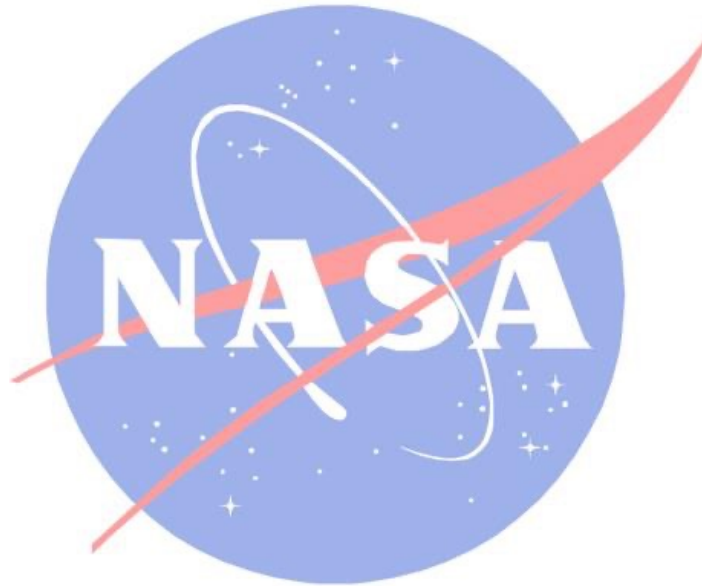




Flutter and Stochastic Gust Constraint Studies of the Undeflected CRM using MPhys



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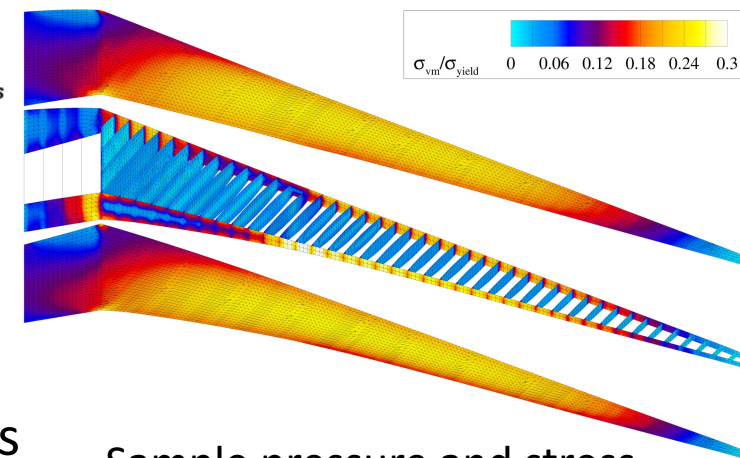
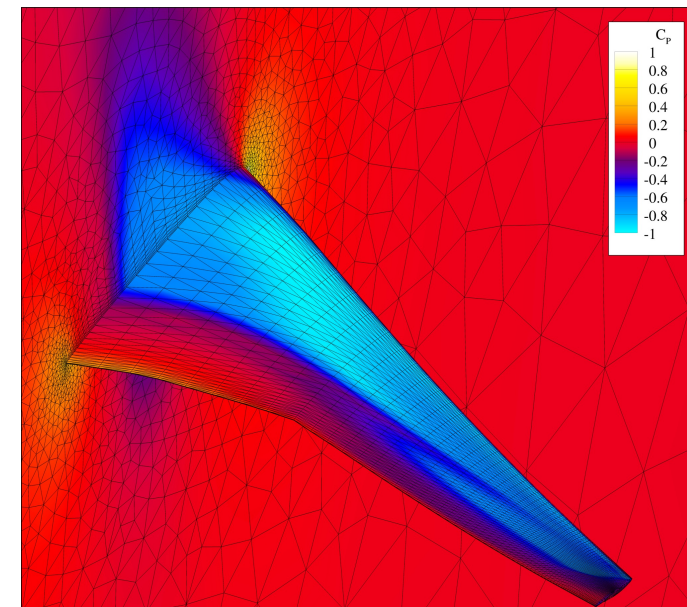
Objective



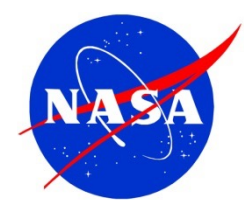
- Stochastic (or continuous) gust constraints have recently been implemented in OpenMDAO/MPhys
 - Important for certification or ride quality
 - Logical continuation of previous MPhys flutter work
 - Panel- or CFD-based aerodynamics via VLM/DLM or FUN3D SFE/LFD
 - Analytic derivatives for gradient-based optimization



- For optimization, current work is limited to:
 - Steady FUN3D Euler (with added empirical profile drag) and unsteady DLM aerodynamics, rather than RANS+LFD
 - Gust constraints based on tip displacement or steady+unsteady root bending moment, rather than stress



