Aeroelastic Tailoring Study of an N+2 Low-boom Supersonic Commercial Transport Aircraft

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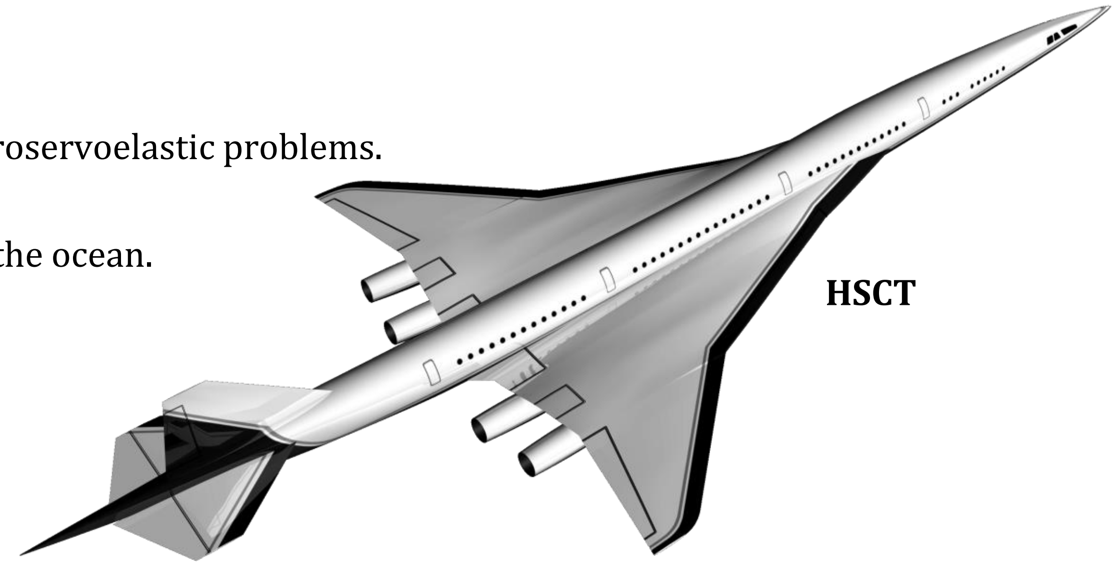
Overview

- Supersonic Commercial Transport Aircraft Design
- Game Change Approach in Aircraft Design
- Multidisciplinary Design Optimization tool
- Multidisciplinary Analysis of the Baseline Configuration
    - Structural and Aerodynamic Models
    - Modal Analyses
    - Flutter Analyses
    - Trim Analyses
    - Landing and Ground Control Loads
    - Buckling and Strength Analyses
- First Optimization Run
- Second Optimization Run
- Third Optimization Run
- Conclusions
- Future Studies

Supersonic Commercial Transport Aircraft Design

- Major Issues
  - Safety
    - Light weight airframe can cause strength, buckling, aeroelastic, and aeroservoelastic problems.
  - Sonic boom
    - Supersonic flight of "commercial transport" aircraft allowed only over the ocean.
    - Perceived Loudness in decibels
      - ✓ NASA's N+2 goal: 85 PLdB
      - ✓ Concorde: 104 PLdB
      - ✓ High Speed Civil Transport (HSCT): 99 PLdB
  - Fuel efficiency
    - Light weight airframe
    - Reduced drag
- Developing N+2 Low-boom Supersonic Commercial Transport (LSCT) aircraft
  - Boeing
  - **Lockheed Martin: 79 PLdB**
  - Gulf Stream
  - Aerion with "Airbus"



HSCT

Lockheed Martin

Concorde

Boeing

Gulf Stream

Aerion

Game Change Approach in Aircraft Design

Problem Statement

- ❑ Design innovations are needed to further down the weight of an aircraft which current design technologies can take care of.

Long Term Objective

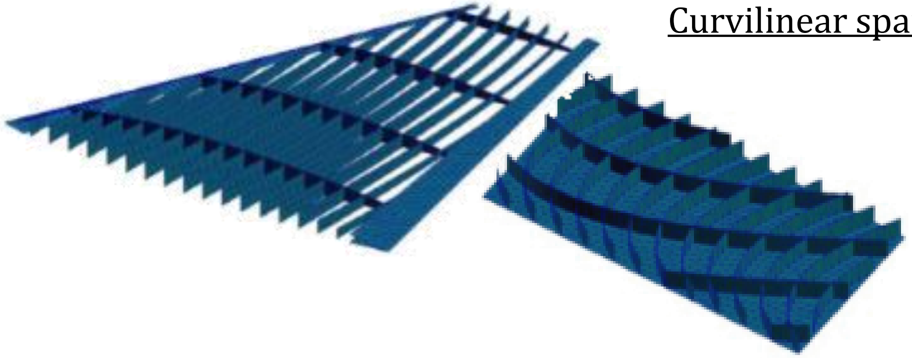
- ❑ Use aeroelastic tailoring theory and active flexible motion control technique to satisfy the overall strain, aeroelastic, and aeroservoelastic instability requirements within given flight envelopes
- ❑ Use curvilinear sparib concept as well as composite ply angles for aeroelastic tailoring

Approach

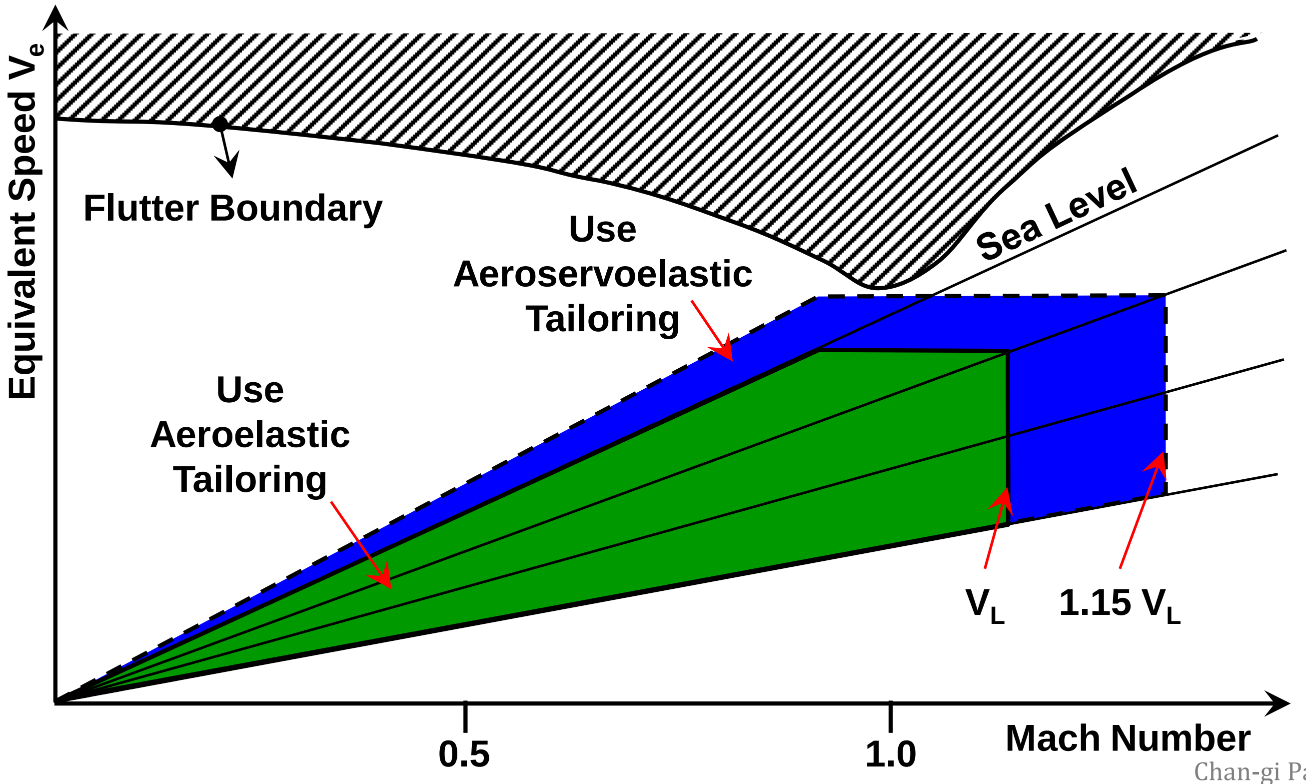
- ❑ Simultaneously update structural as well as control design variables during early design phase
  - ❖ Perform topology optimization with curvilinear sparibs
  - ❖ Use aeroelastic tailoring up to V_L
  - ❖ Use aeroservoelastic tailoring between V_L and 1.15 V_L

Current Study

- ❑ Optimize baseline aircraft model
  - ❖ Use Lockheed Martin's configuration
  - ❖ Use aeroelastic tailoring up to 1.15 V_L

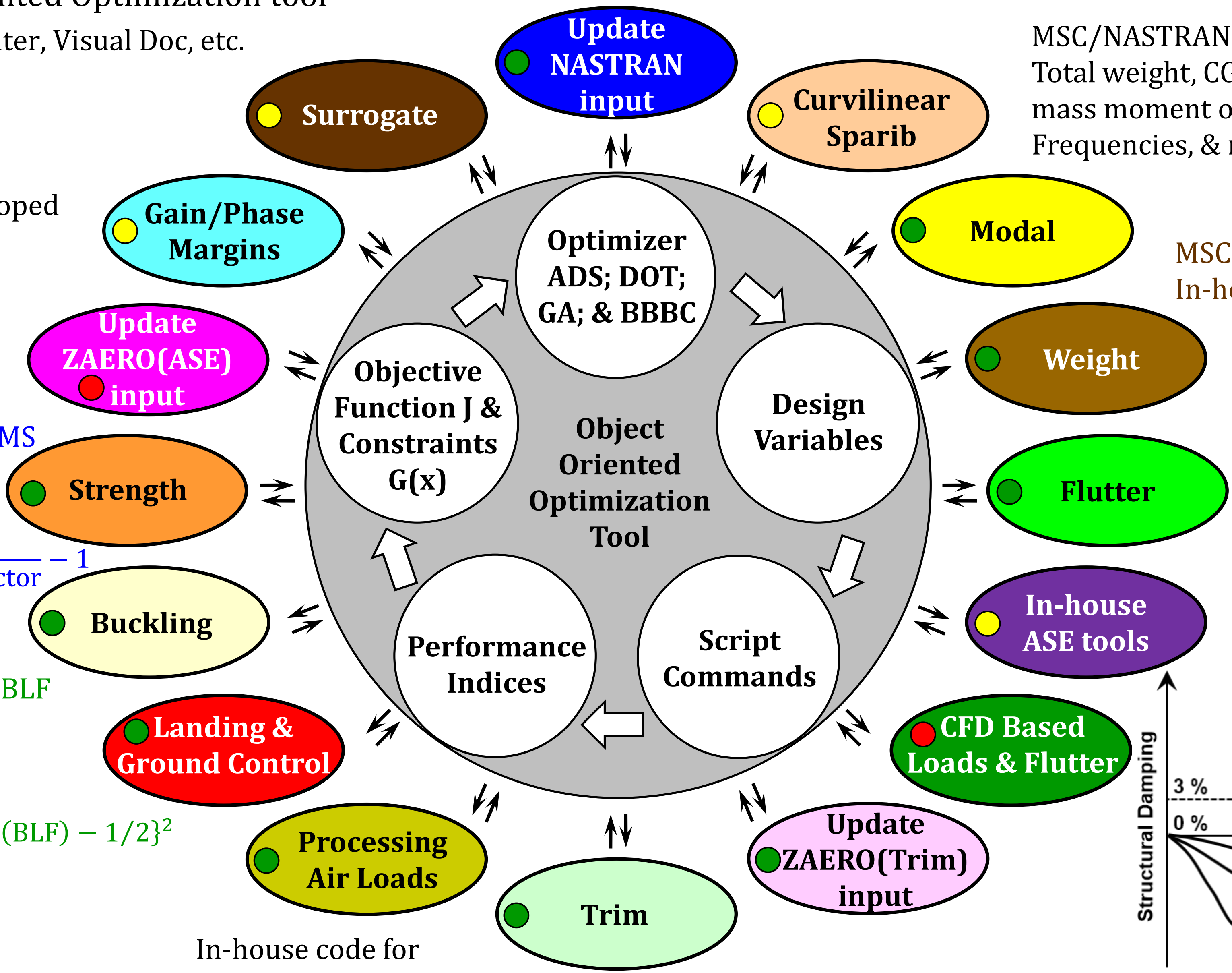


Curvilinear sparibs



Multidisciplinary Design Optimization tool

- ❑ Based on Object-Oriented Optimization tool
  - ❖ Open MDAO, Model Center, Visual Doc, etc.



