Jig-Shape Optimization of a Low-Boom Supersonic Aircraft

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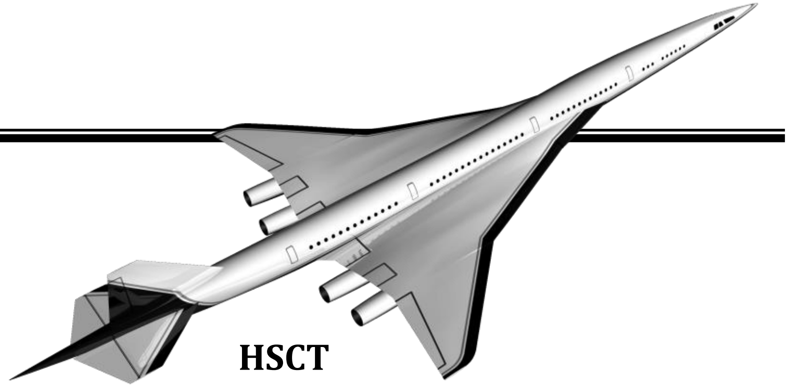
Overview

- Theoretical background (slides 3-10)
- Computational validation (slides 11-28)
- Conclusions (slide 29)

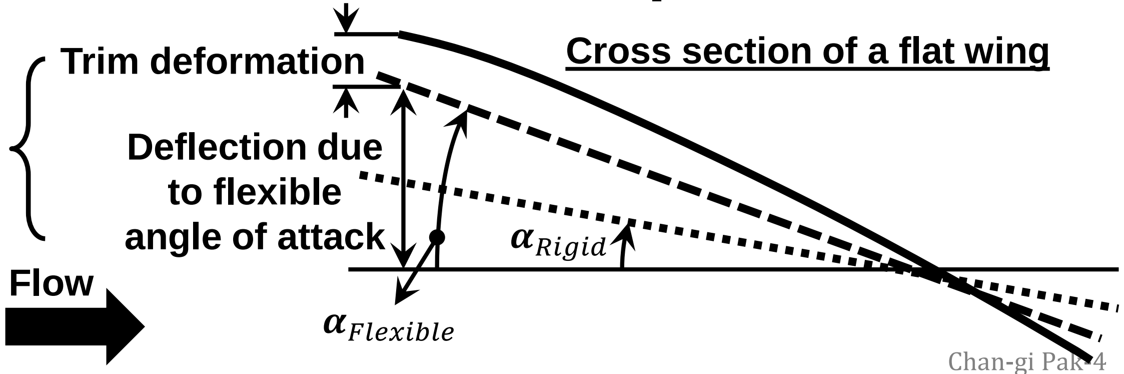
Theoretical background

Introduction



- Supersonic Commercial Transport Aircraft Design
  - Safety
    - Light weight airframe can cause strength, buckling, aeroelastic, and aeroservoelastic issues.
  - Sonic boom
    - Supersonic flight of "commercial transport" aircraft allowed only over the ocean.
    - Perceived Loudness in decibels
      - ✓ **NASA's N+2 goal: 75 PLdB**
      - ✓ Concorde: **104 PLdB**
      - ✓ High Speed Civil Transport (HSCT): **99 PLdB**
  - Fuel efficiency
    - Light weight airframe
    - Reduced drag
- Developing Low Boom Flight Demonstrator (LBFD)
  - Lockheed Martin Skunk Works was the prime contractor for preliminary design of X-plane.
  - **Loudness: 74 PLdB**
- Major Issue
  - Outer-mold-line configuration of an aircraft is design for the desired aerodynamic performance. Assume rigid structure.
  - Flexibility of the structure changes the aerodynamic performance.
  - It has been reported that one degree of the tip twist of a supersonic wing and stabilator under the cruise flight condition can increase the sonic boom level by 0.2 PLdB and 1.3 PLdB, respectively.

Low boom supersonic aircraft



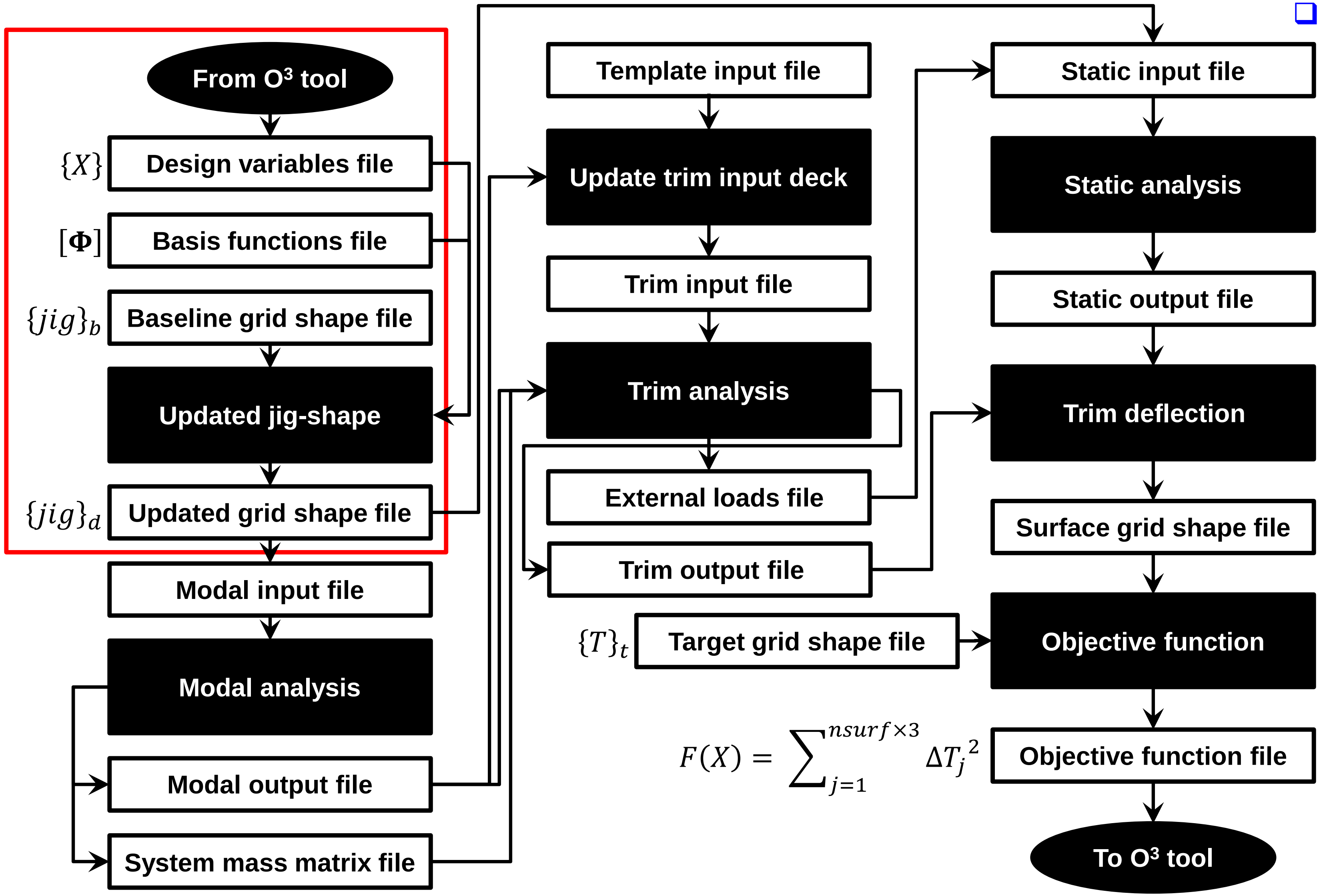
Jig-Shape Optimization Problem Statement

- Assume unconstrained Optimization
- Optimization Problem Statement
  - Find design variables: $\{X\} = \lfloor X_{1,} X_{2,} \ldots, X_{ndv} \rfloor^T$ which

$$minimize \left\{ F(X) = \sum_{j=1}^{nsurf\times 3} \Delta T_j^{\ 2} \right\}$$

  - $\{\Delta T\} \equiv \{T\}_t - \{T\}_d$
  - $\{T\}_t$= target trim shape at surface GRIDs
    - Sonic boom level is computed based on target trim shape.
  - $\{T\}_d$= trim shape based on design jig shape
    - $\{jig\}_d \xRightarrow[trim\ analysis]{} \{T\}_d$
    - $\{jig\}_d \equiv \{jig\}_b + \{\Delta jig\}$
      - ✓ $\{jig\}_d$= design jig-shape
      - ✓ $\{jig\}_b$= baseline jig-shape
      - ✓ $\{\Delta jig\}$= jig-shape changes
    - $\{\Delta jig\} = [\mathbf{\Phi}]\{X\}$
      - ✓ X_i= i-th design variable
      - ✓ $[\mathbf{\Phi}] = [\{\phi\}_1 \{\phi\}_2 \ldots \{\phi\}_{ndv}]$
        - $\{\phi\}_i$ = i-th basis function
          - Eigen vector based on jig shape
          - Eigen vectors are normalized as Max deflection = 1 inch.

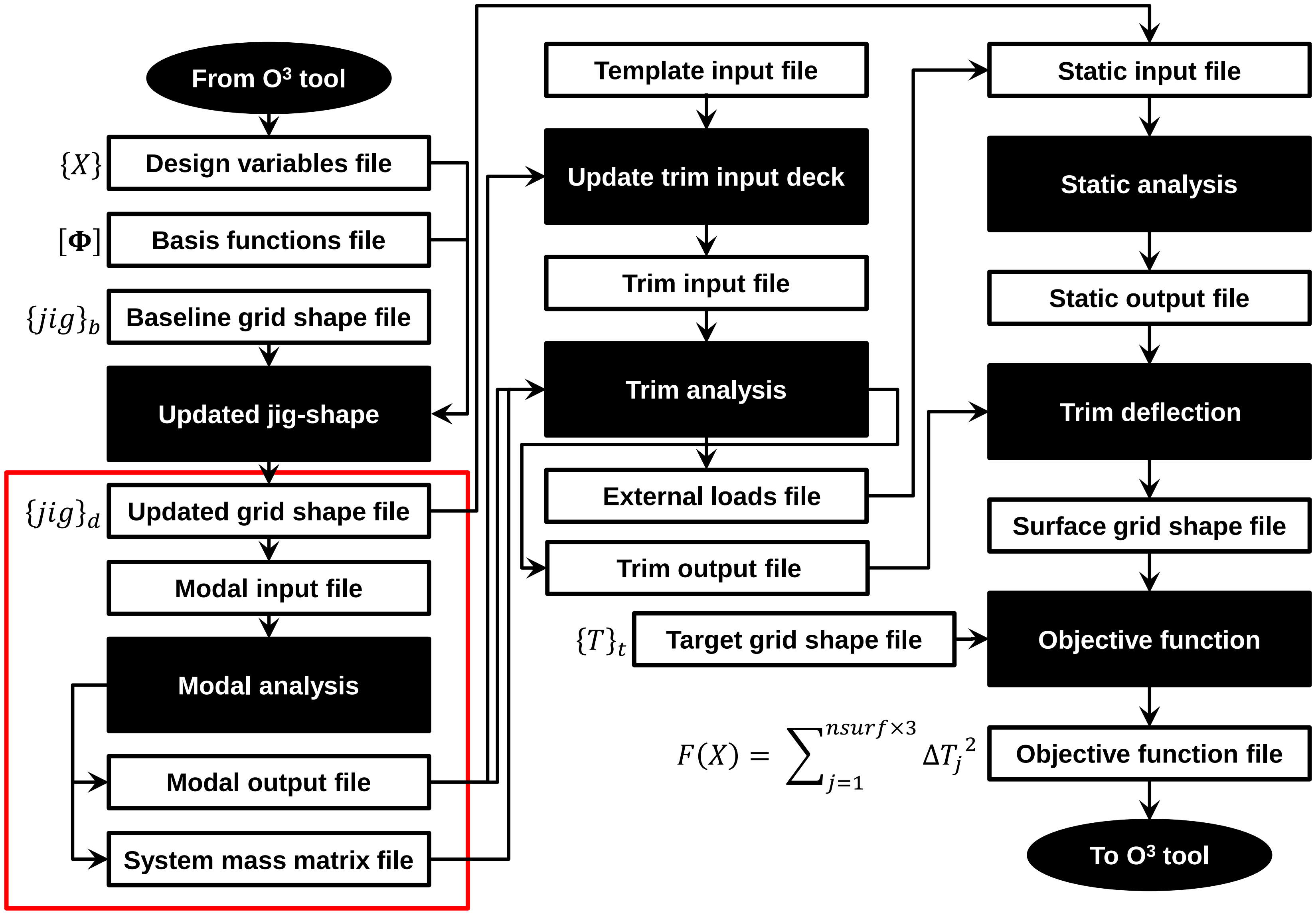
Update Jig-Shape Module: using shape_change.exe



- **Shape_change.exe**: Change jig shape using design variables and basis functions.
  - $\{jig\}_d \equiv \{jig\}_b + [\boldsymbol{\Phi}]\{X\}$
  - Input
    - Design variables file $\{X\}$: basis functions for the shape optimization (basis_functions.dat)
    - Basis functions file $[\boldsymbol{\Phi}]$: design variables of the current optimization step (design_var)
    - Baseline grid shape file $\{jig\}_b$: grid information of the baseline configuration (grid_base.bdf; a template file)
  - Output
    - Updated grid shape file $\{jig\}_d$: grid information of the updated configuration (grid_update.bdf)

Change jig shape using design variables & basis functions.

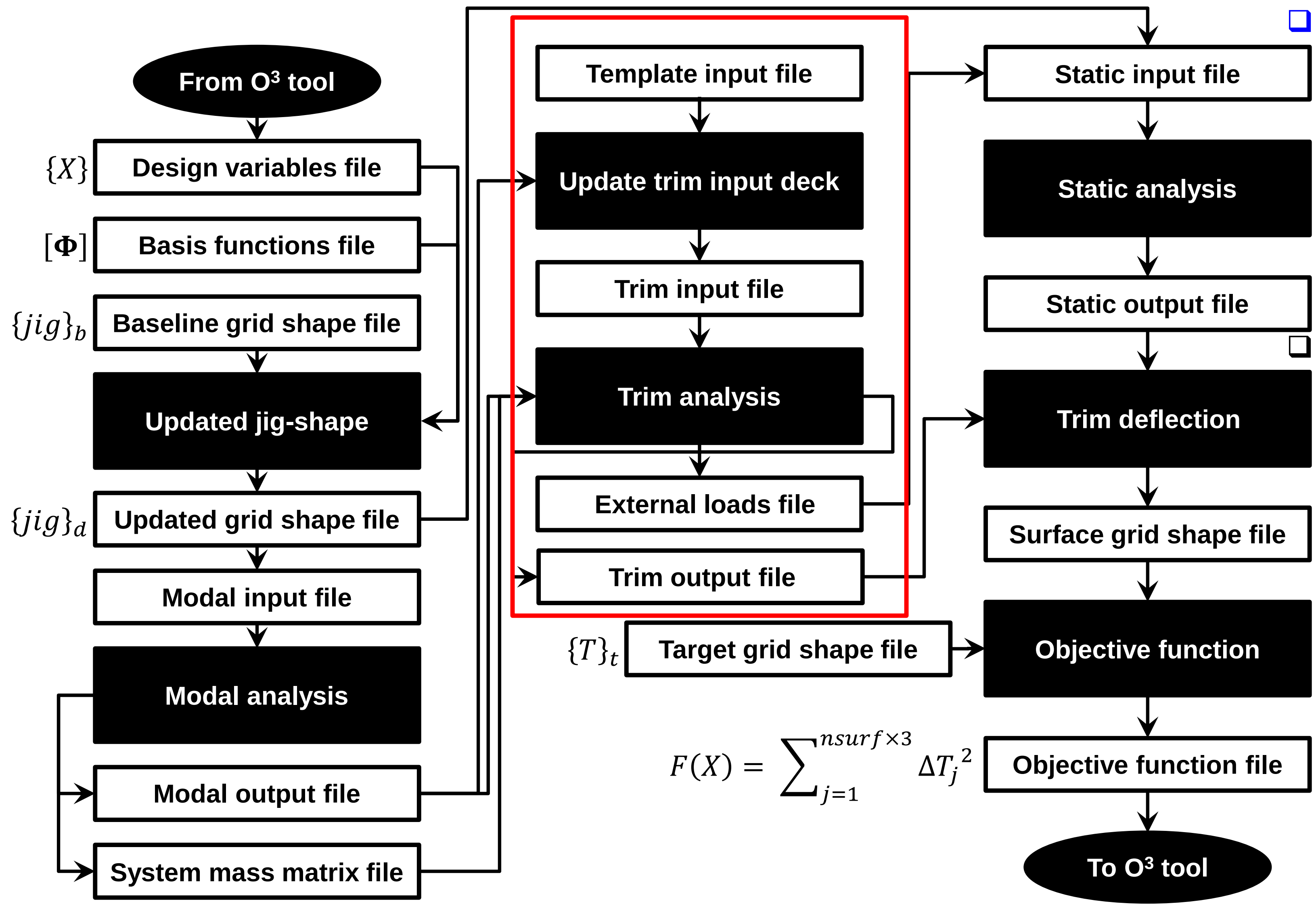
Modal Analysis Module: using MSC/NASTRAN solution 103



- Perform modal analysis using **MSC/NASTRAN solution 103** to change system mass matrix file (MGH matrix), weight, moment of inertia, and CG location for trim analysis.
- Compute six rigid body modes.

