Study of Transonic Flutter and Shock Buffet on Benchmark Supercritical Wing

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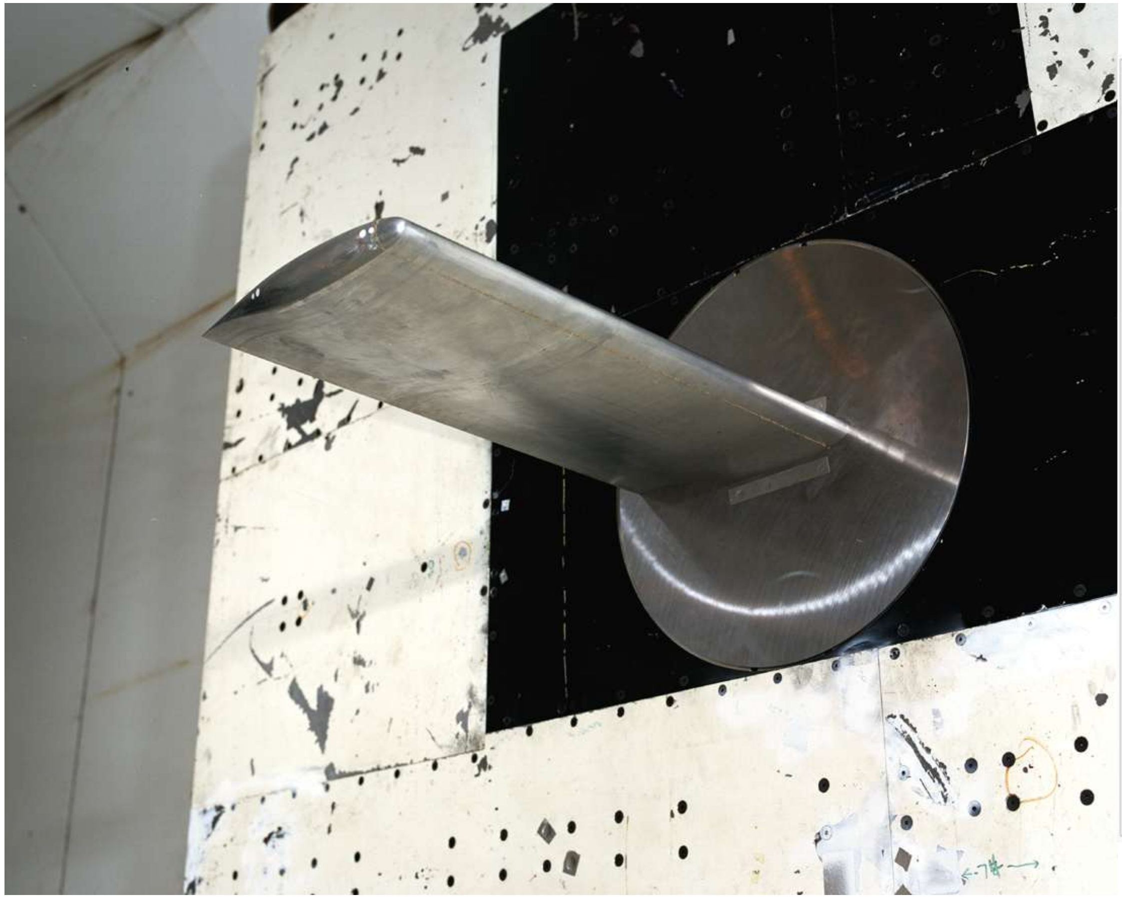
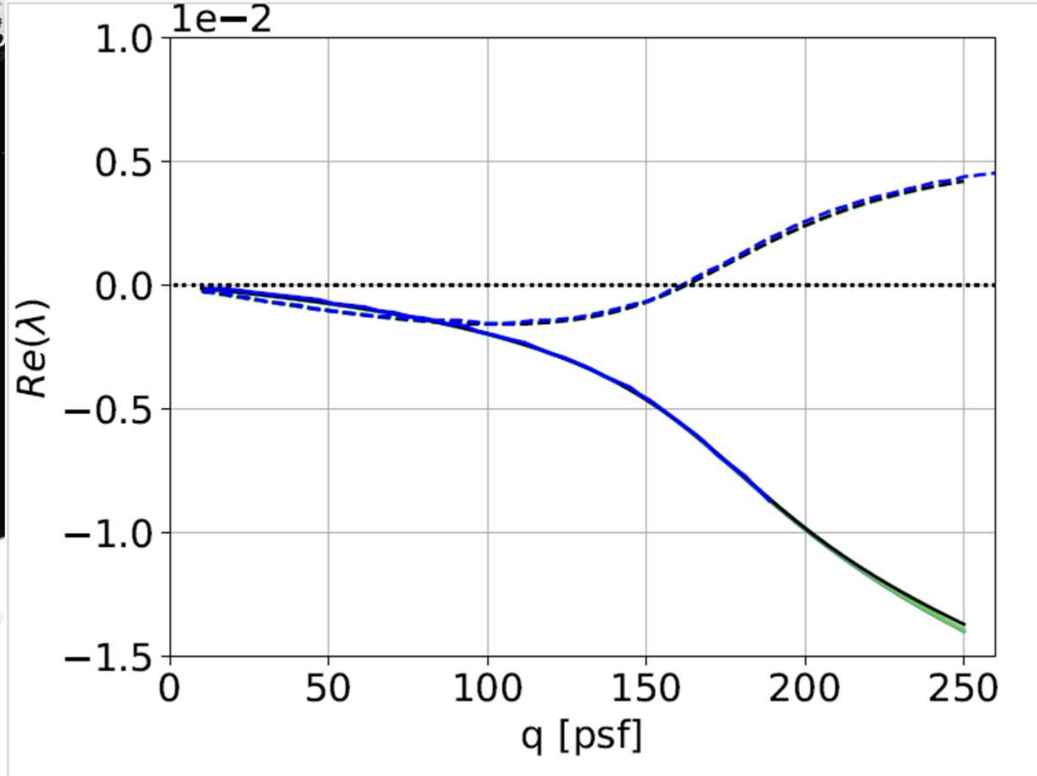
Introduction