Sample pressure and stress



CRM Optimization Problem

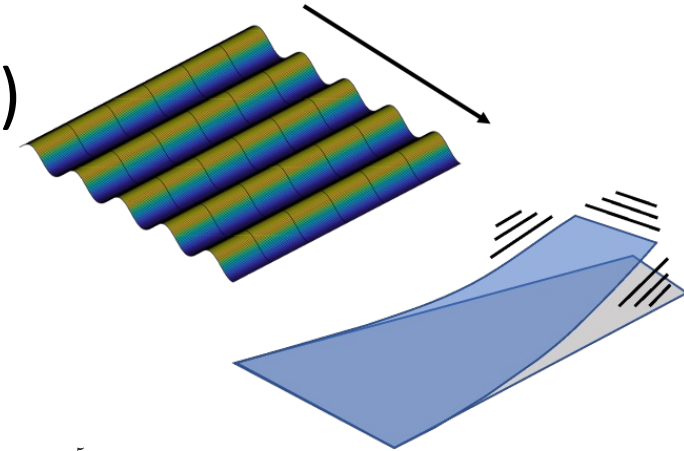


- Two flight conditions based on CRM literature: 1g cruise, 2.5g pull-up
- **737 design variables:** 720 structural, 14 shape, 2 aerodynamic, 1 fuel scaling
- **11-13 constraints:** 2-4 flutter and gust, 1 stress, 8 other mission, consistency, and geometric constraints
- Several problem variations:

Label	Objective(s)	Steady Aerodynamics	Unsteady Aerodynamics	Flutter Constraints	Gust Constraints
1a	FB	VLM	-	0	0
1b	FB	VLM	DLM	2	2 (tip displacement)
2	FB, LGW	VLM	DLM	2	2 (tip displacement)
3a	FB	VLM	DLM	1	1 (root bending moment)
3b	FB	FUN3D Euler	DLM	1	1 (root bending moment)

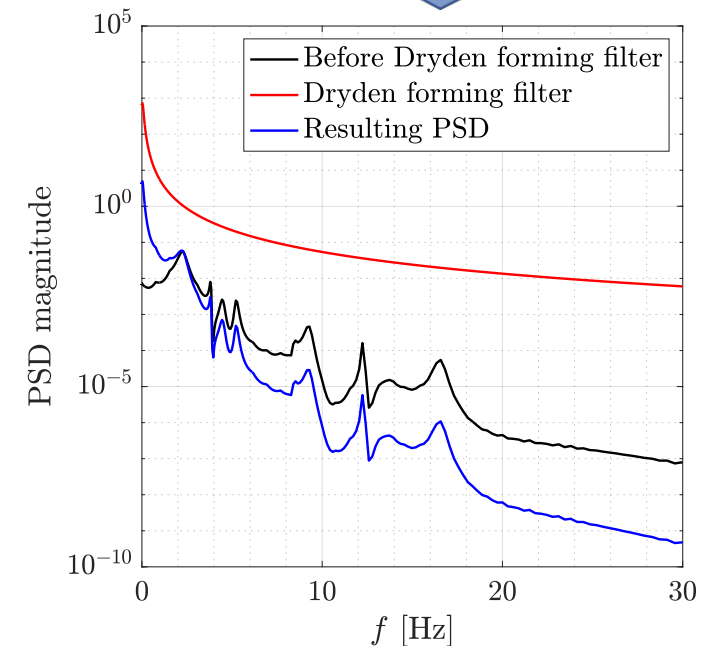
- Structure-on-structure and gust-on-structure GAFs ($\mathbf{Q}$) may be computed by either DLM or FUN3D SFE/LFD:

$$\left(-\omega^2 [\bar{\mathbf{M}}] + i\omega [\bar{\mathbf{C}}] + [\bar{\mathbf{K}}] - q_\infty [\bar{\mathbf{Q}}_{ss}] \right) \{\boldsymbol{\eta}\} = q_\infty \{\bar{\mathbf{Q}}_{gs}\}$$

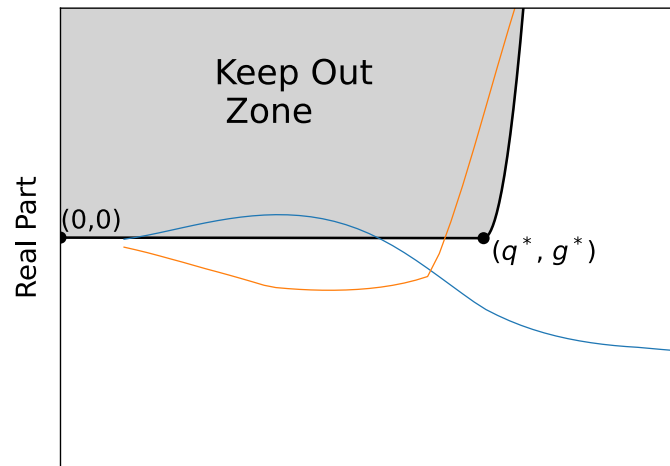


- Gust PSD of a quantity of interest (QOI) is found via
 - $\mathbf{S}$ – QOI induced by unit modal displacements
 - $\boldsymbol{\eta}$ – Complex generalized displacements
 - f – Dryden model of atmospheric velocity perturbations