Change mode shapes, weight, moment of inertia, & CG location for trim analysis.

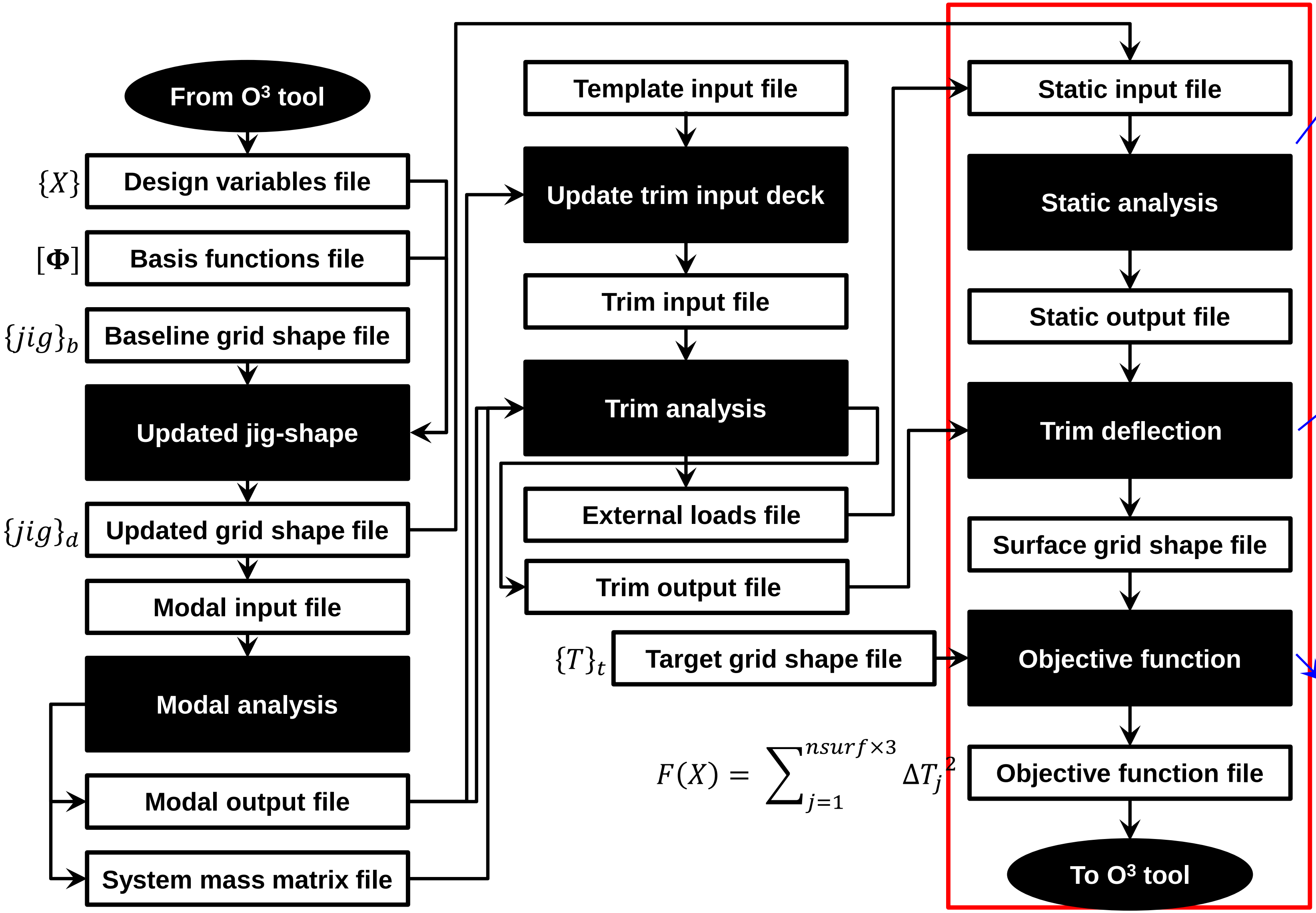
Trim Analysis Module: using ZAERO & change_trim.exe



- **Change_trim.exe**: Update input deck for ZAERO trim analysis.
  - Input
    - Template input file: file for ZAERO based trim analysis (Lbfd_trim.bdf)
    - Modal output file: f06 file from MSC/NASTRAN
  - Output
    - Trim input file: updated ZAERO input file to be used for trim analysis (trim.bdf)
- Perform trim analysis using **ZAERO**
  - Input
    - Trim input file: Trim.bdf
  - Output
    - External loads file: aerodynamic load + inertial load (Extload.dat)
    - Trim output file: ZAERO output (trim results)

Compute external load using ZAERO code.

Objective Function Module: using MSC/NASTRAN solution 101, shape.exe, & differ.exe



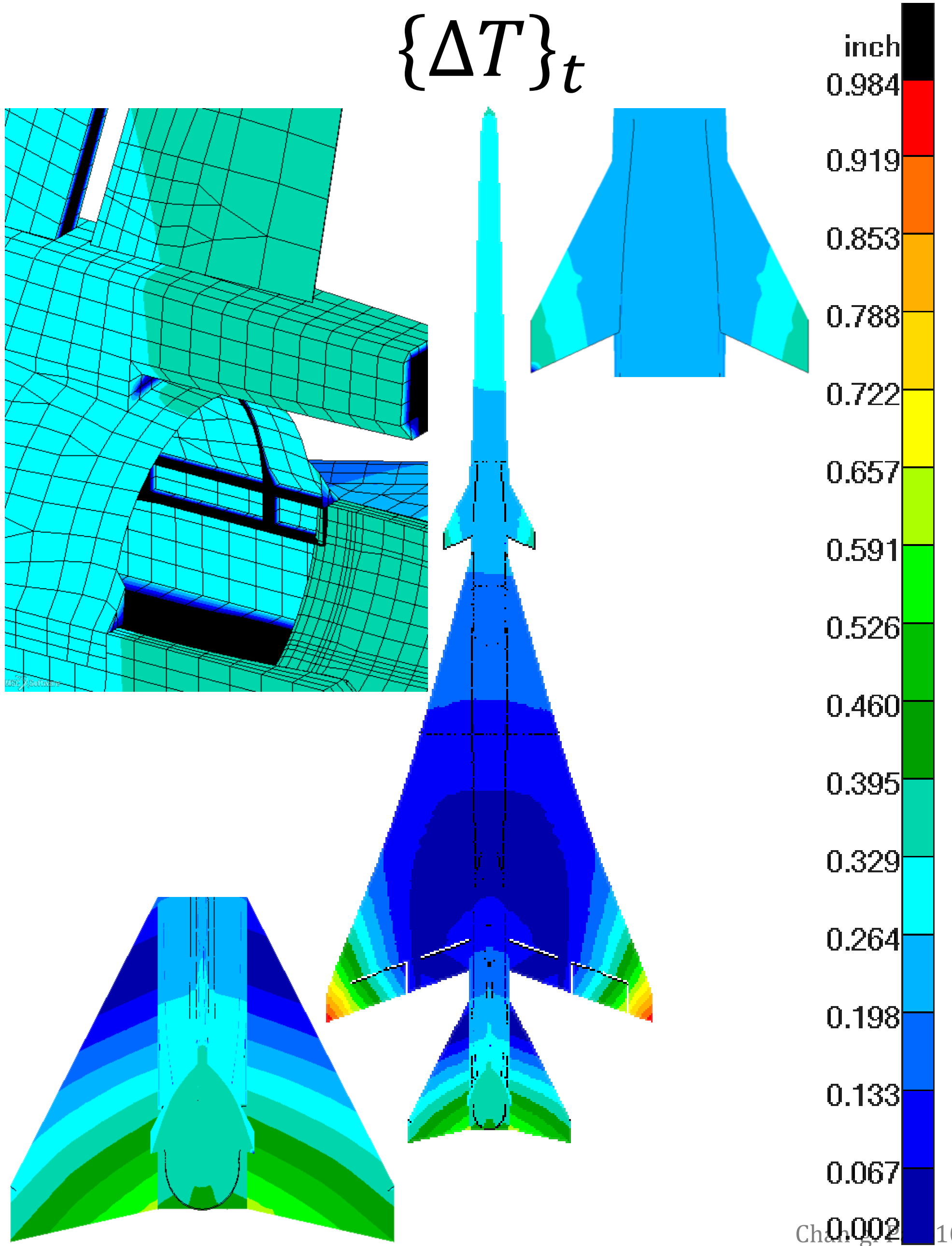
$$F(X) = \sum_{j=1}^{nsurf\times 3} \Delta T_j^{\,2}$$

- **Perform static analysis** using inertia relief. (**MSC/NASTRAN sol. 101**)
  - Input
    - Static input file: external loads file and updated grid shape file are included in this file
  - Output
    - Static output file: MSC/NASTRAN output file, ~f06 file.
- **Trim_deflection.exe**: read deflected shape.
  - Input
    - Static output file: MSC/NASTRAN output from sol. 101
    - Trim output file: ZAERO output file (read trim results)
  - Output
    - Surface grid shape file: grid geom. + rigid rotation + deformed shape (@ all grids; Shape.dat)
- **Differ.exe**: compute objective function value
  - Input
    - Surface grid shape file
    - Target grid shape file: $\{T\}_t$ @ surface grid
  - Output
    - Objective function file: performance index for objective function; $F(X)$

Compute trim deformation using MSC/NASTRAN solution 101 using inertia relief.

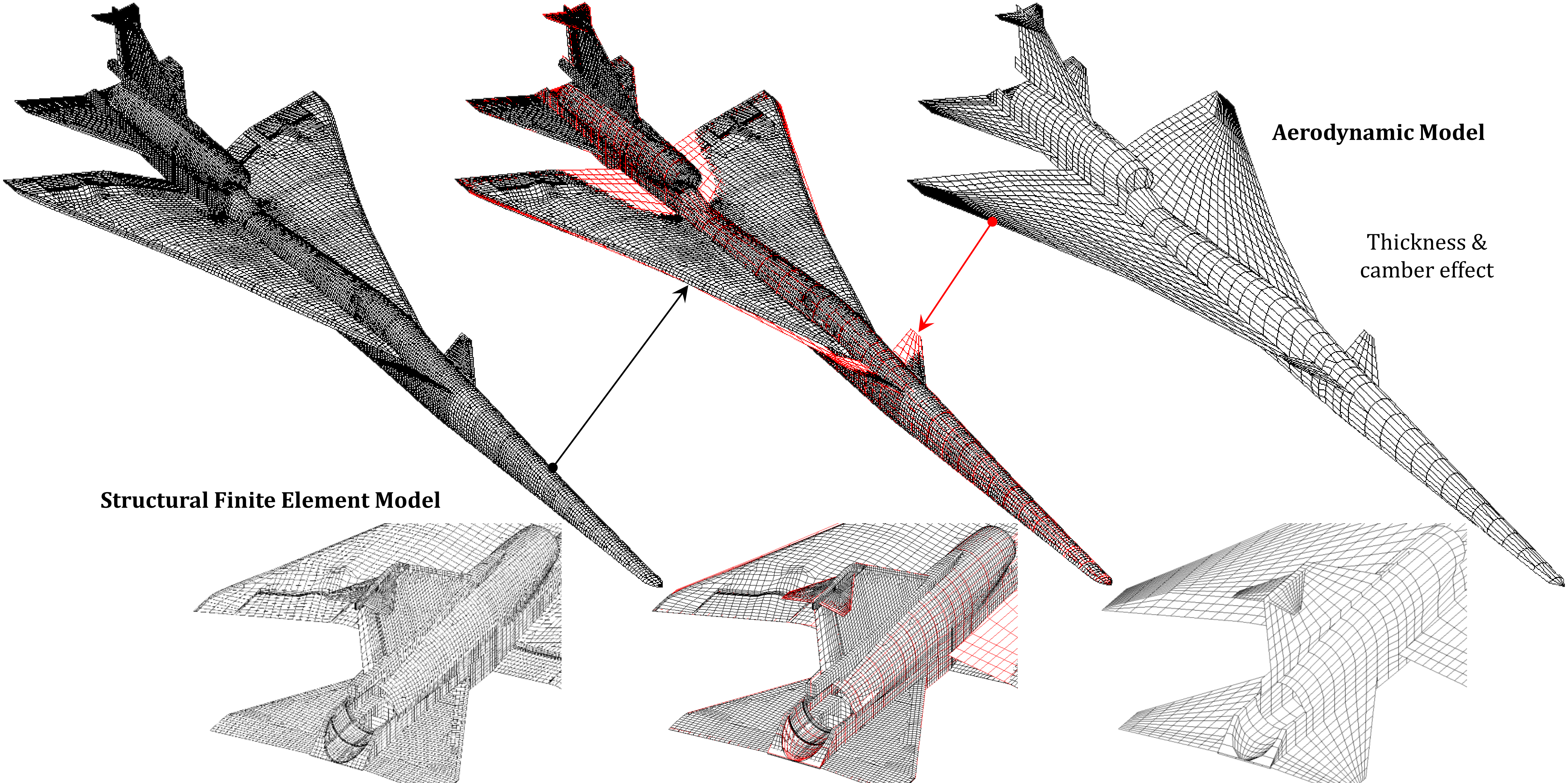
Compute Starting Design Variables: Using Least Squares Surface Fitting Technique

- $\{\Delta T\}_t \equiv \{T\}_t - \{T\}_b$
  - $\{T\}_t$= target trim shape at surface GRIDs
  - $\{T\}_b$= trim shape based on the baseline jig-shape
    - $\{jig\}_b \xrightarrow[trim\ analysis]{} \{T\}_b$
- Fitting $\{\Delta T\}_t$ surface using perturbed shapes $\{\Delta T\}_i, i = 1, 2, \dots, ndv$
  - Perturb baseline jig-shape using basis functions $[\mathbf{\Phi}]$
    - $\{jig\}_d \equiv \{jig\}_b + [\mathbf{\Phi}]\{X\}$
    - Where, $\{\phi\}_i$= i-th basis function
    - $\{jig\}_b + \{\phi\}_i \xrightarrow[trim\ analysis]{} \{T\}_i$
    - $\{\Delta T\}_i \equiv \{T\}_i - \{T\}_b$ (i-th perturbed shape)
  - Define a matrix: $[\boldsymbol{\Psi}] = [\{\Delta T\}_1 \{\Delta T\}_2 \dots \{\Delta T\}_{ndv}]$
- $[\boldsymbol{\Psi}]\{X\} = \{\Delta T\}_t$
  - $[\boldsymbol{\Psi}]^T[\boldsymbol{\Psi}]\{X\} = [\boldsymbol{\Psi}]^T\{\Delta T\}_t$
  - $([\boldsymbol{\Psi}]^T[\boldsymbol{\Psi}])^{-1}[\boldsymbol{\Psi}]^T[\boldsymbol{\Psi}]\{X\} = ([\boldsymbol{\Psi}]^T[\boldsymbol{\Psi}])^{-1}[\boldsymbol{\Psi}]^T\{\Delta T\}_t$
- Starting design variables: $\{X\} = ([\boldsymbol{\Psi}]^T[\boldsymbol{\Psi}])^{-1}[\boldsymbol{\Psi}]^T\{\Delta T\}_t$



Computational validation

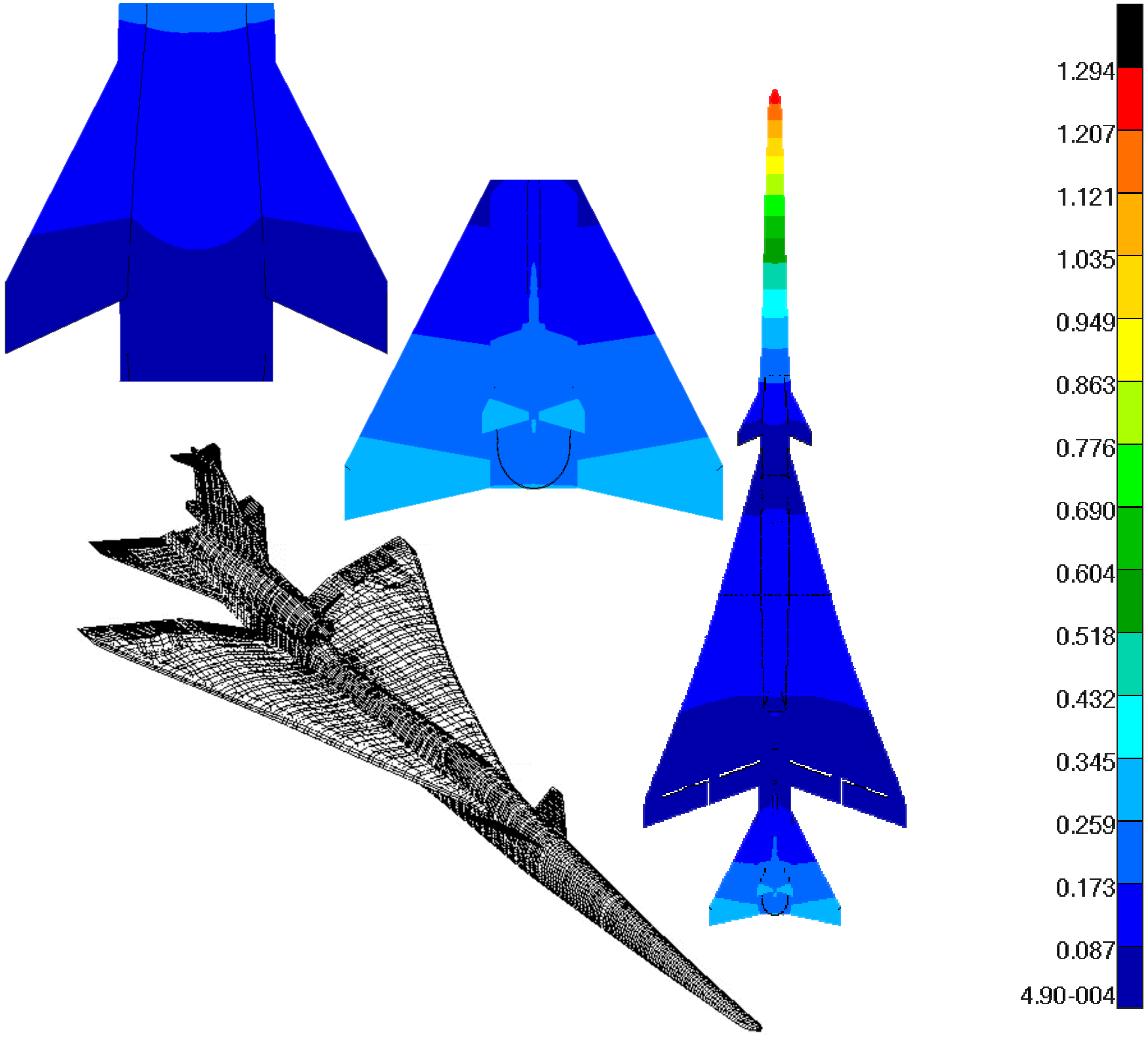
Structural Finite Element Model and Aerodynamic Model