From: https://nescacademy.nasa.gov/workshops/AePW2/public/BSCW



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Outline

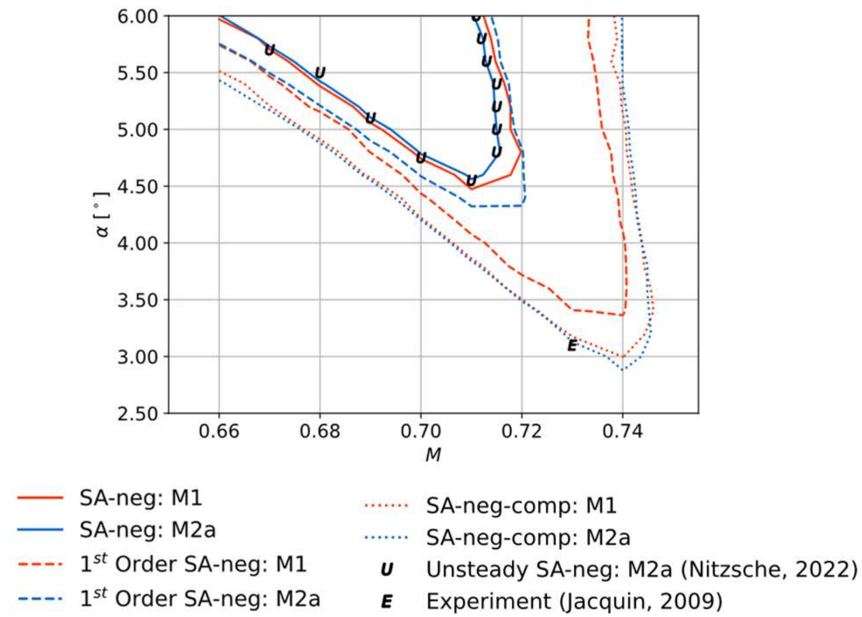
Use linear frequency domain (LFD) analysis and an eigenvalue-based flutter solver to trace the modes and determine the dynamic pressure for flutter onset.

Focus on code-to-code and method-to-method comparisons.

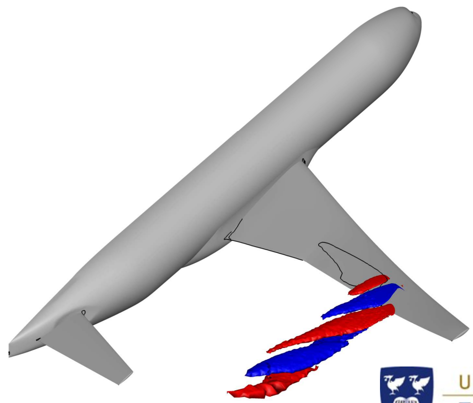
Investigate effect of turbulence model.

Utilise a global stability method to predict shock buffet onset.

Locate flow states where the two instabilities may interact.



Nash, D., and Timme, S., "Influence of Turbulence Model and Mesh Refinement on Aerofoil Shock Buffet Onset," *59th 3AF International Conference on Applied Aerodynamics*, Strasbourg, France, 2025.



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Theory

RANS equations (plus turbulence model) in semi-discrete form:

$$\dot{\boldsymbol{w}} = \mathcal{R}(\boldsymbol{w})$$

Assuming small perturbations of the form $\tilde{\boldsymbol{w}}(t) = \hat{\boldsymbol{w}}e^{\lambda t}$, the eigenvalue problem is written:

$$\lambda_J \hat{\boldsymbol{w}} = \boldsymbol{J}\hat{\boldsymbol{w}}$$

After some manipulations, the equation for LFD analysis is obtained:

$$(\boldsymbol{J}_{\boldsymbol{ff}} - i\omega \boldsymbol{I})\boldsymbol{Y} = -\boldsymbol{J}_{\boldsymbol{f\eta}} - i\omega \boldsymbol{J}_{\boldsymbol{f\dot{\eta}}}$$

Generalised aerodynamic force matrix, $\boldsymbol{Q}$:

$$\boldsymbol{Q} = \boldsymbol{J}_{\boldsymbol{\dot{\eta}f}}\boldsymbol{Y}$$

$\boldsymbol{Q}$ is computed at discrete sample points over a range of frequencies covering structural frequencies.

These are interpolated over the frequencies (one-dimensional) or over both dynamic pressure and frequency (two-dimensional).

From the second equation, the flutter solver computes:

$$\left(\begin{pmatrix} 0 & \boldsymbol{I} \\ -\boldsymbol{\Phi}^{\boldsymbol{T}}\boldsymbol{K}\boldsymbol{\Phi} & 0 \end{pmatrix} - \lambda_J \boldsymbol{I} + \begin{pmatrix} 0 & 0 \\ \boldsymbol{Q}(\omega) & 0 \end{pmatrix}\right)\hat{\boldsymbol{w}}_{\boldsymbol{s}} = \boldsymbol{0}$$

Tools

Used DLR-TAU CFD code with its modal CSM solver and LFD tools.

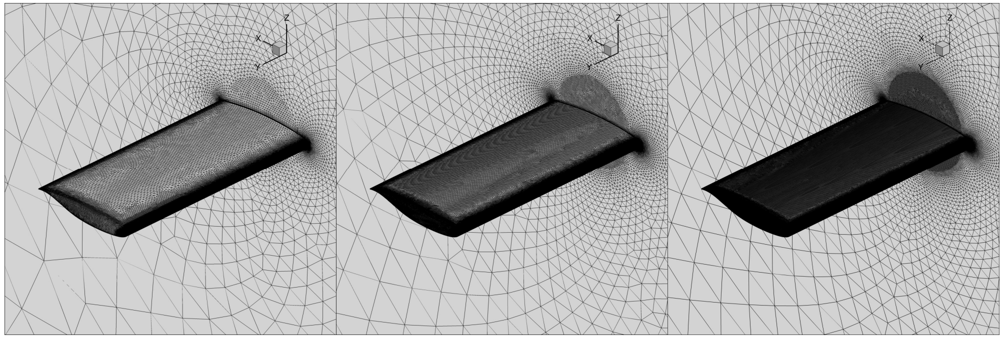
Second-order, finite volume, vertex-centred spatial discretisation.

SA-neg turbulence model with first- and second-order spatial discretisation of convective fluxes.

Static aeroelastic problem solved iteratively, updating fluid and structural degrees of freedom in turn. Structural mode shapes are interpolated onto the fluid mesh.