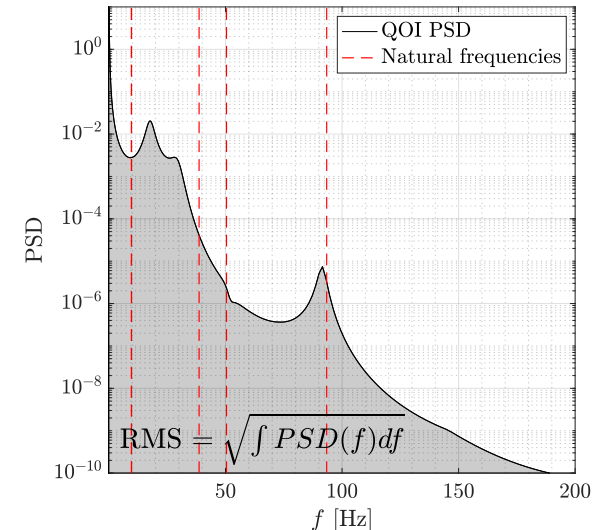
$$PSD(\omega) = |\{\mathbf{S}\}^T \{\boldsymbol{\eta}\}|^2 f_{atm}(\omega)$$



- Flutter is enforced via Kreisselmeier-Steinhauser (KS) damping aggregate
- Gust is enforced using RMS of quantity of interest
 - For tip displacement constraints, RMS must not exceed initial value
 - For root bending moment constraints, steady value is added to DLM-based RMS; limit is based on initial load factors and stress KS