Summary of Natural Frequencies (Baseline Configuration)

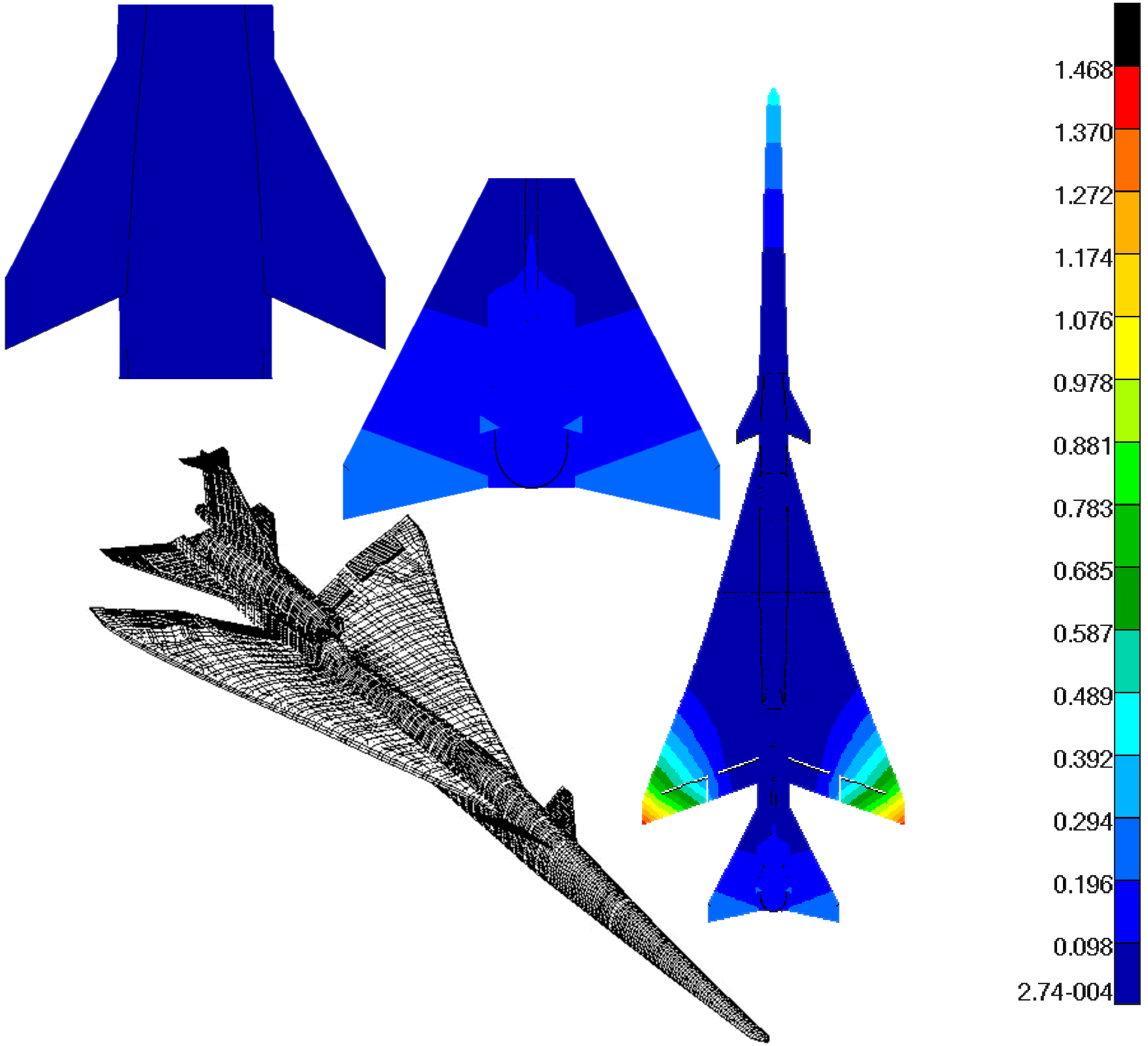
Mode	Frequency (Hz)			Notes
	Baseline	Optimum	% difference	
7	5.634	5.633	-0.02	First fuselage bending
9	9.045	9.032	-0.14	First wing bending + forward fuselage vertical bending + stabilator rotation
11	11.97	11.97	0.00	Forward fuselage vertical bending + first wing bending + stabilator rotation (**Asymmetric**)
15	14.76	14.76	0.00	Stabilator rotation
17	19.23	19.22	-0.05	Wing tip bending + T-tail rotation + flap bending (**Asymmetric**)
19	20.08	20.08	0.00	T-tail rotation (**Asymmetric**)
20	20.54	20.55	0.05	Wing tip bending + T-tail rotation + aileron rotation + flap bending + forward fuselage vertical bending (**Asymmetric**)
22	21.75	21.76	0.05	Aileron rotation + flap rotation + T-tail bending + outboard wing bending torsion
23	22.16	22.16	0.00	Flap rotation + aileron rotation + wing tip bending + T-tail bending (**Asymmetric**)
25	22.70	22.70	0.00	Flap rotation + aileron rotation + T-tail bending (**Asymmetric**)
37	30.79	30.75	-0.13	Canard bending
48	42.96	42.97	0.02	T-tail bending (**Asymmetric**)

Mode 7: 5.634 Hz



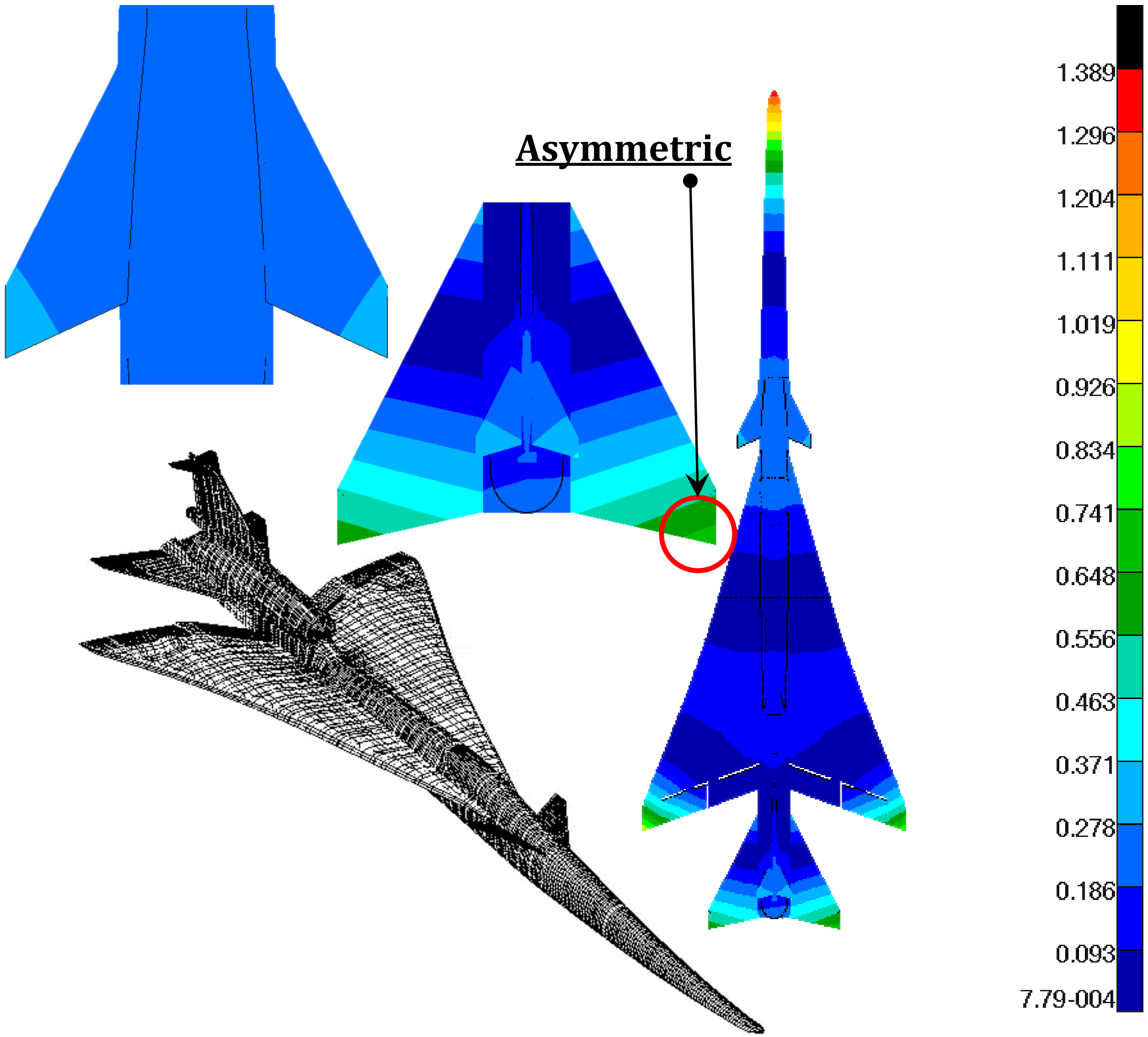
first fuselage vertical bending

Mode 9: 9.045 Hz



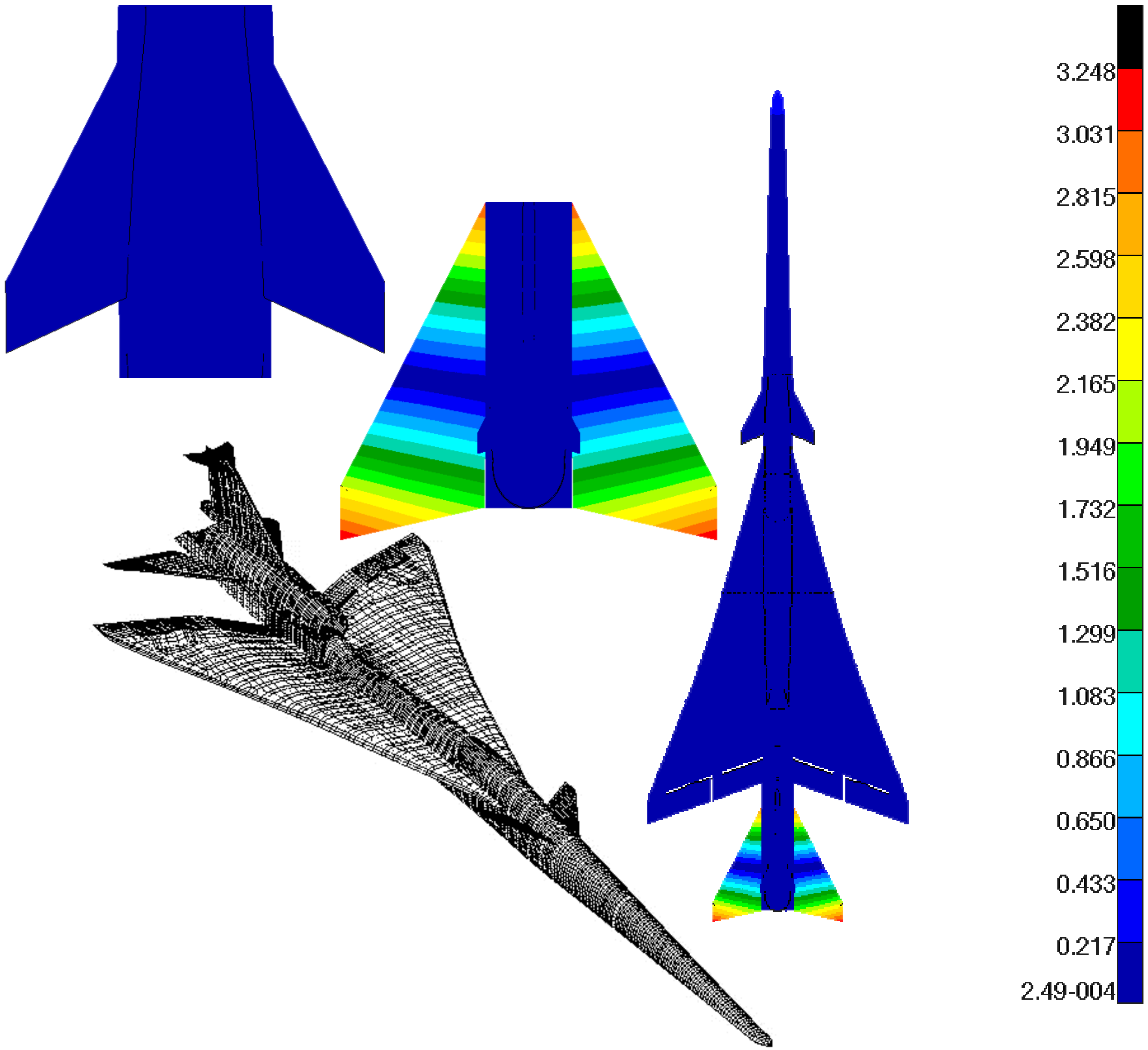
Symmetric first wing bending + forward fuselage vertical bending + horizontal tail rotation (in-phase: forward fuselage & wing)(out-phase: wing and horizontal tail)

Mode 11: 11.97 Hz



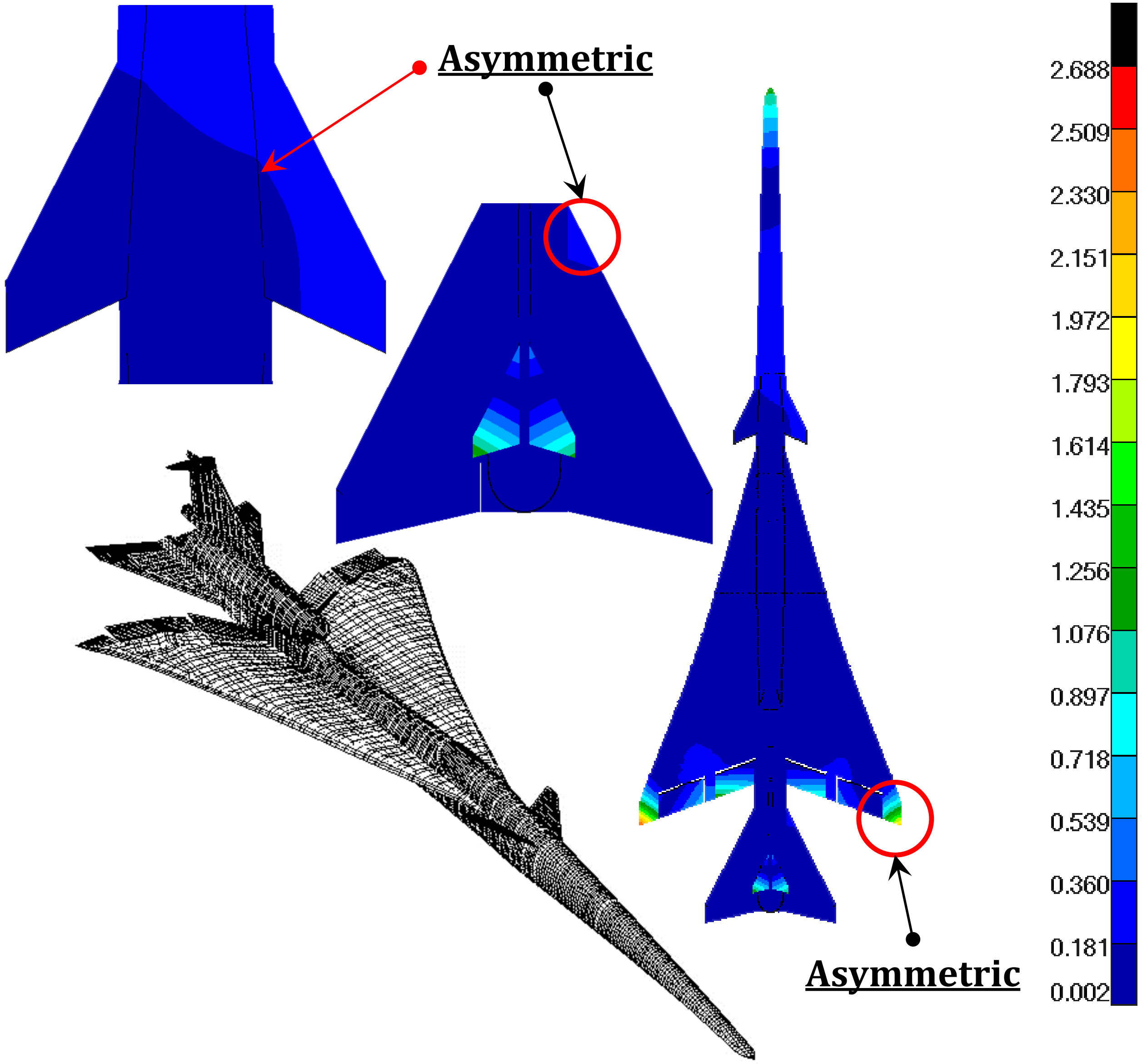
Symmetric first wing bending + forward fuselage vertical bending + horizontal tail rotation (out-phase: forward fuselage & wing)(in-phase: wing and horizontal tail)