LFD solver is used to obtain unsteady aerodynamic response to structural forcing at a given frequency.

Test Case



Used committee-supplied grids with 3×10^6 to 27×10^6 points.

Rigid body modes matching PAPA:
Plunge, 3.33Hz, mode 1
Pitch, 5.20Hz, mode 2

Static aeroelastic solutions calculated for $0.0^o \leq \alpha \leq 3.0^o$ and $25 \leq q \leq 250$psf.

***q* [psf]**	25	50	100	134	143
Re	592,224	1,184,801	2,371,336	3,178,880	3,392,751
***q* [psf]**	152	169	200	225	250
Re	3,606,668	4,006,103	4,748,658	5,343,835	5,939,368

LFD system excited by modes at ten non-dimensional angular frequencies $0.01 \leq \omega \leq 0.10$.

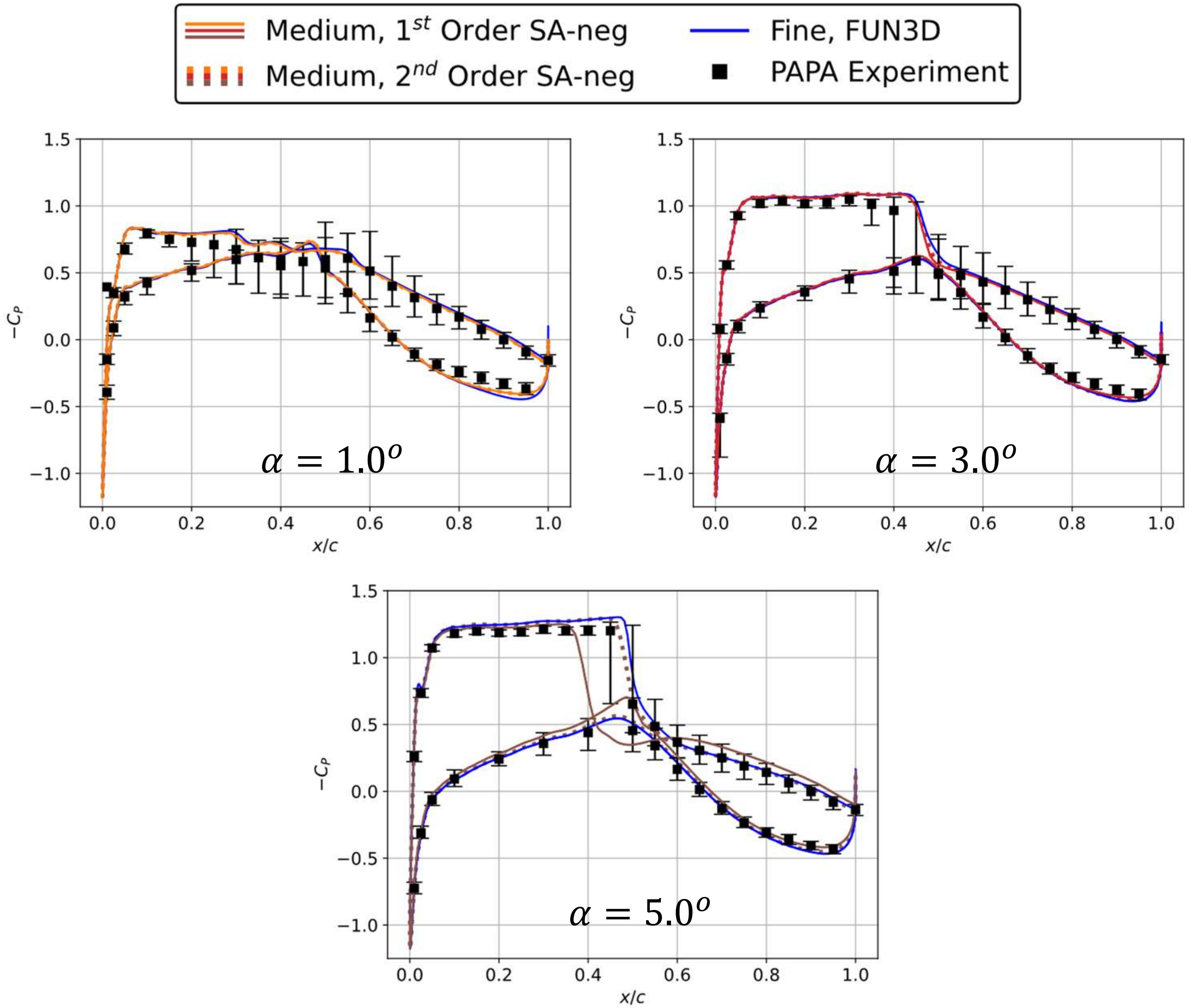
Steady State

(Rigid, no FSI)

Little mesh dependence.

Higher angle sensitive to turbulence convective flux discretisation.

Second-order discretisation shifts shock downstream towards 1st order FUN3D and experiment.



Static Aeroelastic Deformation

Very little mesh influence.

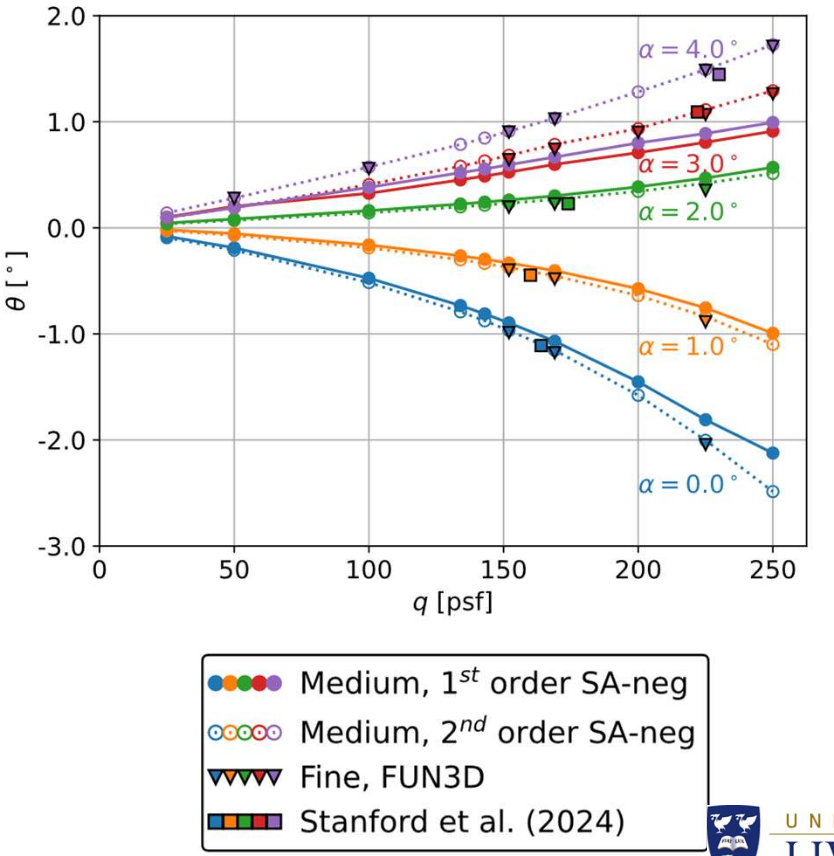
Second-order SA-neg gives larger deformations.