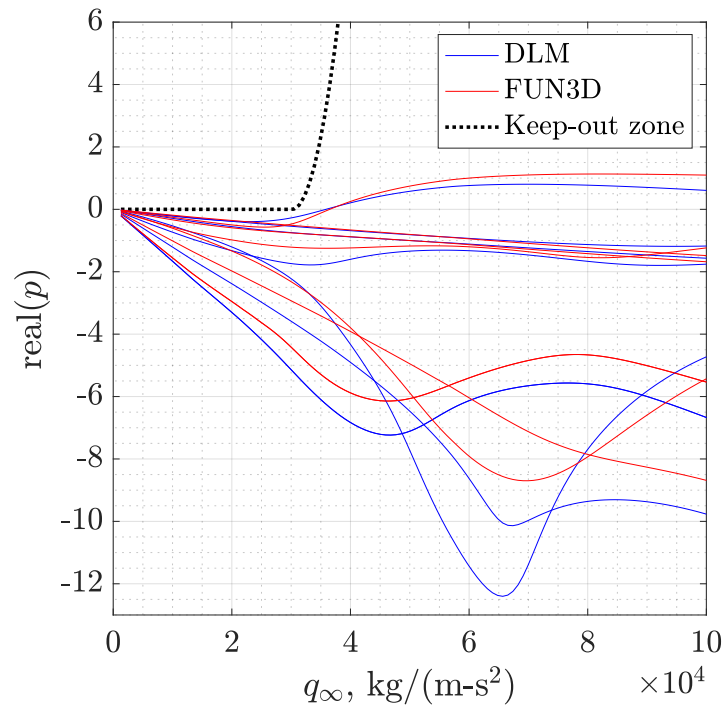


Dynamic Pressure
Notional p - k damping

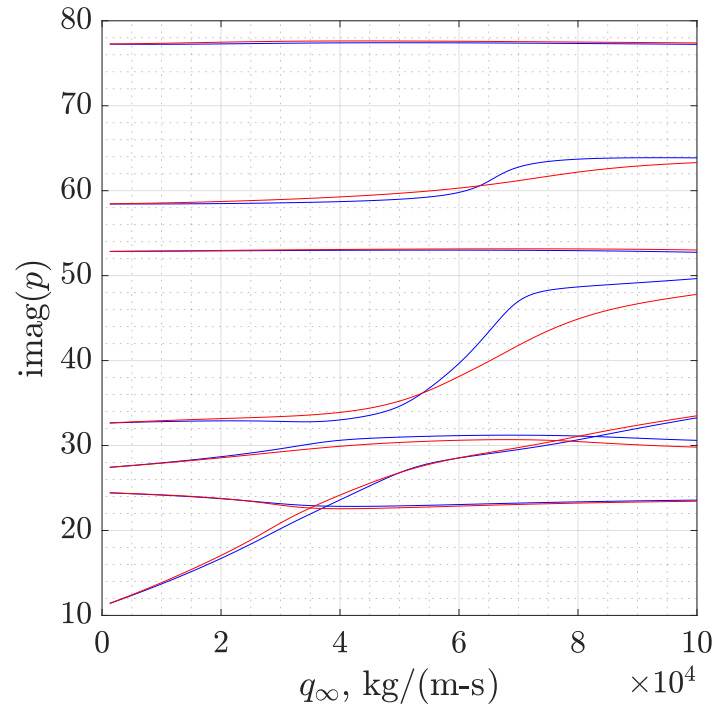


Notional PSD due to gust

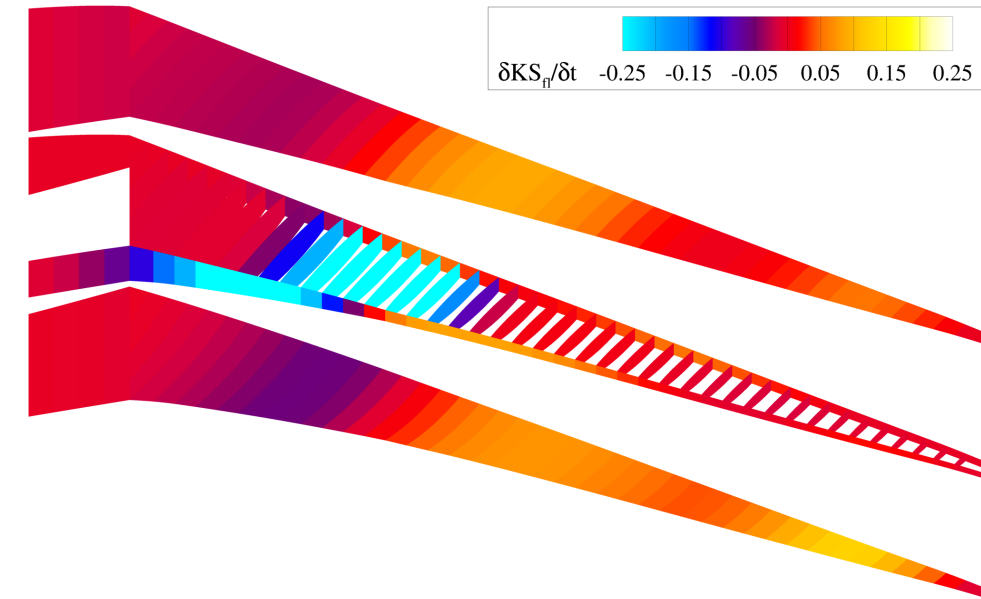
- When using Euler LFD, only shallow transonic dip currently seen; good agreement with DLM



p - k damping



p - k frequency



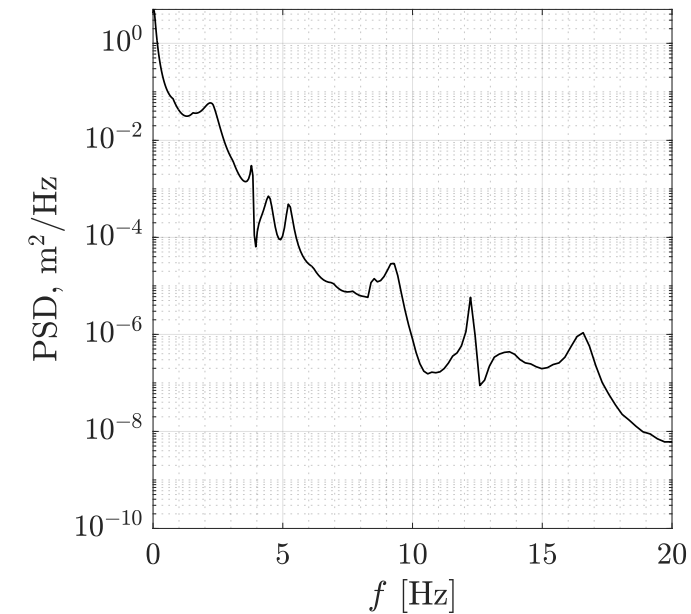
Flutter KS sensitivity wrt thickness design variables (DLM)