🟢 : Incorporated
🟡 : Modules are being developed
🔴 : Not included yet

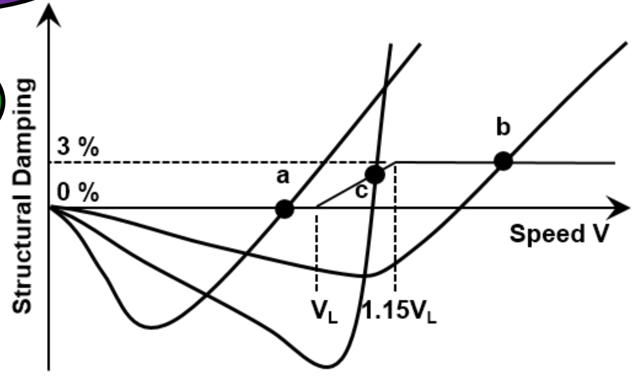
MSC/NASTRAN sol 103
Total weight, CG location, mass moment of inertia, Frequencies, & mode shapes

MSC/NASTRAN for small weight
In-house code for large weight

$$PI_W = W_T$$

ZAERO code for flutter analyses
In-house code for flutter speed tracking

$$PI_F \equiv 1 - \frac{V_F}{1.15V_L}$$



MSC/NASTRAN sol 105
In-house code for computing MS
Use safety factor of 1.5

$$MS \equiv \frac{\text{Failure Load}}{\text{Design Load} \times \text{Safety Factor}} - 1$$

$$PI_s \equiv -\min(MS)$$

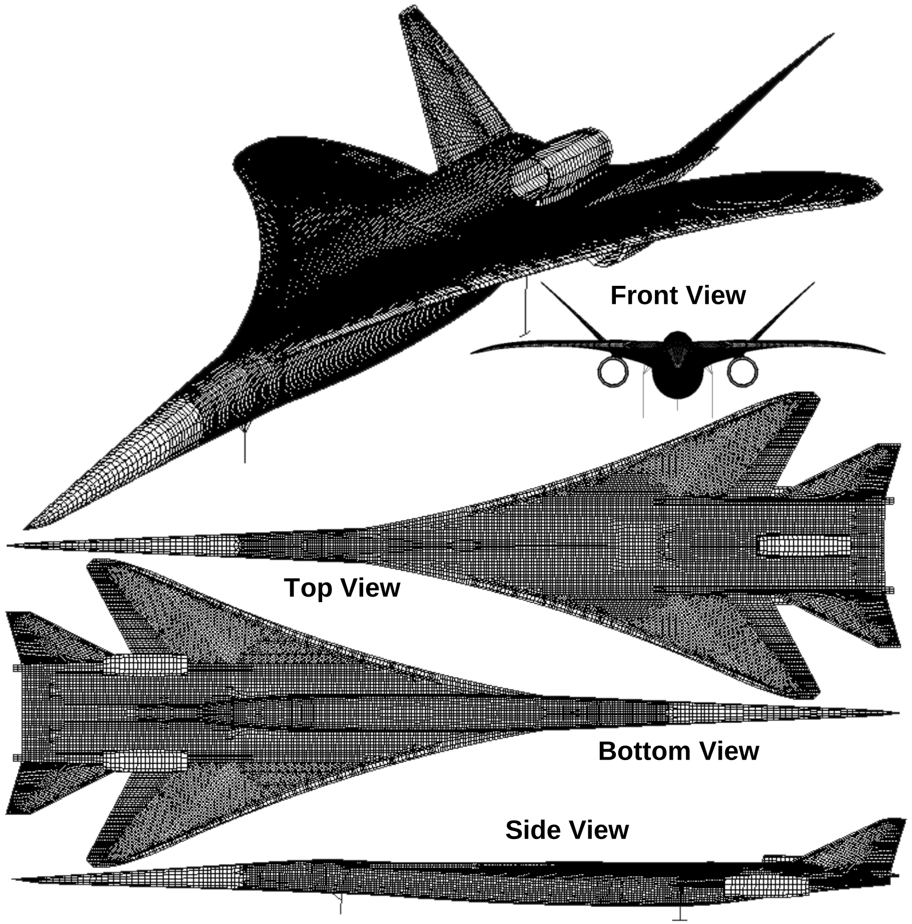
In-house code for computing BLF
Use safety factor of 1.5

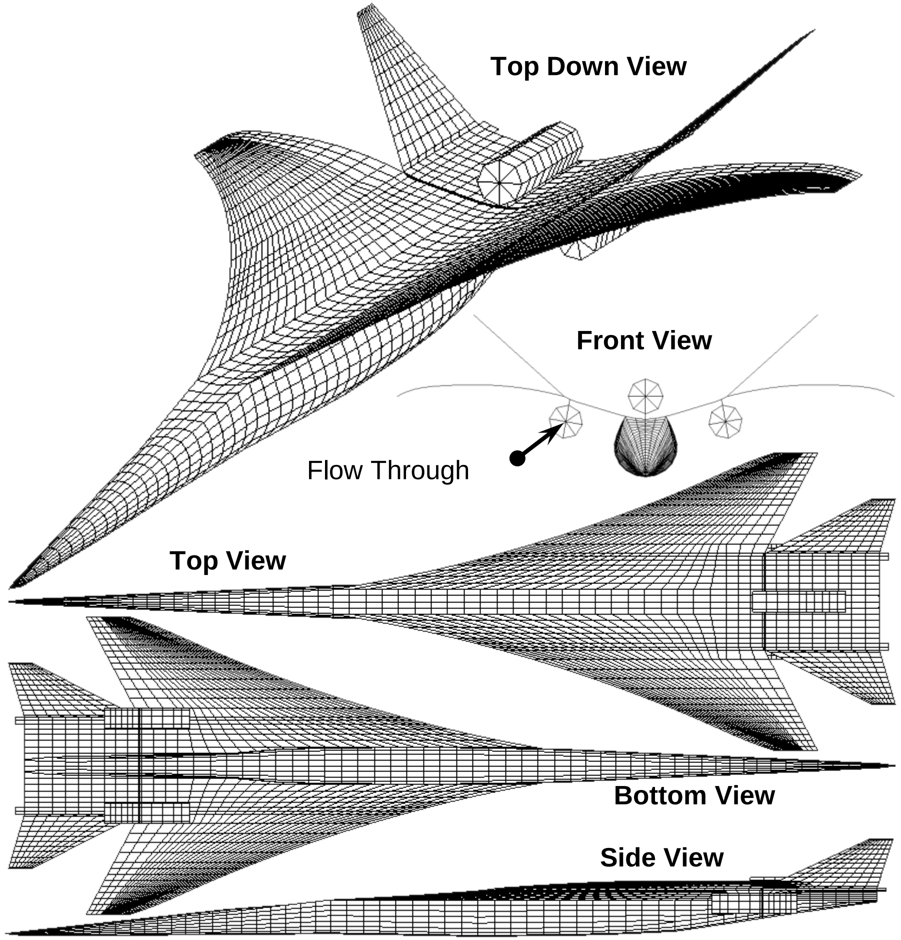
$$PI_B \equiv (1/2)^2 - \{\text{positive}\ \min(BLF) - 1/2\}^2$$

In-house code for massaging splined loads

Multidisciplinary Analysis of the Baseline Configuration

Structural and Aerodynamic Models





- MSC/NASTRAN structural model
  - Total number of grids: 55,635
- ZAERO unsteady aerodynamic model
  - 5,060 surface elements
  - Six Mach numbers: 0.66, 0.89, 1.41, 1.80, 2.00, and 2.30
  - Sixteen reduced frequencies: 0., 0.005, 0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.65, 0.80, 1.0

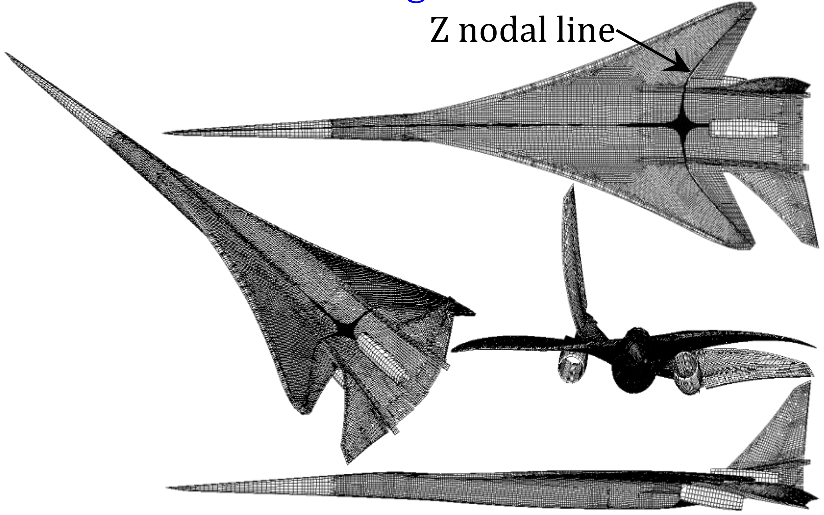
Modal Analyses of the Baseline Configuration

- Based on six configurations
  - Gear up
    - DTOW(Design Take Off Weight), FFEP(Full Fuel Empty Payload), M2W(Mach 2 Weight), & ZFW(Zero Fuel Weight)
      - ✓ DTOW=FFFP (Full Fuel Full Payload)
      - ✓ ZFW=EFFP (Empty Fuel Full Payload)
  - Gear down
    - DTOW(or FFFP) and DLW(Design Landing Weight)

Mode Number	Natural Frequency (Hz)						Notes
	Gear-up				Gear-down		
	DTOW	FFEP	M2W	ZFW	DTOW	DLW	
7	2.049	2.055	2.071	2.266	2.048	2.158	Aft fuselage torsion
8	2.235	2.262	2.277	2.554	2.238	2.424	First symmetric fuselage bending
9	2.498	2.509	2.539	2.993	2.503	2.714	First symmetric wing bending
10	2.754	2.769	2.935	3.415	2.752	3.265	First anti-symmetric wing bending
11	3.060	3.069	3.115	3.731	3.057	3.403	Symmetric tail bending
12	3.562	3.608	3.689	4.044	3.574	3.945	Forward fuselage lateral bending
13	4.440	4.449	4.511	4.790	4.429	4.602	First anti-symmetric tail bending
14	4.456	4.537	4.555	5.532	4.437	5.142	Second symmetric wing bending
15	4.818	4.842	5.146	5.832	4.809	5.542	Second anti-symmetric wing bending
16	5.449	5.465	5.550	6.158	5.444	5.994	Symmetric aft inner wing bending

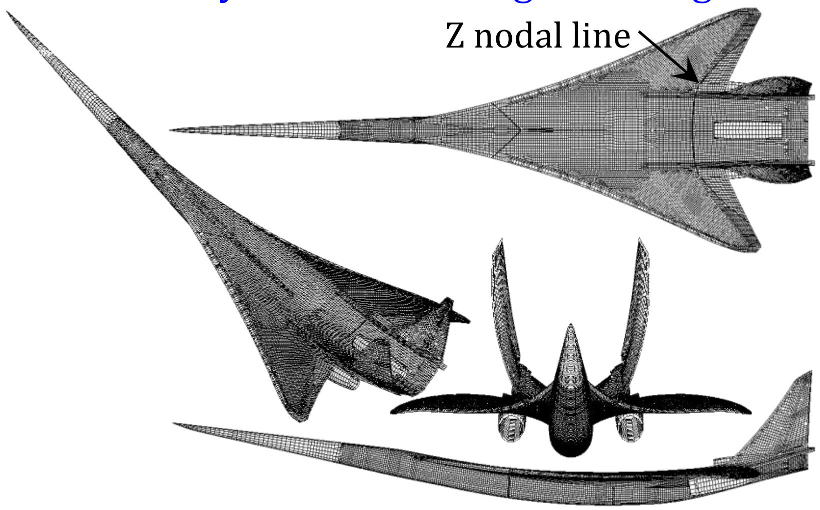
Flexible Mode Shapes (gear up: DTOW)