Best agreement when using second-order turbulent fluxes with:

Fine mesh in FUN3D

Mesh-adaptation method

Elastic pitch angle vs dynamic pressure



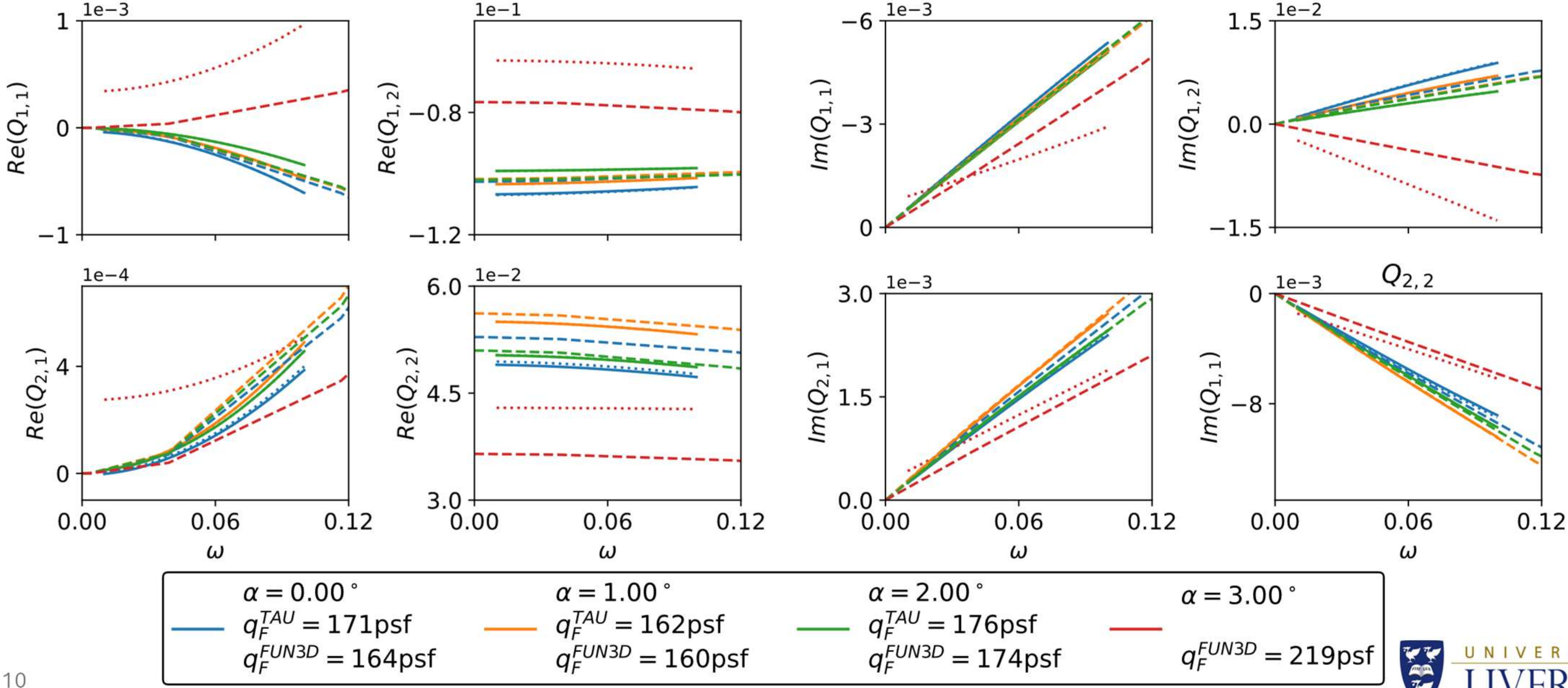
Flutter

Flutter Prediction – GAFs

(First-order spatial discretisation of turbulent fluxes)