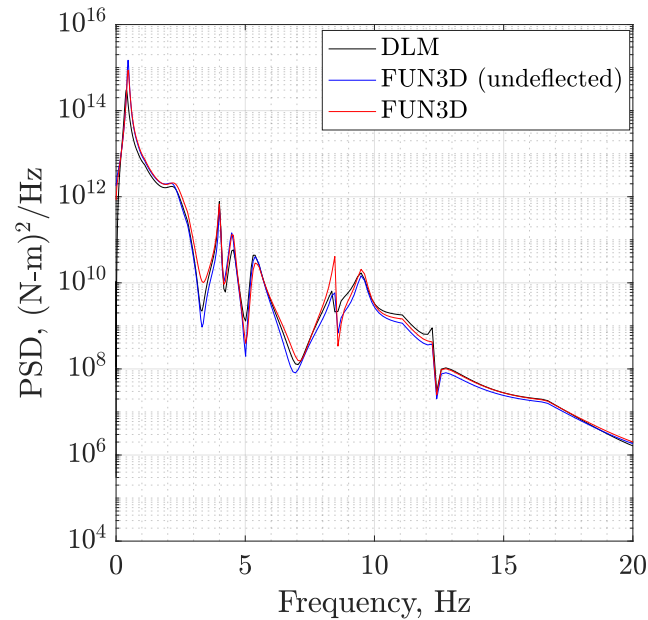
Baseline Gust Responses at Cruise



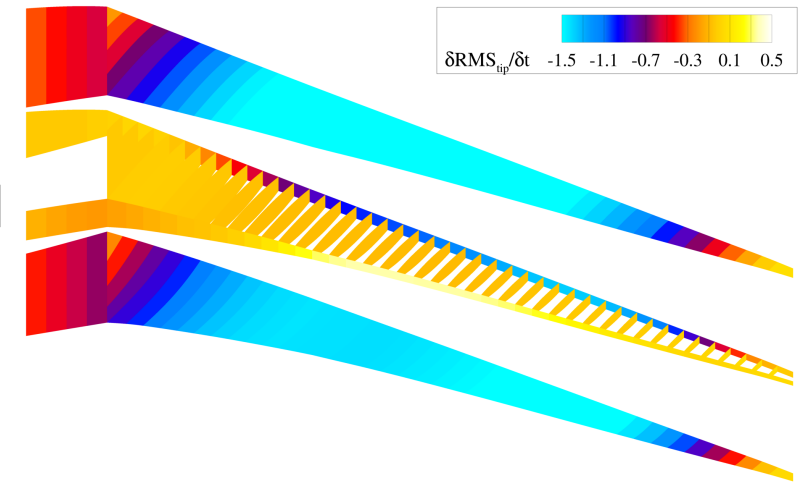
- RMS usually driven by low-frequency response
 - Max often at small non-zero frequency when based on stress/reaction loads **with rigid body modes**
 - Otherwise, max usually at zero frequency



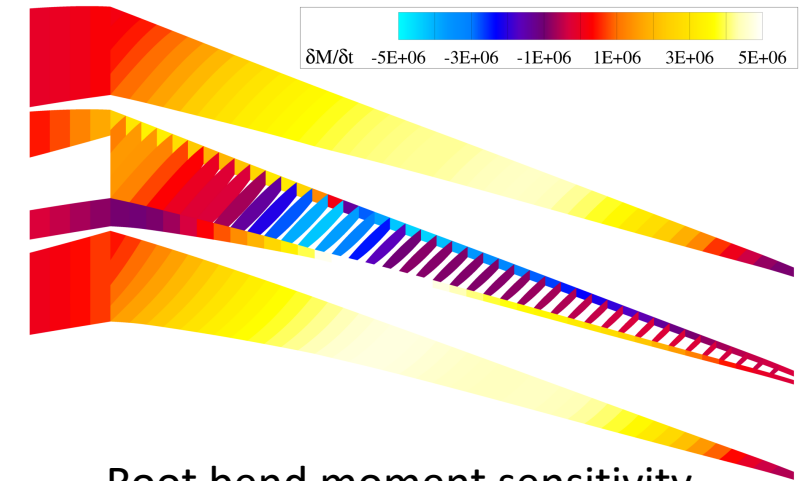
Tip displacement (no rigid body modes)



Root bending moment (rigid body modes)



Tip RMS sensitivity wrt thickness (DLM)