Aft fuselage torsion



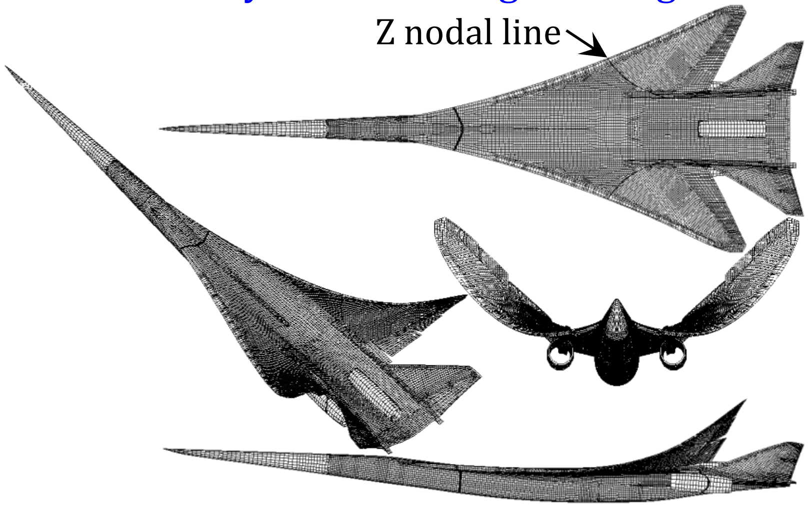
1^{st} Mode: 2.049 Hz

First symmetric fuselage bending



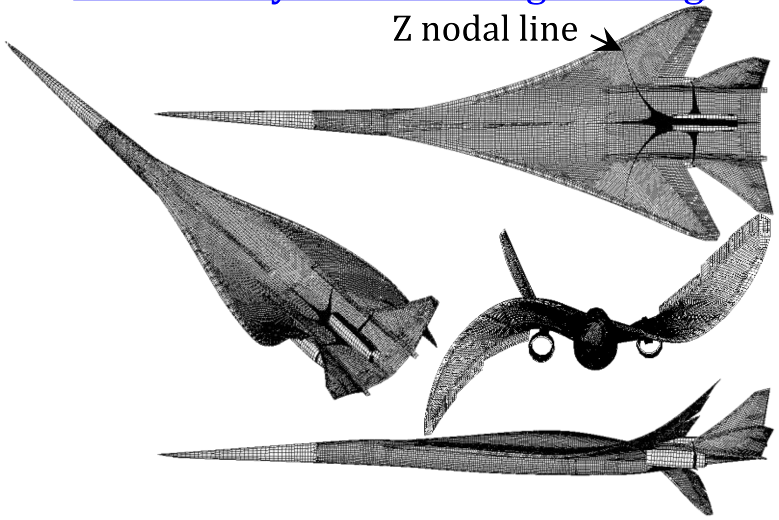
2^{nd} Mode: 2.235 Hz

First symmetric wing bending



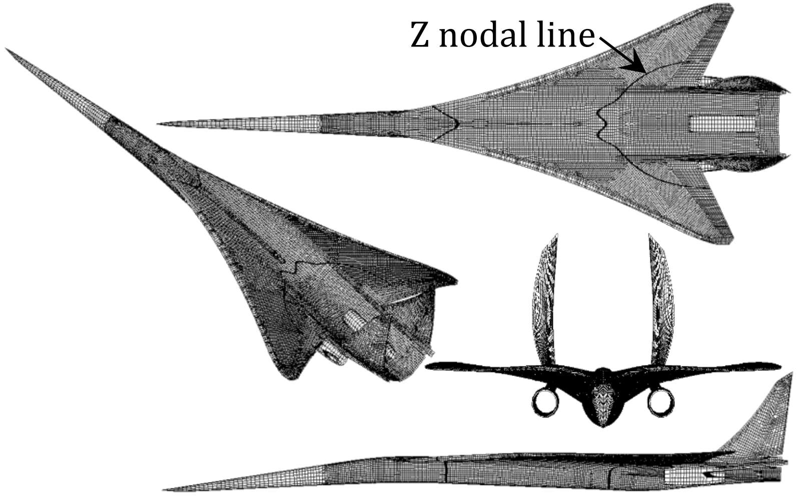
3^{rd} Mode: 2.498 Hz

First anti-symmetric wing bending



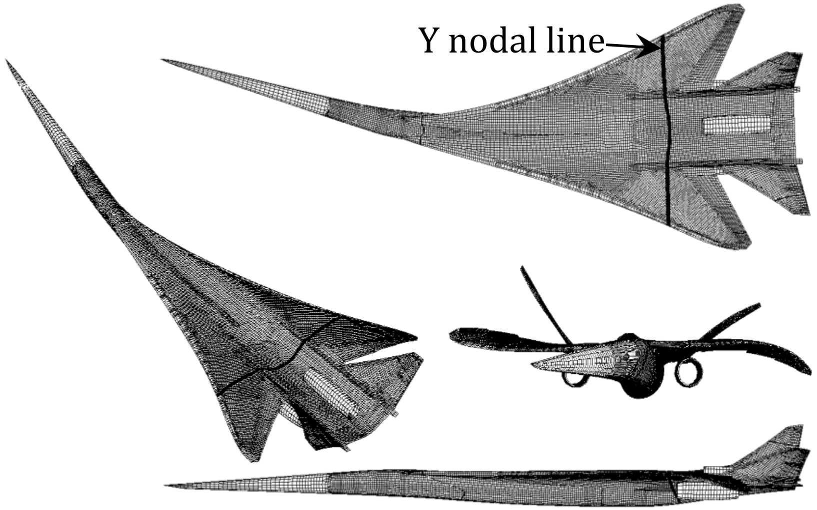
4^{th} Mode: 2.754 Hz

Symmetric tail bending



5^{th} Mode: 3.060 Hz

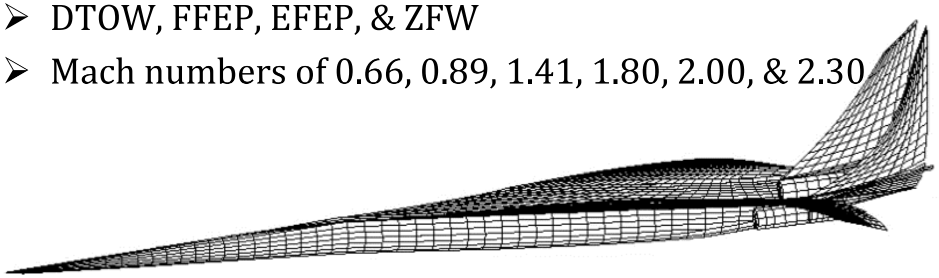
Forward fuselage lateral bending



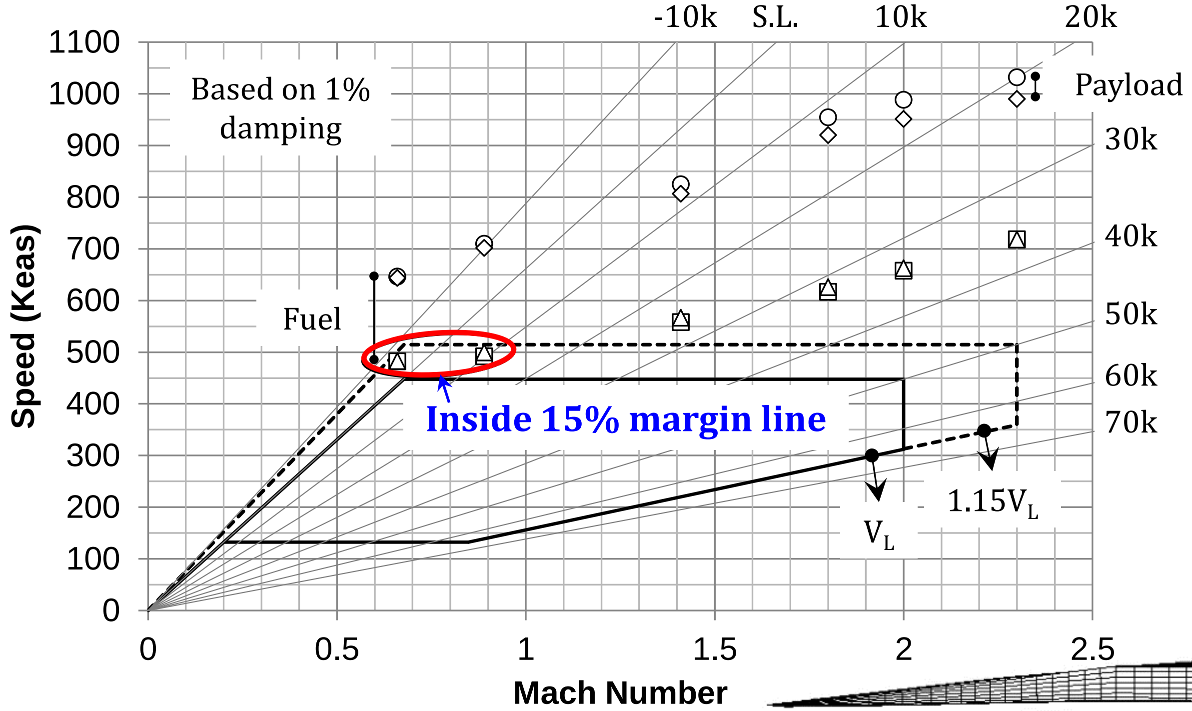
6^{th} Mode: 3.562 Hz

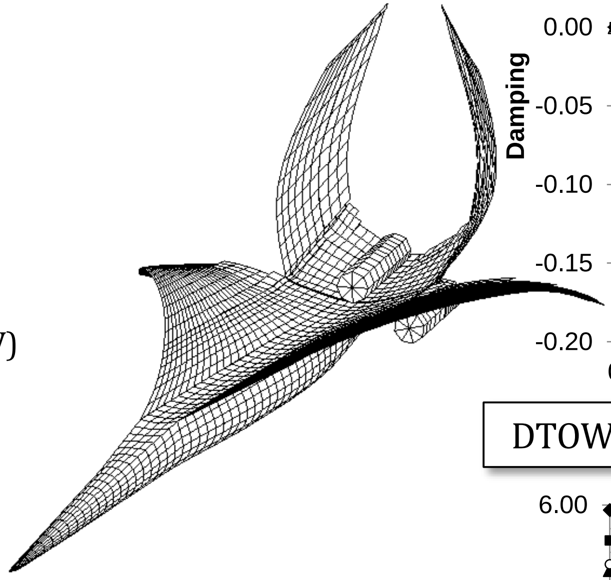
Flutter Analyses of the Baseline Configuration

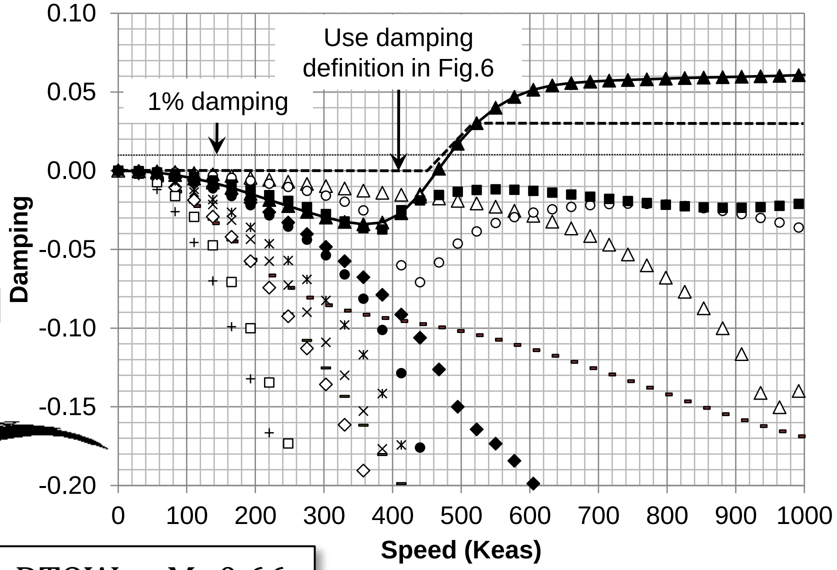
- Based on four structural configurations at six Mach numbers
  - Gear up
    - DTOW, FFEP, EFEP, & ZFW
    - Mach numbers of 0.66, 0.89, 1.41, 1.80, 2.00, & 2.30



○ : Empty Fuel Empty Payload (EFEP) △ : Full Fuel Empty Payload (FFEP)
◇: Zero Fuel Weight (ZLW) □ : Design Take-Off Weight (DTOW)

