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MASSOUD User's Manual (Ver. 2.0)

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MASSOUD

Multidisciplinary
Aerodynamic-Structural
Shape Optimization
Using Deformation

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Introduction

THIS manual is written for the users of Multidisciplinary Aerodynamic–Structural Shape Optimization Using Deformation (MASSOUD)¹ software. The algorithm is based on a set of modifications to the original soft object animation (SOA) algorithms.

For a complete airplane model, creation of computational fluid dynamics (CFD) and computational structural mechanics (CSM) grids is time-consuming and costly: it takes several months to develop detailed CFD and CSM grids based on a computer-aided design (CAD) model. To fit into the product development cycle times, the multidisciplinary shape optimization (MSO) must rely on the parameterization of the analysis grids, for which the SOA algorithms are ideal. The disadvantage of SOA is that the design variables may have no physical significance for the design engineers. This drawback makes it difficult to select an effective and compact set of design variables. Samareh¹ has developed a set of modifications to the original SOA algorithms to alleviate this and other drawbacks. The modified algorithm set is referred to as MASSOUD.

Typically, a wing optimization starts with an existing wing design, and the goal is to improve the wing performance by using numerical optimization. The geometry changes (perturbations) between the initial and optimized wings are very small, but the difference in wing performance can be substantial. By parameterizing the shape perturbations instead of the shape itself, MASSOUD reduces the number of shape design variables.

MASSOUD is a parameterization approach for complex shapes suitable for a multidisciplinary design optimization application. The approach consists of three basic concepts: 1) parameterizing the shape perturbations rather than the geometry itself, 2) utilizing SOA algorithms used in computer graphics, and 3) relating the deformation to aerodynamic shape design variables such as planform, twist, shear, thickness, and camber.

The formulation is independent of grid topology, and that makes MASSOUD suitable for a variety of analysis codes such as CFD and CSM. The analytical sen-

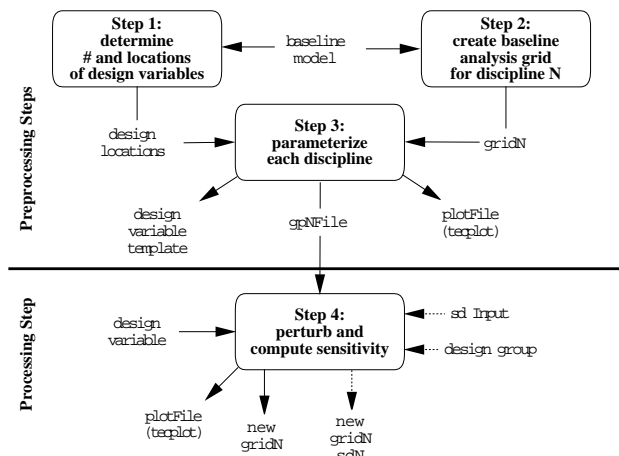


Fig. 1 Parameterization process.

sitivity derivatives are available for use in a gradient-based optimization. This algorithm is suitable for low-fidelity (e.g., linear aerodynamics and equivalent laminated plate structures) and high-fidelity (e.g., nonlinear CFD and detailed finite element modeling) analysis tools.

The algorithm, initially proposed by this author,² was successfully implemented for aerodynamic shape optimization with analytical sensitivity with structured grid^{3,4} and unstructured grid⁵ CFD codes. In addition to ease of use and implementation, MASSOUD has the following benefits: 1) parameterization is consistent, 2) the analytical sensitivity derivatives are available, 3) complex existing grids can be parameterized, 4) there is a strong local control, 5) smoothness can be controlled, and 6) few design variables are required.

Parameterization Process

The parameterization process has four distinct steps (see Fig. 1).

- Step 1: Determine the number and the locations of design variables based on the geometry model (e.g., CAD model). This step is currently a manual preprocessing step.
- Step 2: Create the analysis grids. These grids could be for CFD, CSM, linear aero, and performance analysis. This step is independent of