Generalised aerodynamic force matrix as a function of angular frequency

Dashed = FUN3D **Dotted = TAU GAF at FUN3D q_F**



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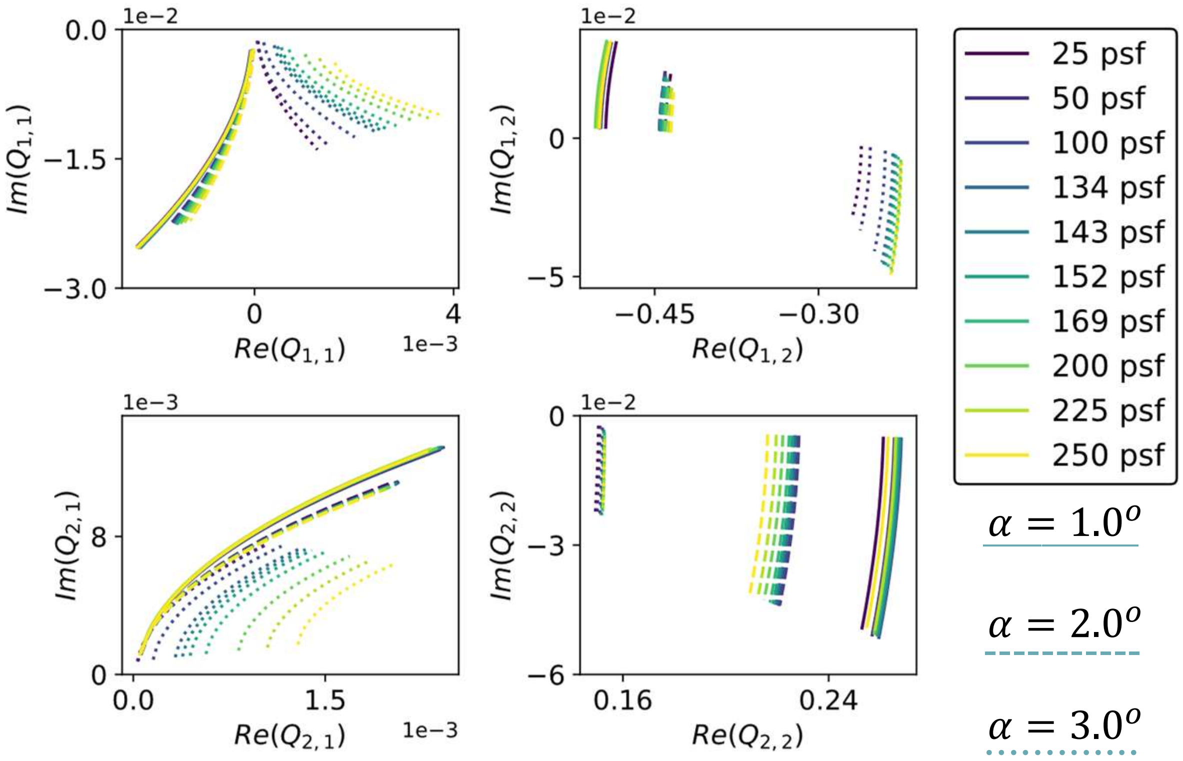
Flutter Prediction – GAFs

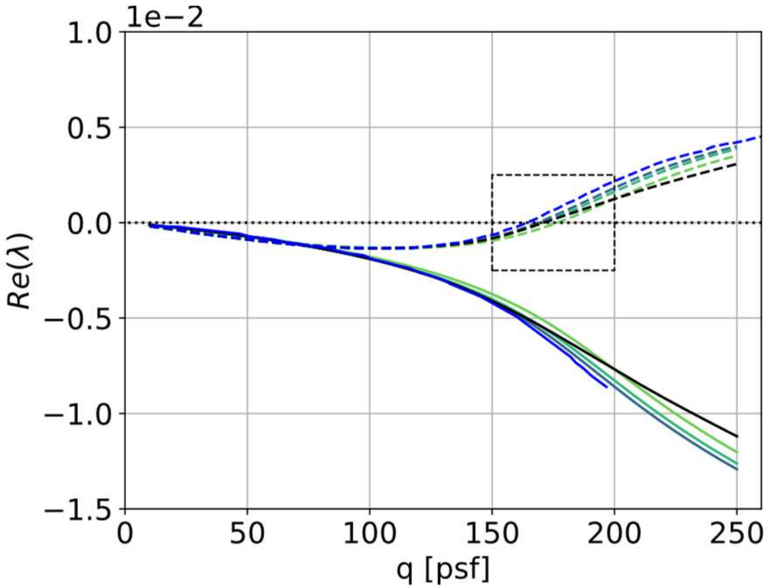
(First-order spatial discretisation of turbulent fluxes)

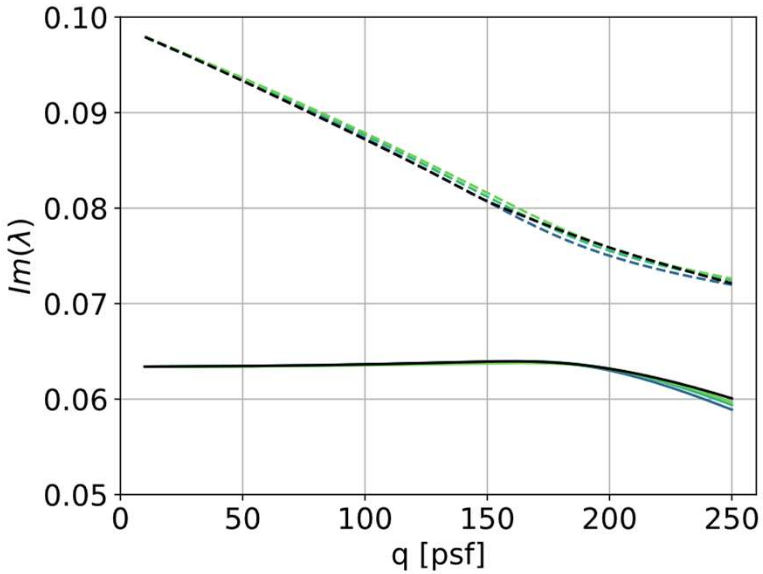
Generalised aerodynamic force matrix shown as imaginary over real part through angular frequencies

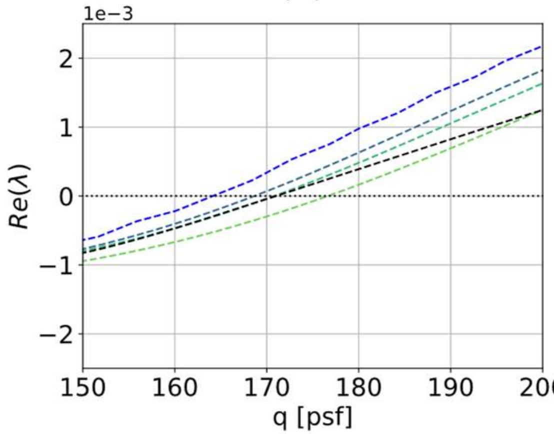


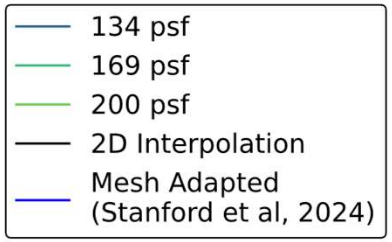
Mode Traces

Mode traces for medium mesh with one- and two-dimensional interpolation in flutter solver $\alpha = 0.0^o$









