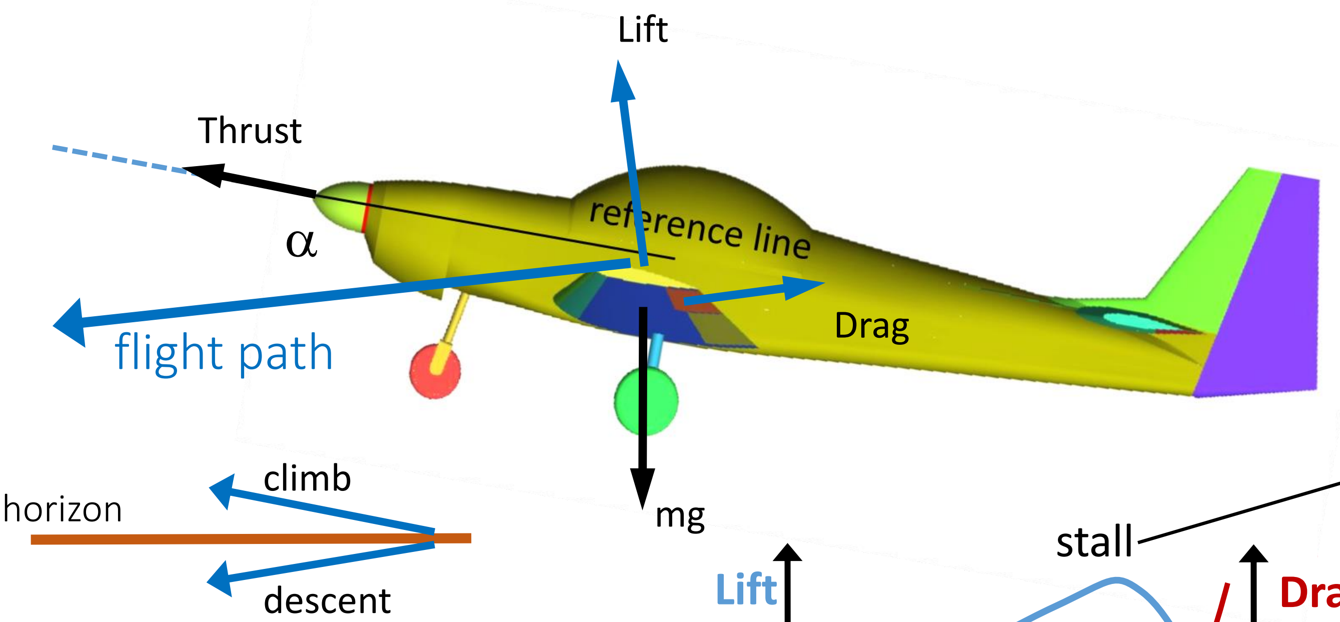
TYPES OF STALL ACCIDENTS: PERSONAL VS. INSTRUCTIONAL FLIGHTS

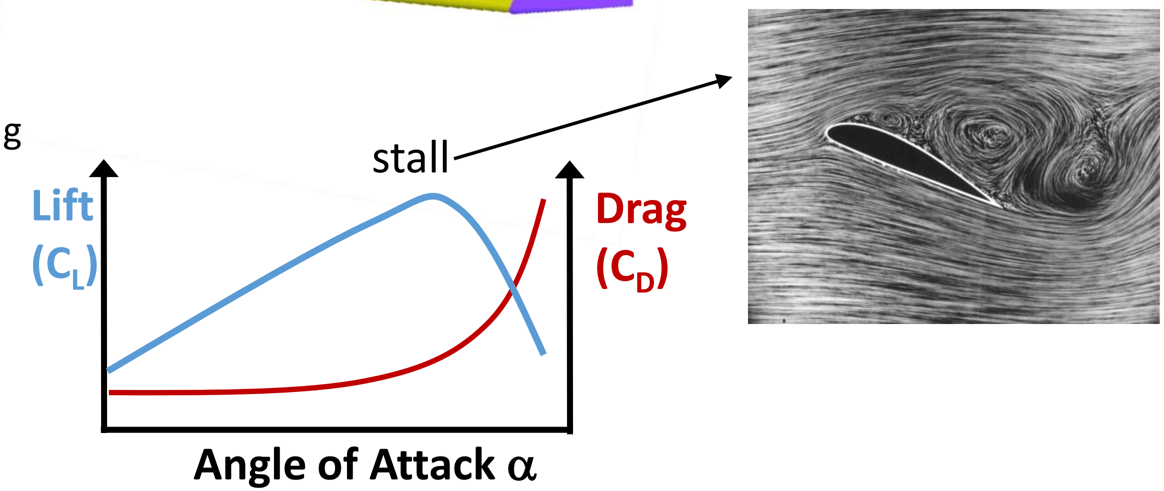


Source: AOPA

Stall and Spin Background

- Stall is a condition with significant BL separation and loss of lift from a wing/body
- Angle of attack α is the key variable for stall and spin
- Flight path & reference line define angle of attack (α), lift & drag vectors





Stall and Spin Movies

- Spin is a stable flight condition with asymmetric wing stall
- the aircraft autorotates about a near vertical axes descending rapidly
- CoG follows helical flight path with aircraft pitching/rolling/yawing
- Recovery (if possible) with rudder and elevator

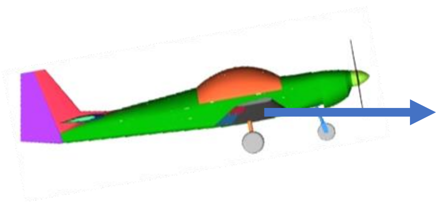
Source: NASA
https://1drv.ms/v/s!AqvNv7Mai6Rqhat0WSpLitjoSLv6og?e=knTTc1

https://1drv.ms/v/s!AqvNv7Mai6Rqhat2vmcVqyniKjI-xA?e=XXXzMa

Stall – Spin: Background

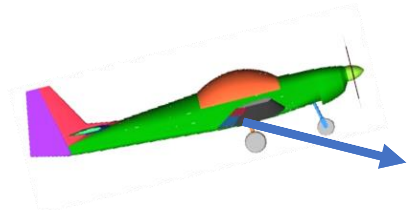
Straight/Level → Stall → Incipient Spin → Stable Spin

Straight/Level



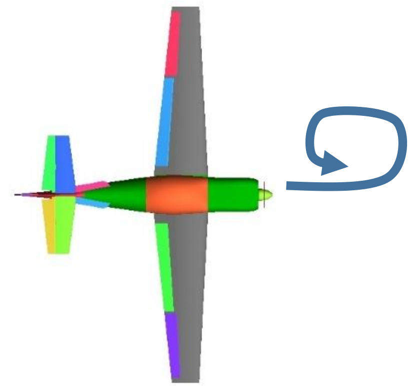
- flight path level
- lift = weight
- drag = thrust
- steady condition
- longitudinally stable
- laterally stable
- directionally stable

Stall



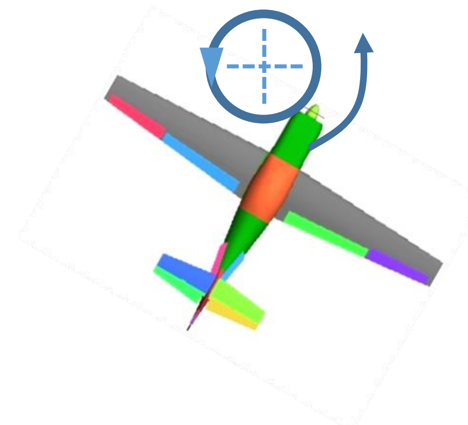
- aircraft descents
- lift < weight
- drag > thrust
- α increasing $>15^o$
- light then heavy stall
- unsteady / dynamic
- longitudinally stable
- laterally unstable
- directionally stable

Incipient Spin



- flight path curved
- lift < weight
- drag > thrust
- ‘wing drop’ then… autorotation
- heavy stall, high α
- longitudinally unstable
- laterally unstable
- directionally stable

Stable Spin

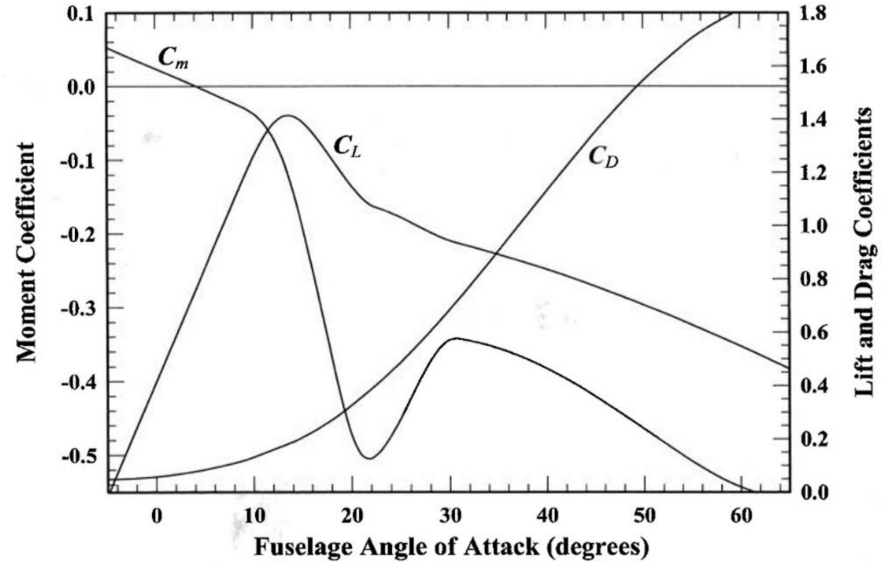


- flight path ~vertical
- lift = centrifugal force
- drag = weight
- gyroscopic balance
- autorotation stable
- v.high $\alpha > 40^o$
- longitudinally stable
- laterally stable
- directionally stable
- steep / flat modes

Basic Spin Modelling

- Defining and testing stall-spin behaviour is a basic certification and safety requirement
- Basic stall models established but behaviour validated by flight test
- Stall stability complex: validated by flight test / wind tunnels
- Basic spin theory available for stable spin
- Theory for transition to spin not known (typically run iterative schemes to get estimations)

aerodynamic coefficients vs α



stable spin theory

$$\Omega^2 = \frac{2W}{\rho S_w C_{N_1}\cos\theta\sin^2\theta}\left[\frac{2(I_{zz_b}-I_{xx_b})}{\rho S_w b_w C_{m_1}\tan\theta} - \frac{C_{m_2} b_w^2}{C_{m_1}} + \frac{C_{N_2} b_w^2}{C_{N_1}}\right]^{-1} \qquad (6.10.22)$$