Mode 15: 14.76 Hz



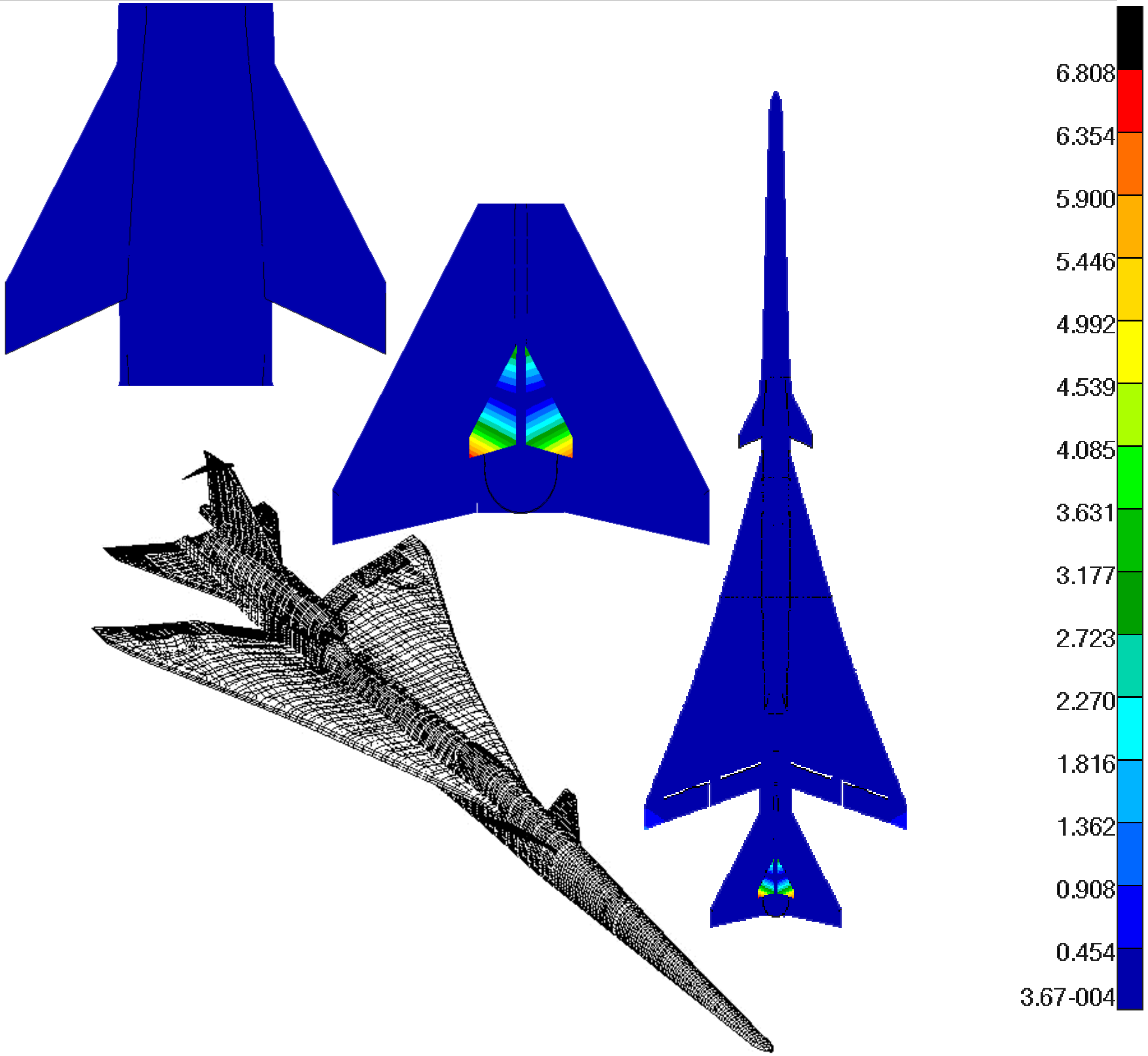
Symmetric horizontal tail rotation

Mode 17: 19.23 Hz



symmetric wing tip bending+Ttail rotation + flap

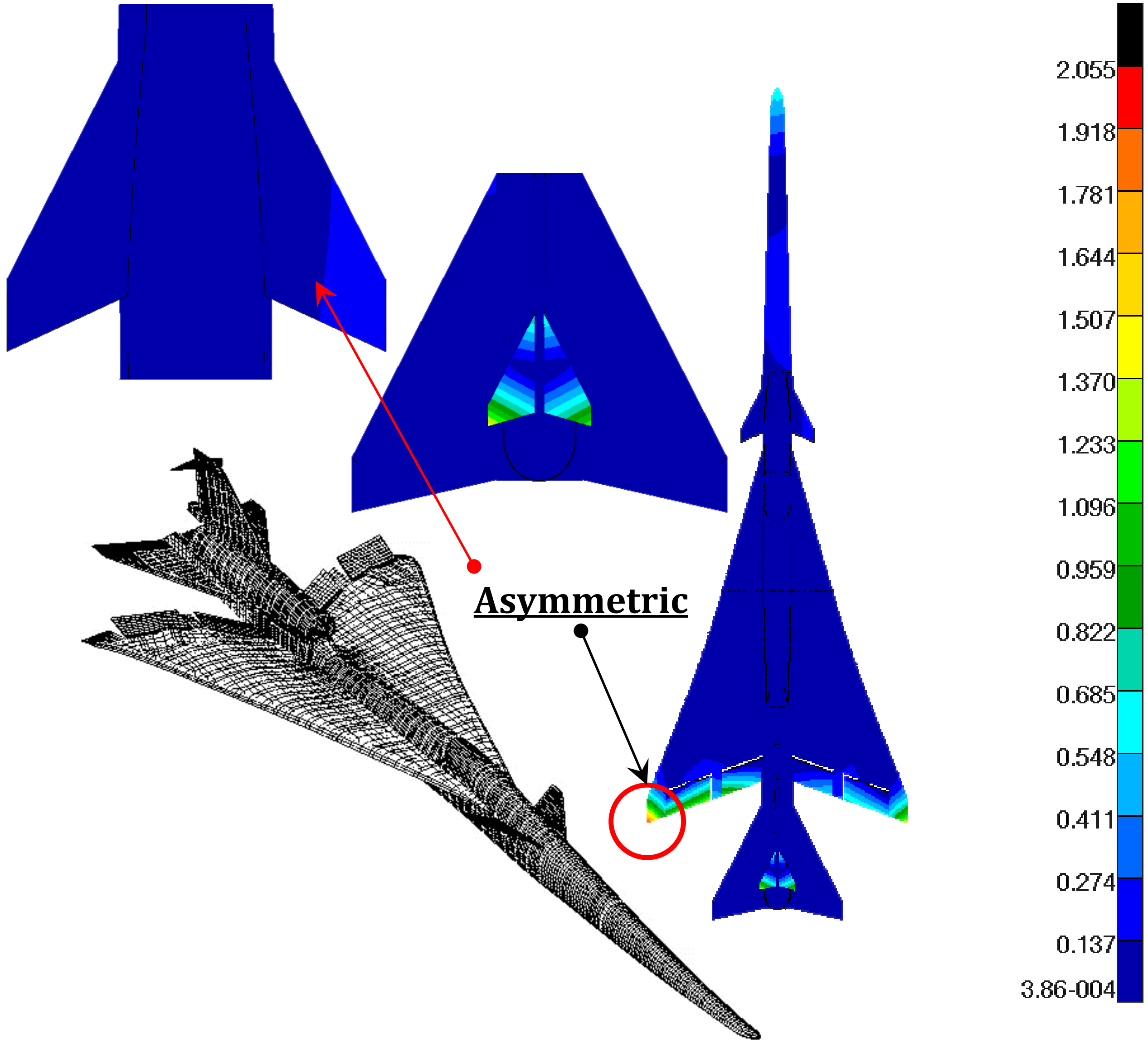
Mode 19: 20.08 Hz



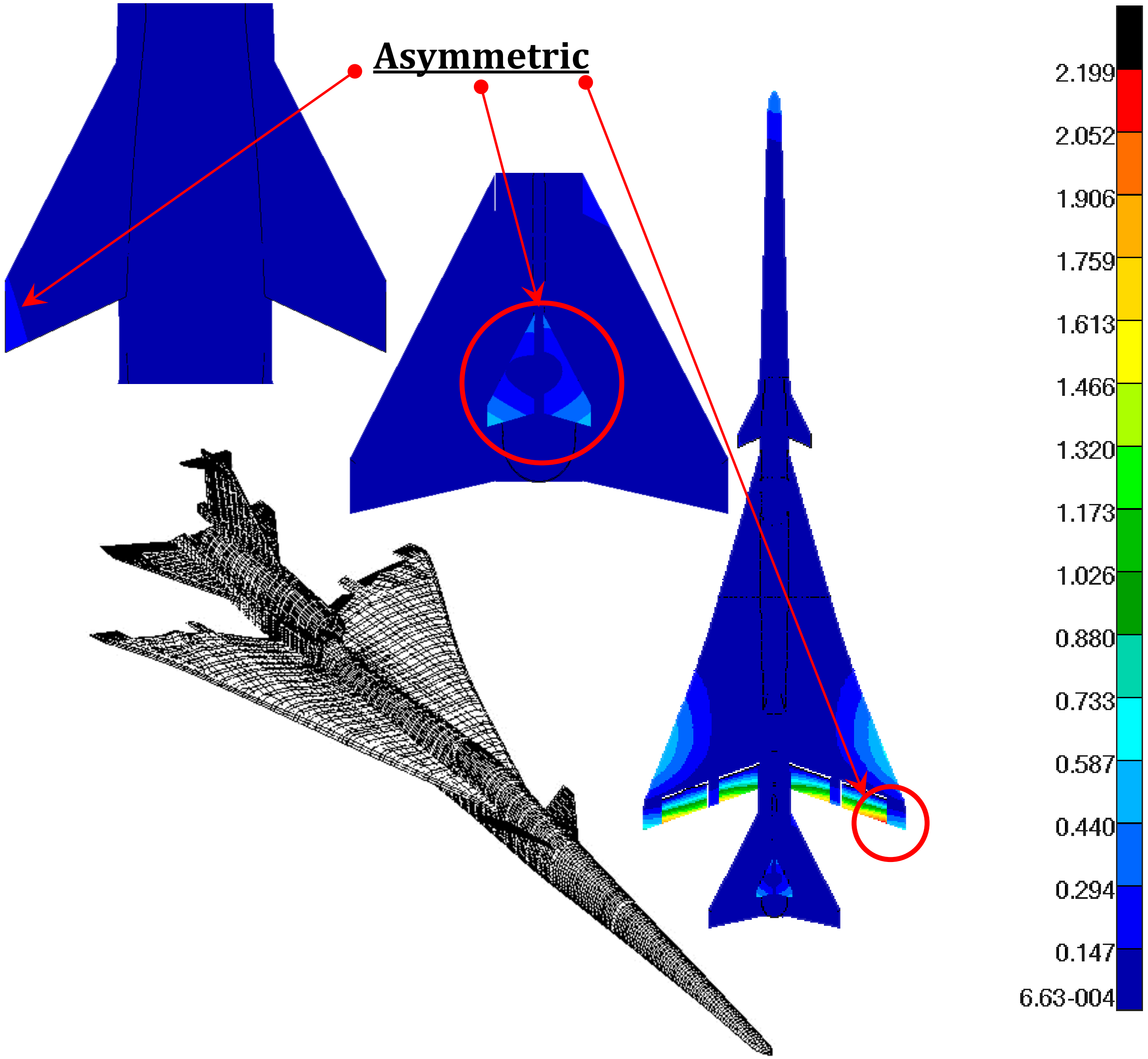
symmetric ttail rotation

Mode 20: 20.54 Hz

Mode 22: 21.75 Hz

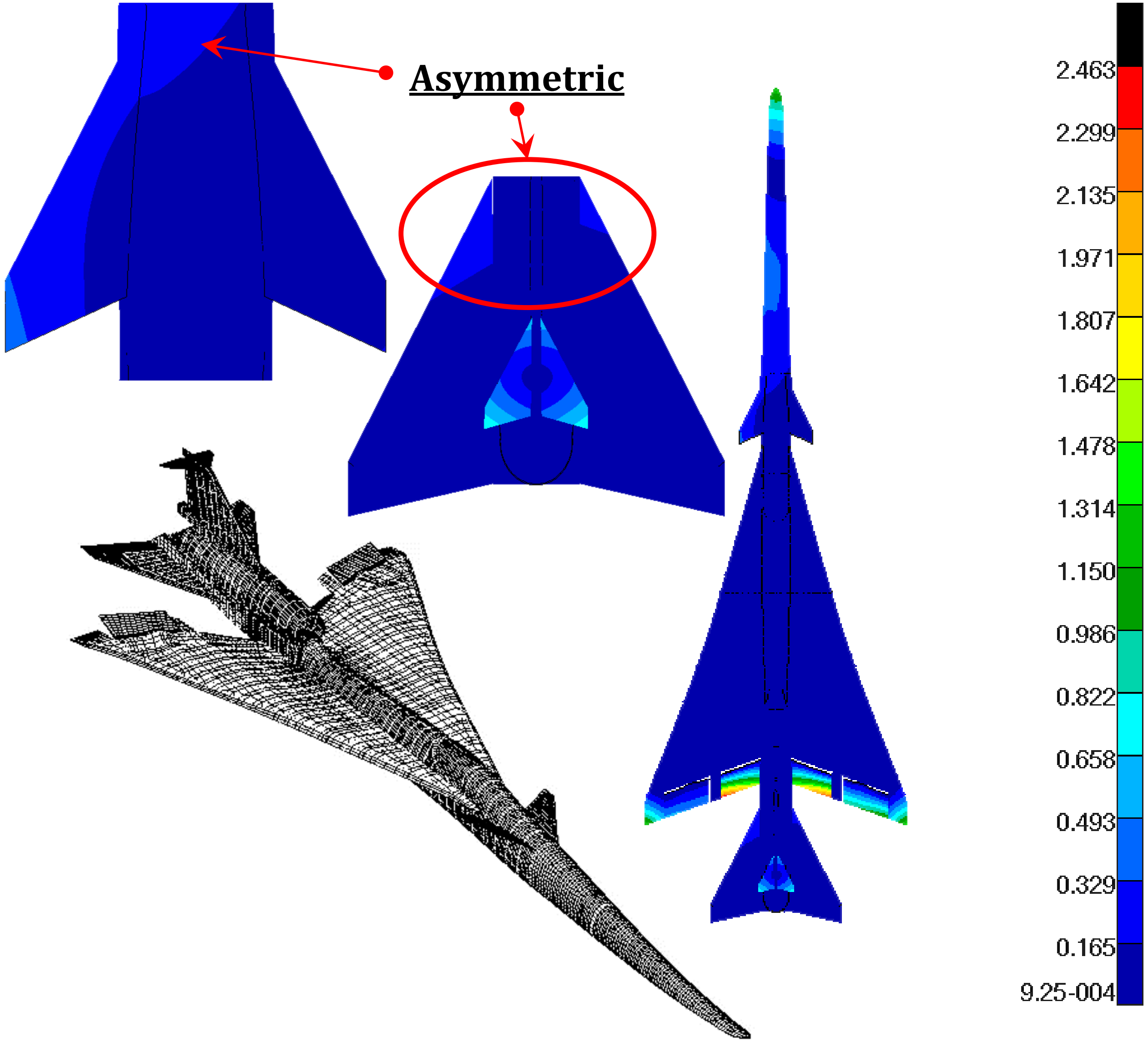


symmetric wing tip bending + ttail rotation flap & airleron rotation + forward fuselage bending + nose landing gear vertical bending (out-phase wing tip & forward fuselage) (out phase wing tip & ttail)



