Shape optimization in SU^2

OpenMDAO / SU^2 joint Workshop

Stanford University

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The Open-Source CFD Code

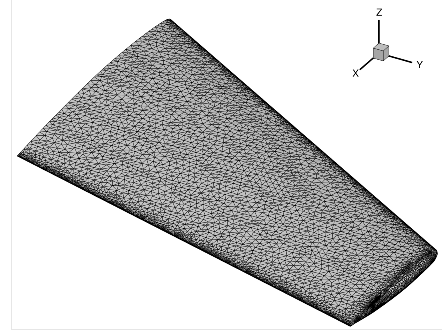
ONERA M6 Shape Optimization

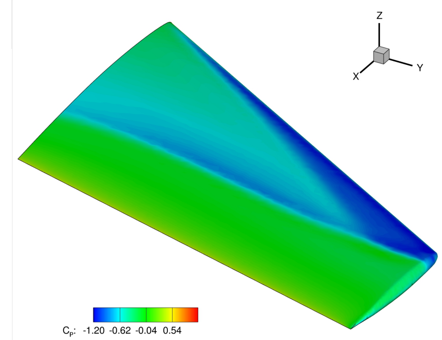
1. Define and run the physical problem.
2. Evaluate geometry (thickness, AoA, etc).
3. Define 3D design variables.
    1. Create the FFD box (.su2 file).
    2. FFD design variables preprocessing.
4. Define the optimization problem
    1. Objective function.
    2. Constraints (flow and geometry).
    3. Design variables based on FFD box.
5. V&V before the optimization (optional).
    1. Compute C_D, and C_L gradients.
    2. Compute geometric gradients.
6. Final checks (optional).
    1. Restart files are available.
    2. The grid contains the FFD information.
    3. The stop criteria is reasonable.
    4. The proposed optimization problem makes sense (scaling).
7. Run the optimization.
8. Analyze the solution.
    1. Folder structure and history_project file.
    2. Restart capability.