$$R = -\frac{g\tan\theta}{\Omega^2} \qquad (6.10.23)$$

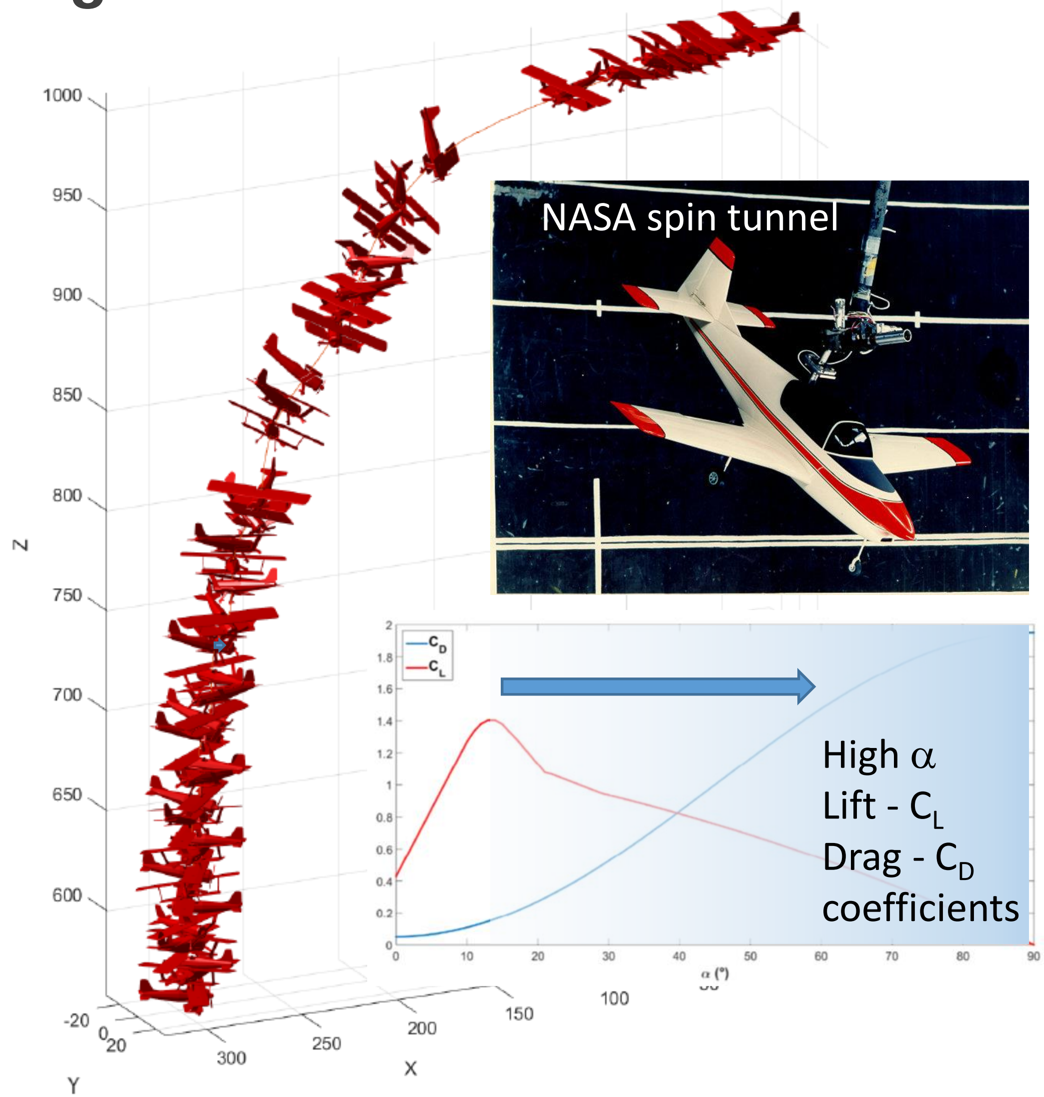
$$V_d^2 = \frac{2W}{\rho S_w C_{N_1}\cos^3\theta} - \frac{C_{N_2} b_w^2 \Omega^2 \tan^2\theta}{C_{N_1}} \qquad (6.10.24)$$

$$(\Delta C_n)_r = \frac{2C_{N_2}(I_{xx_b}-I_{yy_b})b_w\Omega}{(I_{zz_b}-I_{yy_b})V_d} + \frac{V_{p_1}\cos\theta}{V_d\sin^2\theta} - \frac{V_{p_2} b_w \Omega}{V_d^2\sin\theta} - \left(\frac{C_{n_1}R^2}{\sin^2\theta} - \frac{2C_{Y_2} b_w R}{\sin\theta\tan\theta} + \frac{C_{n_2} b_w^2}{\tan^2\theta}\right)\frac{\Omega|\Omega|}{V_d^2} \qquad (6.10.25)$$

figures / theory from Mechanics of Flight 2nd Edition, W.F. Phillips, Wiley (2010): https://1drv.ms/b/s!AqvNv7Mai6Rqhat6-EmnOJkxyN8SRA?e=esen1H

Dynamic Spin Modelling and Motivation

- Dynamic spin modelling requires complex coefficient maps (in α, β, γ)
- Iterative schemes can be used to predict incipient spin to full spin (transition to steady spin)
- Current coefficient maps require costly and detailed spin tunnel experiments
- **New numerical methods may offer a new way to obtain coefficients**



Slingsby Firefly Stall Modelling & Validation

Develop and validate CFD stall model of the Slingsby Firefly light aircraft:

- Experimental (in-flight)
  - Aircraft and preparation
  - Straight and level flight
  - Measurement of stall α
  - In-flight flow visualisation
  - Wing-wake tailplane interact^n
- Numerical
  - Model and Mesh Generation
  - Steady model
  - Unsteady model
- Comparisons and Discussion
- Summary / Conclusions

S&L flight data (C_L, α)

↓

steady CFD sol$^{\underline{n}}$

↓

stall flight data (C_{Lmax}, α, buffet)

↓

unsteady CFD steady sol$^{\underline{n}}$

↓

CFD vs experiment

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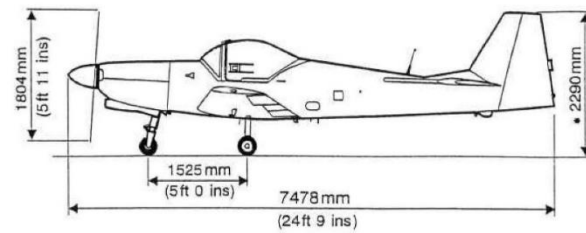
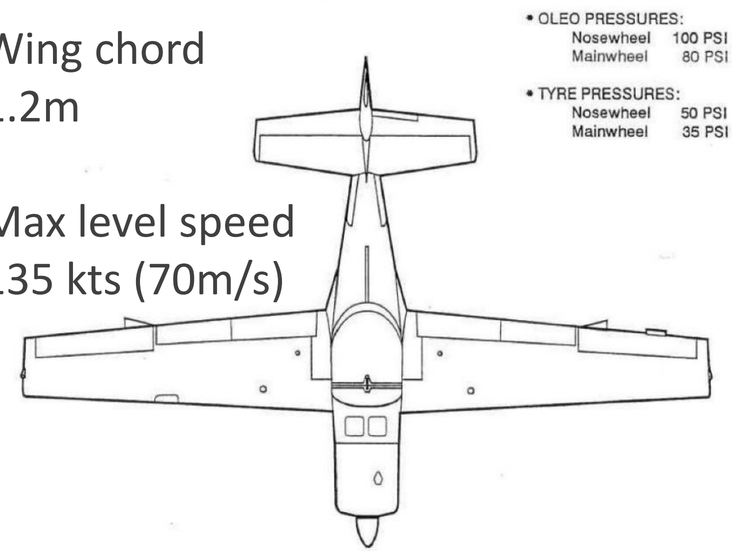
Slingsby Firefly T67M260 Aircraft

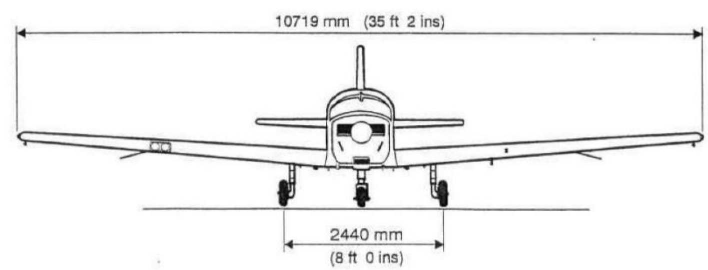
- Aerobatic category (ex-RAF trainer)
- 2 seat side-by-side light aircraft
- Engine 260hp Lycoming AE10-540
- +6 to -3g envelope
- MTOW 1157kg
- @50m/s (ISA) $Re_{chord} = 4.1 \times 10^6$



Wing chord
1.2m

Max level speed
135 kts (70m/s)



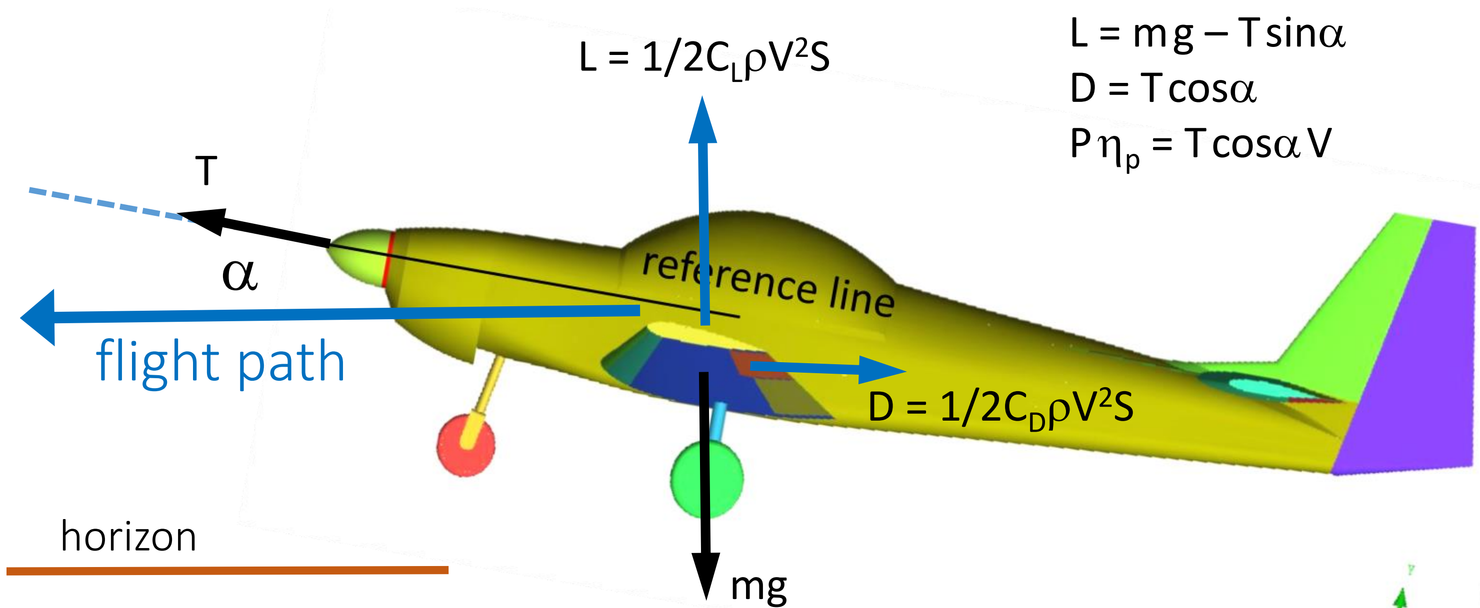


Straight and Level Flight Tests

Straight and level used to find range of angle of attack α up to stall:

- Validate steady CFD model
- Steady CFD sol^{n} is initial condition for unsteady CFD model

Record airspeed, OAT (°C), altitude, power (rpm, manifold press) and equate lift → weight & engine pwr → airframe drag/V

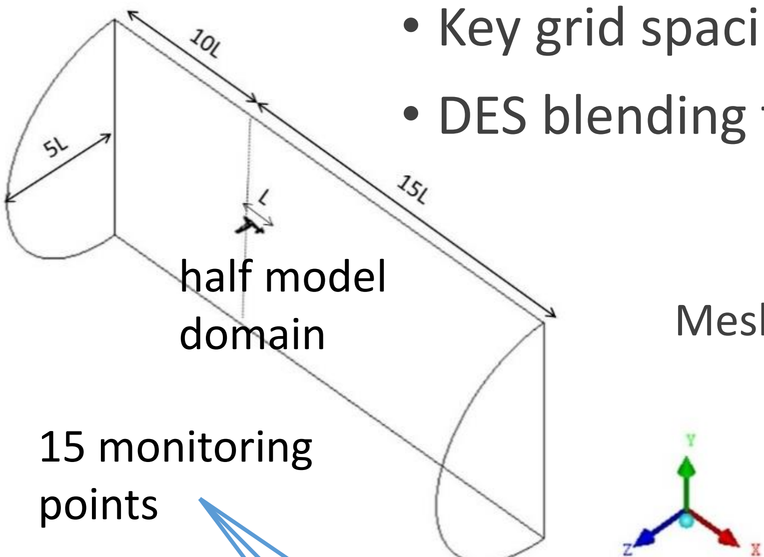


L = lift   D = drag   T = Thrust   V = true airspeed ρ = density C_L = lift coeff.