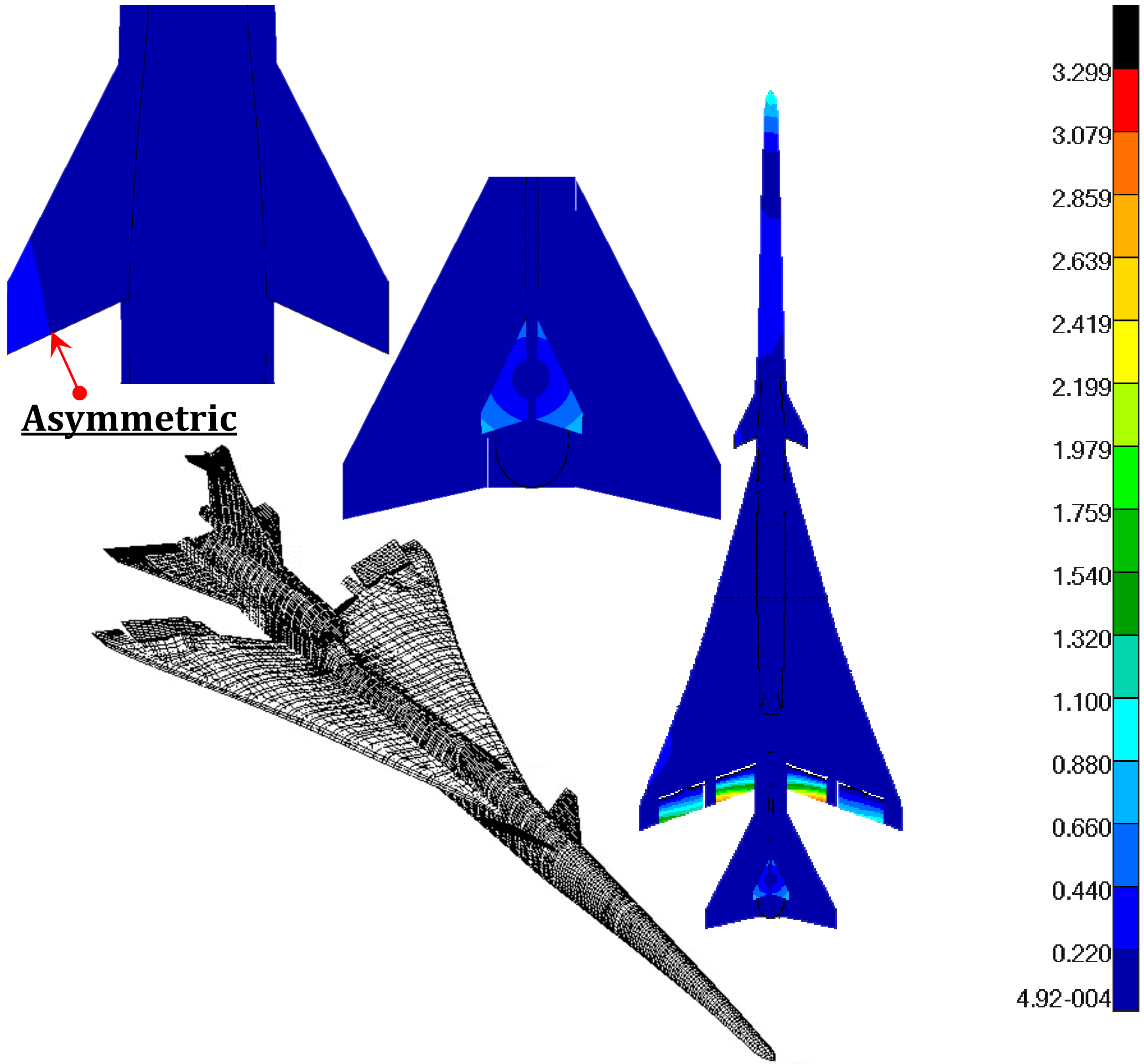
symmetric airleron + flaperon (in-phase)+ttail(pitch +yaw)

Mode 23: 22.16 Hz



symmetric Flaperon+airleron (out-phase) +ttail(pitch+yaw) +forward fulage and airleron(in-phase)

Mode 25: 22.70 Hz

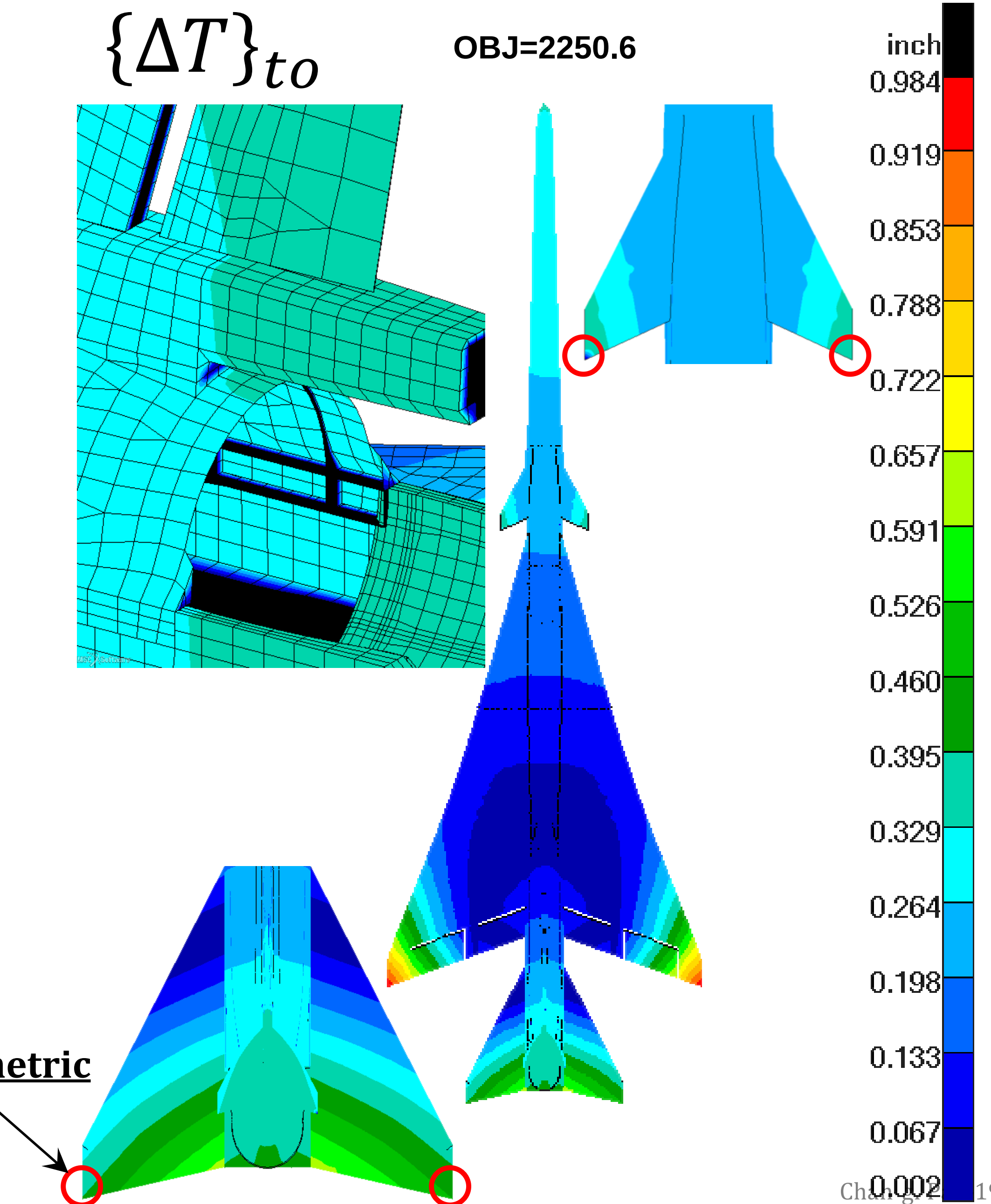


symmetric flaperon+airleron (out-phase)+ttail(pitch+yaw) + forward fulage and airleron(out-phase)

Trim Shape Difference (Baseline Configuration)

- Weight:
  - Cruise = 18500.00 lbf
- Forward CG location
  - x=836.09 inch, **y=-0.1897 inch**, z=100.68 inch
- Mach: 1.42
- Altitude: 55000 ft
- Aileron deflection angle: 0.0 deg
- T-tail deflection angle: 0.0 deg
- $\{\Delta T\}_{to} \equiv \{T\}_t - \{T\}_o$
  - $\{T\}_t$= target trim shape at surface GRIDs
  - $\{T\}_o$= trim shape based on optimum jig shape
    - ✓ $\{jig\}_o \equiv \{jig\}_b + [\boldsymbol{\Phi}]\{X\}_o$
    - ✓ $\{jig\}_o \xRightarrow[trim\ analysis]{} \{T\}_o$

X_i	Value
1	0.0
2	0.0
3	0.0
4	0.0
5	0.0
6	0.0
7	0.0
8	0.0
9	0.0
10	0.0
11	0.0
12	0.0
13	0.0
14	0.0
15	0.0
16	0.0

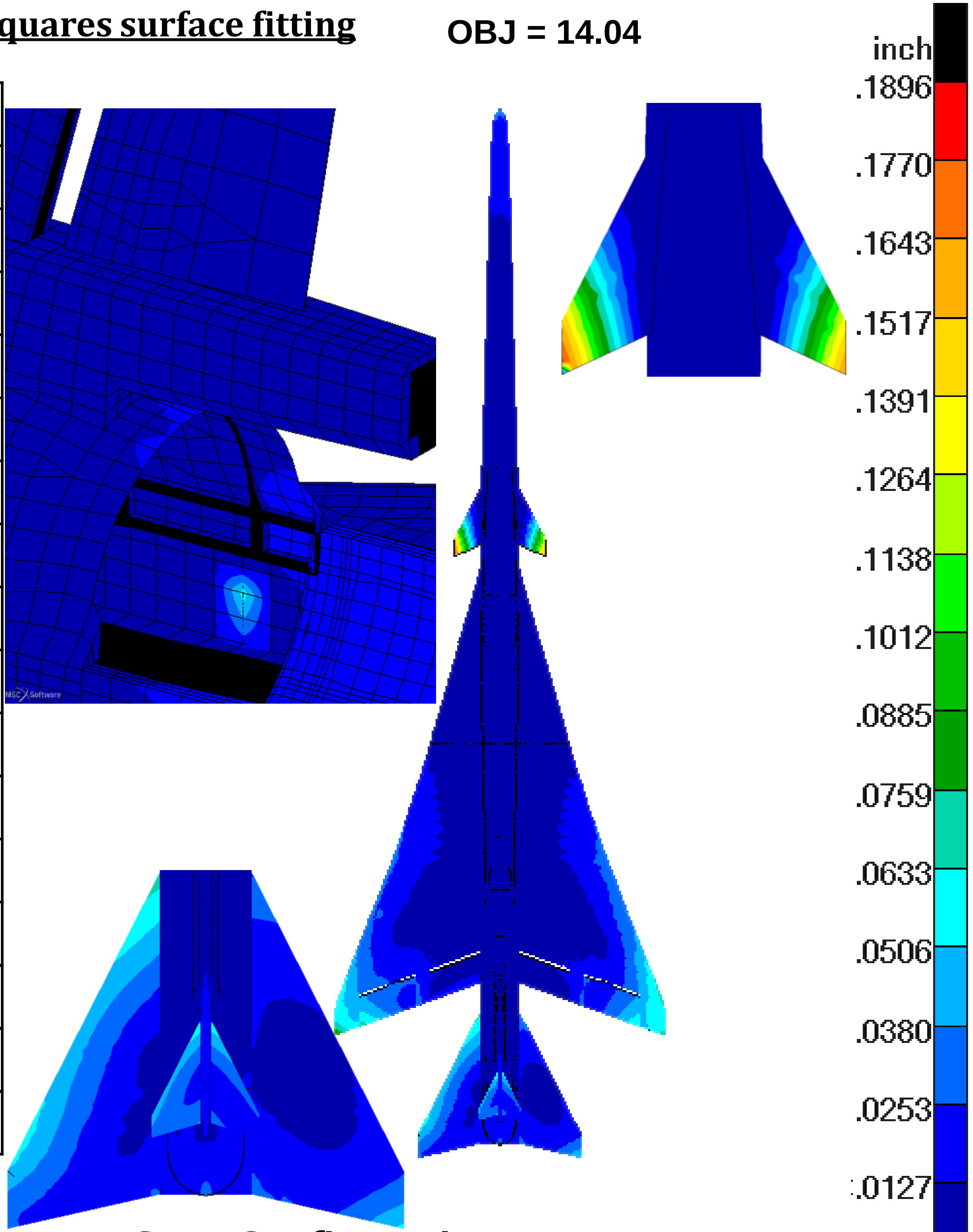


Optimization #1: $\{\Delta T\}_{to} = \{T\}_t - \{T\}_o$

Use least-squares surface fitting

OBJ = 14.04

X_i	Value
1	-0.5795
2	-1.5063
3	-1.4565
4	0.4108
5	-1.0492
6	0.2851
7	1.2202
8	.04660
9	0.1273
10	.05808
11	-.02754
12	-.00712
13	0.1212
14	
15	
16	