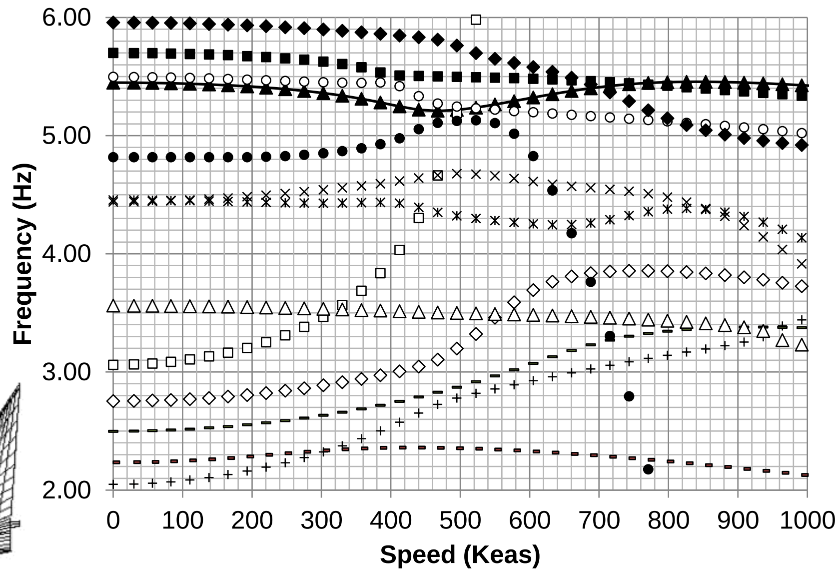




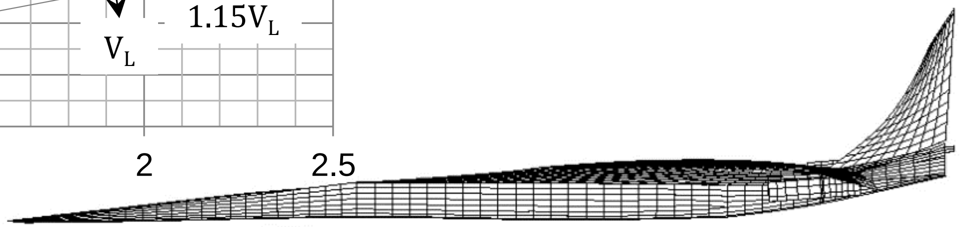


DTOW at M=0.66

(a) V-g Curves



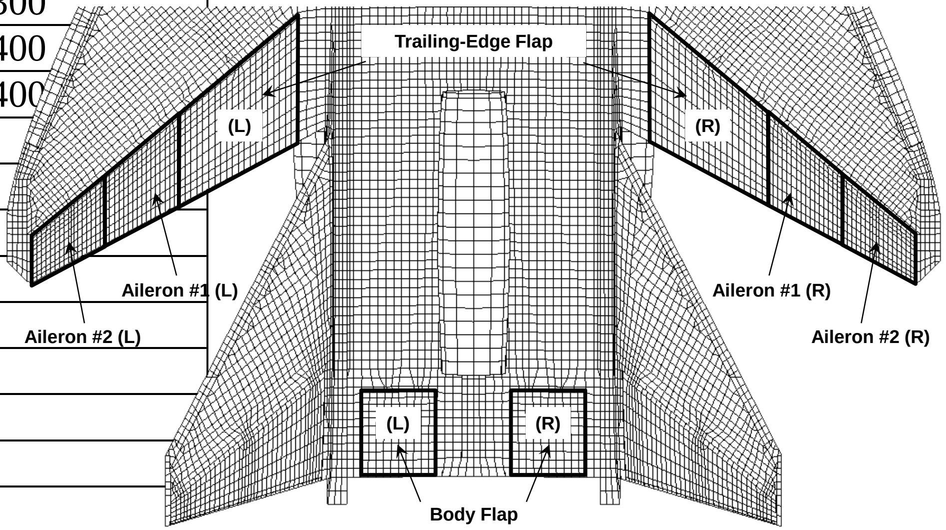
(b) V-f Curves



Trim Analyses of the Baseline Configuration

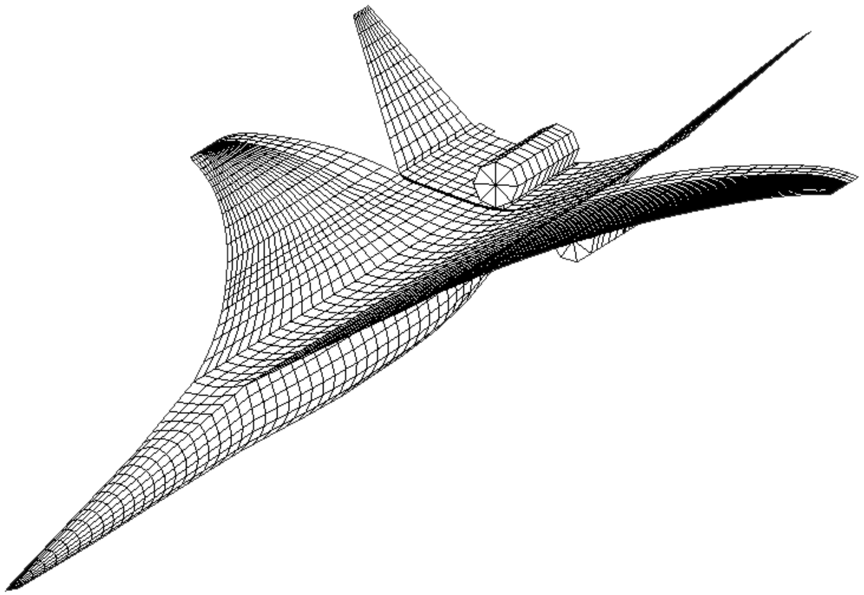
- Trim flight conditions

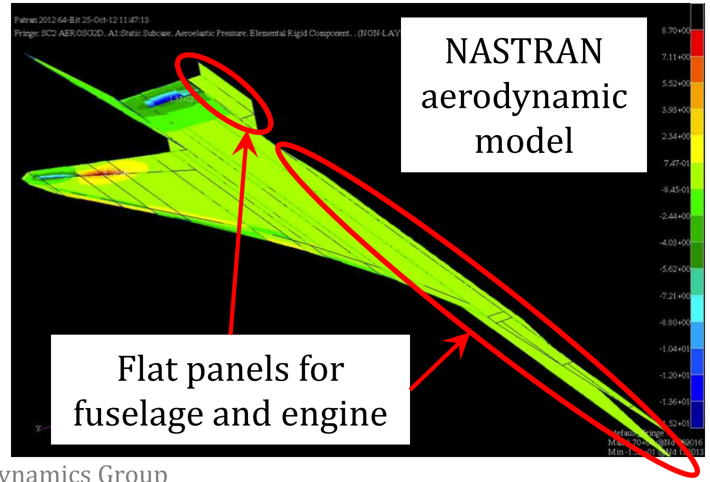
Load Case ID	Maneuver	Load Factor	Mach Number	Weight	Landing Gear	Altitude	Trim Variables
100	Pull up	2.5g	0.66	DTOW	Up	SL	BF(R=L)
200	Push over	-1g	0.66	DTOW	Up	SL	BF(R=L)
300	Pull up	2.5g	0.48	DTOW	Up	SL	BF(R=L)
400	Pull up	2.5g	2.00	M2W	Up	49,770ft	BF=TEF(R=L)
500	Push over	-1g	2.00	M2W	Up	49,770ft	BF(R=L)
600	Pull up	2.5g	1.41	DTOW	Up	49,770ft	BF=TEF=AIL1=AIL2(R=L)
700	Pull up	2.5g	0.66	ZFW	Up	SL	BF(R=L)
800	Push over	-1g	0.66	ZFW	Up	SL	BF(R=L)
900	Pull up	2.5g	2.00	ZFW	Up	49,770ft	BF=TEF(R=L)
1000	Push over	-1g	2.00	ZFW	Up	49,770ft	BF(R=L)
1100	Steady roll	0g	0.48	DTOW	Up	SL	Load Case 2100+2300
1200	Abrupt roll	0g	0.48	DTOW	Up	SL	Load Case 2200+2300
1300	Steady roll	1.67g	0.48	DTOW	Up	SL	Load Case 2100+2400
1400	Abrupt roll	1.67g	0.48	DTOW	Up	SL	Load Case 2200+2400
1500	Landing	1g	0.3092	DTOW	Down	SL	BF(R=L)
1600	Cruise	1g	1.80	DTOW	Up	55,000ft	BF=TEF(R=L)
1700	Gust Loads	2.7g	0.89	ZFW	Up	20,000ft	BF(R=L)
1800	Landing	1g	0.3092	DLW	Down	SL	BF(R=L)
2100	Steady roll	0g	0.48	DTOW	Up	SL	AIL1=AIL2(R=-L)
2200	Abrupt roll	0g	0.48	DTOW	Up	SL	AIL1=AIL2(R=-L)
2300	Pull up	0g	0.48	DTOW	Up	SL	BF(R=L)
2400	Pull up	1.67g	0.48	DTOW	Up	SL	BF(R=L)



Trim Analyses of the Baseline Configuration (continue)

- Trim results
  - In general trim angles are larger than NASTRAN results.





Load Case	100	200	300	400	500	600	700	800	900
Trim Analysis	Symmetric								
Nx (G)	-0.007	-0.003	-0.005	0.001	0.002	-0.004	-0.016	-0.006	0.003
Nz (G)	2.5	-1.0	2.5	2.5	-1.0	2.5	2.5	-1.0	2.5
Pdot (rad/s^2/g)	None	None	None	None	None	None	None	None	None
Qdot (rad/s^2/g)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pb/2V (rad)	None	None	None	None	None	None	None	None	None
Qc/2V (rad)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
α (°)	7.75	-2.50	14.37	8.32	-2.81	16.90	4.10	-1.04	5.07
Body Flap (°)	2.01	-6.07	6.12	-5.25	5.42	-25.68	-8.01	-1.59	-12.9
Trailing-Edge Flap (°)				-5.25		-25.68			-12.9
Aileron #1 (°)						-25.68			
Aileron #2 (°)						-25.68			
Mach Number	0.66	0.66	0.48	2.00	2.00	1.41	0.66	0.66	2.00
Altitude (ft)	SL	SL	SL	49770	49770	49770	SL	SL	49770
Weight Configuration	DTOW	DTOW	DTOW	M2W	M2W	DTOW	ZFW	ZFW	ZFW
Gear Configuration	Up	Up	Up	Up	Up	Up	Up	Up	Up
Load Case	**1000**	**1100**	**1200**	**1300**	**1400**	**1500**	**1600**	**1700**	**1800**
Trim Analysis	Sym.	Asymmetric (sym. + Anti-sym.)				Symmetric			
Nx (G)	0.004	-0.002	-0.002	-0.004	-0.004	-0.002	0.002	-0.022	-0.00
Nz (G)	-1.0	0.0	0.0	1.67	1.67	1.0	1.0	2.7	1.0
Pdot (rad/s^2/g)	None	0.0	0.0014	0.0	0.0014	None	None	None	None
Qdot (rad/s^2/g)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pb/2V (rad)	None	0.0410	0.0	0.0410	0.0	None	None	None	None
Qc/2V (rad)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
α (°)	-1.44	0.40	0.40	9.74	9.74	13.91	6.02	4.95	9.07
Body Flap (°)	11.89	-2.86	-2.86	3.14	3.14	8.00	-9.87	-13.20	22.52
Trailing-Edge Flap (°)							-9.87		
Aileron #1 (°)		19.07	48.63	19.07	48.63				
Aileron #2 (°)		19.07	48.63	19.07	48.63				
Mach Number	2.00	0.48	0.48	0.48	0.48	0.3092	1.80	0.89	0.309
Altitude (ft)	49770	SL	SL	SL	SL	SL	55000	20000	SL
Weight Configuration	ZFW	DTOW	DTOW	DTOW	DTOW	DTOW	DTOW	ZFW	DLW
Gear Configuration	Up	Up	Up	Up	Up	Down	Up	Up	Down

Landing and Ground Control Loads of the Baseline Configuration

- ❑ Landing loads
- ❑ Ground control loads
- ❑ Emergency landing loads (applied to **three engine** structures)
  - ❖ 9G forward loading; 1.5G rearward loading; 3G sideway loading; & 6G downward loading

Landing Loads

Load Cases	Case Number	Load	Right-MLG	Left-MLG	NLG
Level + Trim load	3001 (DTOW) & 4001 (DLW)	FX	$0.25\mathrm{FM}_{Lv}$	$0.25\mathrm{FM}_{Lv}$	$0.25\mathrm{FN}_{Lv}$
		FY	0.0	0.0	0.0
		FZ	$\mathrm{FM}_{Lv} = \mathrm{f}_{LMG}\mathrm{W}_T$	FM_{Lv}	$\mathrm{FN}_{Lv} = \mathrm{f}_{LNG}\mathrm{W}_T$
Spin up + Trim load	3002 (DTOW) & 4002 (DLW)	FX	$(0.8 \times 0.8)\mathrm{FM}_{Lv}$	$(0.8 \times 0.8)\mathrm{FM}_{Lv}$	$(0.8 \times 0.8)\mathrm{FN}_{Lv}$
		FY	0.0	0.0	0.0
		FZ	$0.8\mathrm{FM}_{Lv}$	$0.8\mathrm{FM}_{Lv}$	$0.8\mathrm{FN}_{Lv}$
Spring back + Trim load	3003 (DTOW) & 4003 (DLW)	FX	$-(0.8 \times 0.8)\mathrm{FM}_{Lv}$	$-(0.8 \times 0.8)\mathrm{FM}_{Lv}$	$-(0.8 \times 0.8)\mathrm{FN}_{Lv}$
		FY	0.0	0.0	0.0
		FZ	$0.8\mathrm{FM}_{Lv}$	$0.8\mathrm{FM}_{Lv}$	$0.8\mathrm{FN}_{Lv}$
Lateral drift + Trim load	3004 (DTOW) & 4004 (DLW)	FX	$(0.4 \times 0.75)\mathrm{FM}_{Lv}$	$(0.4 \times 0.75)\mathrm{FM}_{Lv}$	$0.4\mathrm{FN}_{Lv}$
		FY	$(0.25 \times 0.75)\mathrm{FM}_{Lv}$	$(0.25 \times 0.75)\mathrm{FM}_{Lv}$	$0.25\mathrm{FN}_{Lv}$
		FZ	$0.75\mathrm{FM}_{Lv}$	$0.75\mathrm{FM}_{Lv}$	FN_{Lv}
Right one gear + Trim load	3005 (DTOW) & 4005 (DLW)	FX	$0.25\mathrm{FM}_{Lv}$	0.0	0.0
		FY	0.0	0.0	0.0
		FZ	FM_{Lv}	0.0	0.0
Left one gear + Trim load	3006 (DTOW) & 4006 (DLW)	FX	0.0	$0.25\mathrm{FM}_{Lv}$	0.0
		FY	0.0	0.0	0.0
		FZ	0.0	FM_{Lv}	0.0
Side load RtoL + Trim load	3007 (DTOW) & 4007 (DLW)	FX	0.0	0.0	0.0
		FY	$(0.8 \times 0.5)\mathrm{FM}_{Lv}$	$(0.6 \times 0.5)\mathrm{FM}_{Lv}$	0.0
		FZ	$0.5\mathrm{FM}_{Lv}$	$0.5\mathrm{FM}_{Lv}$	0.0
Side load LtoR + Trim load	3008 (DTOW) & 4008 (DLW)	FX	0.0	0.0	0.0
		FY	$-(0.6 \times 0.5)\mathrm{FM}_{Lv}$	$-(0.8 \times 0.5)\mathrm{FM}_{Lv}$	0.0
		FZ	$0.5\mathrm{FM}_{Lv}$	$0.5\mathrm{FM}_{Lv}$	0.0
DTOW		f_{LMG}=0.36; f_{LNG}=0.0639; Trim load case ID = 1500			
DLW		f_{LMG}=1.20; f_{LNG}=0.1477; Trim load case ID = 1800			