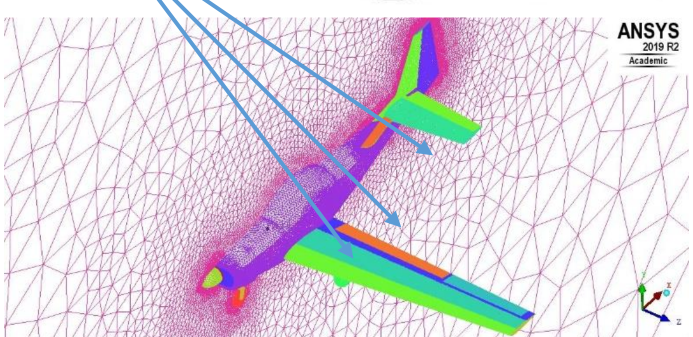
CFD Model Set-up

Single mesh refined for steady and unsteady model with wake density region:

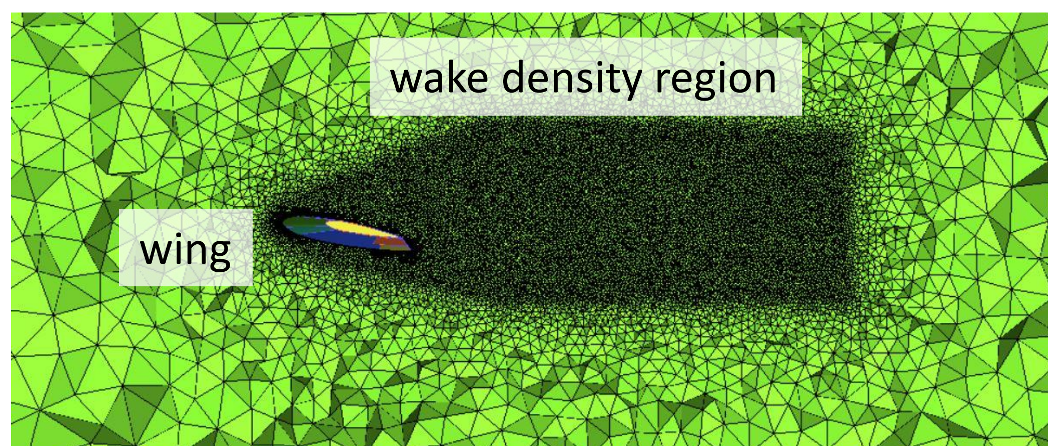
- SA / k-ω SST models tested – k-ω SST chosen
- Key grid spacing follows the Smagorinski LES model (y+~1)
- DES blending through $C_{DES} = (1 - F_1)C_{DES}^{k-\varepsilon} + F_1 C_{DES}^{k-\omega}$



15 monitoring points

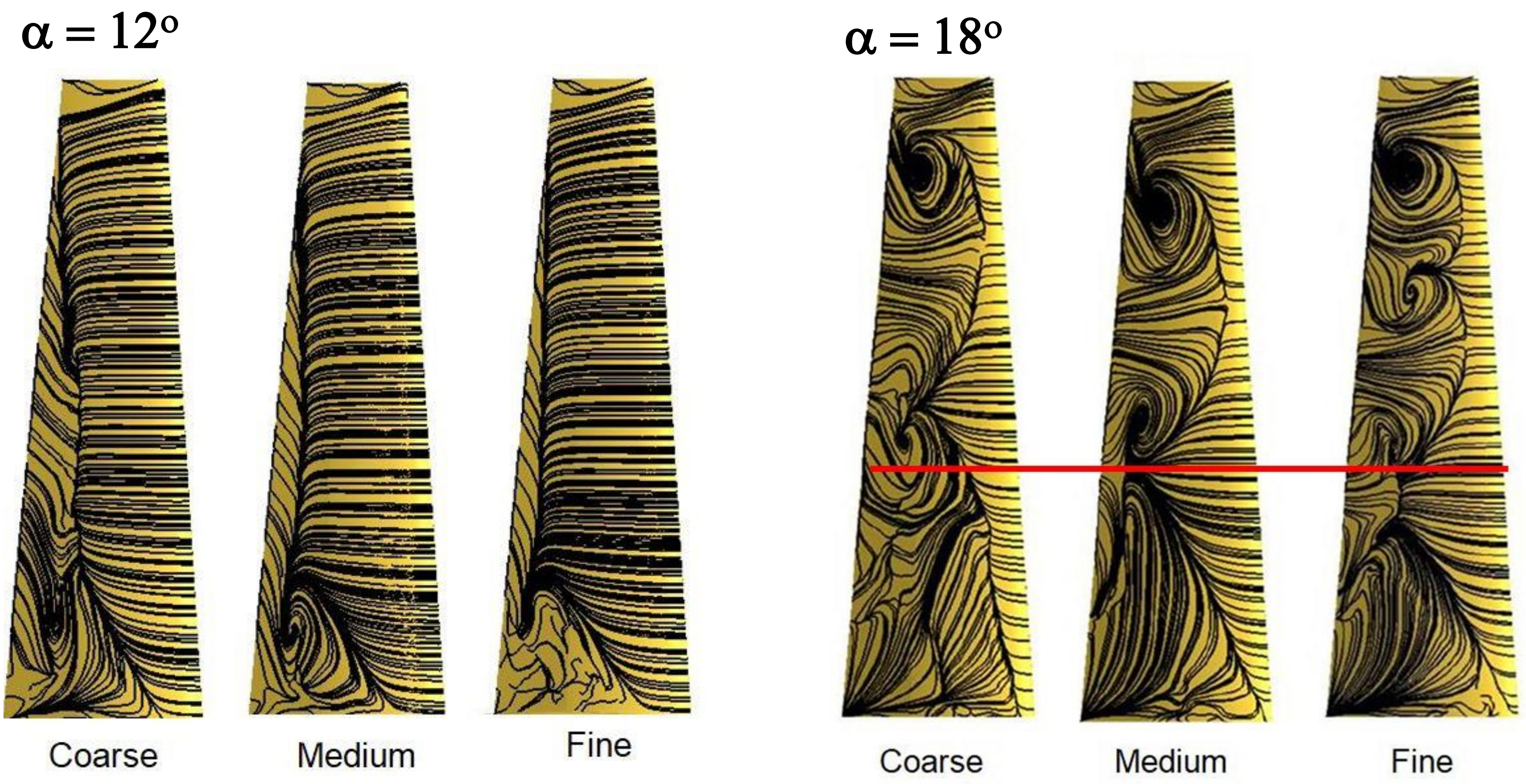


Mesh sizes: Coarse (7.6M) Medium (11.3M) Fine (17.2M)



solutions converged with residuals $10^{-3} – 10^{-5}$ (GCI 3.5% – 4.4%):

CFD Model Set-up: Mesh Refinement

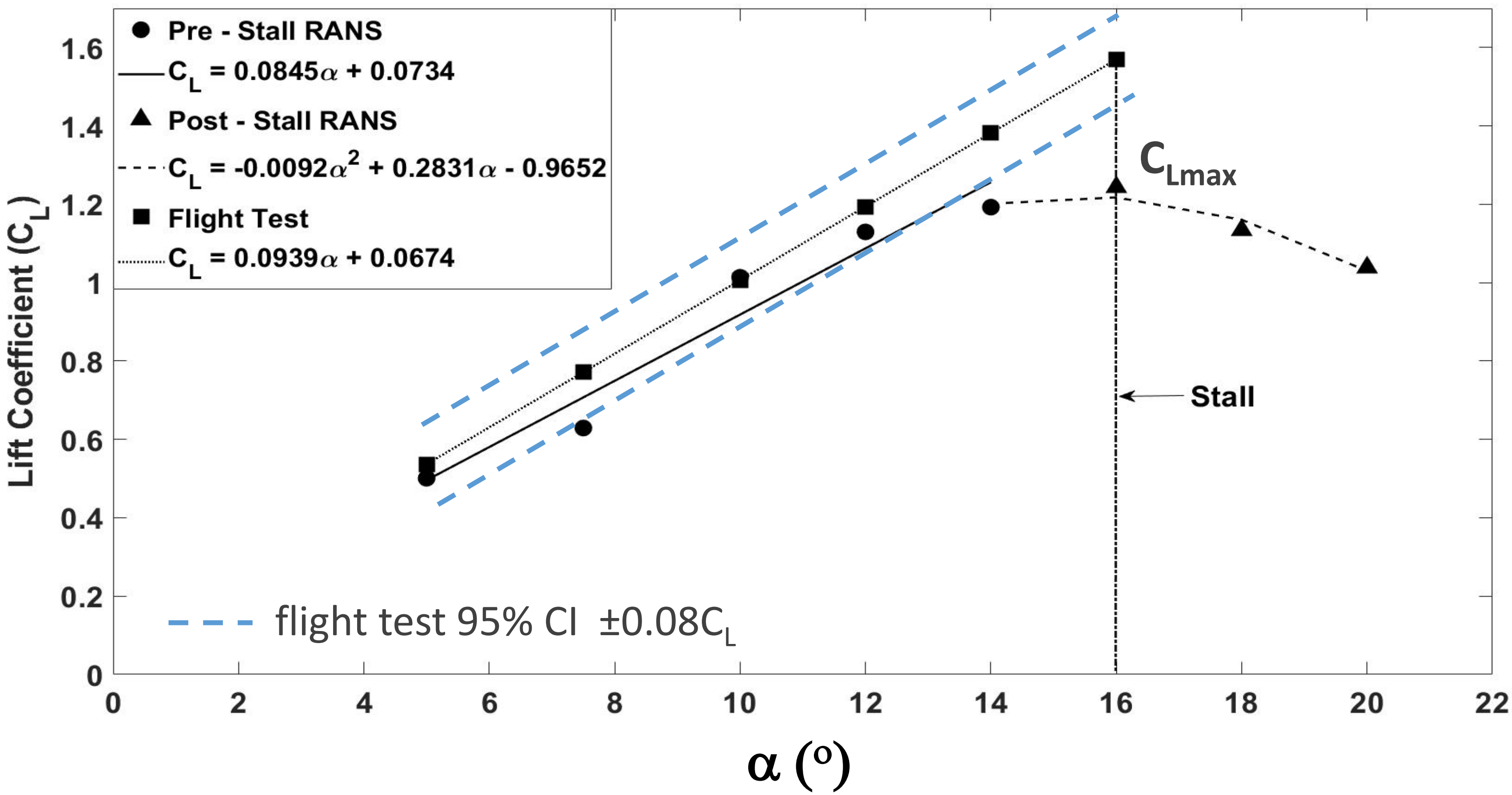


surface flow vis used to assess mesh suitability – medium mesh selected

Figures from: Neves et al (2020) Aerospace Science and Technology, https://doi.org/10.1016/j.ast.2020.106179

Straight and Level Flight: Comparisons

- CFD vs flight test to within ΔC_L ~ 0.1 – 0.2
- CFD stall α estimated 15º – 18º
- ΔC_L , C_{Lmax} CFD discrepancy – propeller slipstream effects