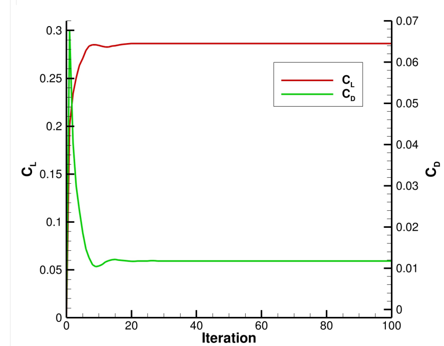
inv_ONERAM6.cfg

```
% ------------- DIRECT, ADJOINT, AND LINEARIZED PROBLEM DEFINITION ------------%
%
% Physical governing equations (EULER, NAVIER_STOKES,
%                               PLASMA_EULER, PLASMA_NAVIER_STOKES,
%                               FLUID_STRUCTURE_EULER, FLUID_STRUCTURE_NS,
%                               AEROACOUSTIC_EULER, AEROACOUSTIC_NAVIER_STOKES,
%                               WAVE_EQUATION, HEAT_EQUATION, LINEAR_ELASTICITY)
PHYSICAL_PROBLEM= EULER
%
% Mathematical problem (DIRECT, ADJOINT)
MATH_PROBLEM= DIRECT
%
% Restart solution (NO, YES)
RESTART_SOL= YES

% -------------------- COMPRESSIBLE FREE-STREAM DEFINITION --------------------%
%
% Mach number (non-dimensional, based on the free-stream values)
MACH_NUMBER= 0.8395
%
% Angle of attack (degrees)
AoA= 3.06
%
% Free-stream pressure (101325.0 N/m^2 by default, only for Euler equations)
FREESTREAM_PRESSURE= 101325.0
%
% Free-stream temperature (273.15K by default)
FREESTREAM_TEMPERATURE= 273.15

% -------------- COMPRESSIBLE AND INCOMPRESSIBLE FLUID CONSTANTS --------------%
%
% Ratio of specific heats (1.4 (air), only for compressible flows)
GAMMA_VALUE= 1.4
%
% Specific gas constant (287.87 J/kg*K (air), only for compressible flows)
GAS_CONSTANT= 287.87

% ---------------------- REFERENCE VALUE DEFINITION ---------------------------%
%
% Conversion factor for converting the grid to meters
CONVERT_TO_METER= 1.0
%
% Reference origin for moment computation
REF_ORIGIN_MOMENT= ( 0.2015, 0.00, 0.00 )
%
% Reference length for pitching, rolling, and yawing non-dimensional moment
REF_LENGTH_MOMENT= 0.64607
%
% Reference area for force coefficients (0 implies automatic calculation)
REF_AREA= 0
%
% Reference pressure (101325.0 N/m^2 by default)
REF_PRESSURE= 101325.0
%
% Reference temperature (273.15 K by default)
REF_TEMPERATURE= 273.15
%
% Reference density (1.2886 Kg/m^3 (air), 998.2 Kg/m^3 (water))
REF_DENSITY= 1.2886
%
% Reference element length for computing the slope and sharp edges limiters.
REF_ELEM_LENGTH= 0.1
%
% Reference coefficient (sensitivity) for detecting sharp edges.
REF_SHARP_EDGES= 3.0

% ----------------------- BOUNDARY CONDITION DEFINITION -----------------------%
%
% Marker of the Euler boundary (0 implies no marker)
MARKER_EULER= ( UPPER_SIDE, LOWER_SIDE, TIP )
%
% Marker of the far field (0 implies no marker)
MARKER_FAR= ( XNORMAL_FACES, ZNORMAL_FACES, YNORMAL_FACE )
%
% Marker of symmetry boundary (0 implies no marker)
MARKER_SYM= ( SYMMETRY_FACE )
%
% Marker of the surface which is going to be plotted or designed
MARKER_PLOTTING= ( UPPER_SIDE, LOWER_SIDE, TIP )
%
% Marker of the surface where the functional (Cd, Cl, etc.) will be evaluated
MARKER_MONITORING= ( UPPER_SIDE, LOWER_SIDE, TIP )
```

```
parallel_computation.py -p 4 -f inv_ONERAM6.cfg
```