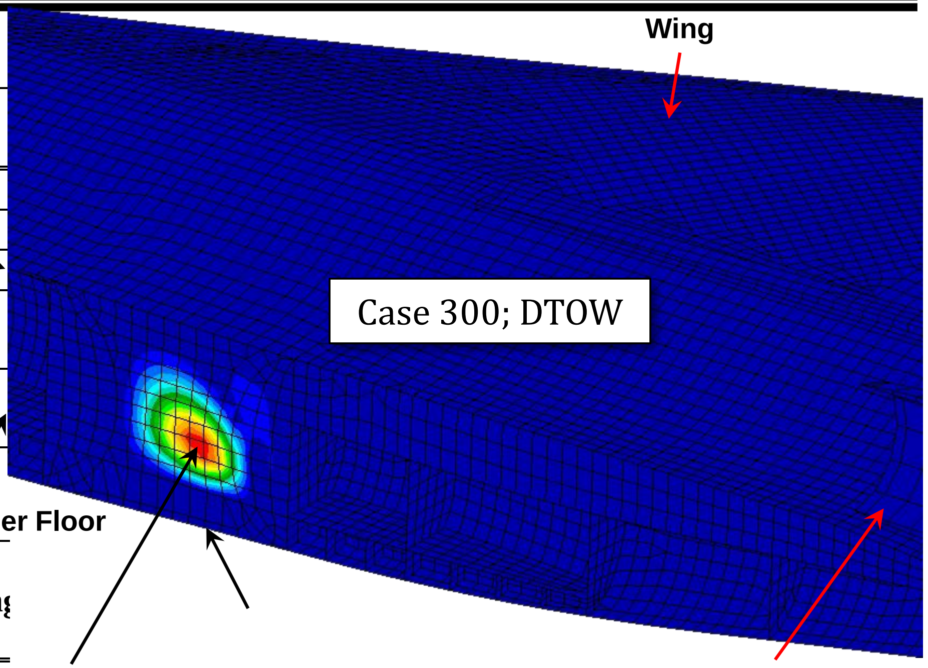
Ground Control Loads

Load Cases	Case Number	Load	Right-MLG	Left-MLG	NLG
Static Condition		FX	0.0	0.0	0.0
		FY	0.0	0.0	0.0
		FZ	$\mathrm{FM}_{St} = \frac{0.5\mathrm{d}_{CG2NG}\mathrm{W}_T}{\mathrm{d}_{NG2MG}}$	FM_{St}	$\mathrm{FN}_{St} = \frac{\mathrm{d}_{CG2MG}\mathrm{W}_T}{\mathrm{d}_{NG2MG}}$
3-point braked roll	3009 (DTOW) & 4009 (DLW)	FX	$0.8\mathrm{FM}_{St}$	$0.8\mathrm{FM}_{St}$	0.0
		FY	0.0	0.0	0.0
		FZ	FM_{St}	FM_{St}	$\frac{2\mathrm{d}_{CG2MG}\mathrm{FM}_{St} + 2(Z_{CG} - Z_{MGCP})0.8\mathrm{FM}}{\mathrm{d}_{CG2NG}}$
2-point braked roll	3010 (DTOW) & 4010 (DLW)	FX	$0.8\mathrm{FM}_{St}$	$0.8\mathrm{FM}_{St}$	0.0
		FY	0.0	0.0	0.0
		FZ	FM_{St}	FM_{St}	0.0
Dynamic roll braking	3011 (DTOW) & 4011 (DLW)	FX	$0.8\mathrm{FM}_{St}$	$0.8\mathrm{FM}_{St}$	0.0
		FY	0.0	0.0	0.0
		FZ	FM_{St}	FM_{St}	$\frac{\mathrm{W}_T}{\mathrm{d}_{NG2MG}}\left[\mathrm{d}_{CG2MG} + \frac{\mathrm{fd}_{CG2NG}\mu E}{\mathrm{d}_{NG2MG} + \mu E}\right]$ where, $E = \{Z_{CG} - Z_{NGCP} - (X_{CG} - X_{NGCP})S\}$ and $S = (X_{CG} - X_{NGCP})\frac{Z_{MGCP} - Z_{NGCP}}{X_{MGCP} - X_{NGCP}}$
Turning Condition	3012 (DTOW) & 4012 (DLW)	FX	0.0	0.0	$0.25\mathrm{FN}_{St}$
		FY	$0.5\mathrm{FM}_{St}$	$0.5\mathrm{FM}_{St}$	$0.5\mathrm{FN}_{St}$
		FZ	FM_{St}	FM_{St}	FN_{St}
Nose wheel yaw & steering (1)	3013 (DTOW) & 4013 (DLW)	FX	0.0	0.0	0.0
		FY	0.0	0.0	$0.8\mathrm{FN}_{St}$
		FZ	FM_{St}	FM_{St}	FN_{St}
Nose wheel yaw & steering (2)	3014 (DTOW) & 4014 (DLW)	FX	$0.8\mathrm{FM}_{St}$	0.0	0.0
		FY	0.0	0.0	0.0
		FZ	FM_{St}	FM_{St}	$\frac{2\mathrm{d}_{CG2MG}\mathrm{FM}_{St} + (Z_{CG} - Z_{MGCP})0.8\mathrm{FM}}{\mathrm{d}_{CG2NG}}$
Nose wheel yaw & steering (3)	3015 (DTOW) & 4015 (DLW)	FX	0.0	$0.8\mathrm{FM}_{St}$	0.0
		FY	0.0	0.0	0.0
		FZ	FM_{St}	FM_{St}	$\frac{2\mathrm{d}_{CG2MG}\mathrm{FM}_{St} + (Z_{CG} - Z_{MGCP})0.8\mathrm{FM}}{\mathrm{d}_{CG2NG}}$
Reversed braking	3016 (DTOW) & 4016 (DLW)	FX	$-0.55\mathrm{FM}_{St}$	$-0.55\mathrm{FM}_{St}$	0.0
		FY	0.0	0.0	0.0
		FZ	FM_{St}	FM_{St}	0.0
2G Taxi	3017 (DTOW) & 4017 (DLW)	FX	0.0	0.0	0.0
		FY	0.0	0.0	0.0
		FZ	$2\mathrm{FM}_{St}$	$2\mathrm{FM}_{St}$	$2\mathrm{FN}_{St}$
$\mu = 0.80$; f=2.00					

Buckling and Strength Analyses

- Based on five analysis sets

Analysis Set	Gear Configuration	Weight Condition	Load Cases
1	Up	DTOW	100, 200, 300, 600, 1100, 1200, 1300, 1400, & 1600
2	Up	ZFW	700, 800, 900, 1000, & 1700
3	Up	M2W	400 & 500
4	Down	DTOW	3001 ~ 3017 + 3018 ~ 3021 (emergency) + 1500 (for landing)
5	Down	DLW	4001 ~ 4017 + 4018 ~ 4021 (emergency) + 1800 (for landing)



- Minimum buckling load factors from each analysis set

Analysis Set	Gear Configuration	Weight Condition	Case Number	Load Case	Minimum Buckling Load Factor	Buckling
1	Up	DTOW	300	2.5G pull up; M=0.48	0.152	yes
2	Up	ZFW	1700	2.7G gust loads; M=0.89	0.195	yes
3	Up	M2W	400	2.5G pull up; M=2.00	0.151	yes
4	Down	DTOW	3006	Left one gear landing	1.71	no
5	Down	DLW	4006	Left one gear landing	1.52	no

Buckling Load Factor > 1 or
Buckling Load Factor < 0 : requirement

- Minimum margins of safety from each analysis set

Analysis Set	Gear Configuration	Weight Condition	Case Number	Load Case	Minimum Margin of Safety	Failure
1	Up	DTOW	1400	1.67G abrupt roll; M=0.48	-0.999	yes
2	Up	ZFW	1700	2.7G gust loads; M=0.89	-0.998	yes
3	Up	M2W	400	2.5G pull up; M=2.00	-0.997	yes
4	Down	DTOW	3013	Nose wheel yaw & steering (1)	-0.781	yes
5	Down	DLW	4003	Spring back landing	-0.657	yes

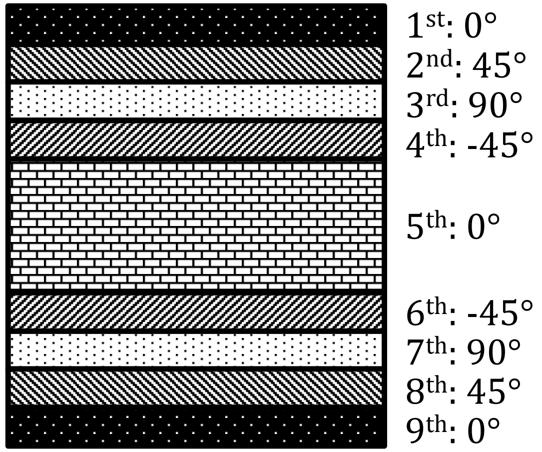
Margin of safety > 0 : requirement
Safety factor = 1.5

$$MS \equiv \frac{\text{Failure Load}}{\text{Design Load} \times \text{Safety Factor}} - 1$$

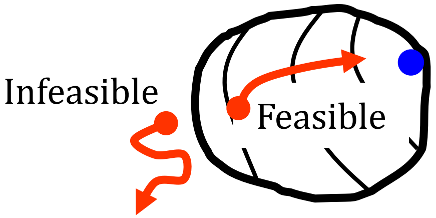
First Optimization Run

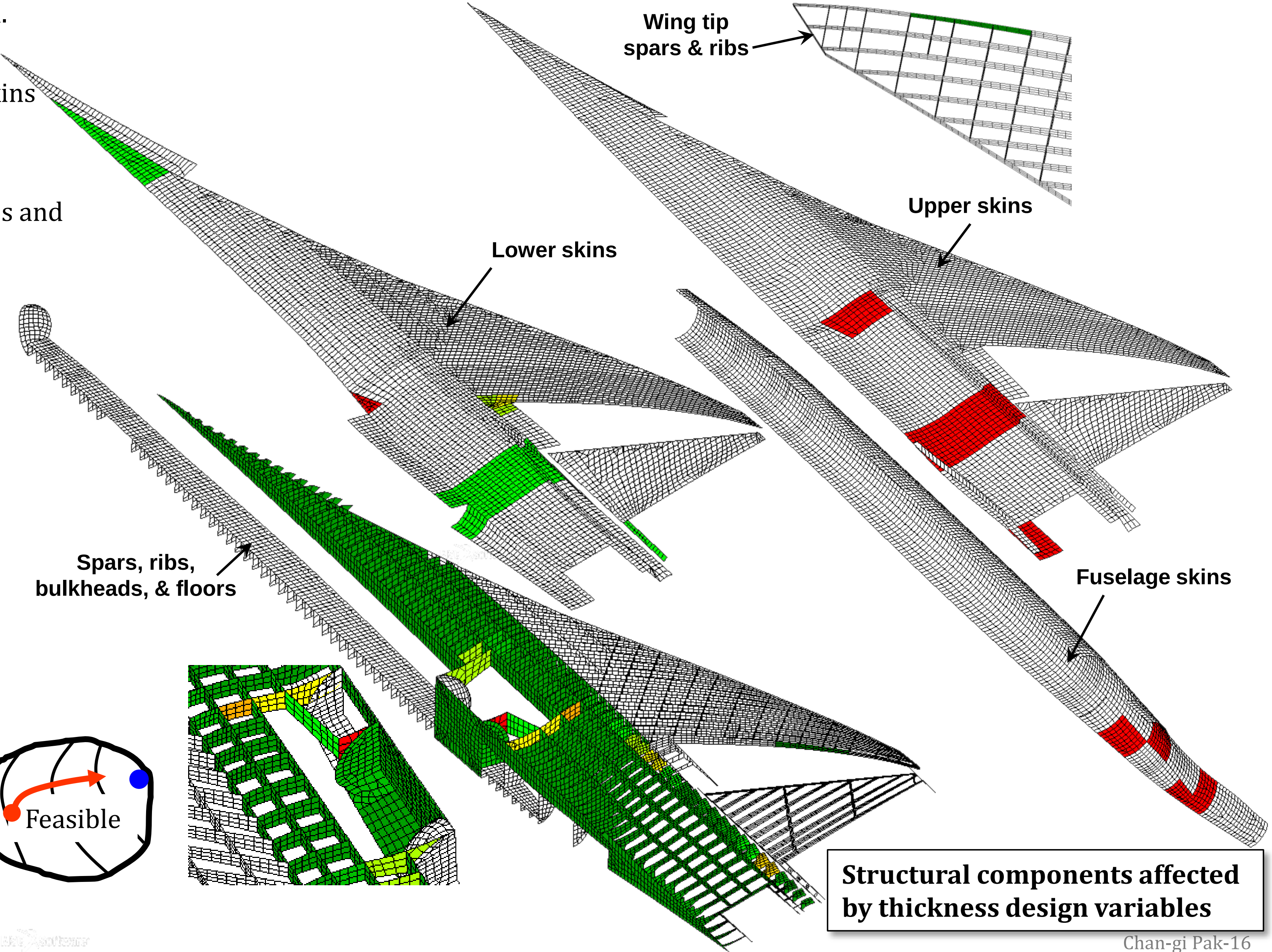
Design Variables for the First Optimization Run

- Baseline configuration is in infeasible domain.
  - Manually increase 111 ply thicknesses.
    - Wing, tail, inner-wing, and fuselage skins
      - ✓ Three variables
        - 1^{st}, 3^{rd} , & 2^{nd} = 4^{th}
    - Wing, inner-wing, and tail spars & ribs and fuselage bulkheads and walls
      - ✓ One variable
        - 1^{st}=2^{nd}=3^{rd}=4^{th}
    - Inner-wing spars & ribs
      - ✓ One variable
        - 5^{th}



Symmetric stacking of nine plies into a composite laminate





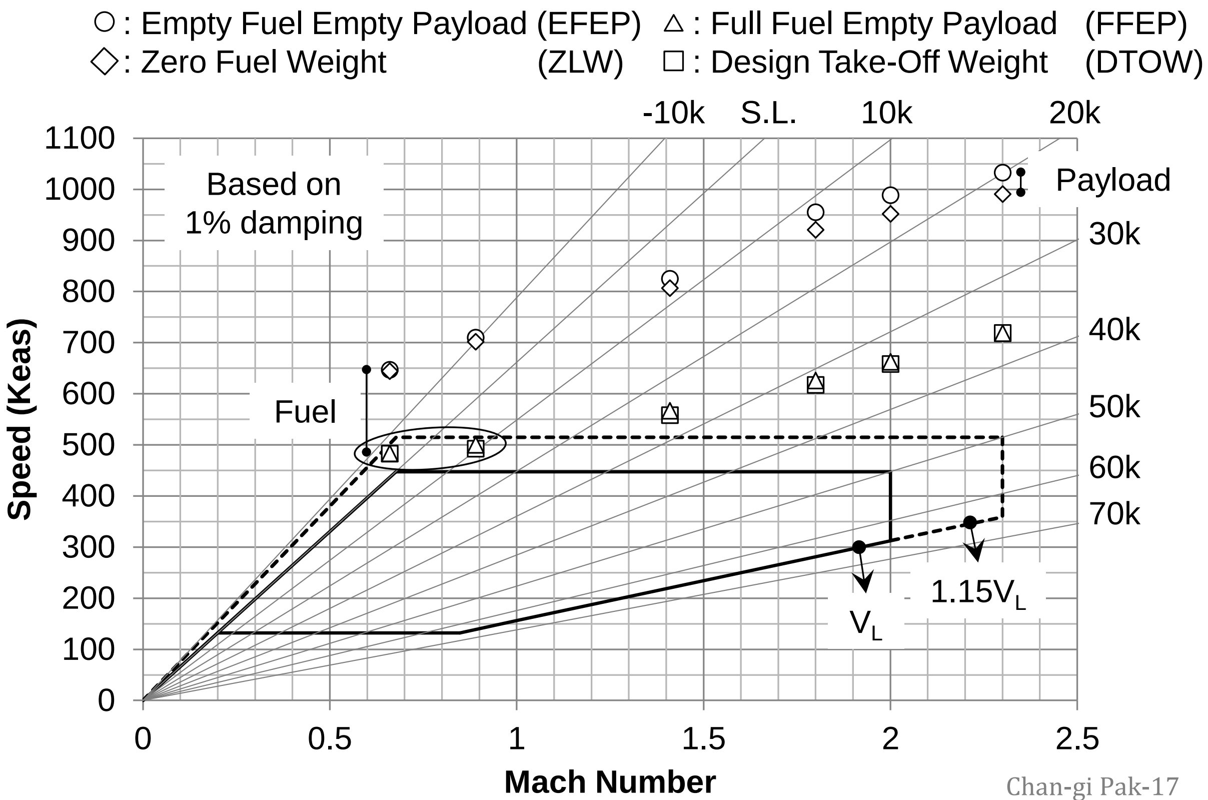
Structural components affected by thickness design variables

First Optimization Run

Functions	Performance indices	Notes
Objective	$F(\mathbf{X}) = (\mathrm{PI_W})^2 = W_T^2$	DTOW
Flutter constraint	$g_j(\mathbf{X}) = \mathrm{PI_F} = 1. - \frac{\mathrm{V_F}}{1.15\mathrm{V_L}} < 0.$ $\mathrm{j} = 1, 2, \ldots, 6$	15% margin
Buckling constraint	$g_j(\mathbf{X}) = \mathrm{PI_B} = (1/2)^2 - \{\text{positive}\ \min(\mathrm{BLF}) - 1/2\}^2 < 0.$ $\mathrm{j} = 7, 8, \ldots, 11$	Safety factor = 1.5
Strength constraint	$g_j(\mathbf{X}) = \mathrm{PI_s} = -\min(\mathrm{MS}) < 0.$ $\mathrm{j} = 12, 13, \ldots, 16$	Safety factor = 1.5

- Objective: total weight of gear up DTOW case
- Flutter constraints
  - Gear Up DTOW at M=0.66, 0.89, & 1.41
  - Gear up FFEP at M=0.66, 0.89, & 1.41
- Buckling & strength constraints
  - Minimum "buckling load factor" & minimum "margin of safety" from five analysis sets