Flight Stall α: Flight Measurement

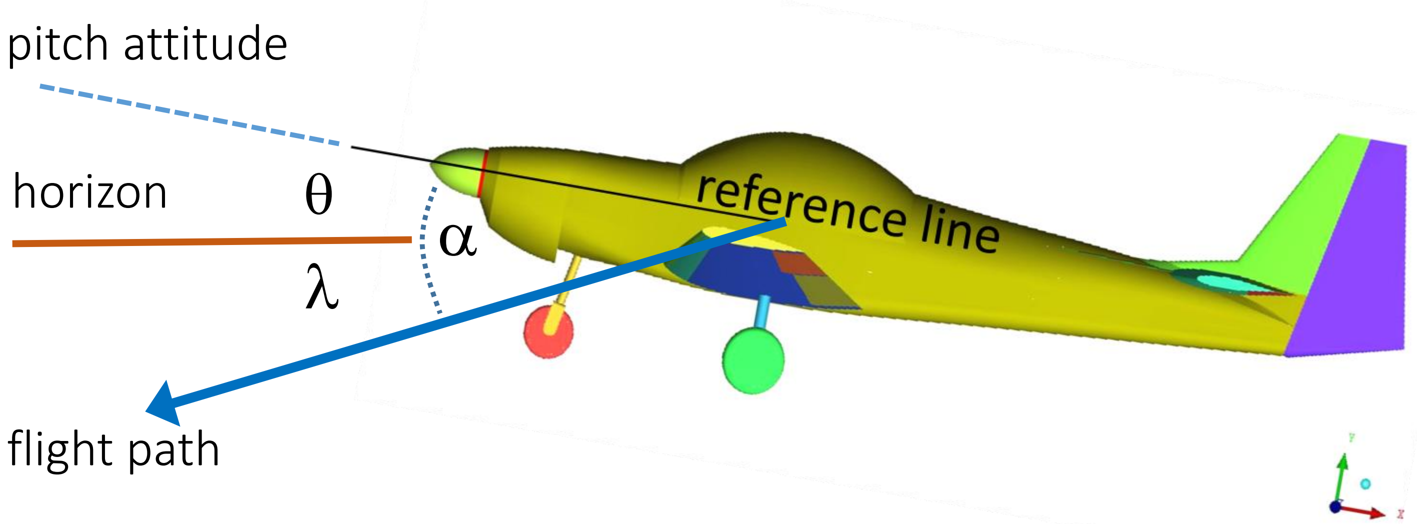
Stalled flight (engine idle) results in aircraft descending with changing α:

- Stalled flight must measure FPA - λ and pitch attitude - θ simultaneously
- α is the sum of λ and θ

For test, record ground speed (cross wind), altitude, pitch attitude

N.B. airspeed indication unreliable in stall

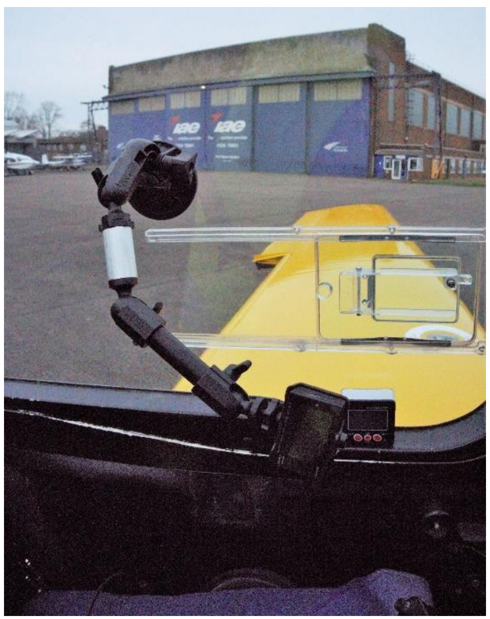
FPA – flight path angle λ



Flight Stall α: Test Set-up 1

Video pitch attitude (digital level) and altitude, record GPS speed

- Digital level, (resolution 0.1°) video with 30Hz HD camera
- Cockpit altimeter video with 30 Hz HD camera
- GPS ground speed source (basic data only 1Hz)



digital level camera

digital level

cockpit altimeter

iPad ground speed

Flight Stall α: Test Set-up 2

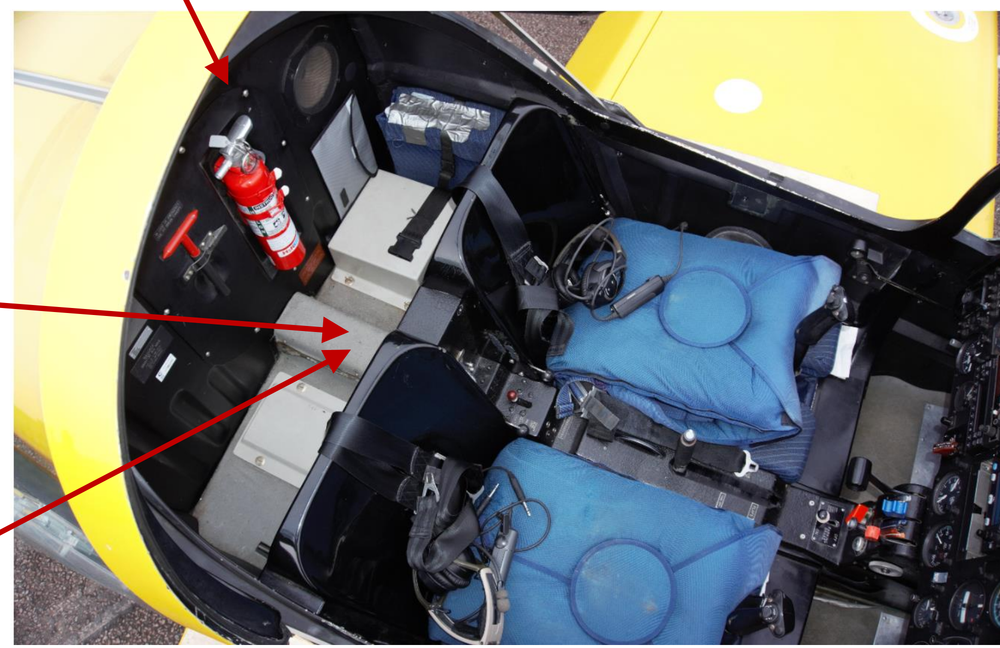
Use Pixhawk4 inertial and GPS unit (drone autopilot ~ US$200)

- GPS ground speed at 5Hz
- Common timestamp / clock
- Pitch attitude, (resolution 0.1^{o}) 250 Hz
- GPS altimeter at 5Hz

Errors

- GPS ground speed at 5Hz
- Common timestamp / clock

Cockpit camera



Pixhawk unit: secured near CoG

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Flight Measurement Errors

Errors during straight / level:

- Resolutions from the cockpit gauges
- Digital level res 0.1°, in flight 1° – 2°
- lift / thrust from masses, greatest errors from gauges

Errors during stall (GPS sources):

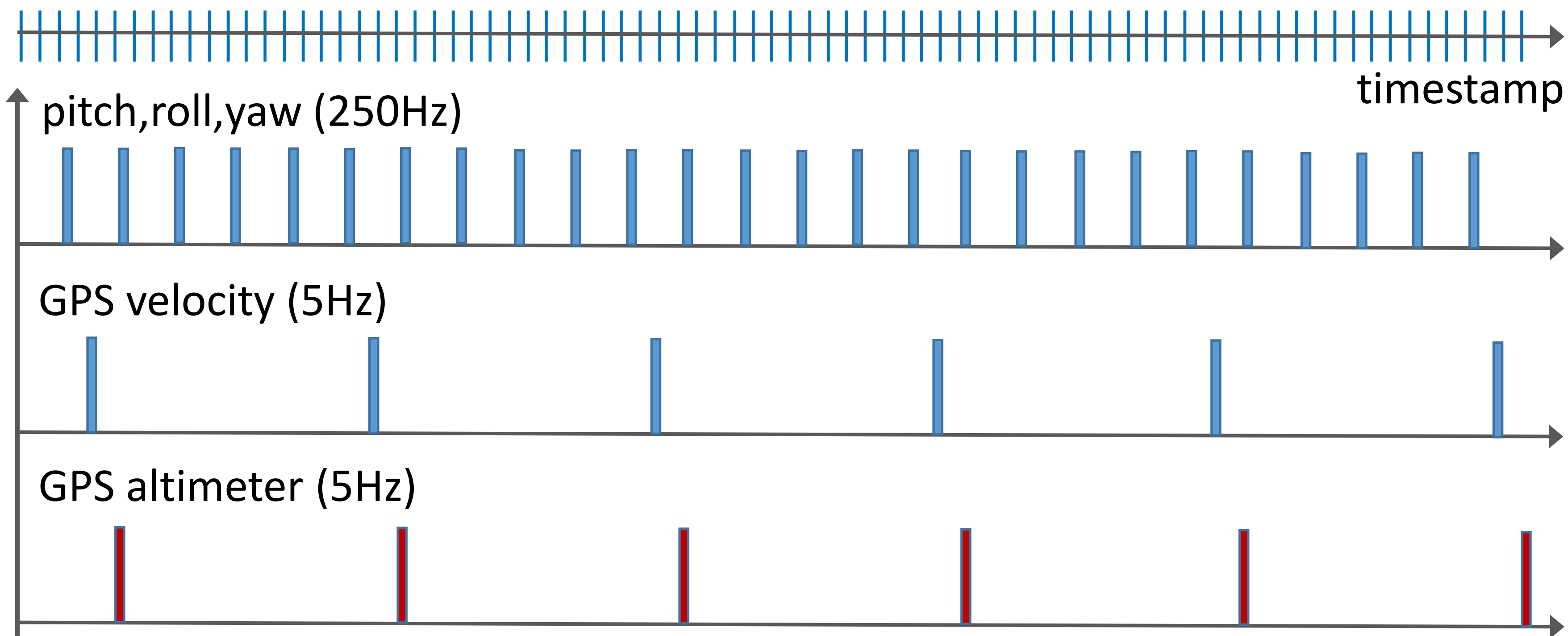
- iPad mini, no info on filters or smoothing: λ and α errors ±3°
- Pixhawk4 λ and α errors from stable data stats ±4°
- 5 knot head/tail wind at 30m/s equates to FPA error λ ~8°
- INS 0.5% of full scale (~0.1° pitch)
- GPS 0.1m/s in velocity / 0.6° in heading

Variable	Error	Source	Comments
outside air temperature (°C)	±5	gauge	cockpit instrument
altitude (ft)	±10	gauge	cockpit instrument
indicated airspeed (knots)	±2.5	gauge	cockpit instrument
calibrated airspeed (knots)	±1	AFM	AFM airspeed correction data for zero flap
true airspeed (% FS)	±3.4	calculated	conversion from [15] including airspeed, altitude and temperature errors (FS – 129 knots)
fuel quantity (kg)	±10	gauge	cockpit instrument
aircraft empty mass (kg)	±20	AFM	estimated from weighing schedule
manifold pressure (inHg)	±1	gauge	cockpit instrument
engine speed (rpm)	±50	gauge	cockpit instrument
power (%)	±2	AFM	performance tables
thrust (% FS)	±3.9	calculated	use variables power, true airspeed and pitch attitude, assume propeller 90% efficient [14] (FS – 2280N)
lift (% FS)	±3.1	calculated	use total weight (FS – 9640 N)
lift coefficient (C_L)	±4.9	calculated	including weight, calculated density and true airspeed errors (FS – 1.13)
drag coefficient (C_D)	±5.4	calculated	including thrust, calculated density and true airspeed errors (FS – 0.199)
pitch attitude (°)	±2.5	attitude indicator	cockpit instrument - gross error check for λ

Table from: Neves et al (2020) Aerospace Science and Technology, https://doi.org/10.1016/j.ast.2020.106179

Flight Stall α: Test Set-up 2 (Pixhawk4)