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```

m6 Shape Optimization (designLocations)(SECTION 1)
np      ne      ntwtst  ncmx  x      y      z
4       1       5       20    0      1      2
Pt      X      Y      Z (SECTION 2)
0       9.8000503e-01 1.0500000e+00 0.0000000e+00
1       6.8757999e-01 0.0000000e+00 0.0000000e+00
2       -9.9599998e-03 0.0000000e+00 0.0000000e+00
3       5.9375000e-01 1.0500000e+00 0.0000000e+00
0 1 2 3
#Twist curves (SECTION 3)
#Ax     Ay     Az
0.0     1.0     0.0
# x     y     z     ir     or
6.9531375e-01 1.0500000e+00 0.0000000e+00 1000.0 10000.0
5.6383407e-01 7.8749999e-01 0.0000000e+00 1000.0 10000.0
4.3235439e-01 5.2499998e-01 0.0000000e+00 1000.0 10000.0
3.0087471e-01 2.6249999e-01 0.0000000e+00 1000.0 10000.0
1.6939500e-01 0.0000000e+00 0.0000000e+00 1000.0 10000.0
#le/te definitions (SECTION 4)
2
0.0000000e+00 0.0000000e+00 0.0000000e+00
6.0374999e-01 1.0500000e+00 0.0000000e+00
2
6.7758000e-01 0.0000000e+00 0.0000000e+00
9.7000498e-01 1.0500000e+00 0.0000000e+00
5 2 #number of ncp, degx for thickness streamwise (SECTION 5)
0.0
0.1
0.5
0.75
1.0
3 2 #number of ncpy, degy for thickness spanwise
0.0000000e+00
0.5000000e+00
1.0500000e+00
5 2 #number of ncp, degx for camber streamwise (SECTION 6)
0.0
0.1
0.5
0.75
1.0
3 2 #number of ncpy, degy for camber spanwise
0.0000000e+00
0.5000000e+00
1.0500000e+00

```

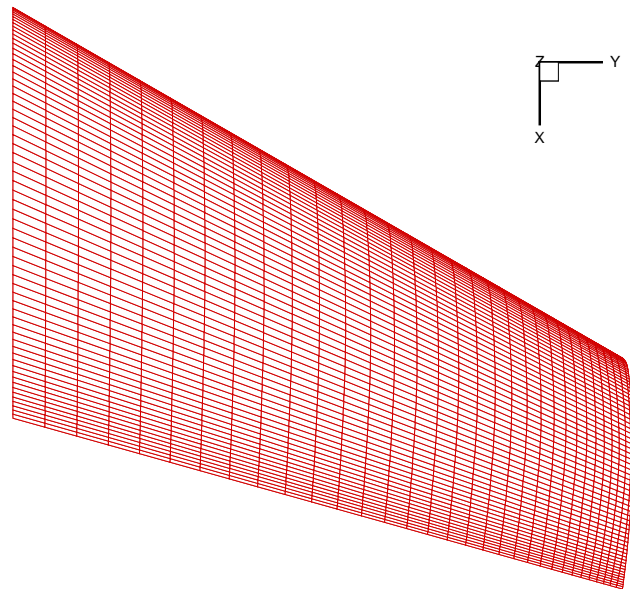


Fig. 3 ONERA M6 wing.

Fig. 2 Sample design locations for the ONERA M6 wing.

the parameterization process and will not be discussed in this manual.

- Step 3: Parameterize the analysis grids. This process is automated.
- Step 4: Perturb the analysis grids and compute sensitivity derivatives of grids with respect to design variables.

Step 1: Identify Design Variables

The locations and the numbers of design variables are determined in the first step. The information is stored in a file (e.g., `designLocations`) in an ASCII format. The file consists of planform, twist, shear, thickness and camber definitions. Figure 2 shows a sample `designLocations` input file for the ONERA M6 wing shown in Fig. 3. The following section describes the content of `designLocations` file shown in Fig. 2.

- Section 1: Global parameters
 - lines 1–2: comments
 - line 3:
 - * np: number of points defining the planform polygon
 - * ne: number of elements defining the planform polygon
 - * ntwtst: number of points defining the twist and shear

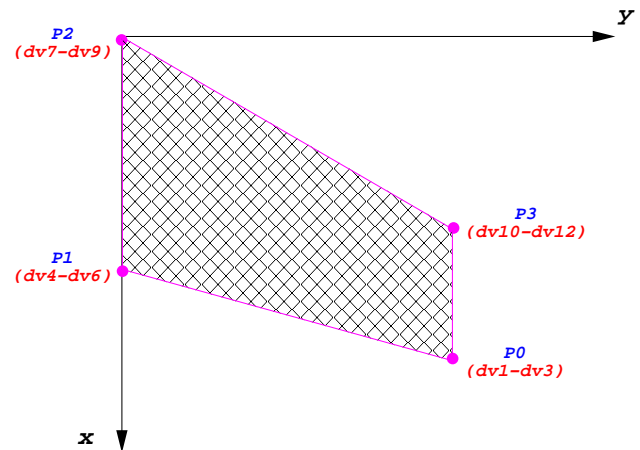


Fig. 4 Points defining the planform polygon for the ONERA M6 wing.

- * ncmx: maximum number of design points defining the thickness and camber