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3. Define 3D design variables.
   1. Create the FFD box (.su2 file).
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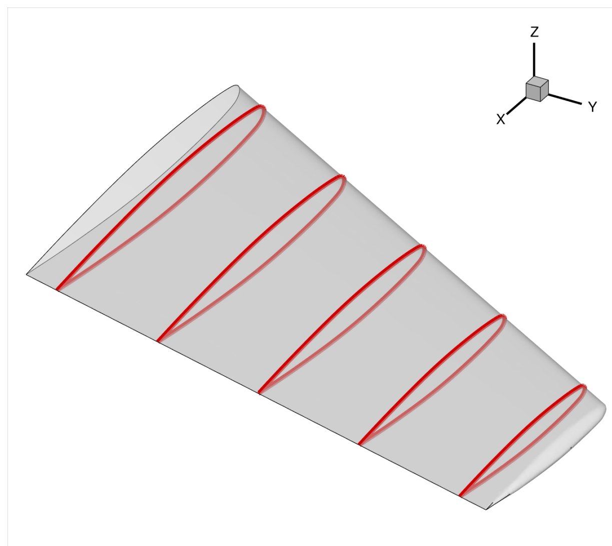
inv_ONERAM6.cfg

```
% ---------------------- GEOMETRY EVALUATION PARAMETERS ---------------------%
%
% Airfoil sections definition, Ycoord (root, tip)
GEO_SECTION_LIMIT= (0.0806, 1.1284)
%
% Geometrical evaluation mode (FUNCTION, GRADIENT)
GEO_MODE= FUNCTION
```

```
SU2_GDC inv_ONERAM6.cfg
```




```
Section 1. Plane (yCoord): 0.0806.
Maximum thickness: 0.0760726.
1/4 chord thickness: 0.0722079.
1/3 chord thickness: 0.075645.
1/2 chord thickness: 0.0718373.
2/3 chord thickness: 0.054966.
3/4 chord thickness: 0.0436146.
Area: 0.0417745.
Angle of attack: 0.
Chord: 0.782102.

Section 2. Plane (yCoord): 0.34255.
Maximum thickness: 0.0684805.
1/4 chord thickness: 0.0650278.
1/3 chord thickness: 0.0681138.
1/2 chord thickness: 0.0646917.
2/3 chord thickness: 0.0495041.
3/4 chord thickness: 0.0392899.
Area: 0.0338872.
Angle of attack: 0.
Chord: 0.704434.

Section 3. Plane (yCoord): 0.6045.
Maximum thickness: 0.060948.
1/4 chord thickness: 0.0578653.
1/3 chord thickness: 0.060569.
1/2 chord thickness: 0.0575322.
2/3 chord thickness: 0.0440336.
3/4 chord thickness: 0.0349501.
Area: 0.0268216.
Angle of attack: 0.
Chord: 0.626766.

Section 4. Plane (yCoord): 0.86645.
Maximum thickness: 0.0533332.
1/4 chord thickness: 0.0506826.
1/3 chord thickness: 0.0531113.
1/2 chord thickness: 0.0504042.
2/3 chord thickness: 0.0385875.
3/4 chord thickness: 0.0306302.
Area: 0.0205833.
Angle of attack: 0.
Chord: 0.549098.

Section 5. Plane (yCoord): 1.1284.
Maximum thickness: 0.0458274.
1/4 chord thickness: 0.0435065.
1/3 chord thickness: 0.0456027.
1/2 chord thickness: 0.0432516.
2/3 chord thickness: 0.0331341.
3/4 chord thickness: 0.0262889.
Area: 0.0151681.
Angle of attack: 0.
Chord: 0.47143.
```

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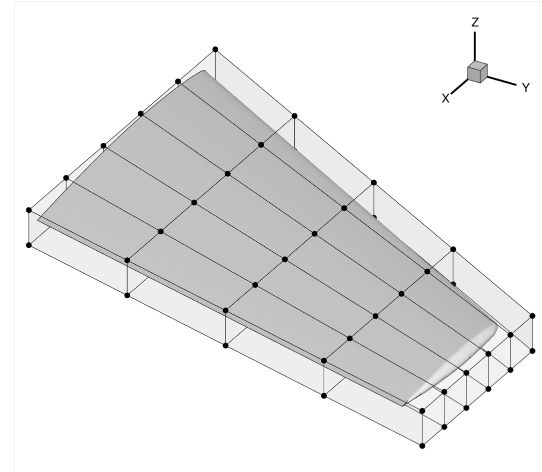
mesh_ONERAM6_inv.su2

```
5 3069  4634  3067
5 3461  3678  3462
5 88  91  4765
5 3576  3573  9065
5 3054  4618  3053
5 3055  3056  4617
5 16838 16840 16839
5 9202  9205  9201
5 483 1677  8773
5 4678  19336 19323
FFD_NBOX= 1
FFD_NLEVEL= 1
FFD_TAG= 0
FFD_LEVEL= 0
FFD_DEGREE_I= 5
FFD_DEGREE_J= 4
FFD_DEGREE_K= 1
FFD_PARENTS= 0
FFD_CHILDREN= 0
FFD_CORNER_POINTS= 8
-0.0403    0.0000   -0.04836
 0.8463    0.0000   -0.04836
 1.2090    1.2896   -0.04836
 0.6851    1.2896   -0.04836
-0.0403    0.0000    0.04836
 0.8463    0.0000    0.04836
 1.2090    1.2896    0.04836
 0.6851    1.2896    0.04836
FFD_CONTROL_POINTS= 0
FFD_SURFACE_POINTS= 0
```