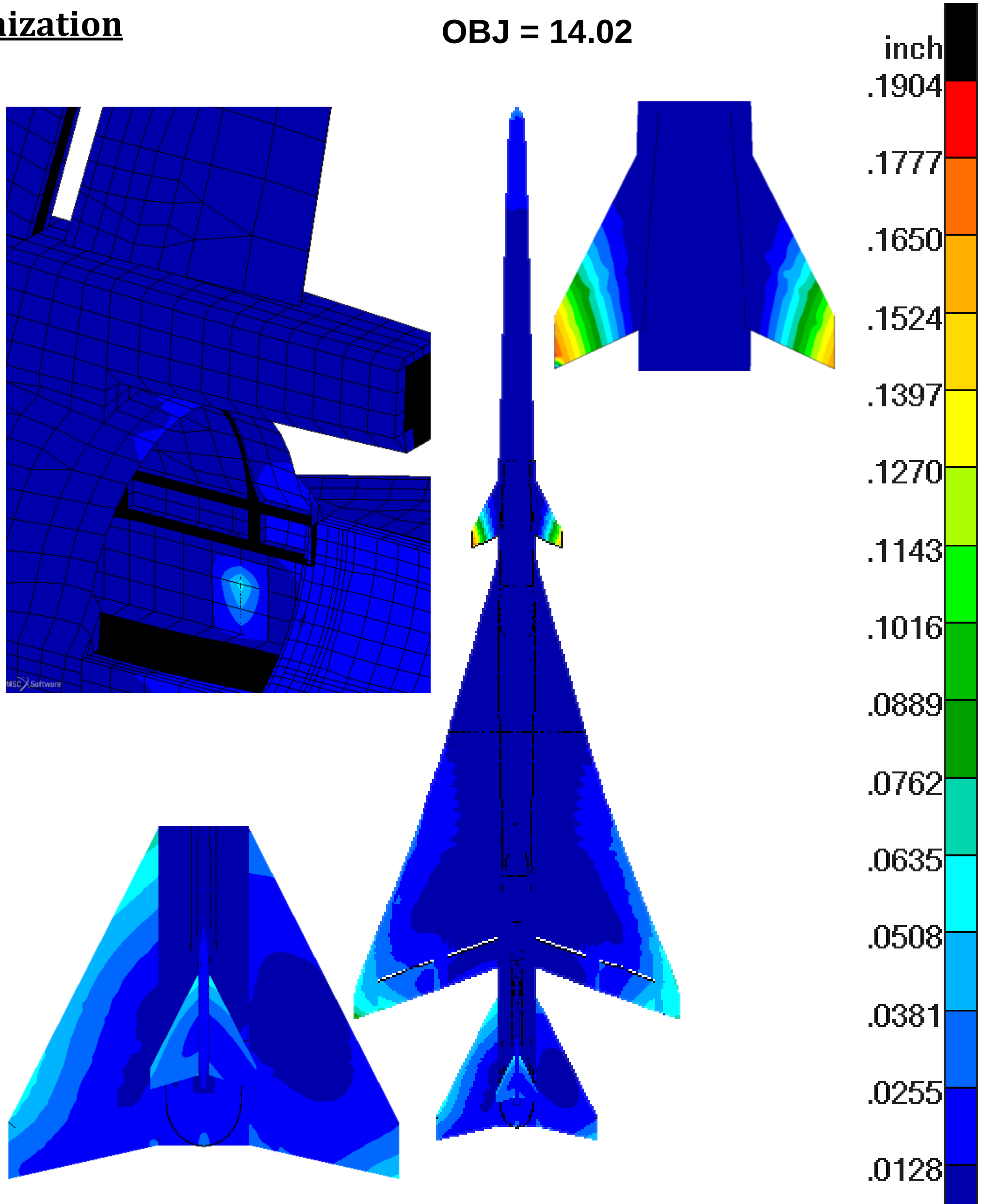


Start Configuration

Use Optimization

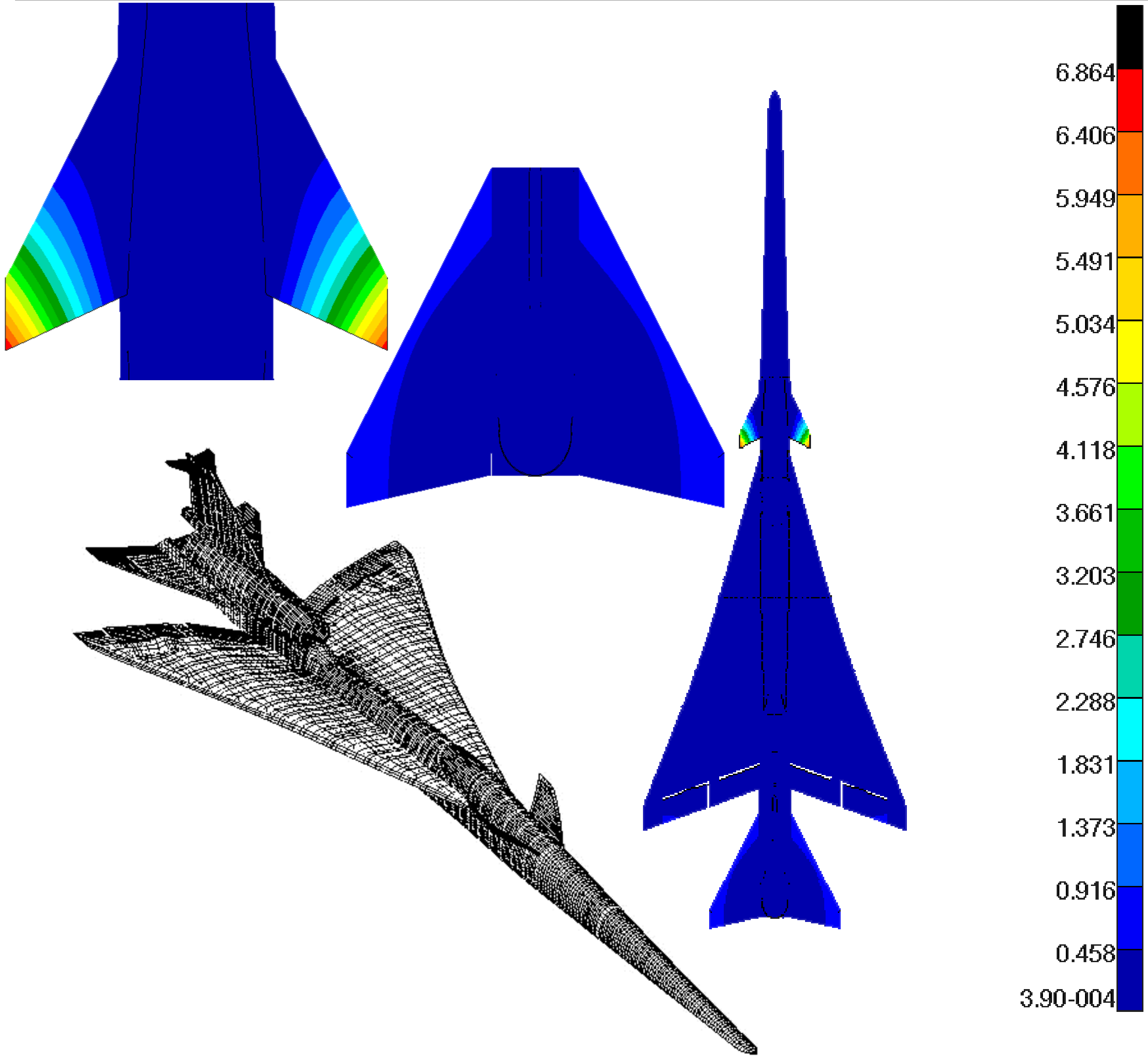
OBJ = 14.02

X_i	Value
1	-0.5776
2	-1.5078
3	-1.4574
4	0.4106
5	-1.0495
6	0.2848
7	1.2190
8	.04569
9	0.1275
10	.05803
11	-.02746
12	-.00697
13	0.1211
14	
15	
16	



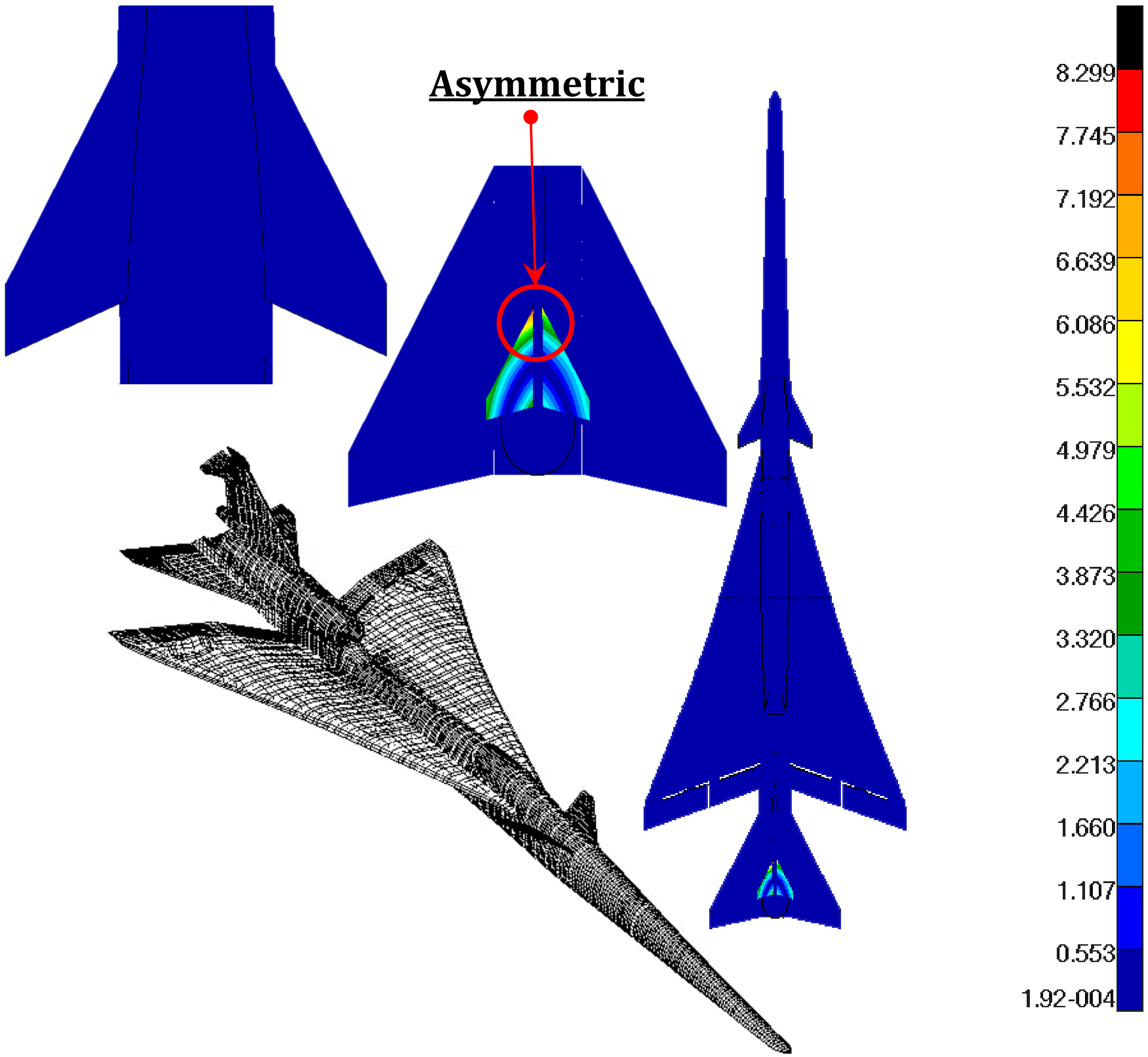
Optimum Configuration

Mode 37: 30.79 Hz



symmetric canard bending

Mode 48: 42.96 Hz



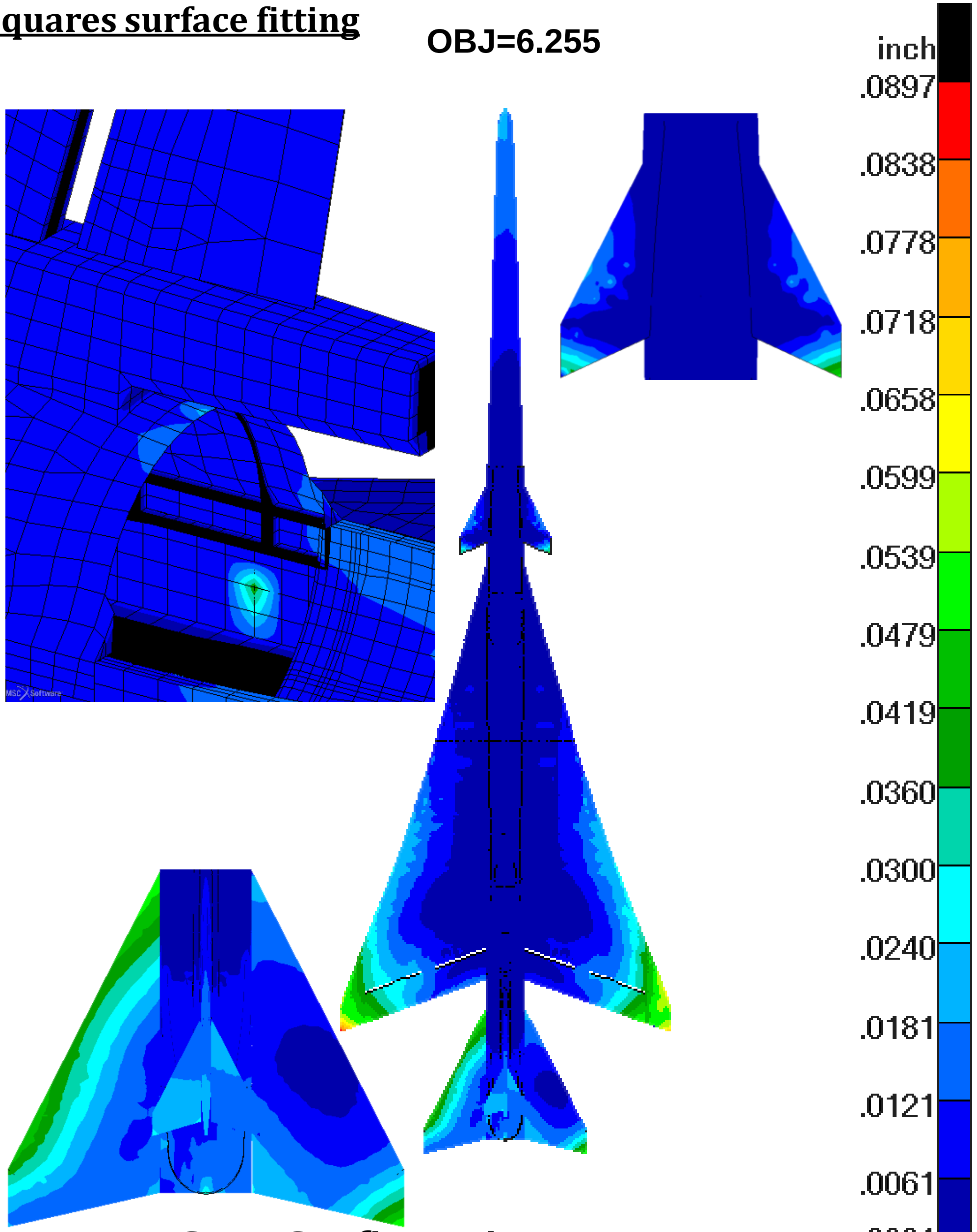
symmetric ttail

Optimization #2: $\{\Delta T\}_{to} = \{T\}_t - \{T\}_o$

Use least-squares surface fitting

OBJ=6.255

X_i	Value
1	-0.5783
2	-1.3482
3	-1.3008
4	0.4226
5	-1.0585
6	0.2544
7	1.0823
8	.00555
9	0.1242
10	.02061
11	-.04842
12	-.02884
13	0.1055
14	0.2174
15	-.07665
16	

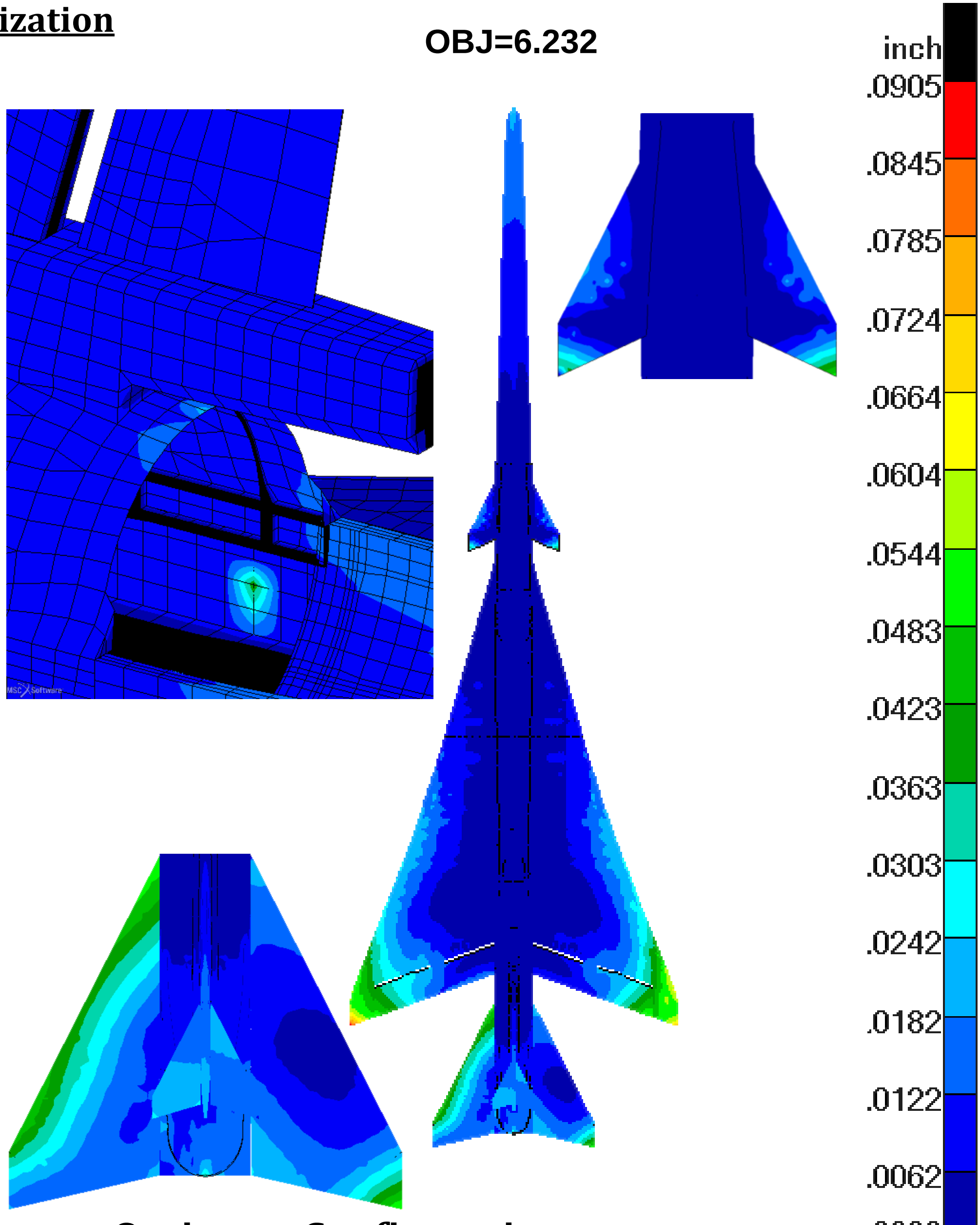


Start Configuration

Use Optimization

OBJ=6.232

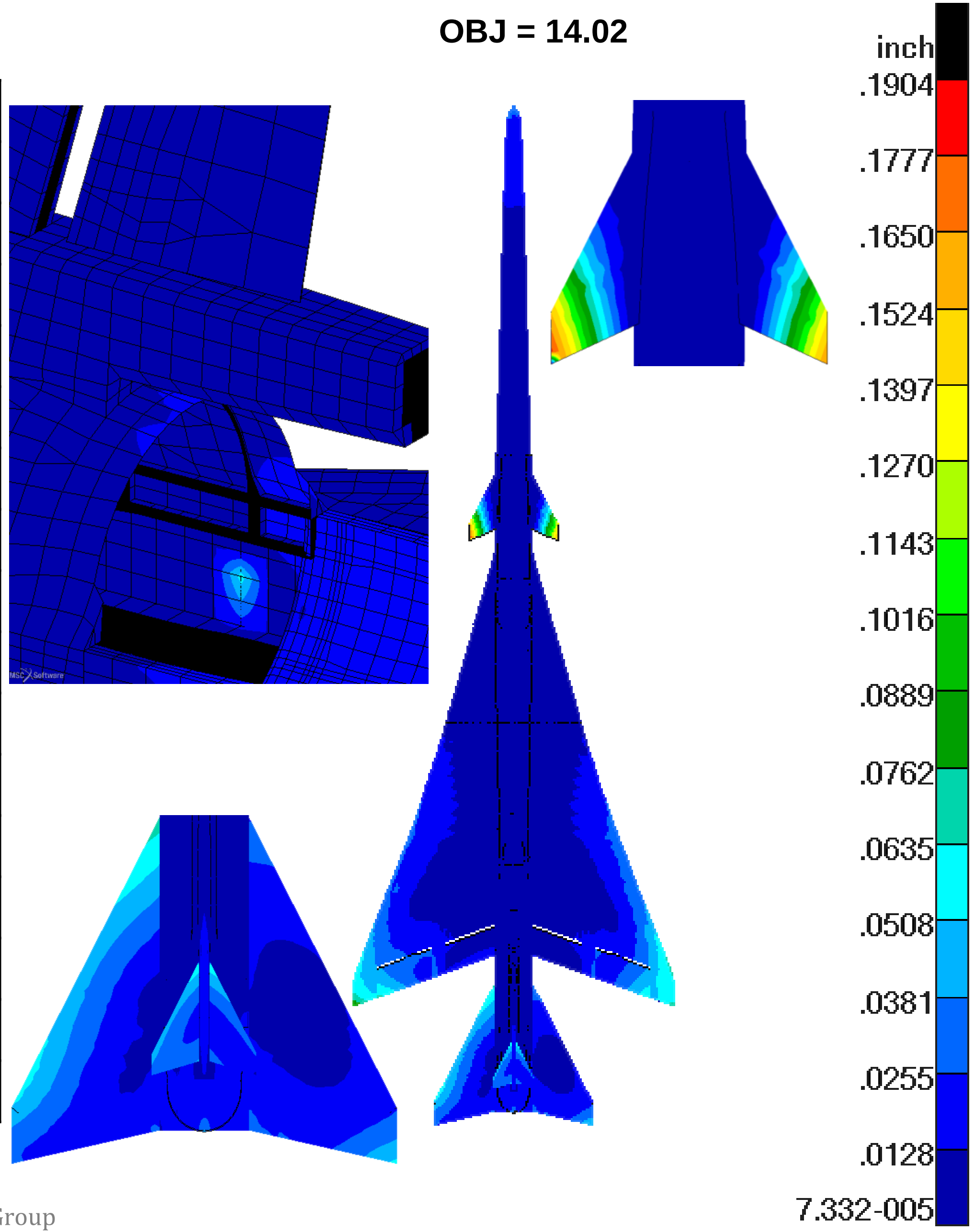
X_i	Value
1	-0.5759
2	-1.3489
3	-1.3013
4	0.4228
5	-1.0587
6	0.2541
7	1.0814
8	.00513
9	0.1243
10	.02058
11	-.04848
12	-.02907
13	0.1056
14	0.2172
15	-.07671
16	