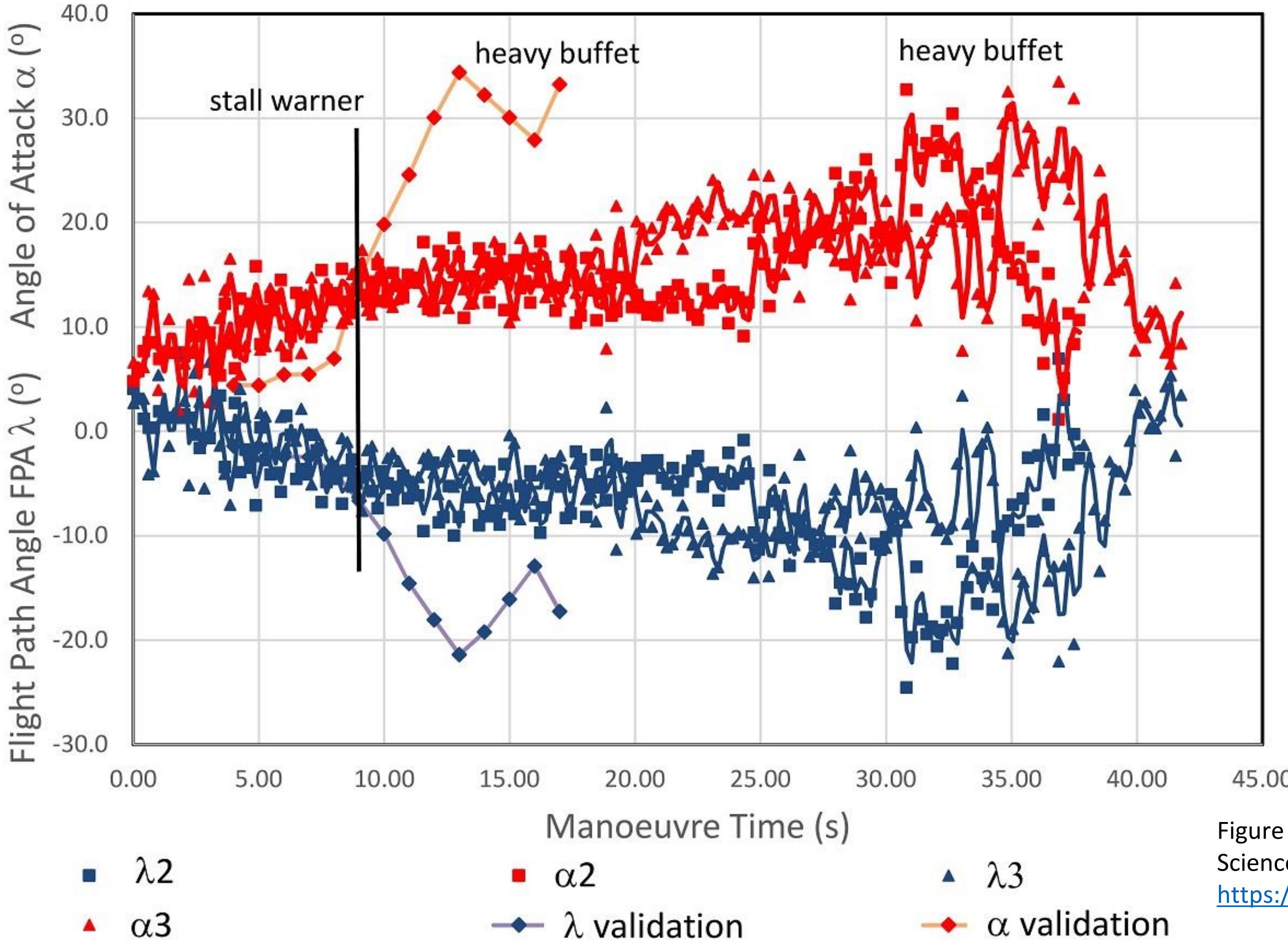
Common timestamp requires resampling



- One 5Hz sample source used as a master
- Other sources resampled (250Hz >> 5Hz) then interpolated to 5Hz master

Flight Stall α: Results

Both tests indicated stall characteristics around α = 15º – 20º



Heavy buffet and wing drop at:

α = 20º – 30º

Unsteady CFD modelled through range:

α = 14º – 18º

N.B.: 'validation' from iPad / digital level

λ2/λ3, α2/α3 from Pixhawk4

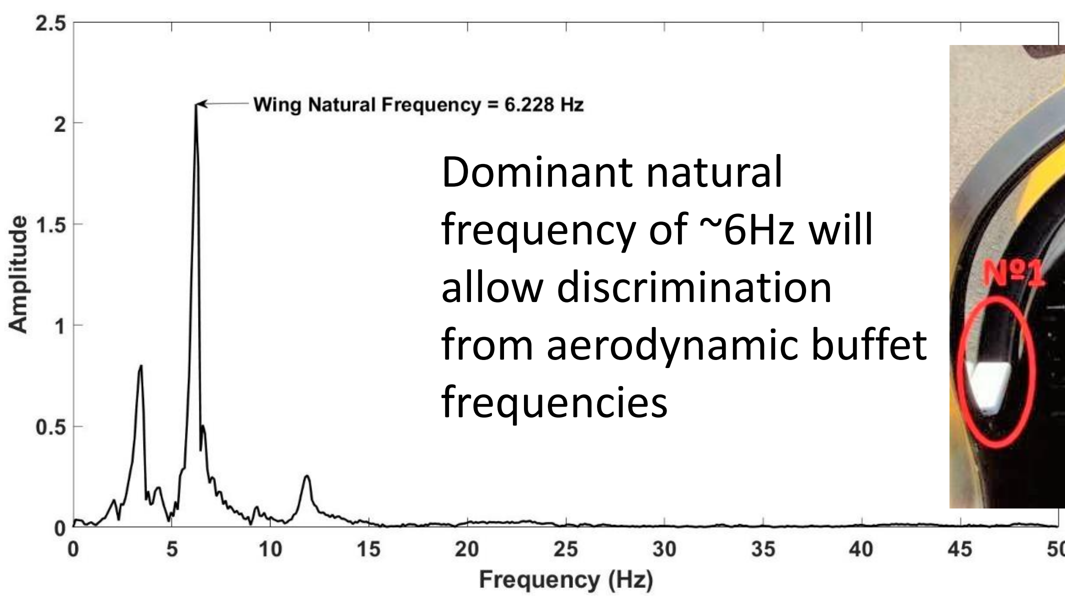
Figure from: Neves et al (2020) Aerospace Science and Technology, https://doi.org/10.1016/j.ast.2020.106179

Flight Stall Buffet: Tests

Aircraft bought into a stall and buffet recorded before ‘wing drop’:

- Shimmer3 IMUs for in-flight aerodynamic buffet frequency (up to 1kHz)
- Wing surface flow visualisation using wing tufts / HD video
- Altimeter and pitch attitude monitored using cockpit HD video

Ground tests of natural wing frequency (6.2Hz) using IMUs



Dominant natural frequency of ~6Hz will allow discrimination from aerodynamic buffet frequencies

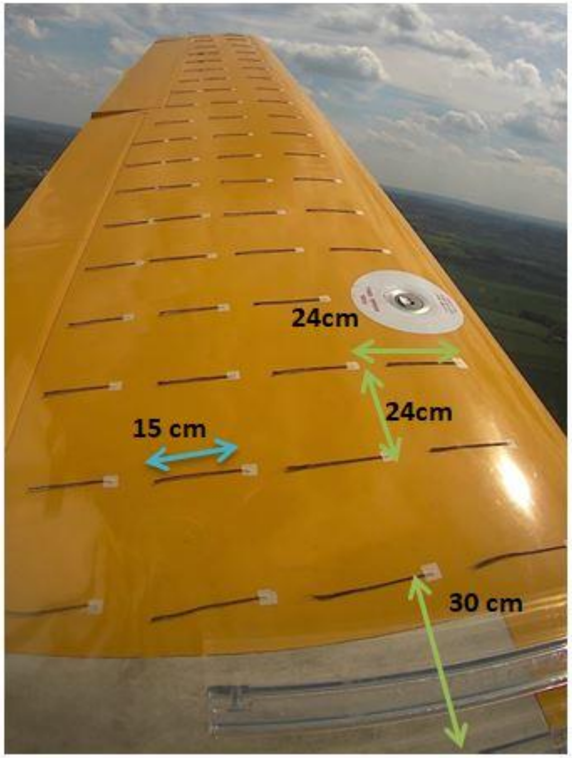
IMU in-flight set-up

http://www.shimmersensing.com/images/uploads/docs/Shimmer_User_Manual_rev3p.pdf

Flight Stall Buffet: Tests

Wing surface flow vis based on work by Gratton and Hoff:

- Woollen tufts 15cm long fixed onto a wing surface grid
- 30Hz video recorded during flight of wing and cockpit



wing camera

cockpit camera

Gratton, G. and Hoff, RI. (2012) 'Camera Tracking and Qualitative Airflow Assessment of a 2-turn Erect Spin'. The Aeronautical Journal, 116 (1179). pp. 541 - 562.

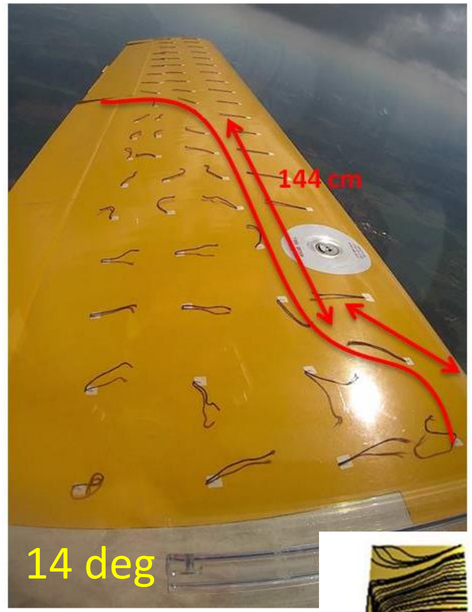
Flight Stall Buffet: Movies

https://1drv.ms/v/s!AqvNv7Mai6Rq
hatyIjhGnK4I2kZmuQ?e=GTXgPZ

https://1drv.ms/v/s!AqvNv7Mai6Rqhat3LYpQk9LL9X6kHQ?e=R34Cve

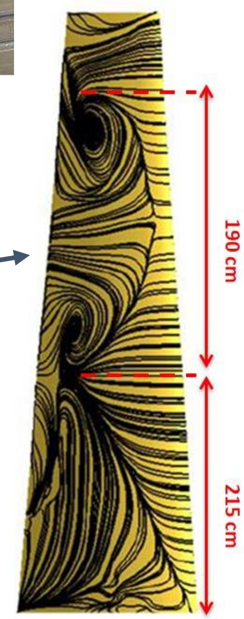
Flow Visualisation: In-Flight vs CFD

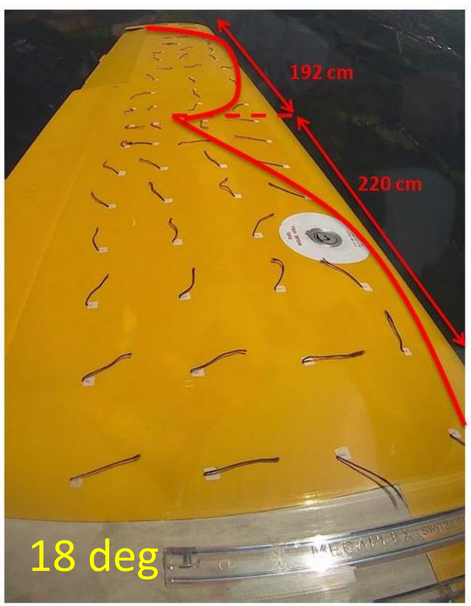
Figures from: Neves et al (2020) Aerospace Science and Technology, https://doi.org/10.1016/j.ast.2020.106179