inv_ONERAM6.cfg

```
% ----------------------- DESIGN VARIABLE PARAMETERS -------------------------%
%
% Kind of deformation (NO_DEFORMATION, HICKS_HENNE, PARABOLIC, NACA_4DIGITS,
%                      DISPLACEMENT, ROTATION, FFD_CONTROL_POINT,
%                      FFD_DIHEDRAL_ANGLE, FFD_TWIST_ANGLE,
%                      FFD_ROTATION, FFD_CAMBER, FFD_THICKNESS, FFD_VOLUME)
DV_KIND= NO_DEFORMATION
%
% Marker of the surface in which we are going apply the shape deformation
DV_MARKER= ( UPPER_SIDE, LOWER_SIDE, TIP )
%
% Parameters of the shape deformation
%   - FFD_CONTROL_POINT ( Chunk, i_Ind, j_Ind, k_Ind, x_Disp, y_Disp, z_Disp )
%   - FFD_DIHEDRAL_ANGLE ( Chunk, x_Orig, y_Orig, z_Orig, x_End, y_End, z_End )
%   - FFD_TWIST_ANGLE ( Chunk, x_Orig, y_Orig, z_Orig, x_End, y_End, z_End )
%   - FFD_ROTATION ( Chunk, x_Orig, y_Orig, z_Orig, x_End, y_End, z_End )
%   - FFD_CAMBER ( Chunk, i_Ind, j_Ind )
%   - FFD_THICKNESS ( Chunk, i_Ind, j_Ind )
%   - FFD_VOLUME ( Chunk, i_Ind, j_Ind )
DV_PARAM= ( 0, 1, 0, 0, 0.0, 0.0, 1.0 )
%
% New value of the shape deformation
DV_VALUE= 0.0
```

```
SU2_MDC inv_ONERAM6.cfg
```

```
mv mesh_out.su2 mesh_ONERAM6_inv_FFD.su2
```