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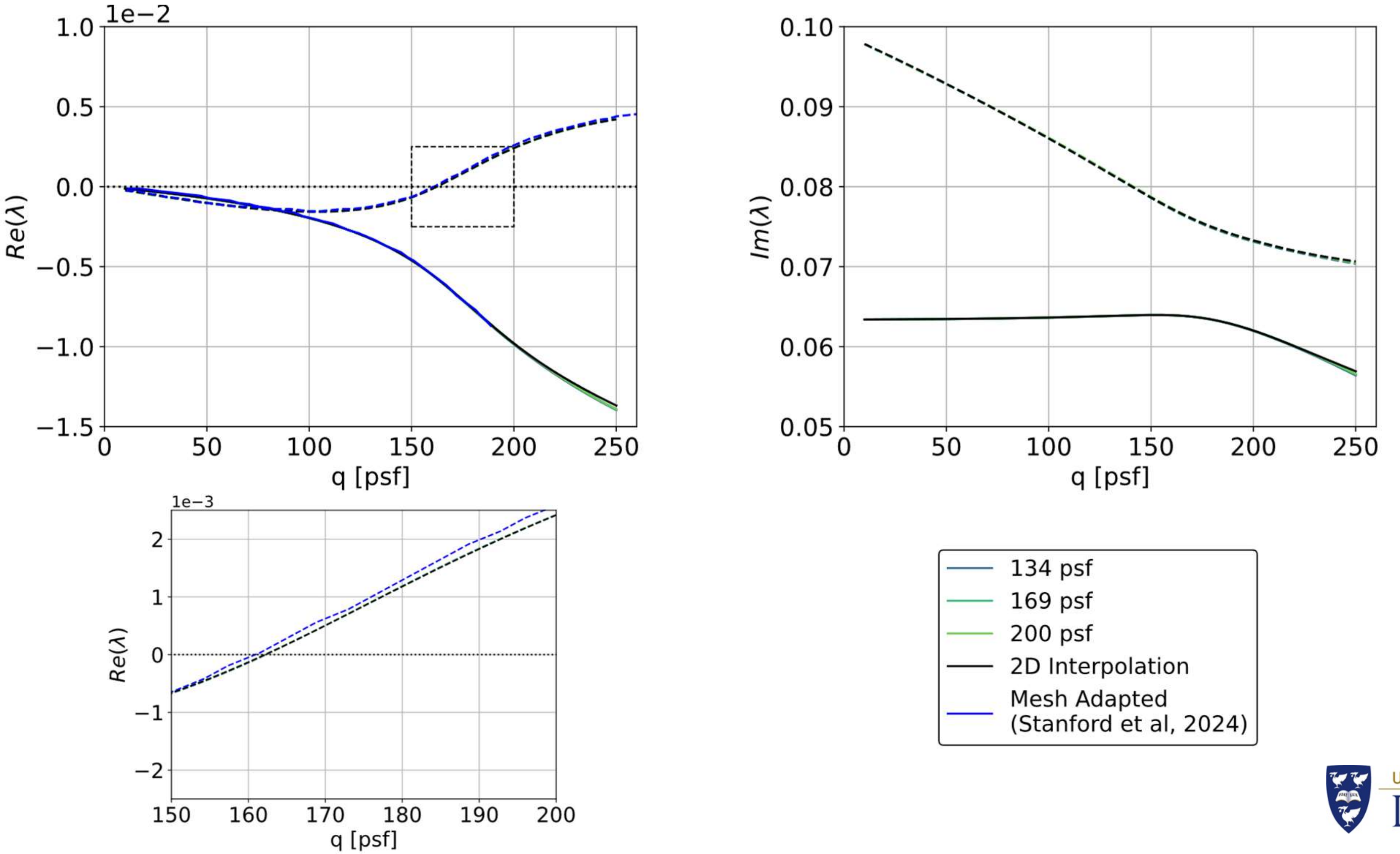
Mode Traces

Mode traces for medium mesh with one- and two-dimensional interpolation in flutter solver $\alpha = 1.0^o$



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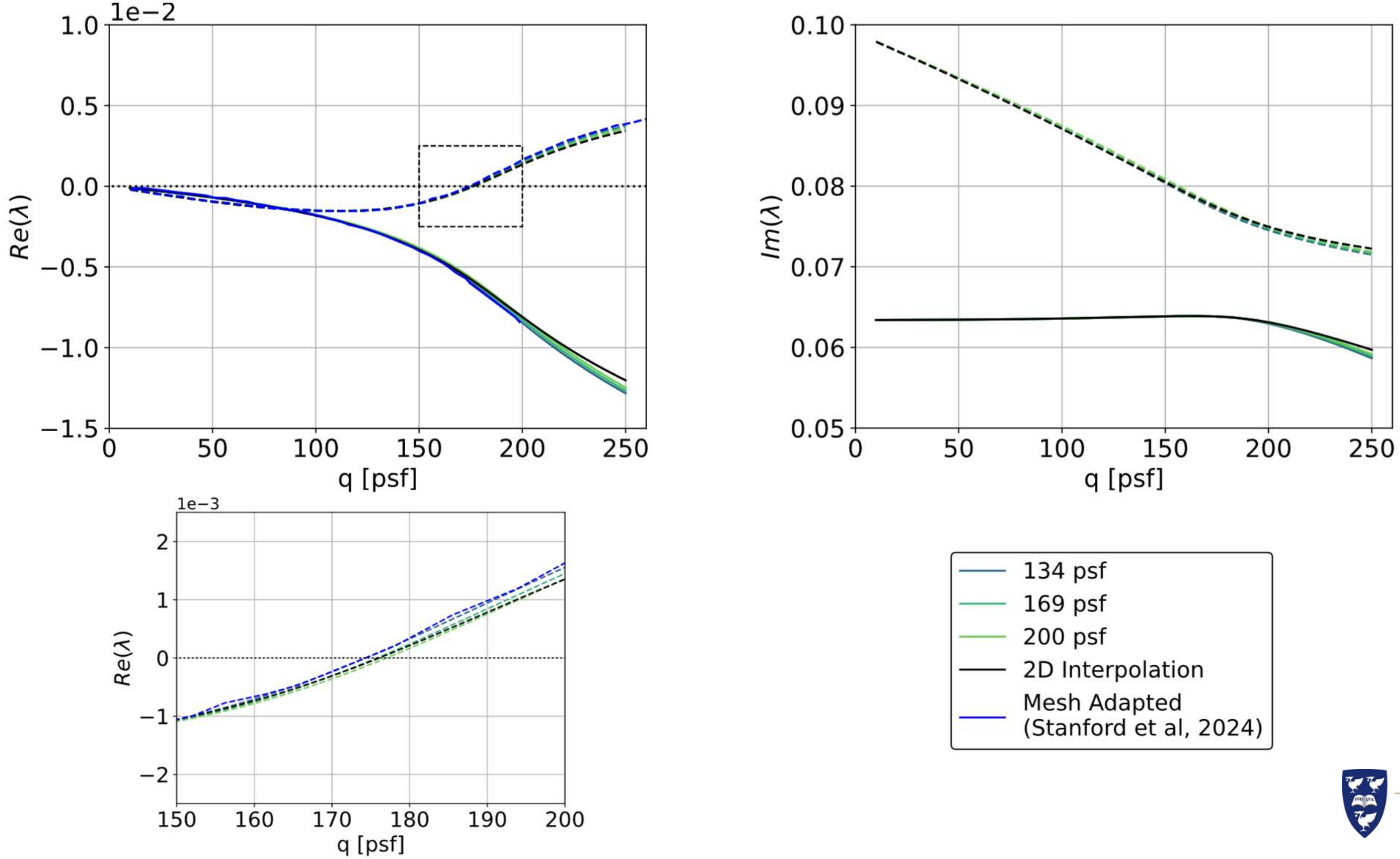
Mode Traces