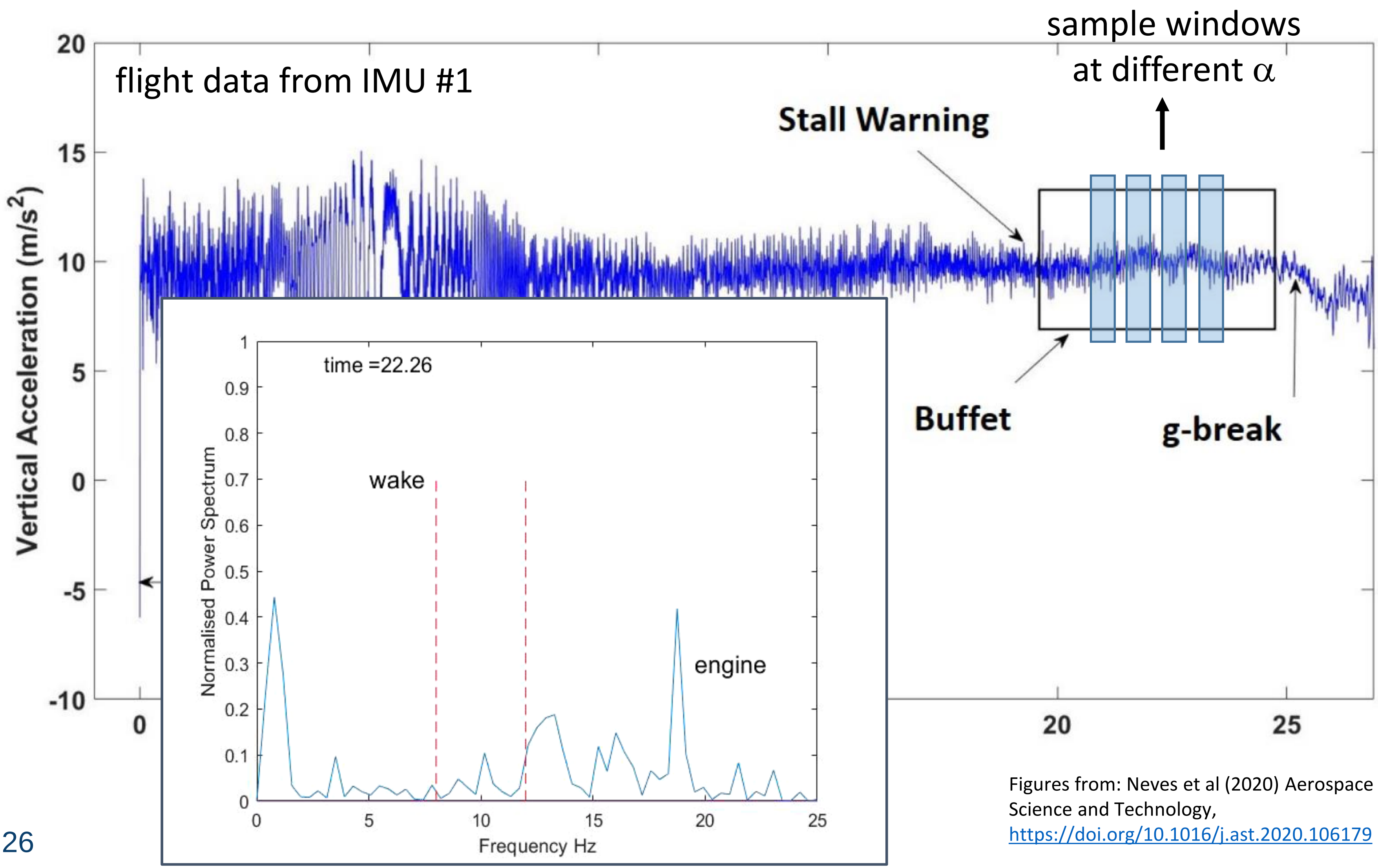
Weihs & Katz paper: https://1drv.ms/b/s!AqvNv7Mai6Rqhat7bz3H9Ydw5HTXMQ?e=HMLcbl

cellular 'mushroom' structure Weihs & Katz (1983)





Flight Stall Buffet: In-Flight Data



Figures from: Neves et al (2020) Aerospace Science and Technology, https://doi.org/10.1016/j.ast.2020.106179

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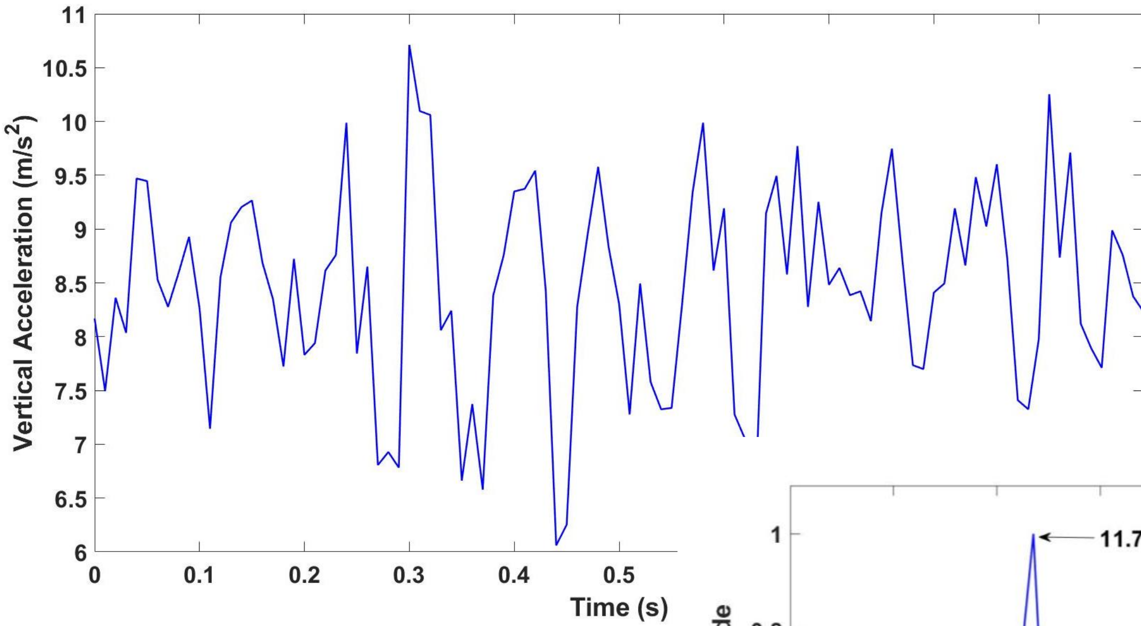
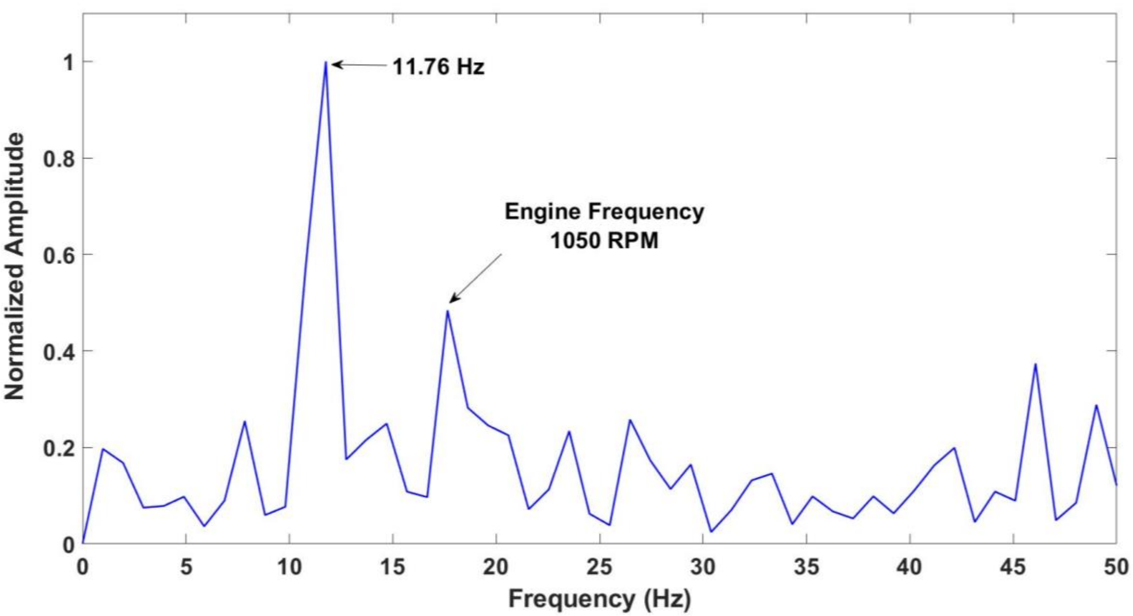
Flight Stall Buffet: In-Flight Data