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inv_ONERAM6.cfg

inv_ONERAM6.cfg 〉 No Selection

```
% -------------------- OPTIMAL SHAPE DESIGN DEFINITION ----------------------%
% Available flow based objective functions or constraint functions
%    DRAG, LIFT, SIDEFORCE, EFFICIENCY,
%    FORCE_X, FORCE_Y, FORCE_Z,
%    MOMENT_X, MOMENT_Y, MOMENT_Z,
%    THRUST, TORQUE, FIGURE_OF_MERIT,
%    EQUIVALENT_AREA, NEARFIELD_PRESSURE,
%    FREE_SURFACE
%
% Available geometrical based objective functions or constraint functions
%    MAX_THICKNESS, 1/4_THICKNESS, 1/2_THICKNESS, 3/4_THICKNESS, AREA, AOA, CHORD,
%    MAX_THICKNESS_SEC1, MAX_THICKNESS_SEC2, MAX_THICKNESS_SEC3, MAX_THICKNESS_SEC4, MAX_THICKNESS_SEC5,
%    1/4_THICKNESS_SEC1, 1/4_THICKNESS_SEC2, 1/4_THICKNESS_SEC3, 1/4_THICKNESS_SEC4, 1/4_THICKNESS_SEC5,
%    1/2_THICKNESS_SEC1, 1/2_THICKNESS_SEC2, 1/2_THICKNESS_SEC3, 1/2_THICKNESS_SEC4, 1/2_THICKNESS_SEC5,
%    3/4_THICKNESS_SEC1, 3/4_THICKNESS_SEC2, 3/4_THICKNESS_SEC3, 3/4_THICKNESS_SEC4, 3/4_THICKNESS_SEC5,
%    AREA_SEC1, AREA_SEC2, AREA_SEC3, AREA_SEC4, AREA_SEC5,
%    AOA_SEC1, AOA_SEC2, AOA_SEC3, AOA_SEC4, AOA_SEC5,
%    CHORD_SEC1, CHORD_SEC2, CHORD_SEC3, CHORD_SEC4, CHORD_SEC5
%
% Available design variables
%    HICKS_HENNE  (  1, Scale | Mark. List | Lower(0)/Upper(1) side, x_Loc )
%    COSINE_BUMP  (  2, Scale | Mark. List | Lower(0)/Upper(1) side, x_Loc, x_Size )
%    SPHERICAL    (  3, Scale | Mark. List | ControlPoint_Index, Theta_Disp, R_Disp )
%    NACA_4DIGITS (  4, Scale | Mark. List |  1st digit, 2nd digit, 3rd and 4th digit )
%    DISPLACEMENT (  5, Scale | Mark. List | x_Disp, y_Disp, z_Disp )
%    ROTATION   (  6, Scale | Mark. List | x_Axis, y_Axis, z_Axis, x_Turn, y_Turn, z_Turn )
%    FFD_CONTROL_POINT  (  7, Scale | Mark. List | Chunk, i_Ind, j_Ind, k_Ind, x_Mov, y_Mov, z_Mov )
%    FFD_DIHEDRAL_ANGLE (  8, Scale | Mark. List | Chunk, x_Orig, y_Orig, z_Orig, x_End, y_End, z_End )
%    FFD_TWIST_ANGLE  (  9, Scale | Mark. List | Chunk, x_Orig, y_Orig, z_Orig, x_End, y_End, z_End )
%    FFD_ROTATION   ( 10, Scale | Mark. List | Chunk, x_Orig, y_Orig, z_Orig, x_End, y_End, z_End )
%    FFD_CAMBER   ( 11, Scale | Mark. List | Chunk, i_Ind, j_Ind )
%    FFD_THICKNESS  ( 12, Scale | Mark. List | Chunk, i_Ind, j_Ind )
%    FFD_VOLUME   ( 13, Scale | Mark. List | Chunk, i_Ind, j_Ind )
%    FOURIER    ( 14, Scale | Mark. List | Lower(0)/Upper(1) side, index, cos(0)/sin(1) )
%
% Optimization objective function with scaling factor
% ex= Objective * Scale
OPT_OBJECTIVE= DRAG * 0.1
%
% Optimization constraint functions with scaling factors, separated by semicolons
% ex= (Objective = Value ) * Scale, use '>','<','='
OPT_CONSTRAINT= (LIFT > 0.2864) * 0.1; (MAX_THICKNESS_SEC1 > 0.0570) * 0.1; (MAX_THICKNESS_SEC2 > 0.0513) * 0.1;
    (MAX_THICKNESS_SEC3 > 0.0457) * 0.1; (MAX_THICKNESS_SEC4 > 0.0399) * 0.1; (MAX_THICKNESS_SEC5 > 0.0343) * 0.1
%
% Optimization design variables, separated by semicolons
DEFINITION_DV= ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 0, 0, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP |
    0, 1, 0, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 2, 0, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE,
    LOWER_SIDE, TIP | 0, 3, 0, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 4, 0, 0, 0.0, 0.0, 1.0 ); ( 7,
    1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 0, 1, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 1, 1, 0,
    0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 2, 1, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE,
    TIP | 0, 3, 1, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 4, 1, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 |
    UPPER_SIDE, LOWER_SIDE, TIP | 0, 0, 2, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 1, 2, 0, 0.0, 0.0,
    1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 2, 2, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0,
    3, 2, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 4, 2, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE,
    LOWER_SIDE, TIP | 0, 0, 3, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 1, 3, 0, 0.0, 0.0, 1.0 ); ( 7,
    1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 2, 3, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 3, 3, 0,
    0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 4, 3, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE,
    TIP | 0, 0, 4, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 1, 4, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 |
    UPPER_SIDE, LOWER_SIDE, TIP | 0, 2, 4, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 3, 4, 0, 0.0, 0.0,
    1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 4, 4, 0, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0,
    0, 0, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 1, 0, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE,
    LOWER_SIDE, TIP | 0, 2, 0, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 3, 0, 1, 0.0, 0.0, 1.0 ); ( 7,
    1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 4, 0, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 0, 1, 1,
    0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 1, 1, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE,
    TIP | 0, 2, 1, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 3, 1, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 |
    UPPER_SIDE, LOWER_SIDE, TIP | 0, 4, 1, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 0, 2, 1, 0.0, 0.0,
    1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 1, 2, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0,
    2, 2, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 3, 2, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE,
    LOWER_SIDE, TIP | 0, 4, 2, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 0, 3, 1, 0.0, 0.0, 1.0 ); ( 7,
    1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 1, 3, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 2, 3, 1,
    0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 3, 3, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE,
    TIP | 0, 4, 3, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 0, 4, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 |
    UPPER_SIDE, LOWER_SIDE, TIP | 0, 1, 4, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 2, 4, 1, 0.0, 0.0,
    1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0, 3, 4, 1, 0.0, 0.0, 1.0 ); ( 7, 1.0 | UPPER_SIDE, LOWER_SIDE, TIP | 0,
    4, 4, 1, 0.0, 0.0, 1.0 )
```