- * coordinate system: aircraft coordinate system, values 0, 1, and 2 are used for 1st, 2nd, and 3rd coordinates, respectively
 - x: rolling axis
 - y: pitching axis
 - z: yawing axis
- Section 2: Polygon coordinates defining the planform (see Fig. 4)
 - line 4: comments
 - lines 5–8: coordinates (point number, x , y , z) (Point number must start with zero.)
 - line 9: element connectivity

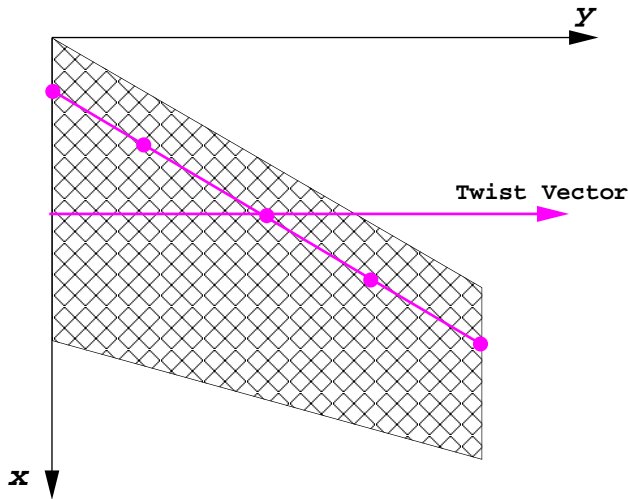


Fig. 5 Locations of twist and shear.

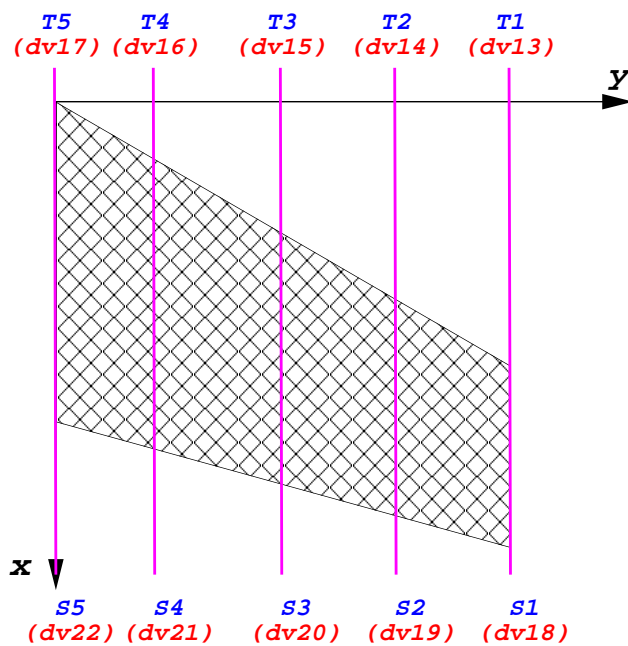


Fig. 6 Twist and shear design variables.

- Section 3: Twist and shear (see Figs. 5-6)
 - lines 10-11: comments
 - line 12: twist vector
 - line 13: comments
 - lines 14-18: twist and shear locations
 - * x, y, z coordinates
 - * inner radius
 - * outer radius
- Section 4: Definitions for the leading and trailing edges (see Fig. 7)
 - line 19: comments
 - line 20: number of points on the leading edge

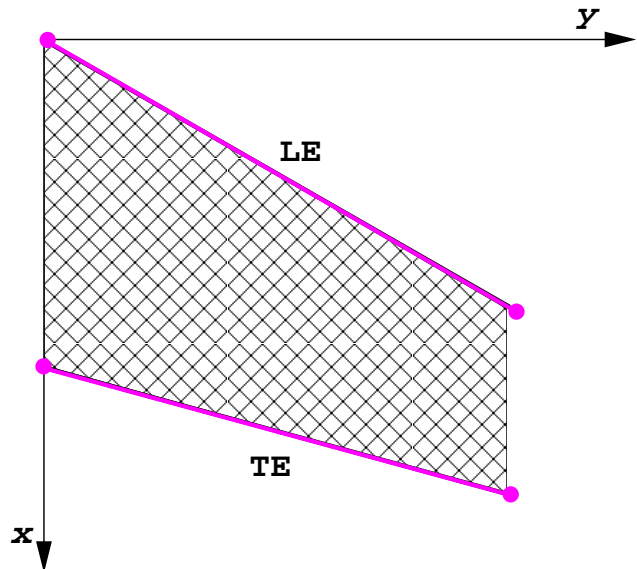


Fig. 7 Location of thickness design variables.

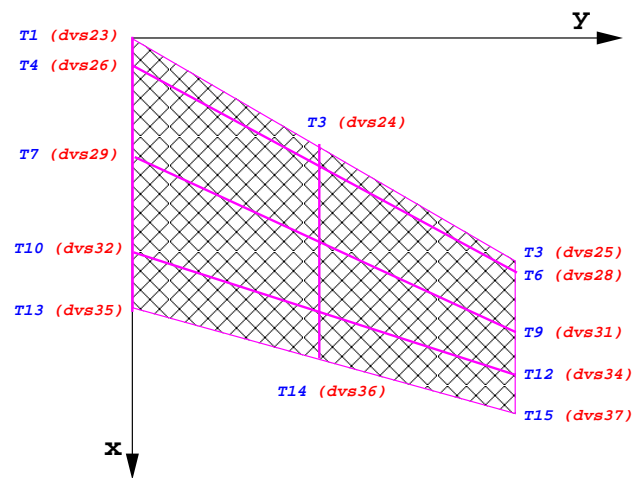


Fig. 8 Thickness design variables.

- lines 21-22: leading edge coordinate locations (x, y, z)
- line 23: number of points on the trailing edge
- lines 24-25: trailing edge coordinate locations (x, y, z)
- Section 5: Design locations for thickness (see Fig. 8)
 - line 26: number of points and degree of the nonuniform rational B-spline (NURBS) surface for thickness in x -direction
 - lines 27-31: knot vector in percent chord for thickness
 - line 32: number of points and degree of the NURBS surface for thickness in y -direction
 - lines 33-35: knot vector along span for thickness

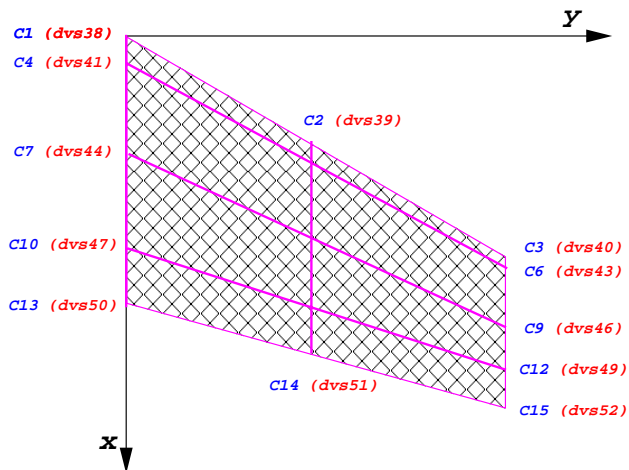


Fig. 9 Camber design variables.

- Section 6: Design locations for camber (see Fig. 9)
 - line 36: number of points and degree of the NURBS surface for camber in x -direction
 - lines 37–41: knot vector in percent chord for camber
 - line 42: number of points and degree of the NURBS surface for camber in y -direction
 - lines 43–45: knot vector along span for camber

Step 2: Create Analysis Grids

This step is accomplished independent of the parameterization process.

Step 3: Parameterize

This step is used to parameterize a grid in NASTRAN,⁶ FAST unstructured,⁷ or PLOT3D⁸ format. The step is automatic, and it needs to be done only once prior to optimization. The result from this step is a parameterized file (e.g., `gpNfile`) that will stay fixed during optimization. The driver code for shape parameterization is called `massoudDesignDriver`, and it can be executed by typing following command:

```
massoudDesignDriver -inputOption inputGrid \
  designLocations outputFile.gp
```

The `inputOption` flag is used to specify format of the input grid file. The valid options are

- n: NASTRAN⁶ small field format
- n16: NASTRAN⁶ large field format
- f: FAST⁷ unstructured
- p: PLOT3D,⁸ formatted, multiblock, surface grid

For example, the command

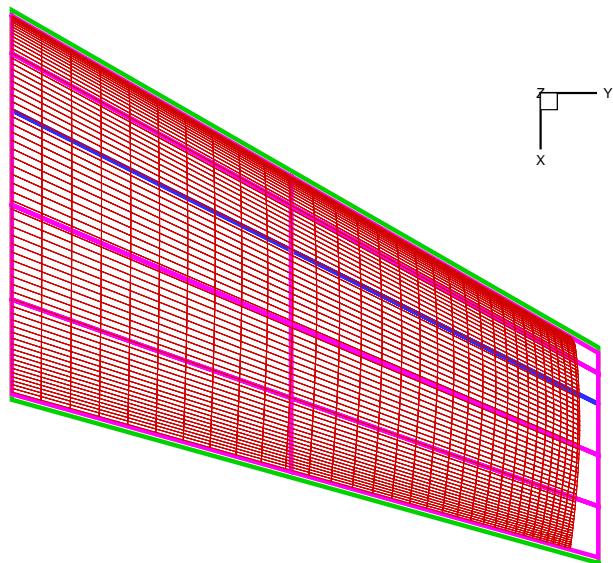


Fig. 10 ONERA M6 parameterized grid.