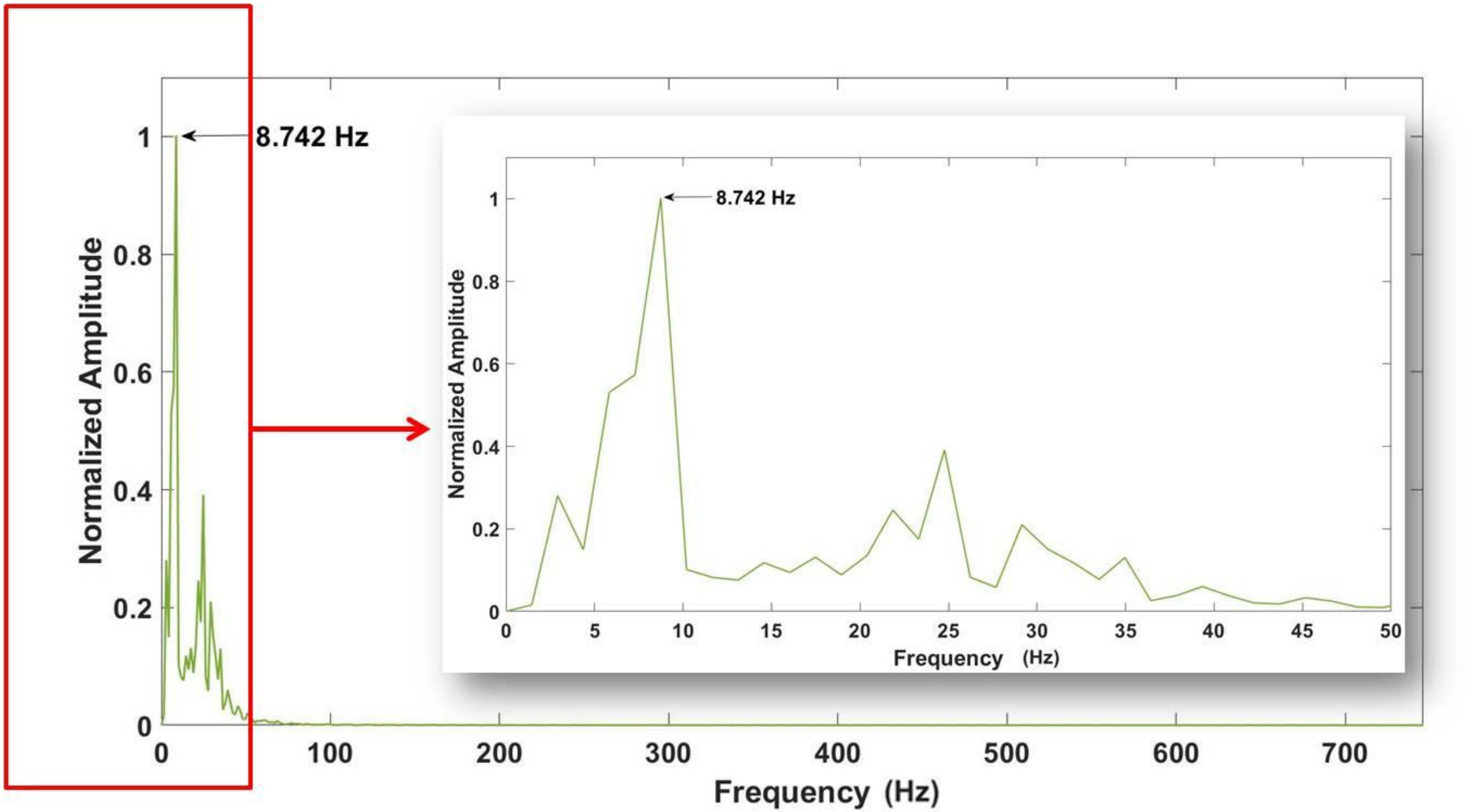
acceleration in-flight data from IMU #1

spectrum in-flight data from IMU #1 at $\alpha = 14^{o}$

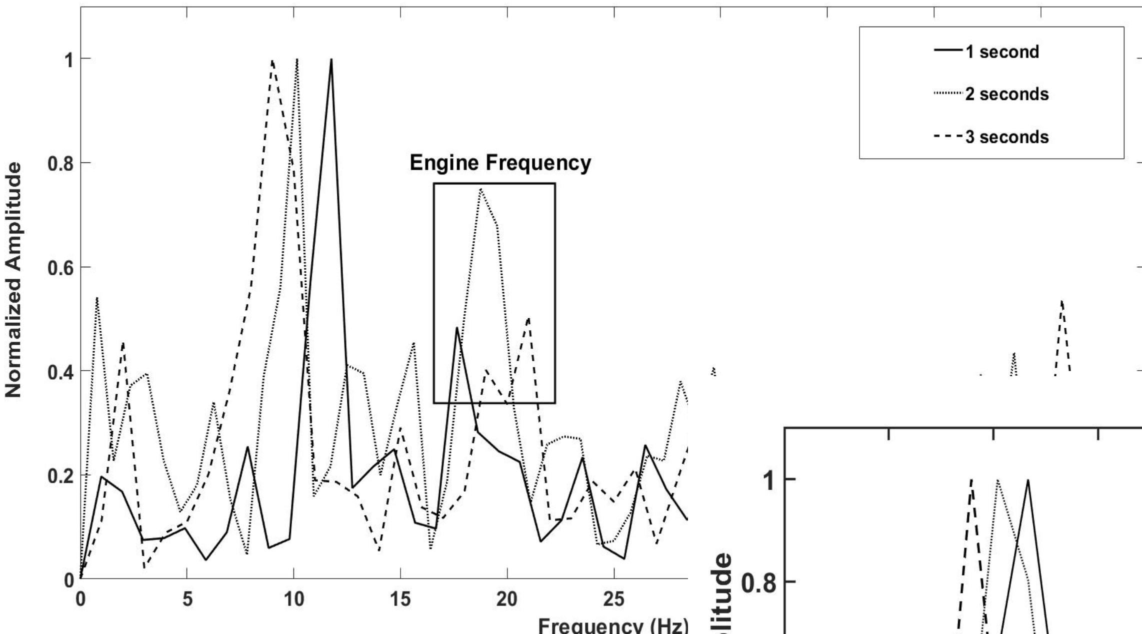


Stall Buffet: In-Flight vs CFD

CFD data $\alpha = 18^o$



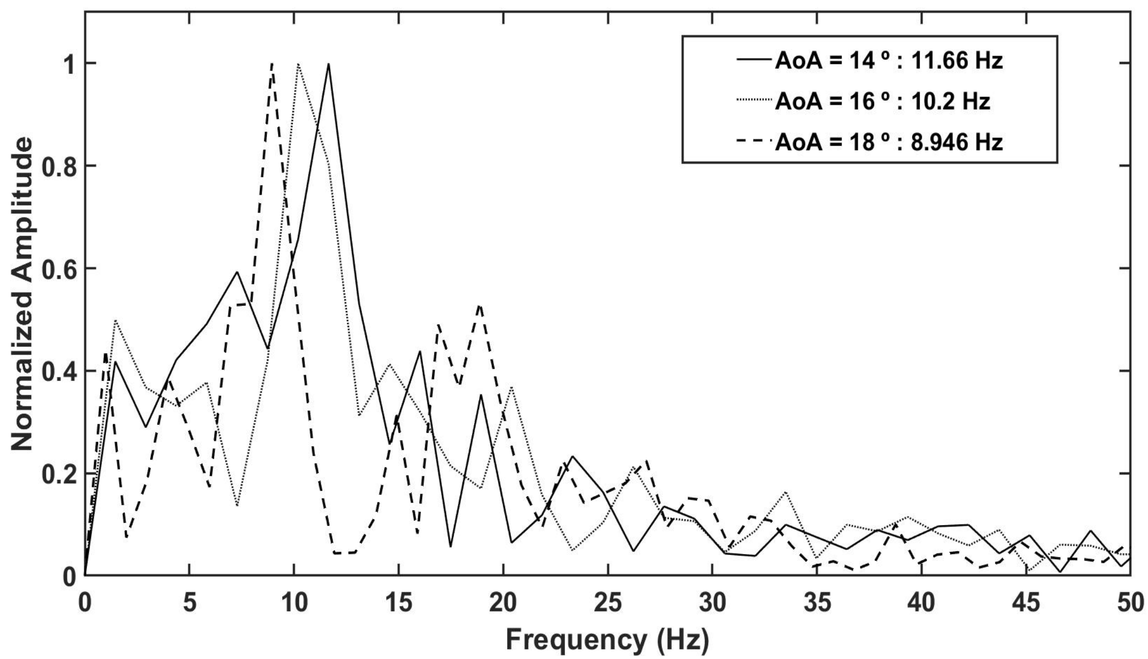
Stall Buffet: In-Flight vs CFD



Flight data with increasing α

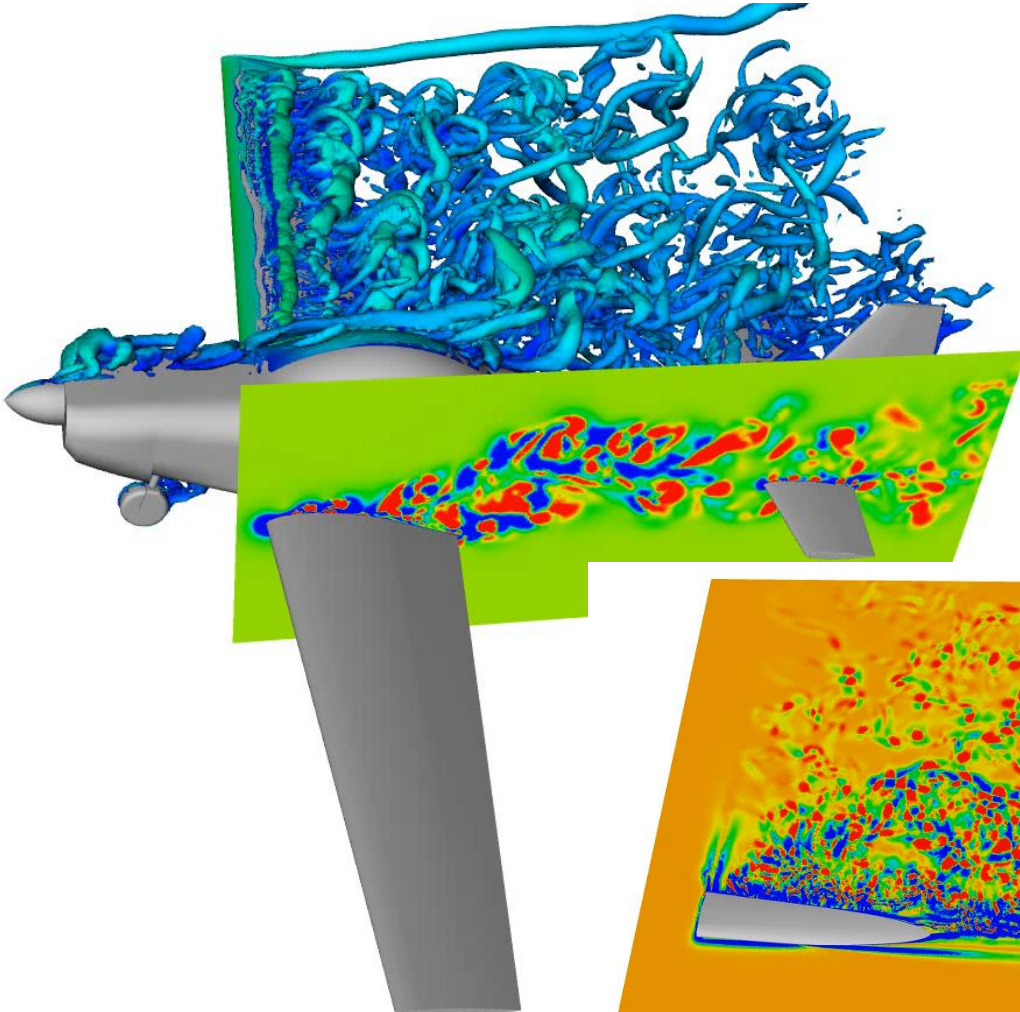
Figures from: Neves et al (2020) Aerospace Science and Technology, https://doi.org/10.1016/j.ast.2020.106179

CFD data



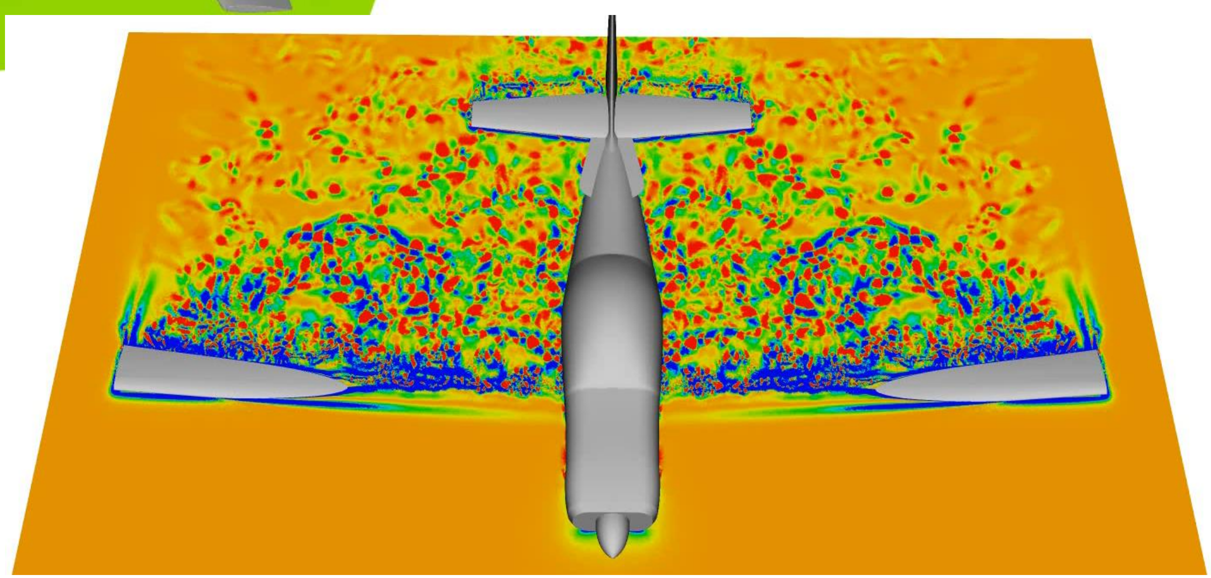
spectral frequency comparison
$\alpha = 16^o$, ~1% error
(dependent on flight α estimate)