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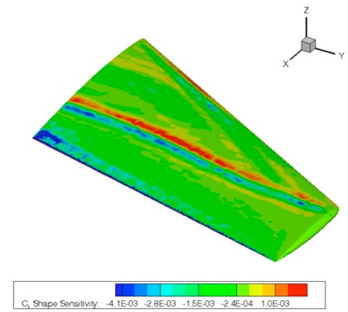
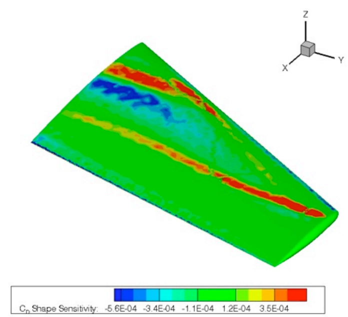
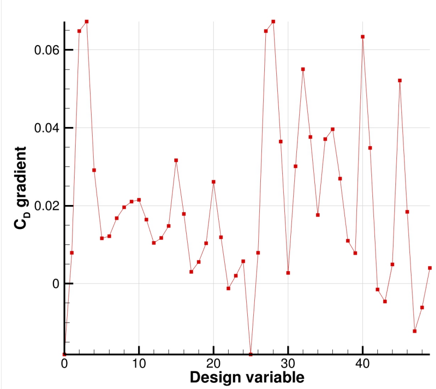
inv_ONERAM6.cfg