```
massoudDesignDriver -p M6.p3d designLocations \
  M6s.gp
```

parameterizes a PLOT3D⁸ file and creates the following three files:

- `M6s.gp`: parameterized grid
- `designVariableTemplate`: template file for design variables that will be used during optimization
- `baselineShape.plt`: tecplot file containing the grid and design locations (This file is used only for viewing.) (see Fig. 10).

The template file contains the baseline design variables. Users should use this file to create a new design file. The following section describes the content of `designVariableTemplate` file based on the ONERA M6 wing shown in Fig. 11.

- lines 1–2: comments
- line 3: number of planform control points (12 design variables)
- lines 4–7: changes in the coordinates of control points
- line 8: comments
- line 9: number of twist design variables (5)
- lines 10–14: changes in twist
- line 15: comments
- line 16: number of shear design variables (5)
- lines 17–21: changes in shear
- line 22: comments

```

#MASSOUD Design Variables
#Planform dvs (1 - 12)
4
0.000000e+00 0.000000e+00 0.000000e+00
0.000000e+00 0.000000e+00 0.000000e+00
0.000000e+00 0.000000e+00 0.000000e+00
0.000000e+00 0.000000e+00 0.000000e+00
#Twist dvs (13 - 17)
5
0.000000e+00
0.000000e+00
0.000000e+00
0.000000e+00
0.000000e+00
#Shear dvs (18 - 22)
5
0.000000e+00
0.000000e+00
0.000000e+00
0.000000e+00
0.000000e+00
#Thickness(do x, do y) dvs (23 - 37)
5 3
0.000000e+00 0.000000e+00 0.000000e+00
0.000000e+00 0.000000e+00 0.000000e+00
0.000000e+00 0.000000e+00 0.000000e+00
0.000000e+00 0.000000e+00 0.000000e+00
0.000000e+00 0.000000e+00 0.000000e+00
#Camber (do x, do y) dvs (38 - 52)
5 3
0.000000e+00 0.000000e+00 0.000000e+00
0.000000e+00 0.000000e+00 0.000000e+00
0.000000e+00 0.000000e+00 0.000000e+00
0.000000e+00 0.000000e+00 0.000000e+00
0.000000e+00 0.000000e+00 0.000000e+00

```

Fig. 11 Sample design variable input file for the ONERA M6 wing.

- line 23: number of design points for thickness
- lines 24–28: control point representing the changes in thickness
- line 29: comments
- line 30: number of design points for camber
- lines 31–35: control point representing the changes in camber

Every real number in `designVariableTemplate` file can be a design variable, and they are numbered sequentially as they appear in the file ($P_i, i = 1, imax$). For example, P_{21} is the second inboard shear design variable (see Figs. 11 and 6). The ONERA M6 example has 52 design variables (i.e., $imax = 52$):

- 12 for planform
- 5 for twist
- 5 for shear
- 15 for camber

```

#MASSOUD INPUT FILE
# runOption (0 analysis), (< 0 sd analysis)
-1
# core (0 incore solution)(1 out of core solution)
0
# input parameterized file
M6s.gp
# design variable input file
newDesign
# input sensitivity file (used for runOption > 0
M6.usd
# output grid file
newM6.p3d
# output tecplot file for viewing
newM6.plt
# file containing the design variables group
designVariableGroups

```

Fig. 12 Sample input file for MASSOUD.

- 15 for thickness

To parameterize a CSM grid of the ONERA M6 wing (e.g., in small field NASTRAN format), the above command must be changed