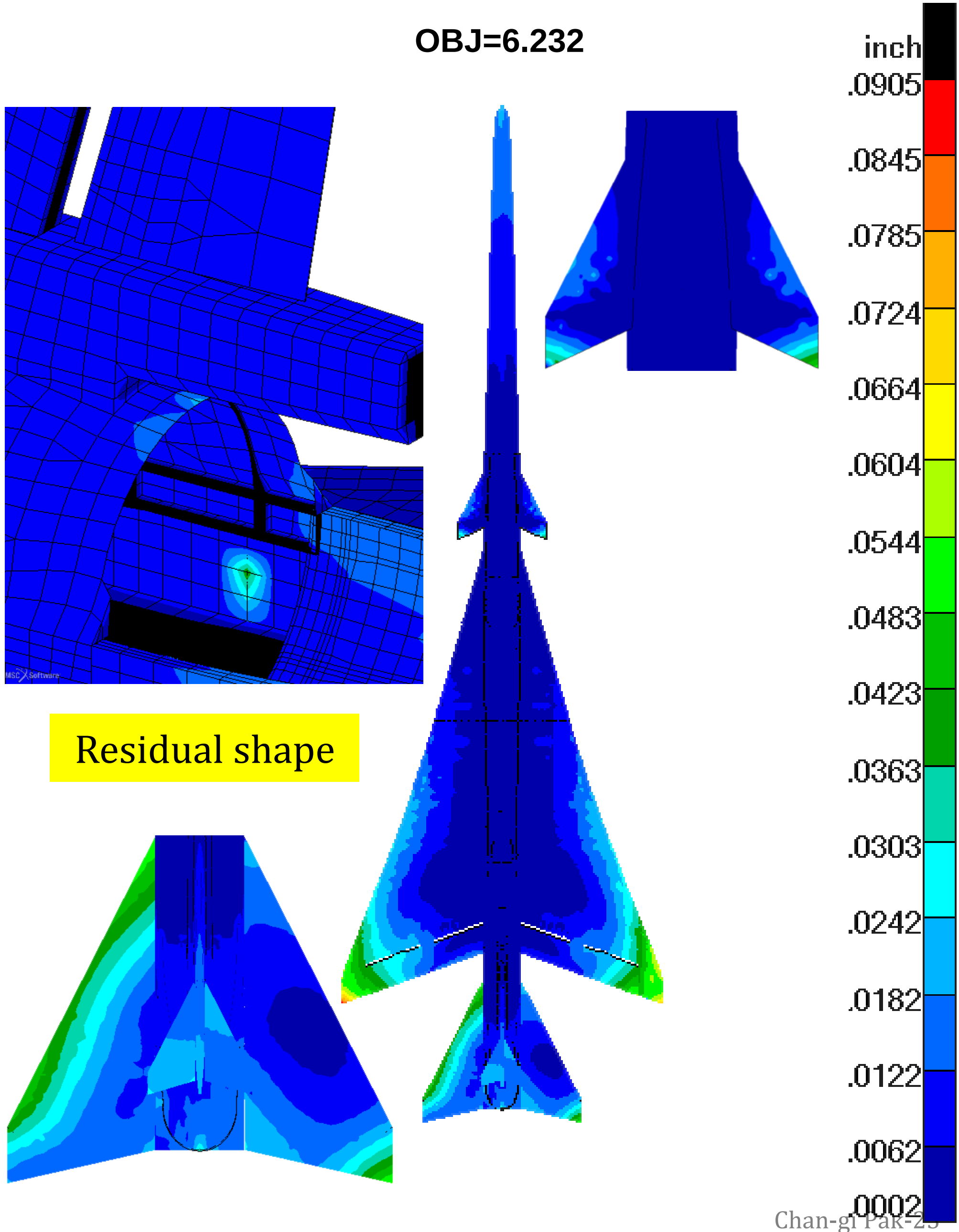
Optimum Configuration

Optimization #1 vs. Optimization #2

X_i	Value
1	-0.5776
2	-1.5078
3	-1.4574
4	0.4106
5	-1.0495
6	0.2848
7	1.2190
8	.04569
9	0.1275
10	.05803
11	-.02746
12	-.00697
13	0.1211
14	
15	
16	



X_i	Value
1	-0.5759
2	-1.3489
3	-1.3013
4	0.4228
5	-1.0587
6	0.2541
7	1.0814
8	.00513
9	0.1243
10	.02058
11	-.04848
12	-.02907
13	0.1056
14	0.2172
15	-.07671
16	

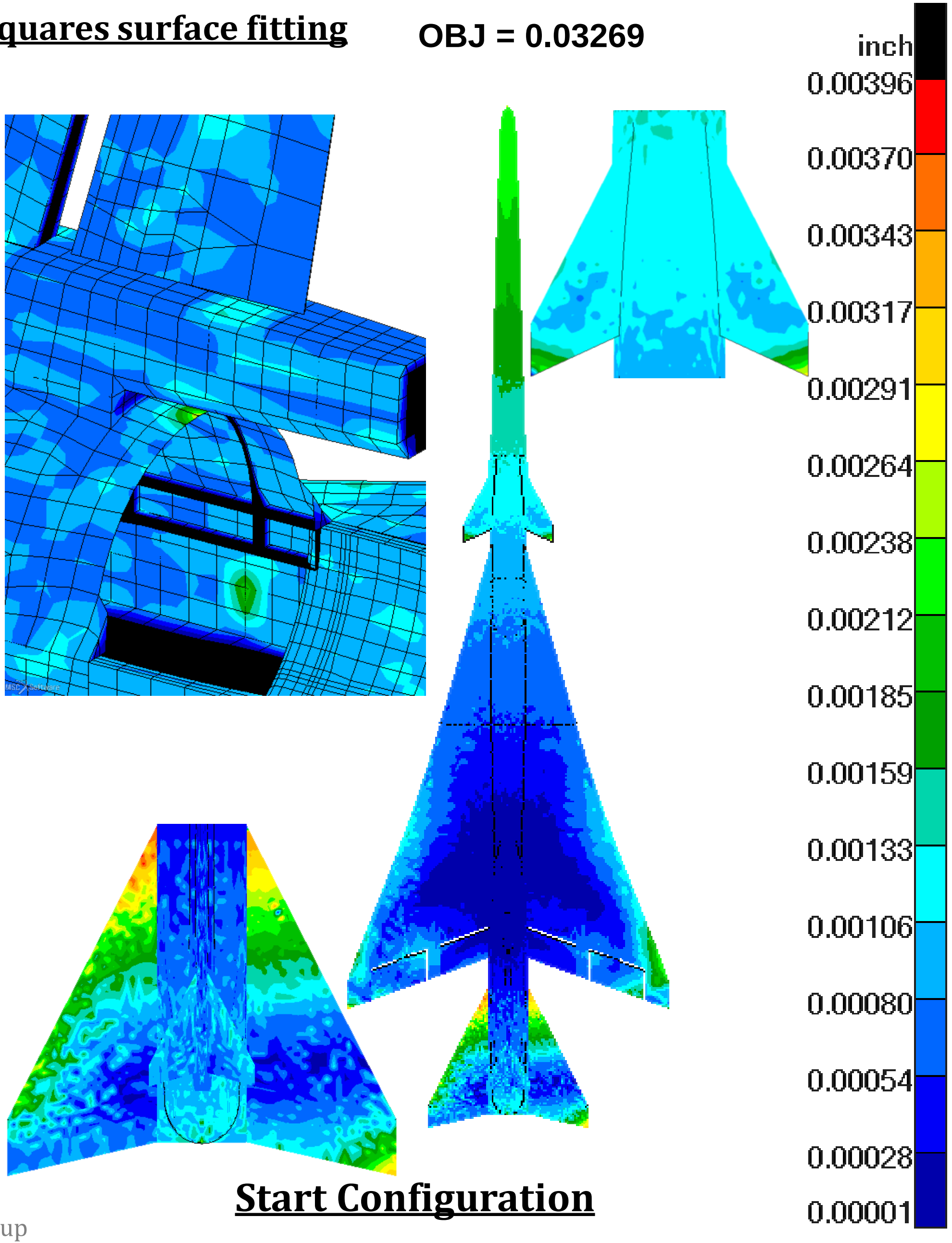


Optimization #3: $\{\Delta T\}_{to} = \{T\}_t - \{T\}_o$

Use least-squares surface fitting

OBJ = 0.03269

X_i	Value
1	-0.5768
2	-1.3427
3	-1.2960
4	0.4215
5	-1.0555
6	0.2533
7	1.0775
8	.00525
9	0.1238
10	.02061
11	-.04840
12	-.02909
13	.1049
14	0.2161
15	-.07589
16	-1.002

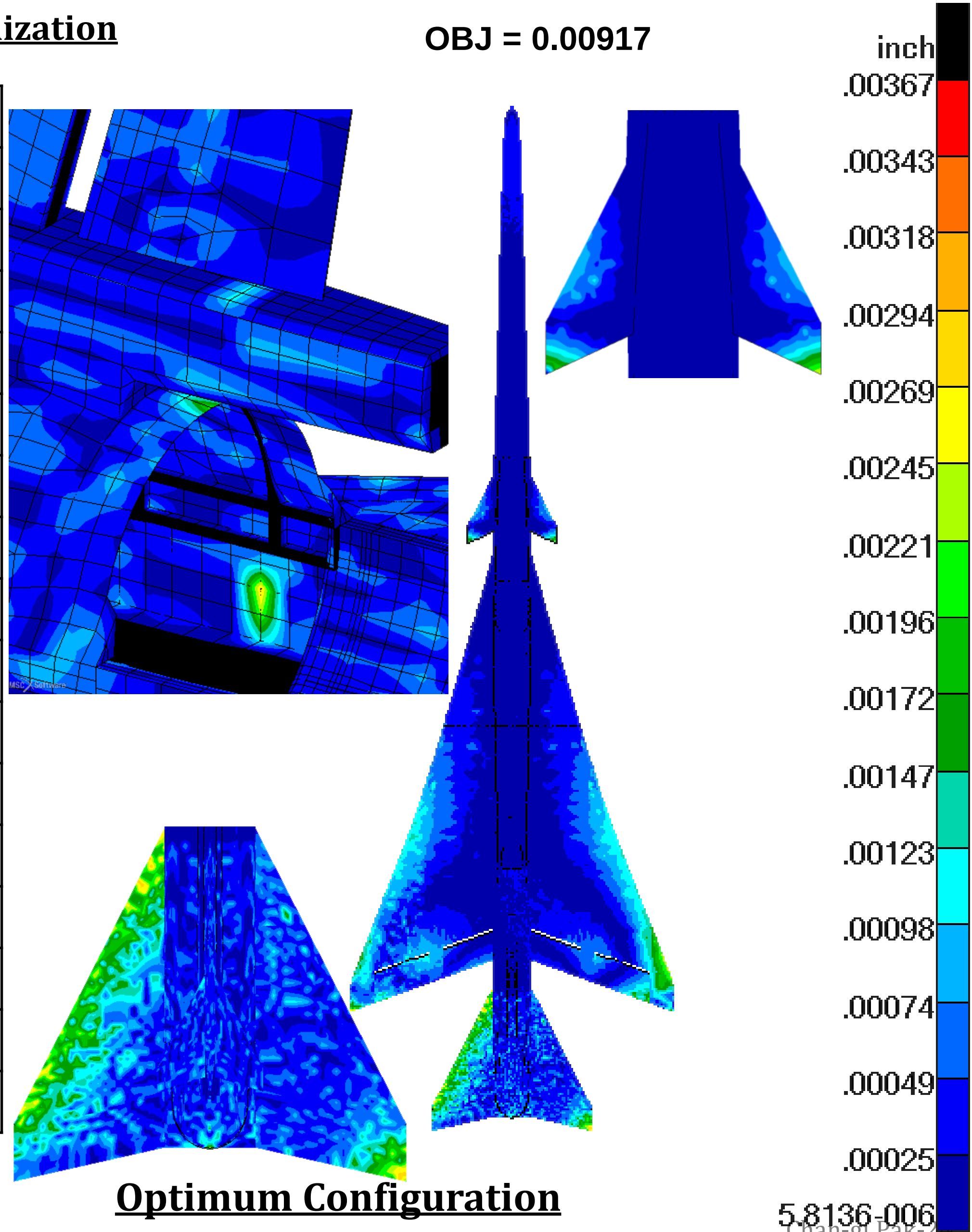


Start Configuration

Use Optimization

OBJ = 0.00917

X_i	Value
1	-0.5745
2	-1.3440
3	-1.2969
4	0.4216
5	-1.0559
6	0.2533
7	1.0762
8	.00499
9	0.1238
10	.02041
11	-.04836
12	-.02898
13	.1050
14	0.2161
15	-.07605
16	-1.002