Analysis Set	Gear Configuration	Weight Condition	Load Cases
1	Up	DTOW	100, 200, 300, 600, 1100, 1200, 1300, 1400, & 1600
2	Up	ZFW	700, 800, 900, 1000, & 1700
3	Up	M2W	400 & 500
4	Down	DTOW	3001 ~ 3017 + 3018 ~ 3021 (emergency) + 1500 (for landing)
5	Down	DLW	4001 ~ 4017 + 4018 ~ 4021 (emergency) + 1800 (for landing)



First Optimization Run (continue)

	Performance Index		Design Configuration	Before Optimization	Iteration 1	Iteration 7
Objective Function	Total Weight		DTOW; GU	332738	425764	364105
Constraint Functions $g_j(\mathbf{X})$	Flutter	$g_1(\mathbf{X})$	DTOW; GU; M=0.66	**0.067(V)**	-0.362	-0.342
		$g_2(\mathbf{X})$	DTOW; GU; M=0.89	**0.048(V)**	-0.543	**-0.096**
		$g_3(\mathbf{X})$	DTOW; GU; M=1.41	-0.079	-1.34	-0.297
		$g_4(\mathbf{X})$	FFEP; GU; M=0.66	**0.066(V)**	-0.365	-0.337
		$g_5(\mathbf{X})$	FFEP; GU; M=0.89	**0.034(V)**	-0.586	**-0.094**
		$g_6(\mathbf{X})$	FFEP; GU; M=1.41	-0.095	-1.32	-0.255
	Buckling	$g_7(\mathbf{X})$	DTOW; GU	**0.152(V)**	-1.05	-1.29
		$g_8(\mathbf{X})$	ZFW; GU	**0.186(V)**	-2.36	-3.09
		$g_9(\mathbf{X})$	M2W; GU	**0.151(V)**	-1.28	-1.91
		$g_{10}(\mathbf{X})$	DTOW; GD	-0.960	-3.27	-3.88
		$g_{11}(\mathbf{X})$	DLW; GD	-0.561	-0.308	-1.07
	Strength	$g_{12}(\mathbf{X})$	DTOW; GU	**0.999(V)**	-0.267	**-0.161**
		$g_{13}(\mathbf{X})$	ZFW; GU	**0.998(V)**	-0.780	**-0.061**
		$g_{14}(\mathbf{X})$	M2W; GU	**0.997(V)**	-0.179	-0.537
		$g_{15}(\mathbf{X})$	DTOW; GD	**0.781(V)**	-0.751	**-5.63e-6**
		$g_{16}(\mathbf{X})$	DLW; GD	**0.657(V)**	-0.210	-0.320
Weight penalty (%)				0	28.0	9.43

Design infeasible

Manual update

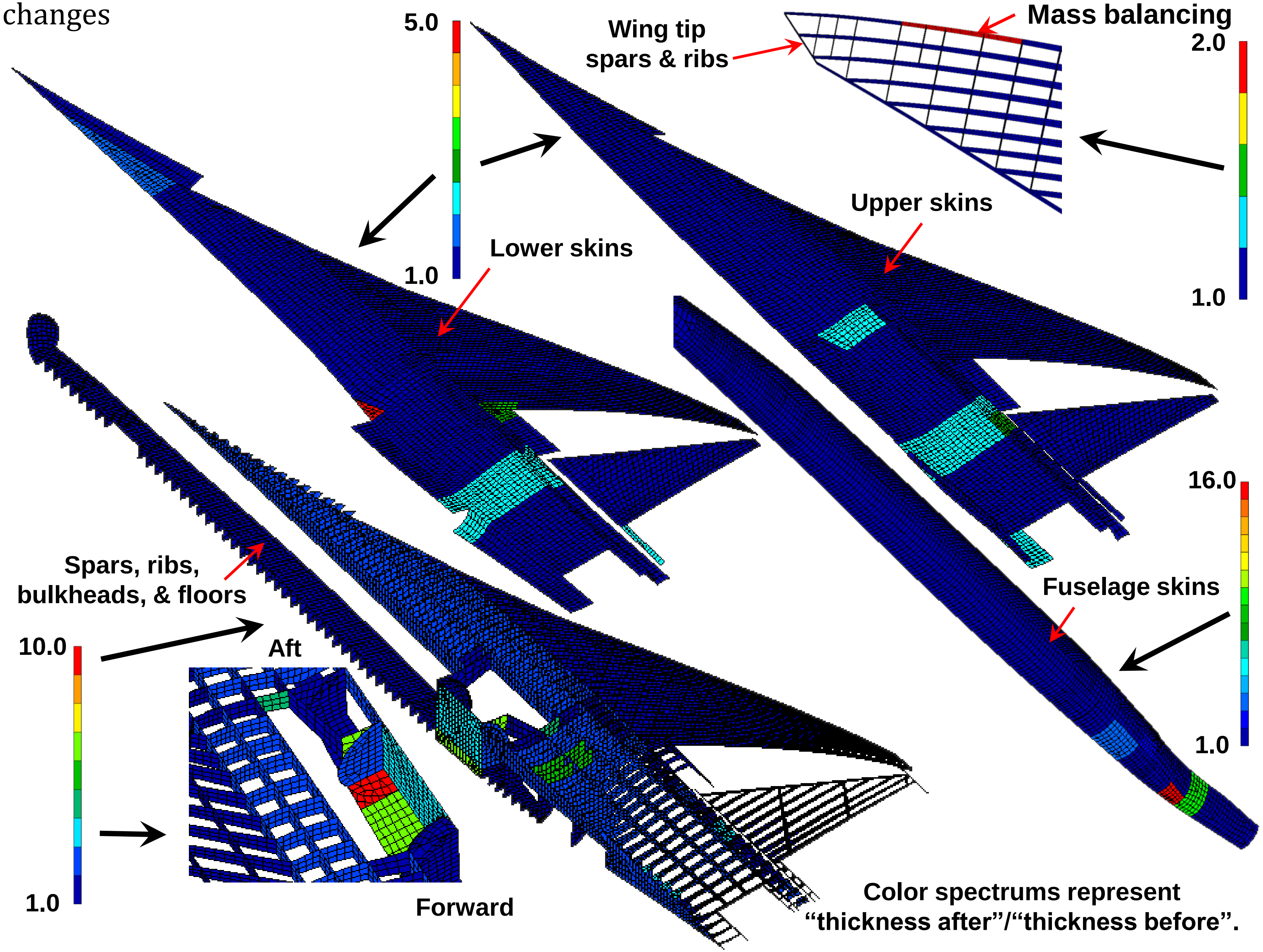
Design feasible

Optimization based on DOT.

Active and near active constraints from strength analyses.

First Optimization Run (continue)

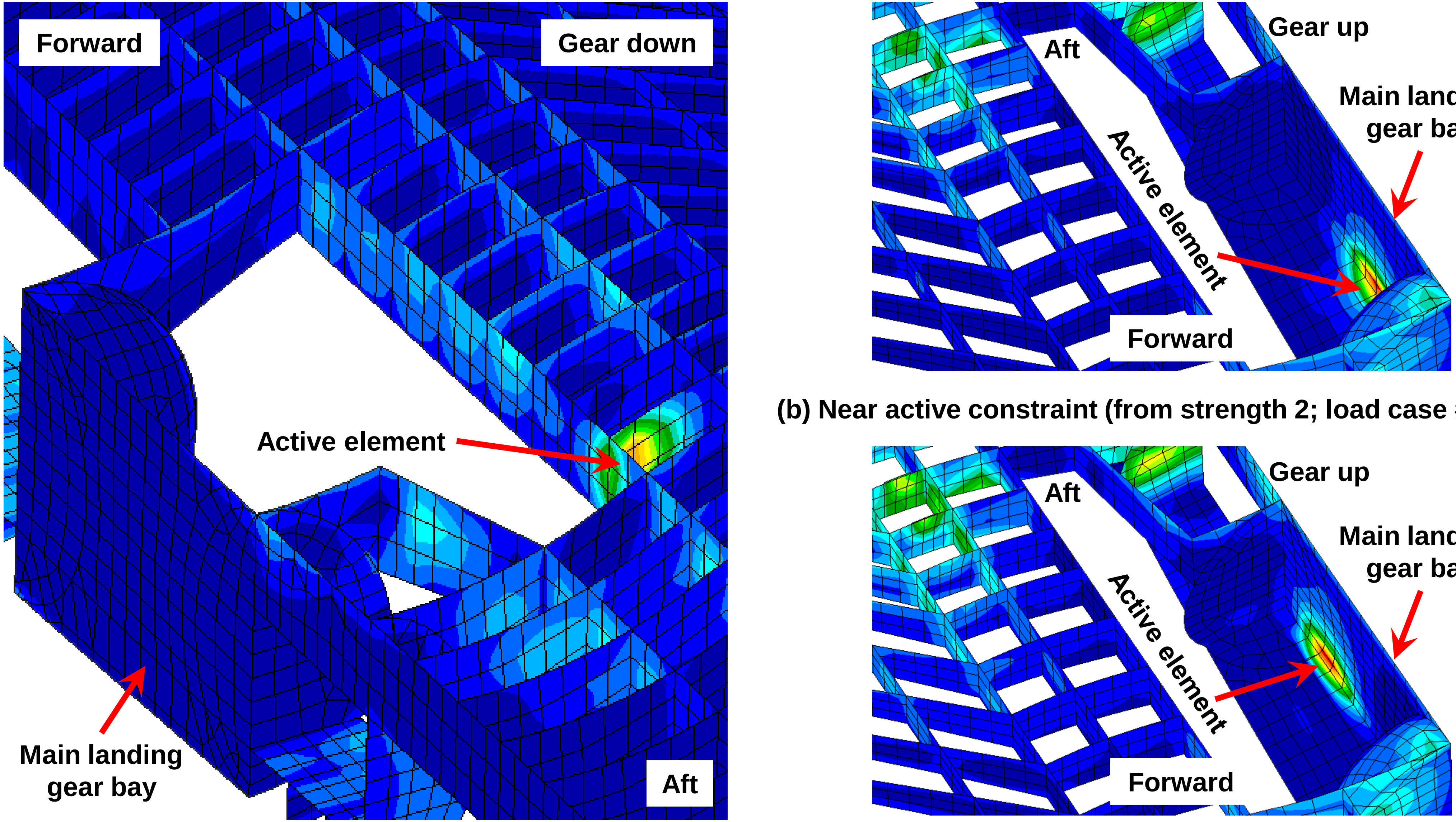
- Total thickness changes



Color spectrums represent “thickness after”/“thickness before”.

First Optimization Run (continue)

- Strain distribution of the active and near active constraints



(a) Active constraint (from strength 4; load case #3013)

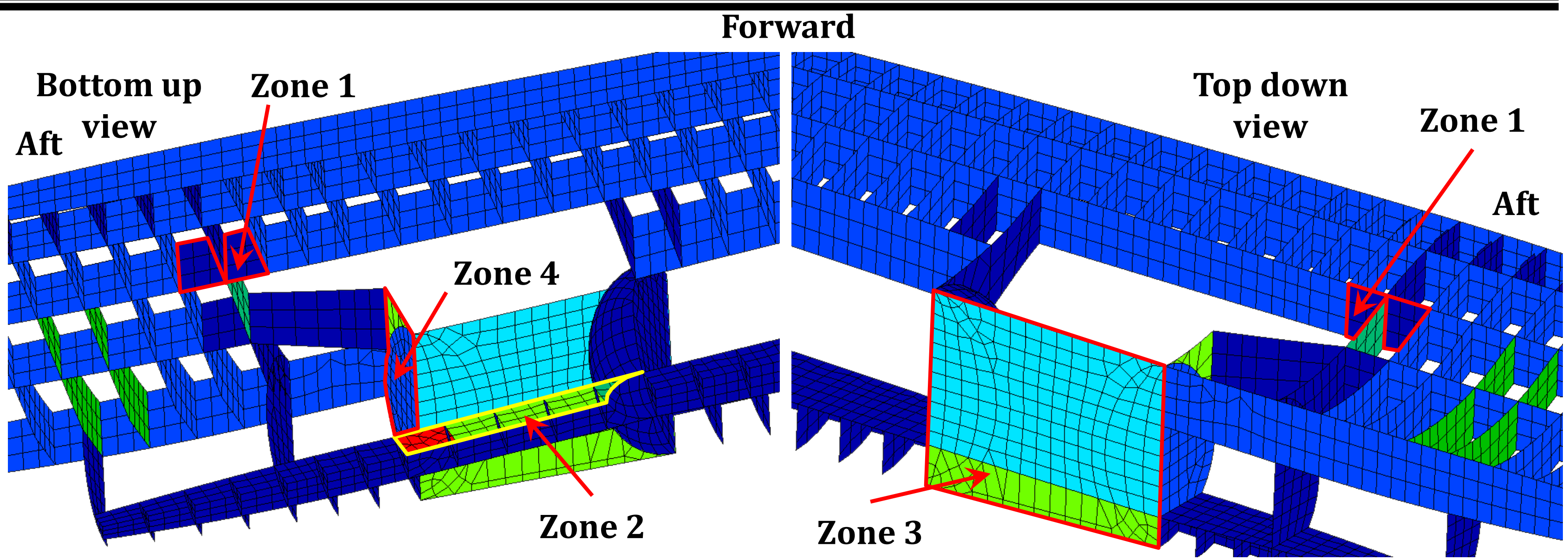
(b) Near active constraint (from strength 2; load case #1700)

(c) Near active constraint (from strength 1; load case #300)