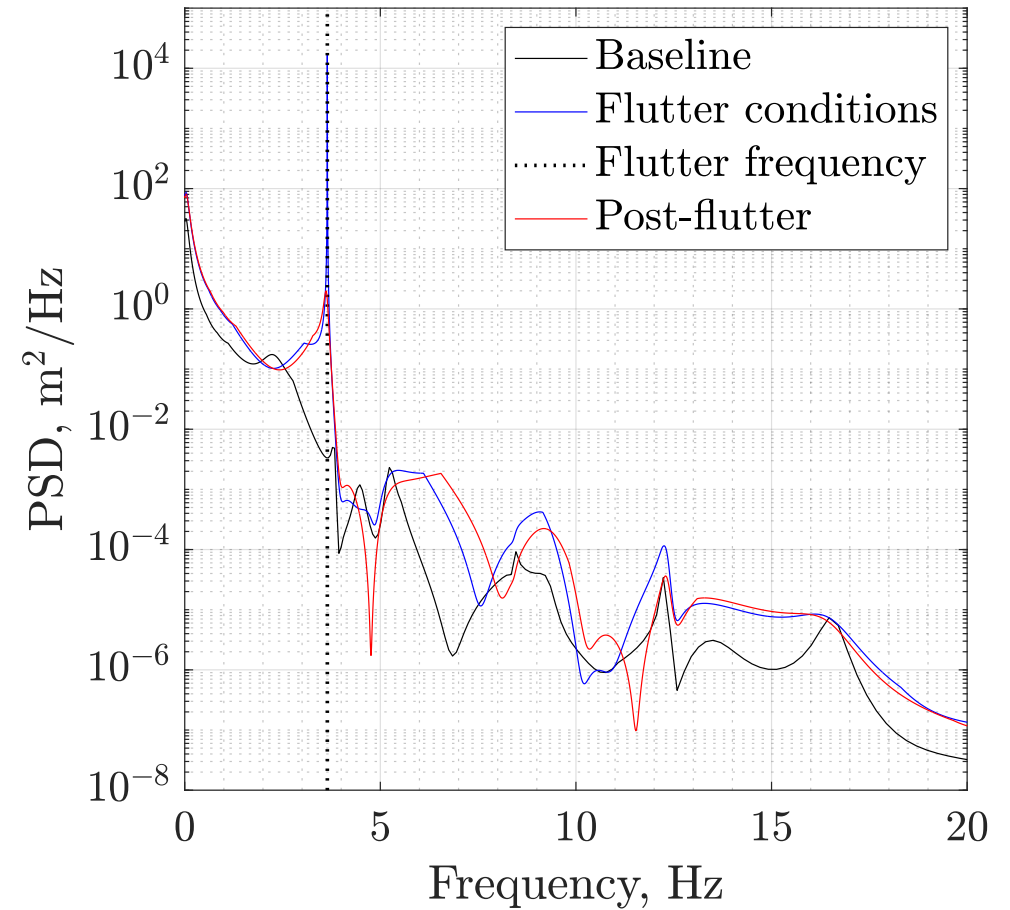
Root bend moment sensitivity wrt thickness (FUN3D+DLM)



Relationship between Gust and Flutter



- With similar equations of motion, flutter and gust responses are somewhat interconnected
- When gust PSD is computed at flutter onset conditions (velocity & density), a peak nearing infinity appears at the flutter frequency
- Peak is at its maximum at flutter onset; post-flutter PSD no longer valid as oscillatory motion is unbounded