Mode traces for medium mesh with one- and two-dimensional interpolation in flutter solver $\alpha = 2.0^o$



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Flutter Onset

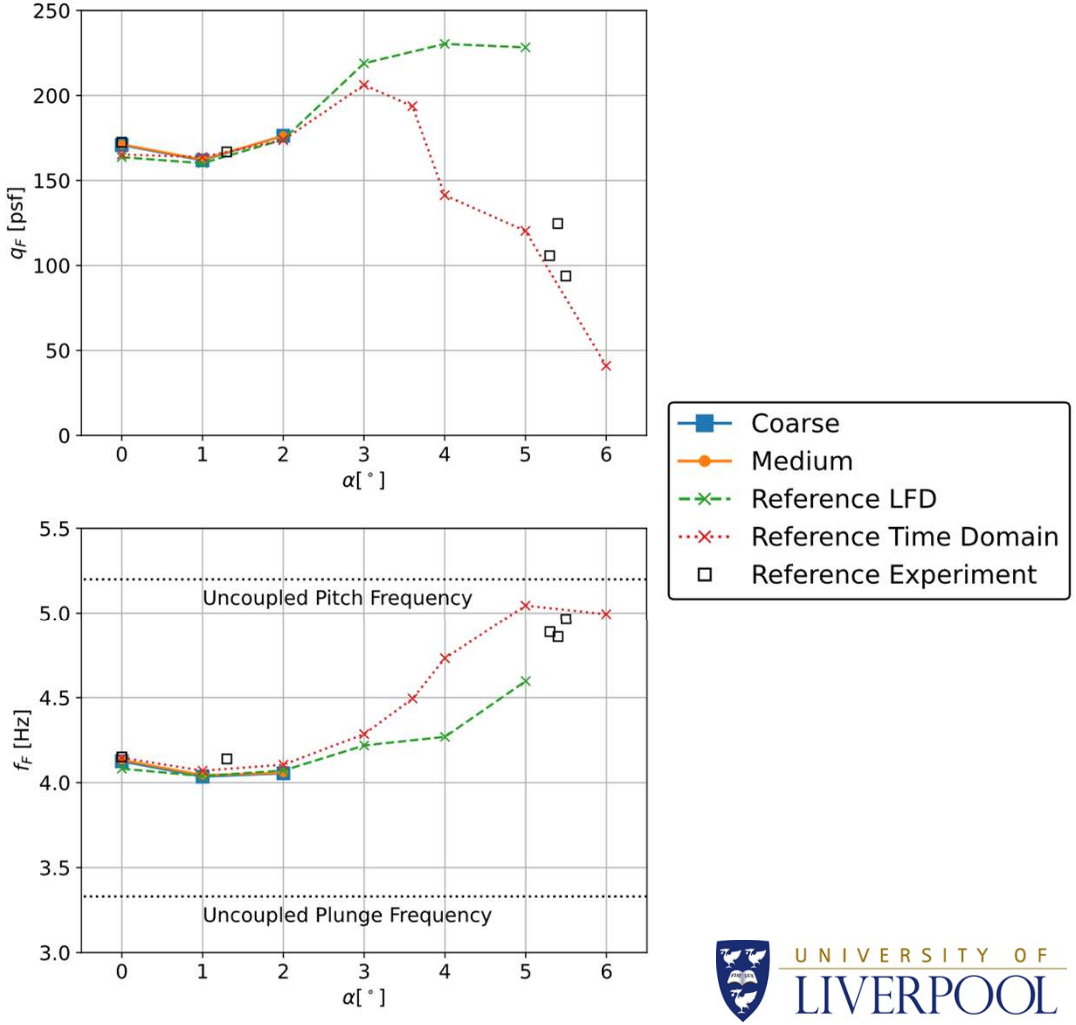
Very little difference in flutter onset and frequency between coarse and medium meshes.

Strong code-to-code and method-to-method agreement.

Results close to experiment.

Beyond $\alpha = 3.0^{o}$, the methods diverge.