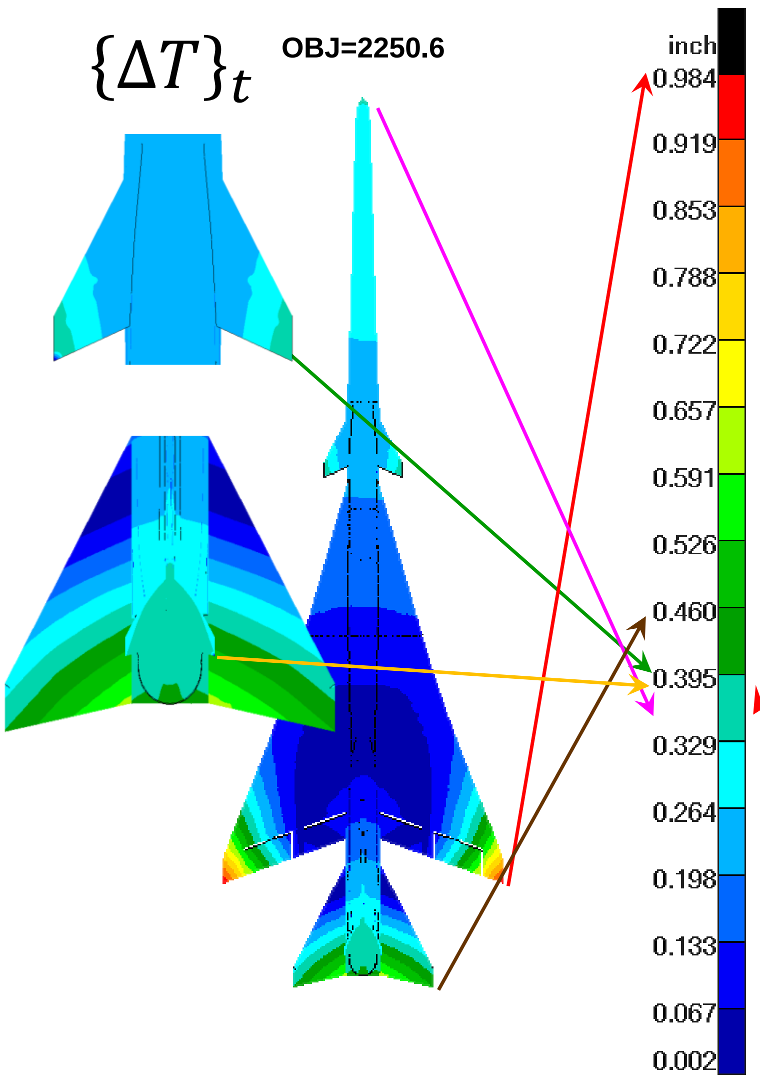


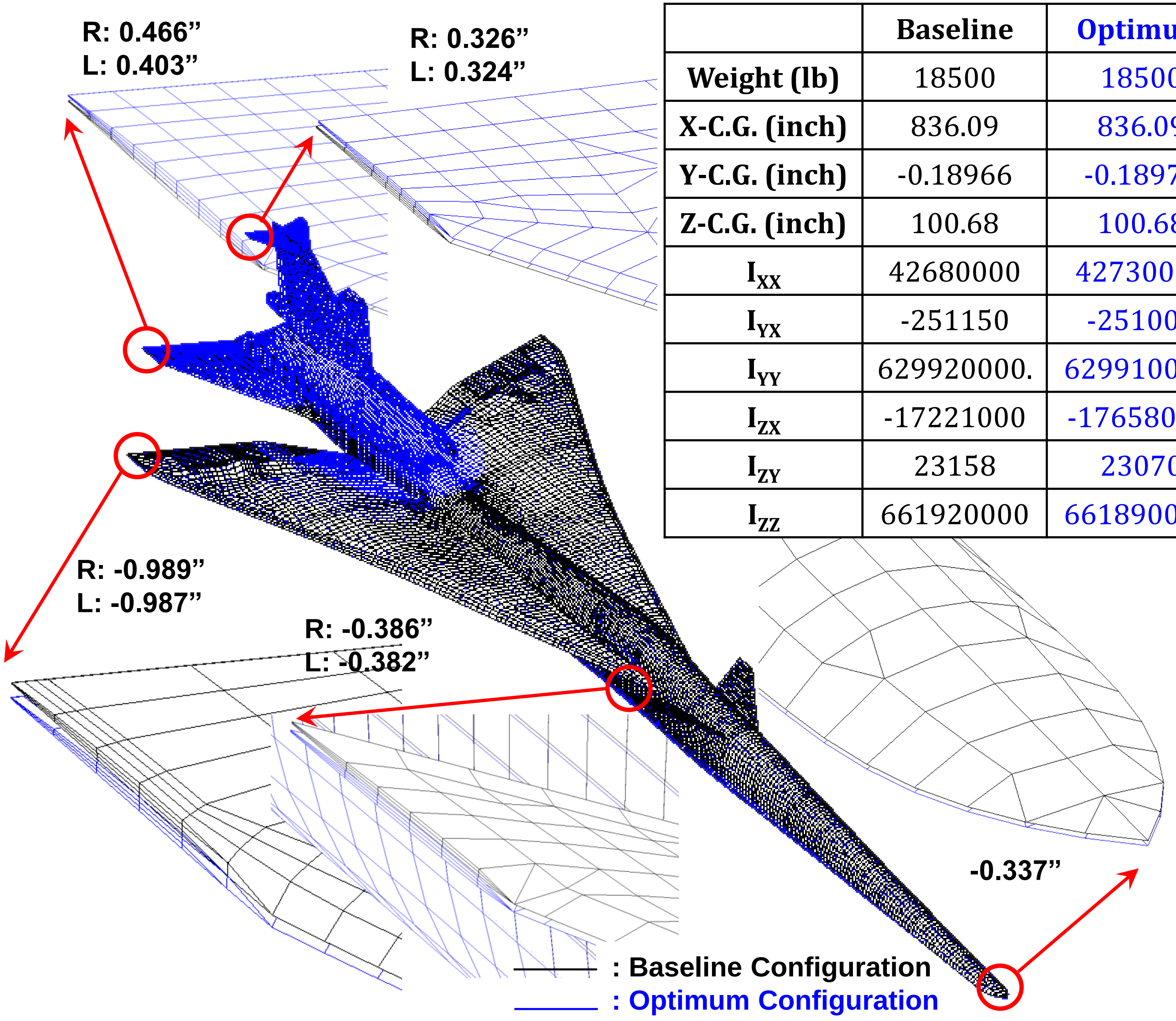
Optimum Configuration

Optimization Results

DESVAR ID	Baseline	Optimization #1		Optimization #2		Optimization #3		Comments
		Start	Optimum	Start	Optimum	Start	Optimum	
1	0.0	-0.5795	-0.5776	-0.5783	-0.5759	-0.5768	-0.5745	Rigid pitch
2	0.0	-1.5063	-1.5078	-1.3482	-1.3489	-1.3427	-1.3440	Stabilator_R
3	0.0	-1.4565	-1.4574	-1.3008	-1.3013	-1.2960	-1.2969	Stabilator_L
4	0.0	0.4108	0.4106	0.4226	0.4228	0.4215	0.4216	Mode 7
5	0.0	-1.0492	-1.0495	-1.0585	-1.0587	-1.0555	-1.0559	Mode 9
6	0.0	0.2851	0.2848	0.2544	0.2541	0.2533	0.2533	Mode 11
7	0.0	1.2202	1.2190	1.0823	1.0814	1.0775	1.0762	Mode 15
8	0.0	.04660	.04569	.00555	.00513	.00525	.00499	Mode 17
9	0.0	0.1273	0.1275	0.1242	0.1243	0.1238	0.1238	Mode 19
10	0.0	.05808	.05803	.02061	.02058	.02061	.02041	Mode 20
11	0.0	-.02754	-.02746	-.04842	-.04848	-.04840	-.04836	Mode 22
12	0.0	-.00712	-.00697	-.02884	-.02907	-.02909	-.02898	Mode 23
13	0.0	0.1212	0.1211	0.1055	0.1056	0.1049	.1050	Mode 25
14	0.0			0.2174	0.2172	0.2161	0.2161	Mode 37
15	0.0			-.07665	-.07671	-.07589	-.07605	Mode 48
16	0.0					-1.002	-1.002	Residual
Maximum Error (inch)	0.9844	0.1896	0.1904	.0897	.0905	.00396	.00367	
Objective Function	**2250.6**	**14.04**	**14.02**	**6.255**	**6.232**	**.03269**	**.00917**	

Optimum Jig-Shape Configuration with rigid rotation modes

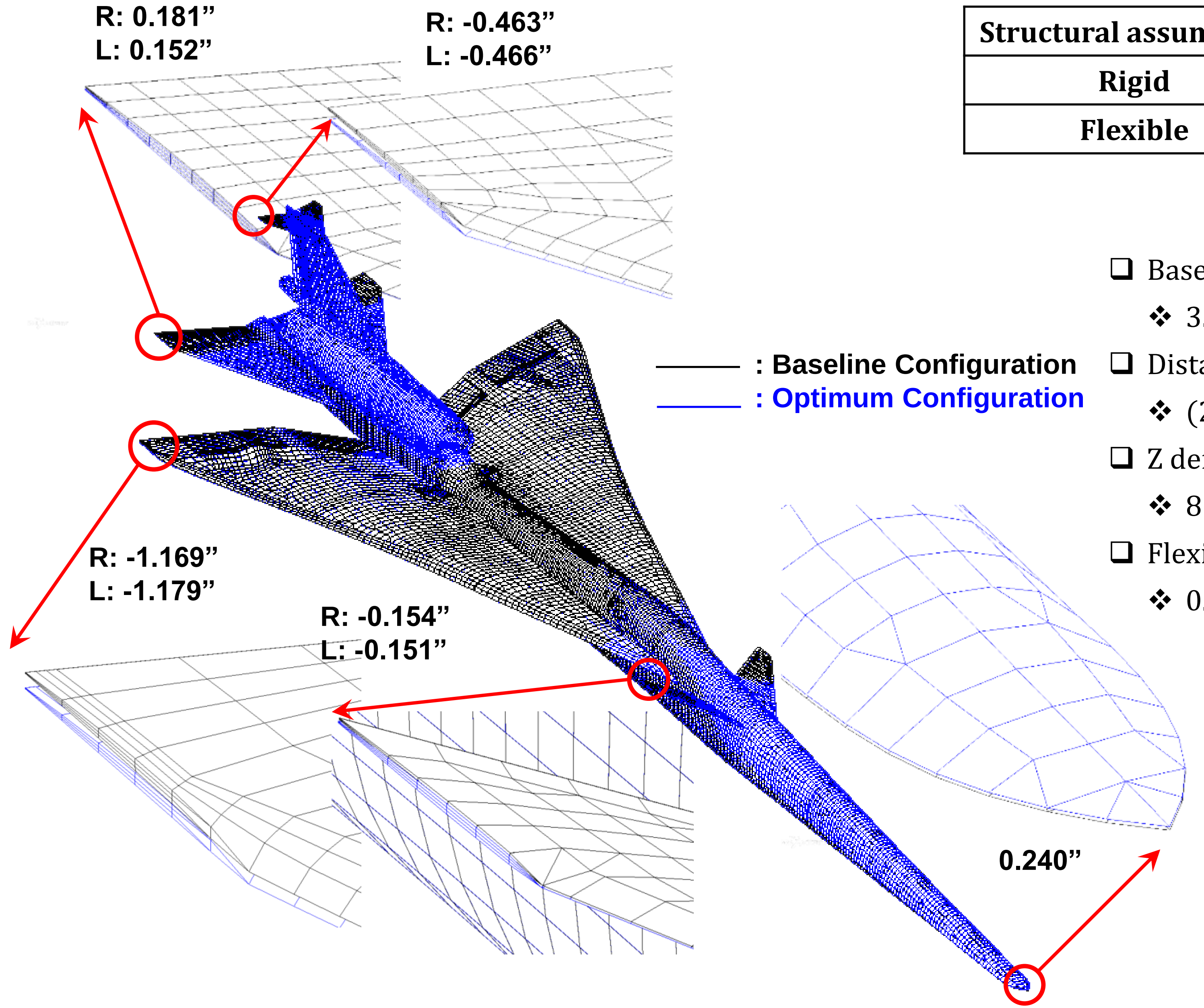




	Baseline	Optimum	% difference
Weight (lb)	18500	18500	0.00
X-C.G. (inch)	836.09	836.09	0.00
Y-C.G. (inch)	-0.18966	-0.18970	0.02
Z-C.G. (inch)	100.68	100.68	0.00
I_{XX}	42680000	42730000	0.12
I_{YX}	-251150	-251008	-0.06
I_{YY}	629920000.	629910000.	0.00
I_{ZX}	-17221000	-17658000.	2.54
I_{ZY}	23158	23070	-0.38
I_{ZZ}	661920000	661890000.	0.00

Optimum Jig-Shape Configuration without rigid rotation modes

Structural assumption	Baseline (degree)	Optimum (degree)
Rigid	3.0624	3.0624
Flexible	3.1036	3.1033



- Baseline rigid AOA – Optimum flexible AOA
  - 3.0624 deg - 3.1033 deg = -0.0409 deg = -0.000713 rad
- Distance from fuselage nose to center of gravity location
  - (25.46, 0.0, 82.51) – (836.09, -0.1897, 100.68) = 810.83 inch
- Z deflection due to AOA difference
  - $810.83 \times \tan(-0.000713) = -0.579\ inch$ **(-0.575 inch)**
- Flexible AOA effect at the fuselage nose
  - 0.240 inch – 0.579 inch = -0.339 inch **(-0.337 inch)**

Summary of Natural Frequencies before and after optimization

Mode	Frequency (Hz)			Notes
	Baseline	Optimum	% difference	
7	5.634	5.633	-0.02	First fuselage bending
9	9.045	9.032	-0.14	First wing bending + forward fuselage vertical bending + stabilator rotation
11	11.97	11.97	0.00	Forward fuselage vertical bending + first wing bending + stabilator rotation (**Asymmetric**)
15	14.76	14.76	0.00	Stabilator rotation
17	19.23	19.22	-0.05	Wing tip bending + T-tail rotation + flap bending (**Asymmetric**)
19	20.08	20.08	0.00	T-tail rotation (**Asymmetric**)
20	20.54	20.55	0.05	Wing tip bending + T-tail rotation + aileron rotation + flap bending + forward fuselage vertical bending (**Asymmetric**)
22	21.75	21.76	0.05	Aileron rotation + flap rotation + T-tail bending + outboard wing bending torsion
23	22.16	22.16	0.00	Flap rotation + aileron rotation + wing tip bending + T-tail bending (**Asymmetric**)
25	22.70	22.70	0.00	Flap rotation + aileron rotation + T-tail bending (**Asymmetric**)
37	30.79	30.75	-0.13	Canard bending
48	42.96	42.97	0.02	T-tail bending (**Asymmetric**)

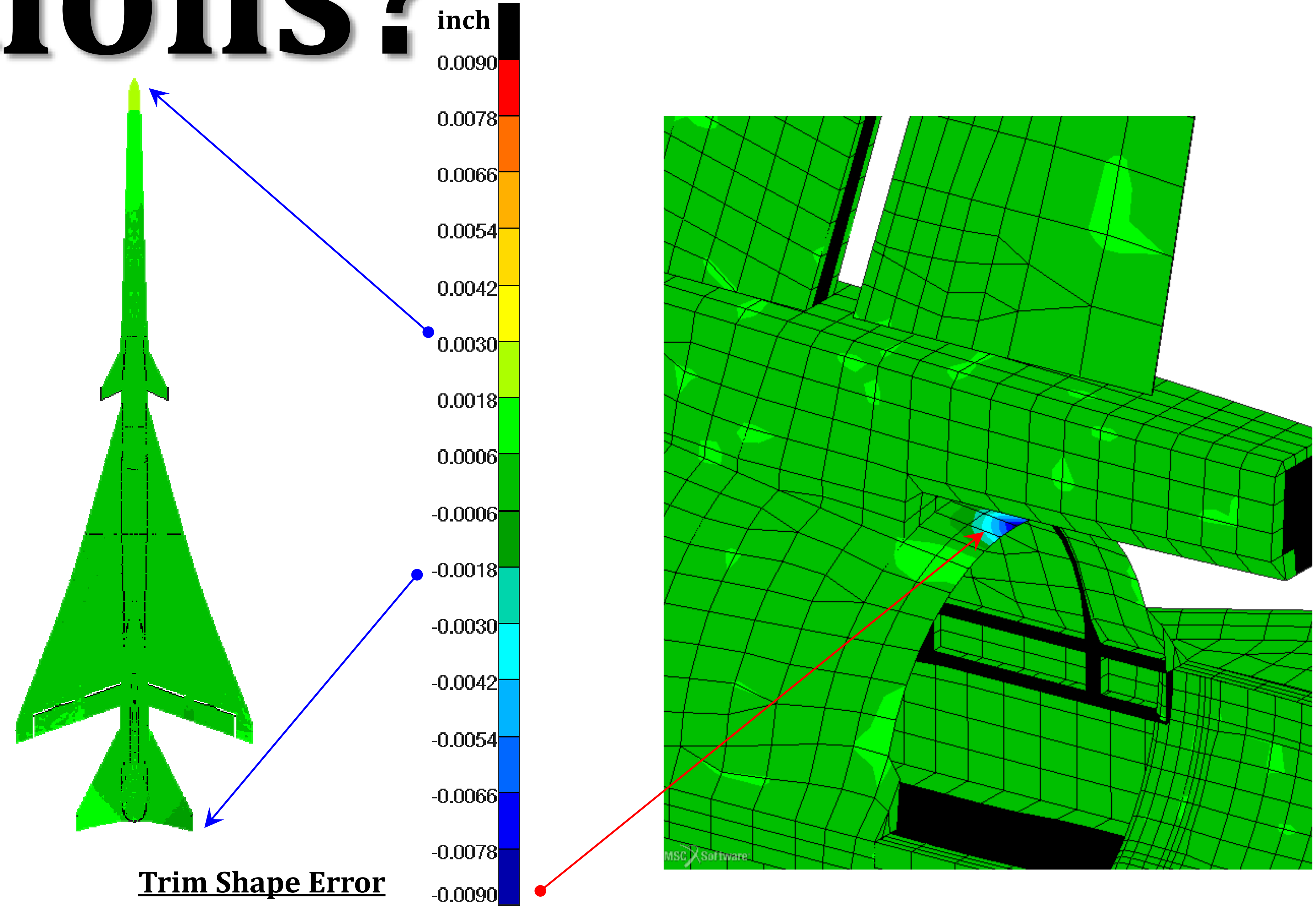
Conclusion

- In this study, the jig-shape optimization is performed using the two step approach.
  - The first step is computing the starting design variables using the **least squares surface fitting technique**.
  - The next step is the fine tune of the jig-shape using the **numerical optimization procedure**.
  - Assume **unconstrained** optimization
    - The maximum frequency change due to the jig-shape optimization is less than 0.14%.
    - The minor changes in mass moment of inertia are observed. (mostly less than 0.38%; maximum 2.54%)

- Sixteen basis function are used in this jig-shape optimization study.
  - Total of **twelve symmetric mode shapes** of the cruise weight configuration. (Asymmetric shapes exist)
    - Fitting trim deformation
  - Three basis functions for trim variables (**rigid pitch shape, rigid left and right stabilator rotation shapes**)
    - Fitting flexibility effect on trim variables
  - **A residual shape** is also selected as a basis function.

- The maximum trim shape error of **0.9844”** at the starting configuration becomes **0.00367”** at the end of the third optimization run.

Questions?



Trim Shape Error