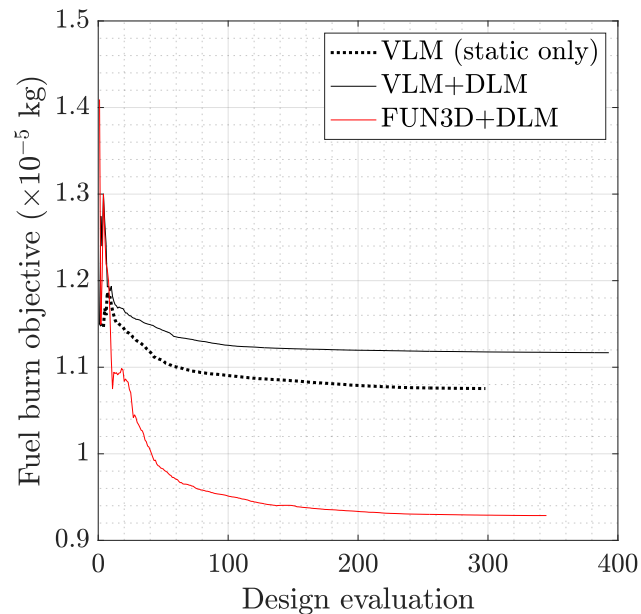




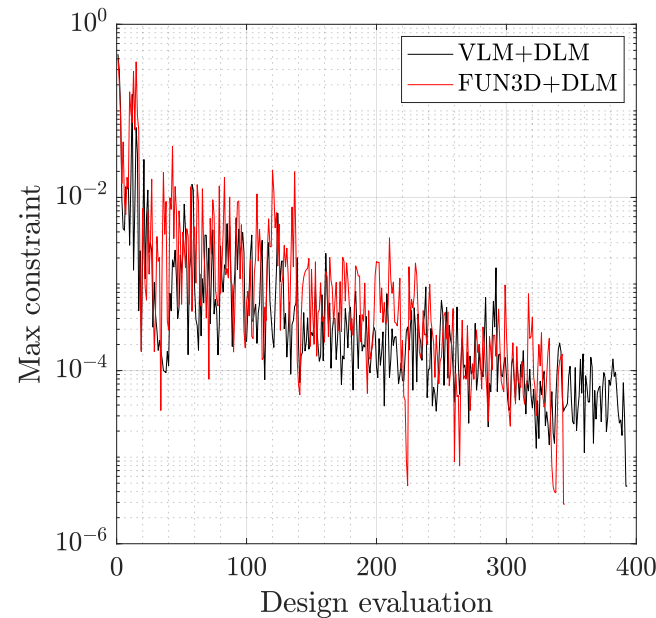
Optimization Convergence



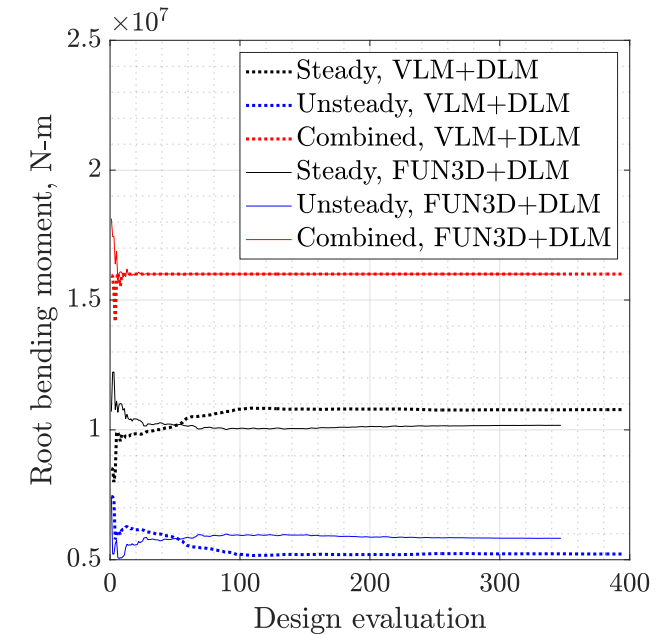
- CFD-based optimization started from VLM-based optimum
 - Ultimately needed similar number of iterations to converge
- Flutter constraint inactive when including gust, but this may change when using LFD aerodynamics



Objective



Max constraint



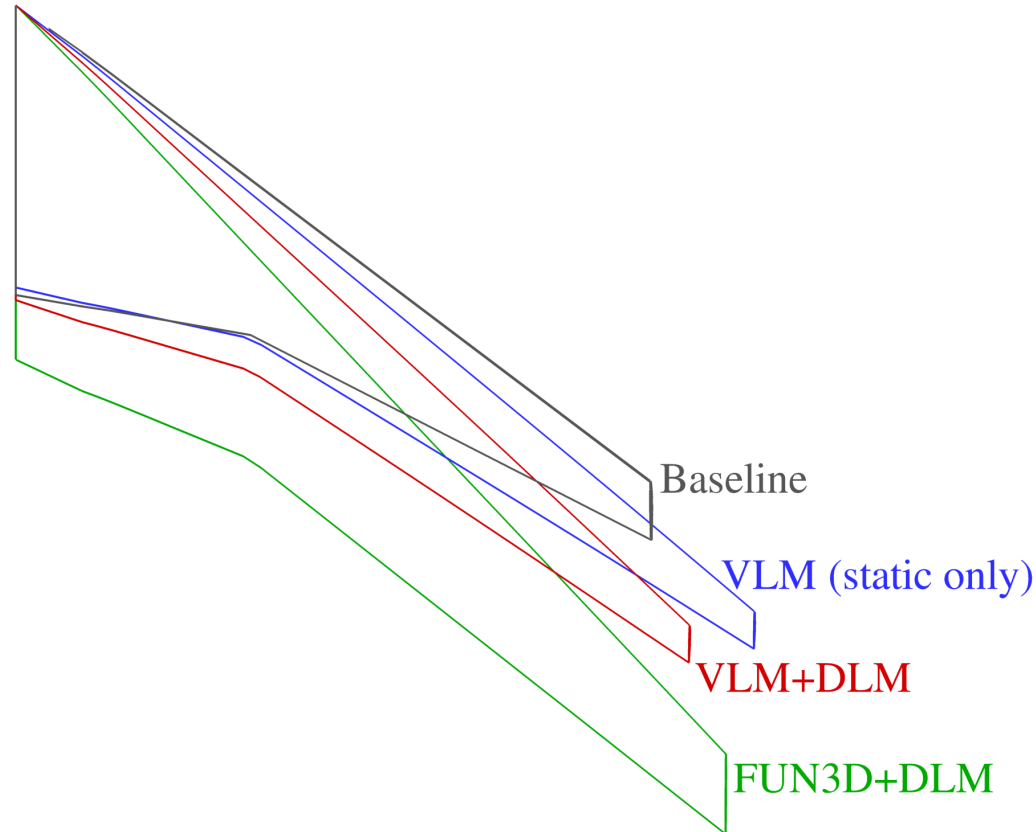
Root bending moment



Resulting planform shapes



- Gust and flutter constraints lead to shorter wing spans
- CFD-based aerodynamics leads to more highly swept wing