Stall Buffet: CFD Movies α = 16º



- results indicates tailplane interaction
- tailplane not heavily stalled

https://1drv.ms/v/s!AqvNv7Mai6Rqhat51vmhLbHs3FaA_Q?e=vYEn8H

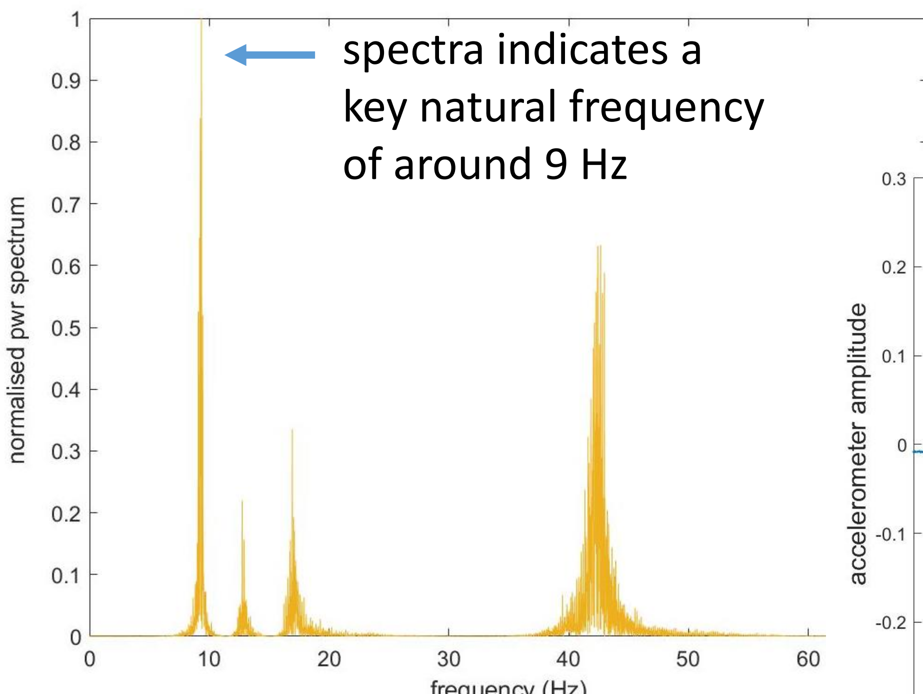


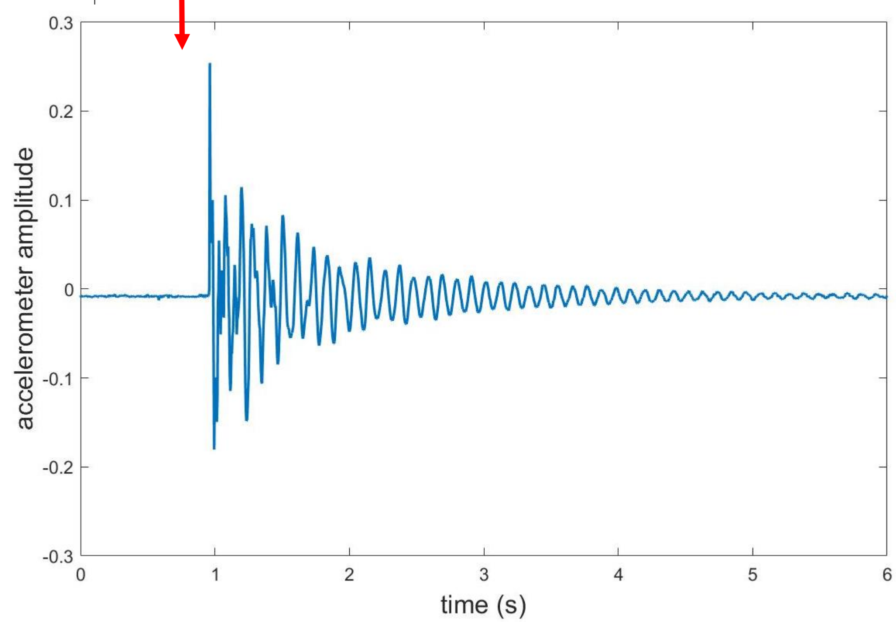
https://1drv.ms/v/s!AqvNv7Mai6Rqhat4dkV0vTgOxsjrPA?e=duKh6a

Flight Stall Buffet: Wake Tailplane Interaction

accelerometer mounted onto tailplane and an impulse disturbance used to excite the structure

spectra indicates a key natural frequency of around 9 Hz





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Flight Stall Buffet: Wake Tailplane Interaction

rear view: progressive stall to heavy buffet and ‘wing drop’

front view: https://1drv.ms/v/s!AqvNv7Mai6Rqhat1RHb-AeOriCqNhg?e=2Yj2Jr
rear view: https://1drv.ms/v/s!AqvNv7Mai6RqhatzgheKAiSgmdqvww?e=3ODRxW

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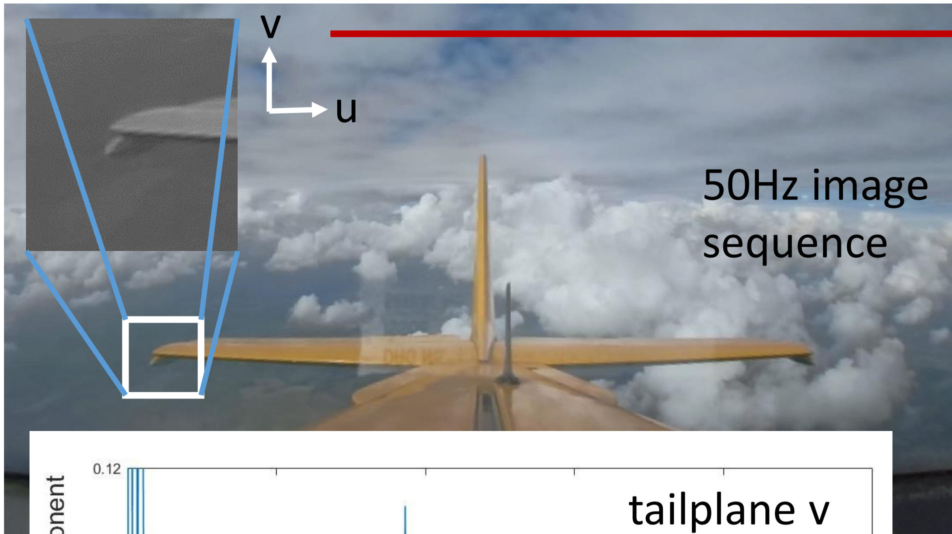
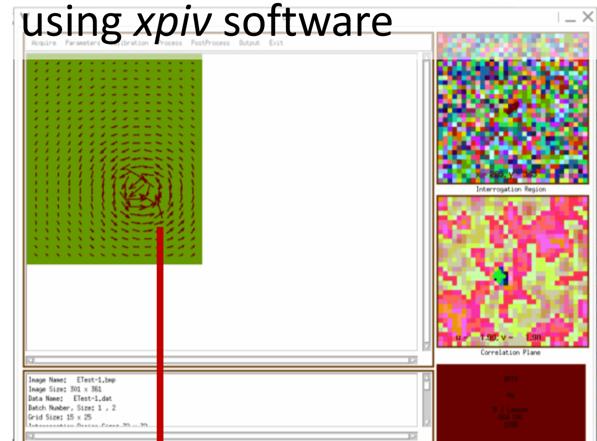
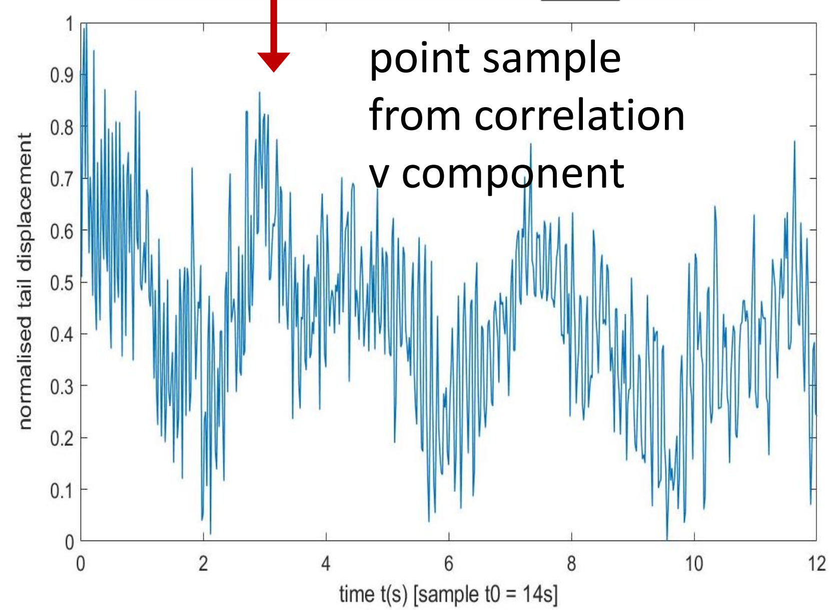
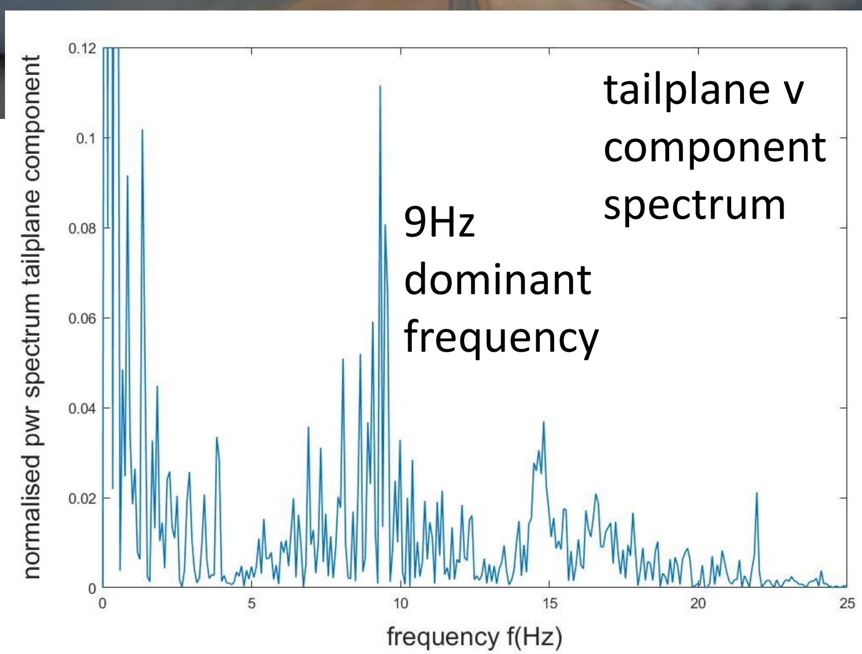
Flight Stall Buffet: Wake Tailplane Interaction



spatially correlate image sequence using *xpiv* software







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Summary / Lessons Learned

- Flight test initially used to validate steady state RANS CFD. Discrepancy in C_L from propeller effects
- Further flight tests used to estimate the range of stall α and study buffet
- Simple application of iPad and drone autopilot Pixhawk4 unit allowed estimations of flight path angle λ and α
- DES CFD extended from initial model to predict buffet behaviour
- Good comparisons with buffet frequencies and CFD indicated a significant tailplane interaction
- Further flight test confirmed tailplane excitation from wake and buffet
- Further work continues to extend DES model and methods for spin analysis
- Questions?

results in this presentation appear in:
Elsevier *Aero. Sci. & Tech.* 2021
CEAS *J. Aero Eng.* 2022