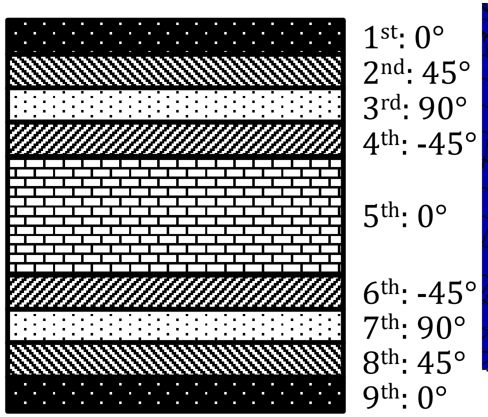
Second Optimization Run

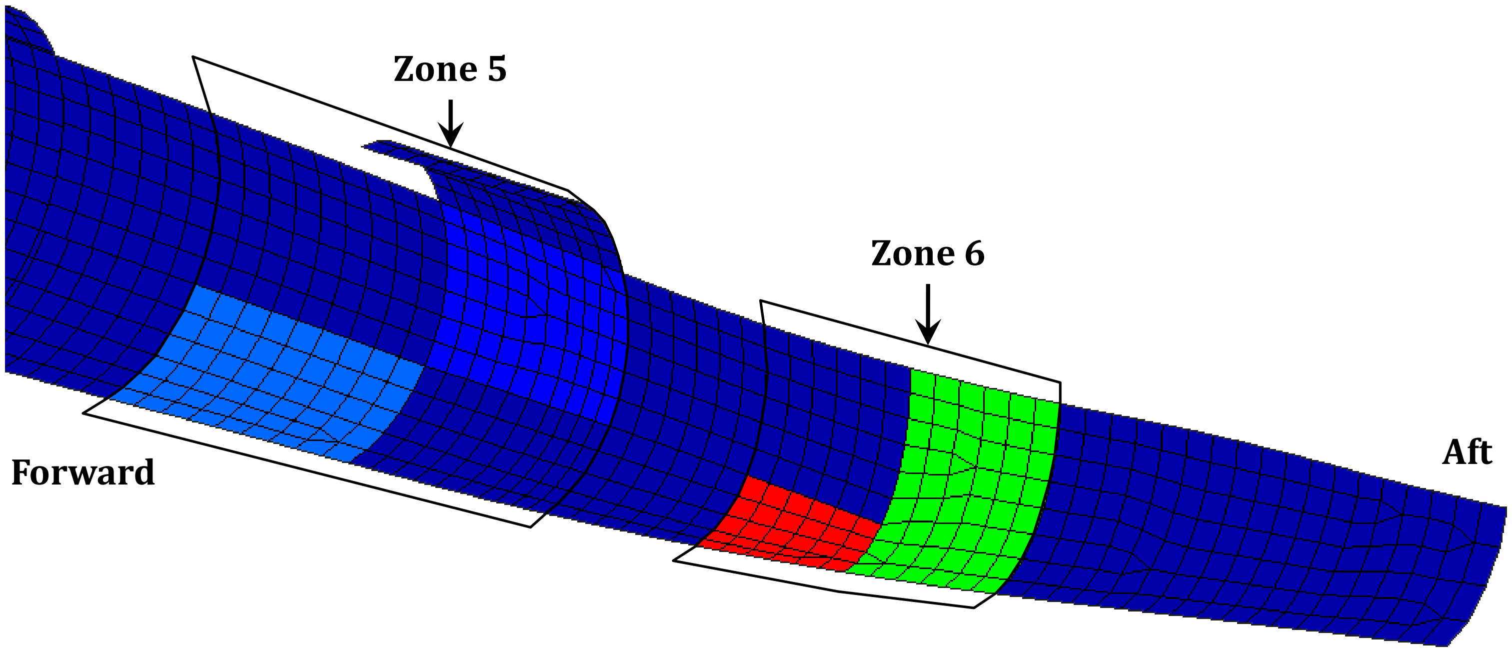
Design Variables for the Second Optimization Run

- Composite ply angles of the six zones
  - Design variables are ply angles of the 2^{nd} and 4^{th} layers.
    - Design variable linking 2^{nd} = -4^{th}
  - Use discrete design variables



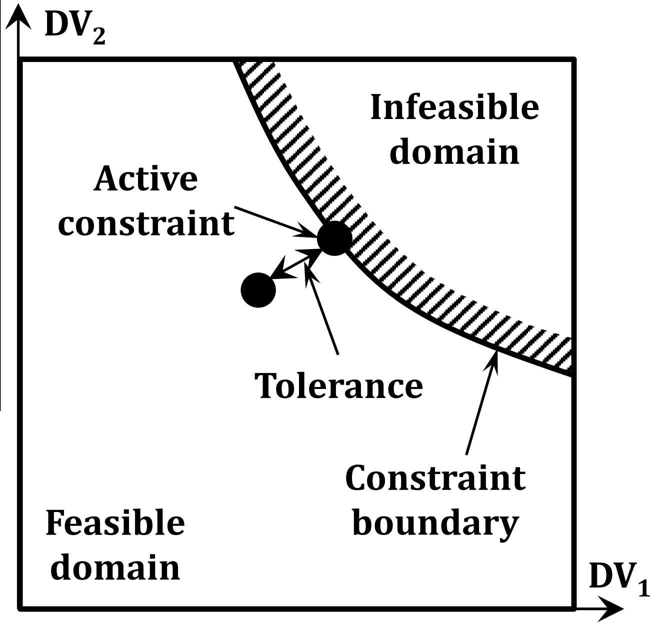
Value Ranges	Discrete values
0.0° ≤ Ply angle < 2.5°	0°
2.5° ≤ Ply angle < 7.5°	5°
7.5° ≤ Ply angle < 12.5°	10°
12.5° ≤ Ply angle < 17.5°	15°
17.5° ≤ Ply angle < 22.5°	20°
22.5° ≤ Ply angle < 27.5°	25°
27.5° ≤ Ply angle < 32.5°	30°
32.5° ≤ Ply angle < 37.5°	35°
37.5° ≤ Ply angle < 42.5°	40°
42.5° ≤ Ply angle < 47.5°	45°
47.5° ≤ Ply angle < 52.5°	50°
52.5° ≤ Ply angle < 57.5°	55°
57.5° ≤ Ply angle < 62.5°	60°
62.5° ≤ Ply angle < 67.5°	65°
67.5° ≤ Ply angle < 72.5°	70°
72.5° ≤ Ply angle < 77.5°	75°
77.5° ≤ Ply angle < 82.5°	80°
82.5° ≤ Ply angle < 87.5°	85°
87.5° ≤ Ply angle ≤ 90.0°	90°





Second Optimization Run

Functions	Performance indices	Notes
Objective	$F(\mathbf{X}) = -\{0.5g_{12}(\mathbf{X}) + 0.5g_{13}(\mathbf{X}) + g_{15}(\mathbf{X})\}$	Safety factor = 1.5
Flutter constraint	$g_j(\mathbf{X}) = \mathrm{PI_F} = 1. - \frac{\mathrm{V_F}}{1.15\mathrm{V_L}} < 0.$ $j = 1, 2, \ldots, 6$	15% margin
Buckling constraint	$g_j(\mathbf{X}) = \mathrm{PI_B} = (1/2)^2 - \{\text{positive} \min(\mathrm{BLF}) - 1/2\}^2 < 0.$ $j = 7, 8, \ldots, 11$	Safety factor = 1.5
Strength constraint	$g_j(\mathbf{X}) = \mathrm{PI_s} = -\min(\mathrm{MS}) < 0.$ $j = 12, 13, \ldots, 16$	Safety factor = 1.5



DV$_i$: Design Variable i

- Purpose: Create more offset for active constraints
- Objective: performance index from the 2nd and 4th strength analysis sets
- Flutter constraints
  - Same as the first optimization run
- Buckling & strength constraints
  - Same as the first optimization run except performance indices for the objective function

Analysis Set	Gear Configuration	Weight Condition	Load Cases
1	Up	DTOW	100, 200, 300, 600, 1100, 1200, 1300, 1400, & 1600
2	Up	ZFW	700, 800, 900, 1000, & 1700
3	Up	M2W	400 & 500
4	Down	DTOW	3001 ~ 3017 + 3018 ~ 3021 (emergency) + 1500 (for landing)
5	Down	DLW	4001 ~ 4017 + 4018 ~ 4021 (emergency) + 1800 (for landing)

Second Optimization Run (continue)

			Performance Index	Design Configuration	Starting	BBBC 1	BBBC 2
Objective Function			$-\{0.5g_{12}(\mathbf{X}) + 0.5g_{13}(\mathbf{X}) + g_{15}(\mathbf{X})\}$		0.111	0.337	0.348
Constraint Functions $g_j(\mathbf{X})$	Flutter		$g_1(\mathbf{X})$	DTOW; GU; M=0.66	-0.342	-0.341	-0.342
			$g_2(\mathbf{X})$	DTOW; GU; M=0.89	**-0.096**	**-0.096**	**-0.096**
			$g_3(\mathbf{X})$	DTOW; GU; M=1.41	-0.297	-0.299	-0.297
			$g_4(\mathbf{X})$	FFEP; GU; M=0.66	-0.337	-0.336	-0.337
			$g_5(\mathbf{X})$	FFEP; GU; M=0.89	**-0.094**	**-0.095**	**-0.094**
			$g_6(\mathbf{X})$	FFEP; GU; M=1.41	-0.255	-0.257	-0.255
	Buckling		$g_7(\mathbf{X})$	DTOW; GU	-1.29	-1.50	-1.38
			$g_8(\mathbf{X})$	ZFW; GU	-3.09	-3.63	-3.09
			$g_9(\mathbf{X})$	M2W; GU	-1.91	-2.00	-2.23
			$g_{10}(\mathbf{X})$	DTOW; GD	-3.88	-4.22	-4.19
			$g_{11}(\mathbf{X})$	DLW; GD	-1.07	-1.07	-1.07
	Strength		$g_{12}(\mathbf{X})$	DTOW; GU	**-0.161**	**-0.214**	**-0.232**
			$g_{13}(\mathbf{X})$	ZFW; GU	**-0.061**	**-0.141**	**-0.145**
			$g_{14}(\mathbf{X})$	M2W; GU	-0.537	-0.204	-0.542
			$g_{15}(\mathbf{X})$	DTOW; GD	**-5.63e-6**	**-0.159**	**-0.159**
			$g_{16}(\mathbf{X})$	DLW; GD	-0.320	-0.435	-0.419

Design Variables	**Starting**	**BBBC 1**	**BBBC 2**
1 (2^{nd} rib at inner-wing)	45°	15°	15°
2 (floor at main landing gear bay)	45°	65°	65°
3 (center wall at main landing gear bay)	45°	65°	55°
4 (aft bulkhead at main landing gear bay)	45°	65°	55°
5 (aft fuselage skin 1)	45°	30°	40°
6 (aft fuselage skin 2)	45°	50°	55°

Big-Bang Big-Crunch algorithm; number of population=60; number of Big-Bang Big-Crunch=2; discrete design variables

Third Optimization Run

Third Optimization Run

Functions	Performance indices	Notes
Objective	$F(\mathbf{X}) = (\mathrm{PI_W})^2 = W_T^2$	DTOW
Flutter constraint	$g_j(\mathbf{X}) = \mathrm{PI_F} = 1. - \frac{\mathrm{V_F}}{1.15\mathrm{V_L}} < 0.$ $\mathrm{j} = 1, 2, \ldots, 6$	15% margin
Buckling constraint	$g_j(\mathbf{X}) = \mathrm{PI_B} = (1/2)^2 - \{\text{positive min(BLF)} - 1/2\}^2 < 0.$ $\mathrm{j} = 7, 8, \ldots, 11$	Safety factor = 1.5
Strength constraint	$g_j(\mathbf{X}) = \mathrm{PI_s} = -\min(\mathrm{MS}) < 0.$ $\mathrm{j} = 12, 13, \ldots, 16$	Safety factor = 1.5

- Objective: total weight of gear up DTOW case
- Flutter constraints
  - Gear Up DTOW at M=0.66, 0.89, & 1.41
  - Gear up FFEP at M=0.66, 0.89, & 1.41
- Buckling & strength constraints
  - Minimum “buckling load factor” & minimum “margin of safety” from five analysis sets

Analysis Set	Gear Configuration	Weight Condition	Load Cases
1	Up	DTOW	100, 200, 300, 600, 1100, 1200, 1300, 1400, & 1600
2	Up	ZFW	700, 800, 900, 1000, & 1700
3	Up	M2W	400 & 500
4	Down	DTOW	3001 ~ 3017 + 3018 ~ 3021 (emergency) + 1500 (for landing)
5	Down	DLW	4001 ~ 4017 + 4018 ~ 4021 (emergency) + 1800 (for landing)