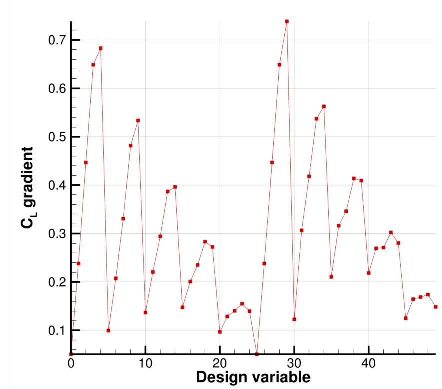
```
% ---------------- ADJOINT-FLOW NUMERICAL METHOD DEFINITION ----------------%
% Adjoint problem boundary condition (DRAG, LIFT, SIDEFORCE, MOMENT_X,
%                                     MOMENT_Y, MOMENT_Z, EFFICIENCY,
%                                     EQUIVALENT_AREA, NEARFIELD_PRESSURE,
%                                     FORCE_X, FORCE_Y, FORCE_Z, THRUST,
%                                     TORQUE, FREE_SURFACE)
ADJ_OBJFUNC= DRAG
%
% Convective numerical method: (JST, LAX-FRIEDRICH, ROE-1ST_ORDER,
%                               ROE-2ND_ORDER)
CONV_NUM_METHOD_ADJ= JST
%
% Slope limiter: (NONE, VENKATAKRISHNAN, SHARP_EDGES)
SLOPE_LIMITER_ADJFLOW= SHARP_EDGES
%
% Coefficient for the sharp edges limiter
SHARP_EDGES_COEFF= 3.0
%
% 1st, 2nd, and 4th order artificial dissipation coefficients
AD_COEFF_ADJ= ( 0.15, 0.5, 0.04 )
%
% Reduction factor of the CFL coefficient in the adjoint problem
ADJ_CFL_REDUCTION= 0.25
%
% Limit value for the adjoint variable
ADJ_LIMIT= 1E6
%
% Remove sharp edges from the sensitivity evaluation (NO, YES)
SENS_REMOVE_SHARP= YES
%
% Time discretization (RUNGE-KUTTA_EXPLICIT, EULER_IMPLICIT)
TIME_DISCRE_ADJ= EULER_IMPLICIT
```

```
continuous_adjoint.py -p 4 -f inv_ONERAM6.cfg
```









ONERA M6 Shape Optimization

1. Define and run the physical problem.
2. Evaluate geometry (thickness, AoA, etc).
3. Define 3D design variables.
    1. Create the FFD box (.su2 file).
    2. FFD design variables preprocessing.
4. Define the optimization problem
    1. Objective function.
    2. Constraints (flow and geometry).
    3. Design variables based on FFD box.
5. V&V before the optimization (optional).
    1. Compute C_D, and C_L gradients.
    2. Compute geometric gradients.
6. **Final checks (optional).**
    1. **Restart files are available.**
    2. **The grid contains the FFD information.**
    3. **The stop criteria is reasonable.**
    4. **The proposed optimization problem makes sense (scaling).**
7. Run the optimization.
8. Analyze the solution.
    1. Folder structure and history_project file.
    2. Restart capability.

```
solution_adj_cd.dat
solution_adj_cl.dat
solution_flow.dat
```

```
% Restart solution (NO, YES)
RESTART_SOL= YES
```

mesh_ONERAM6_inv_FFD.su2

```
FFD_CORNER_POINTS= 8
-0.0403 0       -0.04836
0.8463  0       -0.04836
1.209   1.2896  -0.04836
0.6851  1.2896  -0.04836
-0.0403 0       0.04836
0.8463  0       0.04836
1.209   1.2896  0.04836
0.6851  1.2896  0.04836
FFD_CONTROL_POINTS= 60
0       0       0       -0.0403 0       -0.04836
0       0       1       -0.0403 0       0.04836
0       1       0       0.14105 0.3224  -0.04836
0       1       1       0.14105 0.3224  0.04836
0       2       0       0.3224  0.6448  -0.04836
0       2       1       0.3224  0.6448  0.04836

5       3       1       1.118325        0.9672  0.04836
5       4       0       1.209   1.2896  -0.04836
5       4       1       1.209   1.2896  0.04836
FFD_SURFACE_POINTS= 19893
LOWER_SIDE      13342   8.800257598459620e-02   5.495278239250181e-01   3.716563358902933e-01
LOWER_SIDE      13341   8.482803129010713e-02   5.525066256523129e-01   3.856879894932108e-01
LOWER_SIDE      12920   8.995567784976399e-02   5.521590113639829e-01   3.658012350400292e-01
LOWER_SIDE      7860    7.335924884774424e-01   1.065162196755406e-01   2.847658395767208e-01
```