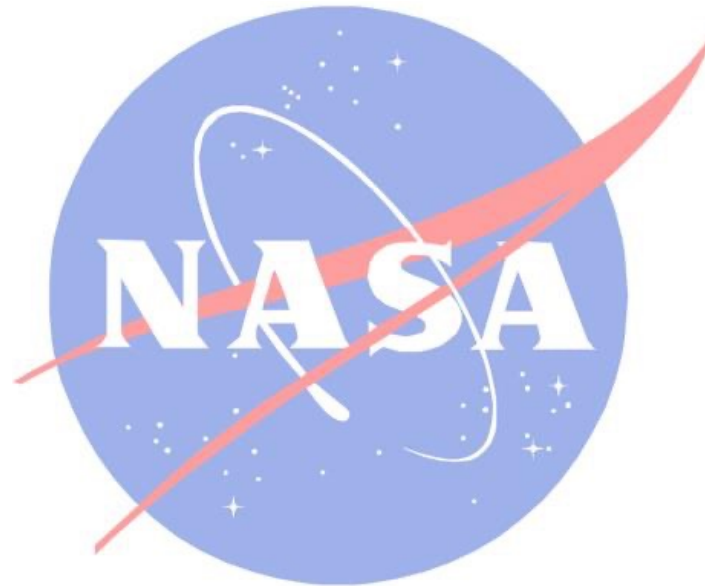
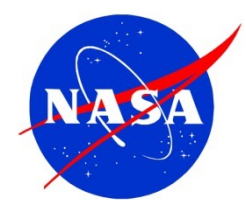




Conclusions and Future Work



- CRM optimization with flutter and stochastic gust constraints has been demonstrated
- Baseline gust and flutter responses have been compared using panel- and CFD-based aerodynamics
- Several areas of growth in MPhys-based analysis chain:
 - Replace DLM with LFD at transonic flight conditions
 - Add more flutter and gust constraints throughout flight envelope, using DLM in subsonic regime
 - Use RANS aerodynamics rather than Euler augmented with empirical profile drag
 - Constrain gust-induced stresses rather than root bending moment
 - Include control surface modeling for gust and maneuver load alleviation
 - Model wing-body-tail rather than wing-only
 - Inclusion of structural damping



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CRM Optimization Problem



- Two flight conditions based on CRM literature: 1g cruise, 2.5g pull-up
- **737 design variables:** 720 structural, 14 shape, 2 aerodynamic, 1 fuel scaling
- **11-13 constraints:** 2-4 flutter and gust, 1 stress, 8 other mission, consistency, and geometric constraints
- Several problem variations:

	Description	Specification	Quantity
minimize:	Cruise fuel burn		
with respect to:	Root chord differential	$\in [-3, 3]$ m	1
	Tip chord differential	$\in [-1, 1]$ m	1
	Span differential	$\in [-10, 10]$ m	1
	Sweep differential	$\in [-10, 10]$ deg	1
	Wing thickness	$t_{wing} \geq 0.5 \times t_{wing,0}$	5
	Wing twist differential	$\in [-10, 10]$ deg	5
	Fuel scaler	$\in [0, 1]$	1
	Shell thickness	$\in [0.003, 0.03]$ m	240
	Stiffener thickness	$\in [0.003, 0.03]$ m	240
	Stiffener height	$\in [0.03, 0.15]$ m	240
	Static angle of attack	$\in [-10, 10]$ deg	2
	Total		737
subject to:	Fuel mismatch	$= 0$	1
	Static load factor	$\eta = [1, 2.5]^T$	2
	Wing area	$A \geq 205.8 \text{ m}^2$	1
	Available fuel mass	$\geq 63,464.28$	1
	Trailing edge spar depth	≥ 0.19 m	1
	Stiffener aspect ratio	$KS_{AR} \leq 1$	1
	Stiffener vs. shell thickness	$KS_{t/t_s} \leq 1$	1
	Pull-up stress	$1.5KS_{\sigma} \leq 1$	1
	Flutter	$KS_{fl} \leq 0$	1-2
	Gust	Varies	1-2
	Total		11-13

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Resulting planform shapes



- FUN3D cases without empirical profile drag (red and green) show similar result: gust/flutter constraints reduce wing span
- Adding empirical drag (purple) increases tip chord length