Third Optimization Run

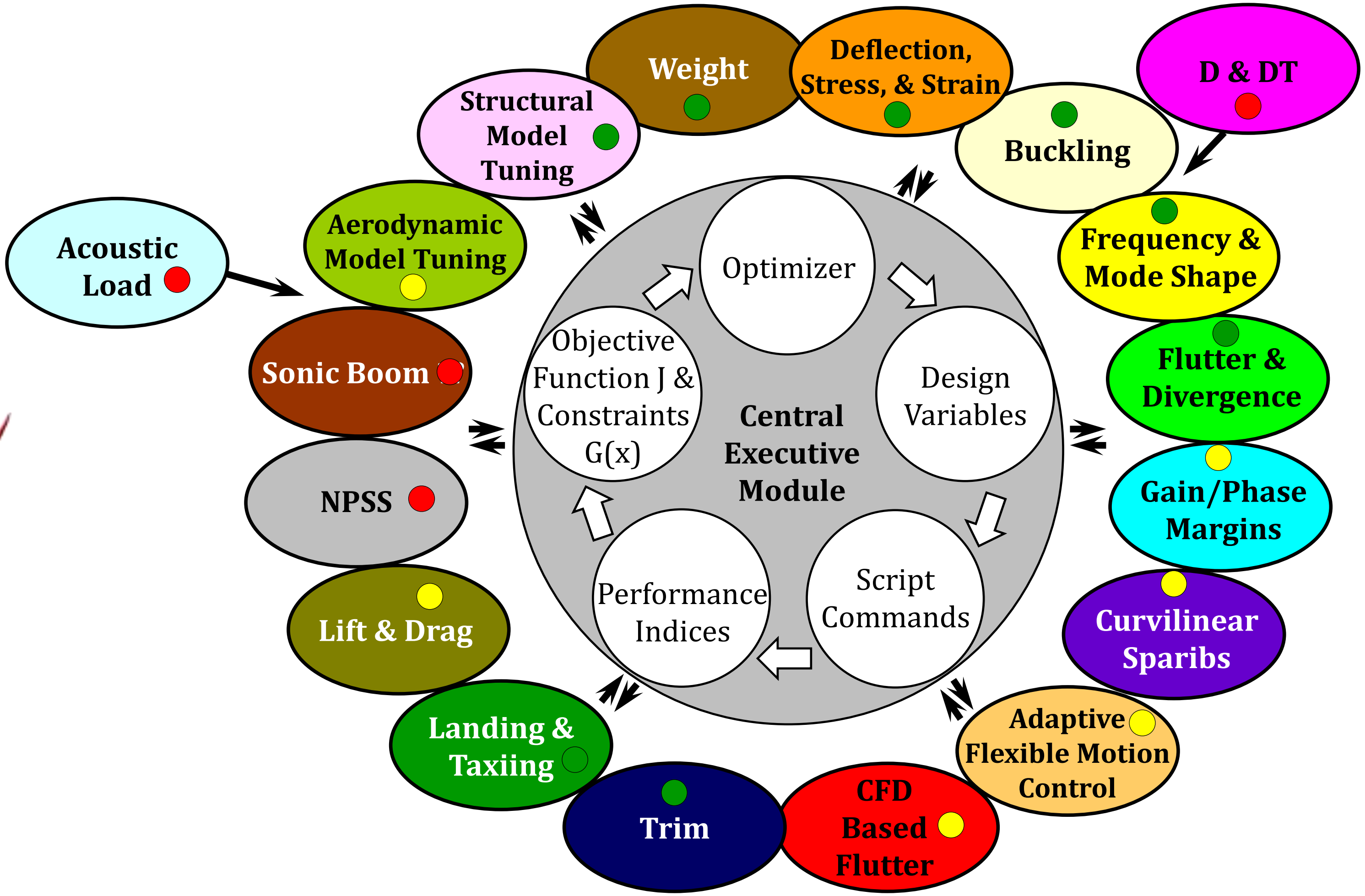
		Performance Index	Design Configuration	Starting	Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5	Iteration 6	Iteration 7
Objective Function		Total Weight	DTOW; GU	364105	363810						
Constraint Functions $g_j(\mathbf{X})$	Flutter	$g_1(\mathbf{X})$	DTOW; M=0.66	-0.342	-0.341						
		$g_2(\mathbf{X})$	DTOW; M=0.89	-0.096	-0.096						
		$g_3(\mathbf{X})$	DTOW; M=1.41	-0.297	-0.297						
		$g_4(\mathbf{X})$	FFEP; M=0.66	-0.337	-0.336						
		$g_5(\mathbf{X})$	FFEP; M=0.89	-0.094	-0.094						
		$g_6(\mathbf{X})$	FFEP; M=1.41	-0.255	-0.256						
	Buckling	$g_7(\mathbf{X})$	DTOW; GU	-1.38	-1.38						
		$g_8(\mathbf{X})$	ZFW; GU	-3.09	-3.44						
		$g_9(\mathbf{X})$	M2W; GU	-2.23	-2.04						
		$g_{10}(\mathbf{X})$	DTOW; GD	-4.19	-3.95						
		$g_{11}(\mathbf{X})$	DLW; GD	-1.07	-1.07						
	Strength	$g_{12}(\mathbf{X})$	DTOW; GU	-0.232	-0.227						
		$g_{13}(\mathbf{X})$	ZFW; GU	-0.145	-0.141						
		$g_{14}(\mathbf{X})$	M2W; GU	-0.542	-0.261						
		$g_{15}(\mathbf{X})$	DTOW; GD	-0.159	**-6.16e-5**						
		$g_{16}(\mathbf{X})$	DLW; GD	-0.419	-0.359						
Weight penalty (%)				9.43	9.34						

Optimization based on DOT.

Conclusions

- The Lockheed Martin's pre-matured N+2 LSCT aircraft is optimized in this study through the use of a multidisciplinary design optimization tool developed at the NASA AFRC.
- The baseline design of the pre-matured N+2 LSCT aircraft was infeasible when ZAERO based aeroelastic analyses were used.
  - This probably means that the aerodynamic loads distribution computed using ZAERO trim analysis are different than the MSC Nastran generated aerodynamic loads.
- The starting configuration of the optimization run should be an achievable design and weight penalty for this was 93,026 lb.
  - **28.0%** increase from baseline
- During the first optimization run, the weight reduction was 61,659 lb, and therefore weight penalty at the end of the first optimization run is 31,367 lb.
  - Optimization was based on DOT optimizer
  - Active constraint: minimum margin of safety value is associated with the structural component located at the second rib of the inner wing near the main landing gear bay area.
    - Nose wheel yaw and steering case number 1
  - First near active constraint: minimum margin of safety value at the floor of main landing gear bay
    - 2.7g gust load case at Mach 0.89 and altitude of 20,000 ft
  - **9.4%** increase from baseline
  - Second near active constraints: flutter speeds with DTOW and FFEP at Mach 0.89
    - Mass balancing effect to increase the flutter speeds
- The second optimization run was prepared to increase tolerance distance for the active and the first near active constraints.
  - Create more room for reducing total weight of the aircraft
  - Use six ply angles as design variables
  - Optimization was based on Big-Bang Big-Crunch algorithm with discrete design variables.
  - Can't change weight property, but can change strength property. Therefore, can create **tolerance** for future weight optimization run

Questions ?


Weight
Deflection, Stress, & Strain
D & DT
Structural Model Tuning
Buckling
Aerodynamic Model Tuning
Frequency & Mode Shape
Acoustic Load
Optimizer
Objective Function J & Constraints G(x)
Central Executive Module
Design Variables
Sonic Boom
Flutter & Divergence
NPSS
Gain/Phase Margins
Performance Indices
Script Commands
Lift & Drag
Curvilinear Sparibs
Landing & Taxiing
Adaptive Flexible Motion Control
Trim
CFD Based Flutter

Future Studies

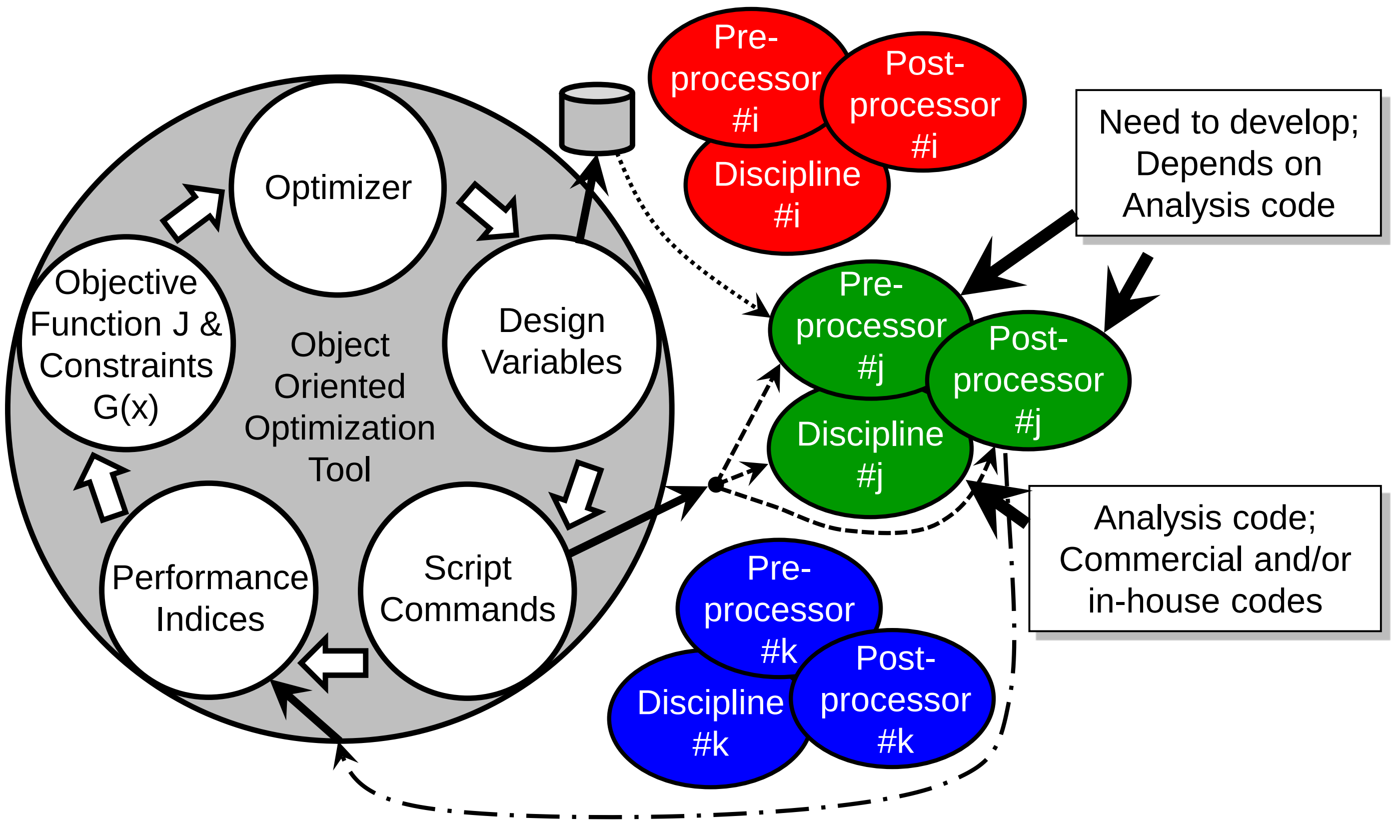
- Use lifting surface based aerodynamics
  - Use curvilinear sparibs to further reduce the weight of N+2 LSCT
    - Find % weight reduction through curvilinear sparibs technique
  - Add active control design variables
    - Use aeroelastic tailoring up to V_L
    - Use active control between V_L and $1.15V_L$
    - Find % weight reduction through game changing approach
- Use CFD based aerodynamics
  - Use more accurate air loads for optimizations

Backup: Object-Oriented MDO Tool

Object-Oriented MDO tool

- Optimization is based on in-house Object-Oriented Optimization tool
  - Equivalent to the following codes
    - Open MDAO, Model Center, Visual Doc, etc.
  - Four optimizer codes are available.
    - Gradient based algorithms (Local optimizers)
      - ✓ DOT
      - ✓ ADS
    - Global optimizers (Gradient free algorithms)
      - ✓ Genetic Algorithm
      - ✓ Big-Bang Big-Crunch Algorithm
- Update design pre-processor module
  - Update MSC/NASTRAN input file
- Modal analysis module
  - Perform modal analysis using MSC/NASTRAN sol. 103
  - Save following data
    - Total weight, CG location, mass moment of inertia
    - Frequencies & mode shapes and global mass matrix
- Weight post-processor module
  - Use MSC/NASTRAN sol 103 results for small weight.
    - MSC/NASTRAN results has number of digit issue.
  - Use in-house weight computation code for large weight.

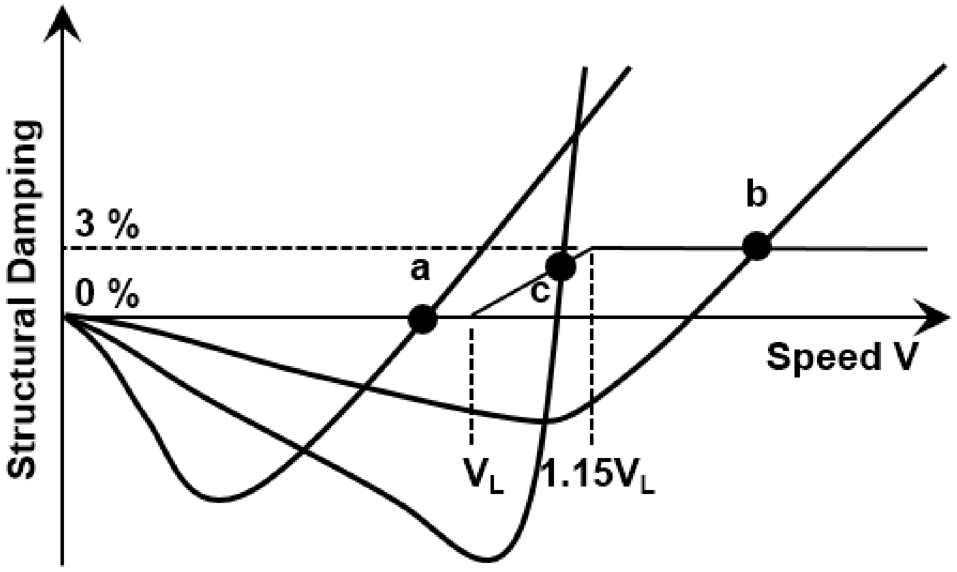
$$\mathrm{PI_W} = W_T$$



Object-Oriented MDO tool (continue)

- Flutter analysis and flutter post-processor modules
  - Use ZAERO code for flutter analyses
  - Use an in-house flutter speed tracking program

$V_F > 1.15V_L$ $\quad 1. - \frac{V_F}{1.15V_L} < 0.$ $\quad PI_F \equiv 1. - \frac{V_F}{1.15V_L}$



- Update ZAERO pre-processor, trim analysis, trim loads pre-processor modules
  - Update ZAERO input data
    - Based on total weight, CG locations, moment of inertias, and global mass matrix
  - Use ZAERO code for trim analysis
    - Create design loads for various design configurations
  - Post-process the splined loads
    - Create symmetric and anti-symmetric loads

- Landing and ground control loads pre-processor module
  - Compute corresponding design loads using in-house code
    - Landing loads
    - Ground control loads
    - Emergency landing loads

Object-Oriented MDO tool (continue)

- Buckling and strength analyses and strength post-processor modules
  - Based on MSC/NASTRAN sol. 105
  - Use in-house strength post-processor code
  - Safety factor of 1.5 is used for all metal and composite materials in this study.

$$\text{Design Load} \times \text{Safety Factor} < \text{Failure Load} \qquad 1 - \frac{\text{Failure Load}}{\text{Design Load} \times \text{Safety Factor}} < 0 \qquad \text{MS} \equiv \frac{\text{Failure Load}}{\text{Design Load} \times \text{Safety Factor}} - 1. \qquad \text{PI}_\text{s} \equiv -\min(\text{MS})$$

- Buckling post-processor module
  - Use in-house code
  - Buckling Load Factor (BLF) 0≤BLF≤1 : Buckling predicted BLF<0 or BLF>1: Buckling not predicted
    - Buckling predicted: $0 \leq \text{BLF} \leq 1 \Rightarrow -1/2 \leq \text{BLF} - 1/2 \leq 1/2 \Rightarrow (\text{BLF} - 1/2)^2 \leq (1/2)^2$
    - Buckling not predicted: $(\text{BLF} - 1/2)^2 > (1/2)^2 \Rightarrow (1/2)^2 - \left(\text{BLF} - \frac{1}{2}\right)^2 < 0.$

$$\text{PI}_\text{B} \equiv (1/2)^2 - \{\text{positive}\ \min(\text{BLF}) - 1/2\}^2$$