Dynamic pressure and frequency at flutter onset



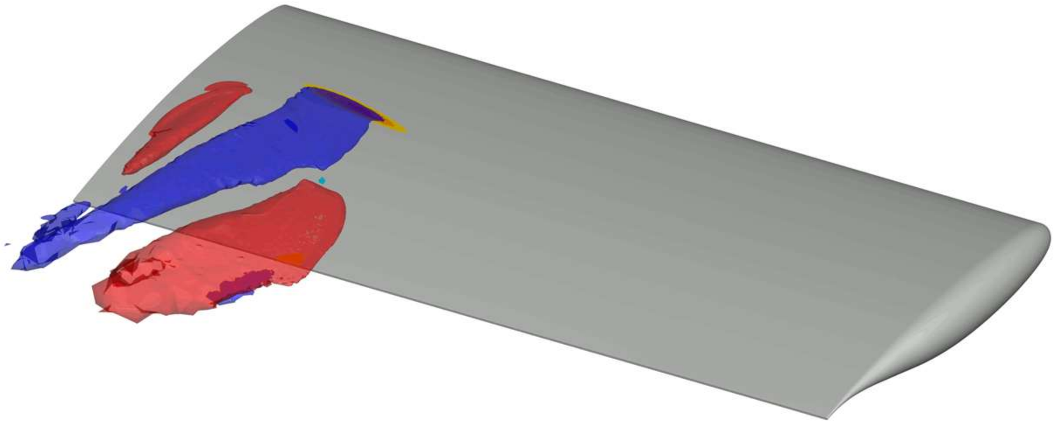
Reference data: Chwalowski et al. 2022

Shock Buffet

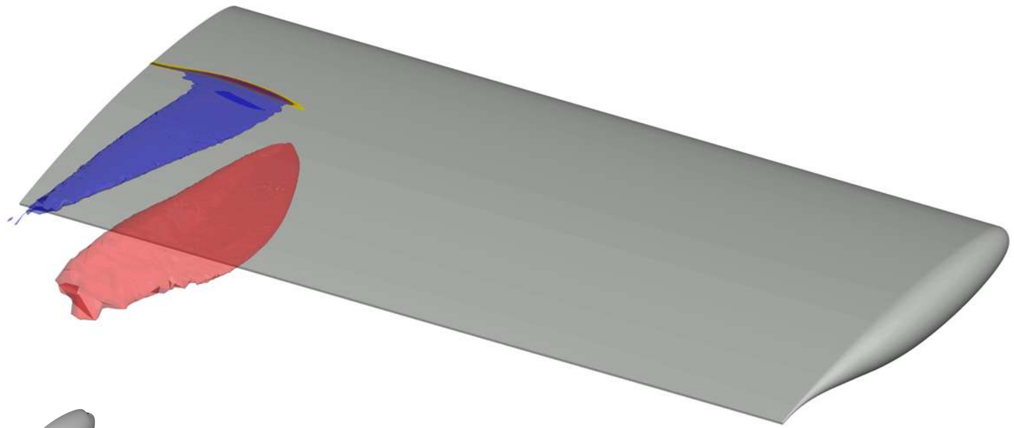
Shock Buffet Mode

(First-order spatial discretisation of turbulent fluxes)

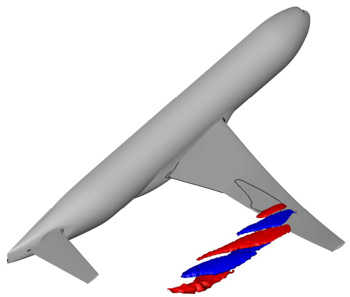
Buffet Mode at $\alpha = 3.5^o$ and flow condition according to $q = 169$ psf with rigid wing.
Surface $\widetilde{C}_p$ and x-momentum iso-surface.



Medium Mesh



Fine Mesh



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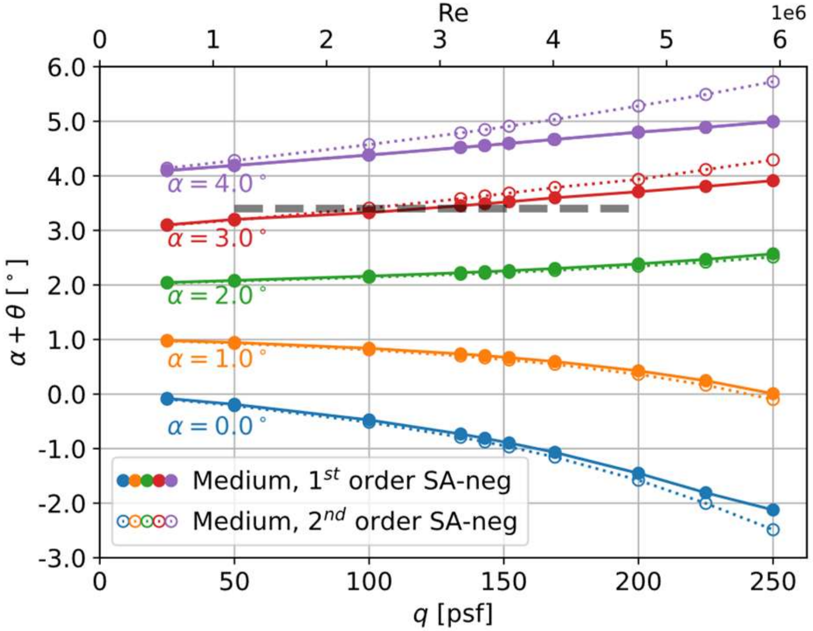
Shock Buffet Mode

Negligible influence of Reynolds number for range tested.

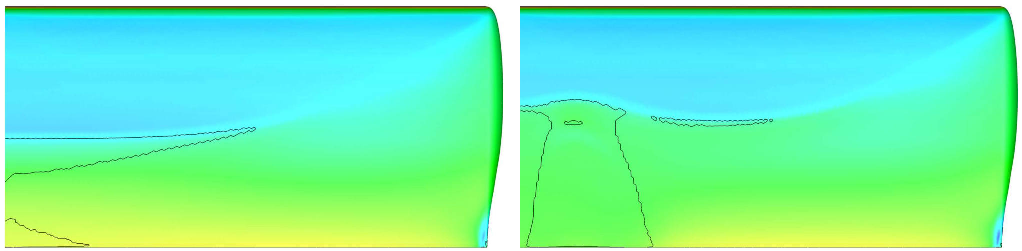
$\alpha = 3.0^o$ could show shock buffet for $q \gtrsim 110$psf.

Distinct curvature of shock where shock buffet is present.

Angle of attack plus pitch over dynamic pressure and Reynolds number



$\alpha = 3.0^o$: $q = 50$ psf $q = 134$ psf



Conclusions

The spatial discretisation of the turbulent convective fluxes is important, primarily where there is strong shock-wave/boundary layer interaction.

At lower angles of attack, our method closely matched the experimental and numerical (mesh-adapted LFD and time-domain) flutter onset points.

Flutter prediction at $\alpha = 3.0^o$, where the wing deforms to more than 3.4^o, was inconclusive, likely due to shock buffet.

Shock buffet was present for the first-order turbulent convective fluxes for $\alpha \gtrsim 3.4^o$.

Outlook

Explore different turbulence models for flutter prediction using a different CFD code:

e.g. second-order turbulence flux discretisation and compressibility correction

Push to higher angles of attack.

Questions?

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