inv_ONERAM6.cfg

```
% ------------------------- INPUT/OUTPUT INFORMATION -------------------------%
% Mesh input file
MESH_FILENAME= mesh_ONERAM6_inv_FFD.su2
%
% Mesh output file
MESH_OUT_FILENAME= mesh_out.su2
%
% Restart flow input file
SOLUTION_FLOW_FILENAME= solution_flow.dat
%
% Restart adjoint input file
SOLUTION_ADJ_FILENAME= solution_adj.dat
%
% Mesh input file format (SU2)
MESH_FORMAT= SU2
%
% Output file format (PARAVIEW, TECPLOT)
OUTPUT_FORMAT= TECPLOT
```

```
% Optimization objective function with scaling factor
% ex= Objective * Scale
OPT_OBJECTIVE= DRAG * 0.1
%
% Optimization constraint functions with scaling factors, separated by semicolons
% ex= (Objective = Value ) * Scale, use '>','<','='
OPT_CONSTRAINT= (LIFT > 0.2864) * 0.1; (MAX_THICKNESS_SEC1 > 0.0570) * 0.1;
    (MAX_THICKNESS_SEC2 > 0.0513) * 0.1; (MAX_THICKNESS_SEC3 > 0.0457) * 0.1;
    (MAX_THICKNESS_SEC4 > 0.0399) * 0.1; (MAX_THICKNESS_SEC5 > 0.0343) * 0.1
```

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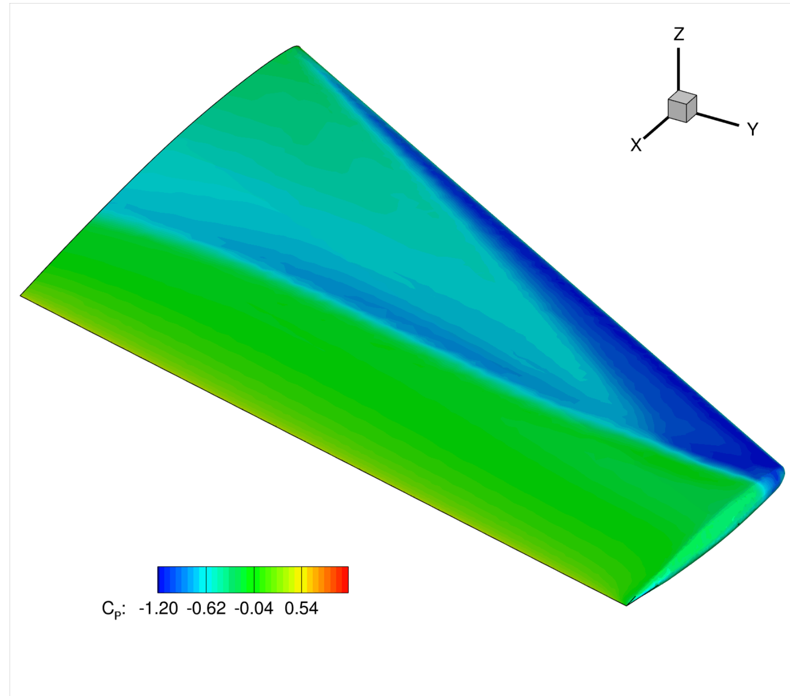
    1. Compute C_D, and C_L gradients.
    2. Compute geometric gradients.
6. Final checks (optional).
    1. Restart files are available.
    2. The grid contains the FFD information.
    3. The stop criteria is reasonable.
    4. The proposed optimization problem makes sense (scaling).
7. **Run the optimization.**
8. Analyze the solution.
    1. Folder structure and history_project file.
    2. Restart capability.

```
shape_optimization.py -p 4 -f inv_ONERAM6.cfg
```



ONERA M6 Shape Optimization

1. Define and run the physical problem.
2. Evaluate geometry (thickness, AoA, etc).
3. Define 3D design variables.
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    3. The stop criteria is reasonable.
    4. The proposed optimization problem makes sense (scaling).
7. Run the optimization.
8. Analyze the solution.
    1. Folder structure and history_project file.
    2. Restart capability.