```

massoudDesignDriver -n M6.NASTRAN\
    designLocations M6n.gp

```

Step 4: Perturb and compute sensitivity

This step is used to perturb the grid and perform sensitivity analysis. The step is automatic, and it needs to be done for every optimization cycle. Users may choose to do the analysis only and bypass the sensitivity analysis. The result from this step is a perturbed grid and its sensitivity with respect to design variables in a user-defined file format. For example, if a NASTRAN file is parameterized, the results from step 4 will also be in NASTRAN format. The parameterization code is called `massoud`, and it can be executed by typing the following command:

```

massoud massoudInputFile

```

Figure 12 shows a sample `massoudInputFile` for the ONERA M6 wing. The input file contains the options and the locations of all necessary input and output files. The following section describes the content of `massoudInputFile` shown in Fig. 12.

- lines 1–2: comments
- line 3: `runOption` (0 analysis), (> 0 number of user-defined design variables) (–1, sensitivity analysis MASSOUD’s design variables)
- line 4: comments
- line 5: `core` (0 in-core solution)(1 out-of-core solution)
- line 6: comments
- line 7: input parameterized file

- line 8: comments
- line 9: design variable input file
- line 10: comments
- line 11: input sensitivity file (used for runOption > 0)
- line 12: comments
- line 13: output grid file, and massoud will create a sensitivity file with same name but sd extension
- line 14: comments
- line 15: output tecplot file for viewing
- line 16: comments
- line 17: file containing the design variables group

For example, the input file shown in Fig. 12 will create the following files:

- new_M6.p3d: new grid
- new_M6.plt: tecplot file containing the grid
- new_M6.p3d.sd: if gpjmax \neq 0
- new_M6.sd.plt.sd: if gpjmax \neq 0, tecplot file

Sensitivity Analysis

Sensitivity derivatives are defined as the derivatives of the coordinate locations with respect to the design variables. As mentioned before, every real number in designVariableTemplate file is considered to be a design variable in MASSOUD. As a result, the default sensitivity analysis (runOption < 0) computes the sensitivity of the grid coordinate locations with respect to massoud design variables.

Users can introduce a different set of design variables ($V_j, j = 1, jmax$), and massoud can compute the sensitivity derivatives with respect to V_j . The computation is based on the chain rule differentiation as

$$\frac{\partial \bar{R}}{\partial V_j} = \frac{\partial \bar{R}}{\partial P_i} \frac{\partial P_i}{\partial V_j} \quad (1)$$

The first and the second terms are computed by massoud, and the last term is a matrix with $imax$ rows and $jmax$ columns.

$$\begin{bmatrix} \frac{\partial P_1}{\partial V_1} & \frac{\partial P_1}{\partial V_2} & \cdots & \frac{\partial P_1}{\partial V_{jmax}} \\ \frac{\partial P_2}{\partial V_1} & \frac{\partial P_2}{\partial V_2} & \cdots & \frac{\partial P_2}{\partial V_{jmax}} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_{imax}}{\partial V_1} & \frac{\partial P_{imax}}{\partial V_2} & \cdots & \frac{\partial P_{imax}}{\partial V_{jmax}} \end{bmatrix} \quad (2)$$

```
#Example 1: this is input sd file for MASSOUD
# number of row == number dvs within MASSOUD,
# number of col == final number dvs
#(row) (col) (# of nonzero rows)
52 1 1
#(row #) (row)
1 1

#Example 2: this is input sd file for MASSOUD
# number of row == number dvs within MASSOUD,
# number of col == final number dvs
#(row) (col) (# of nonzero rows)
52 1 3
#(row #) (row)
50 1
51 1
52 1

#Example 3: this is input sd file for MASSOUD
# number of row == number dvs within MASSOUD,
# number of col == final number dvs
#(row) (col) (# of nonzero rows)
52 1 6
#(row #) (row)
29 1
30 1
31 1
44 -1
45 -1
46 -1

#Example 4: this is input sd file for MASSOUD
# number of row == number dvs within MASSOUD,
# number of col == final number dvs
#(row) (col) (# of nonzero rows)
52 1 6
#(row #) (row)
44 1
45 1
46 1
47 1
48 1
49 1

#Example 5: this is input sd file for MASSOUD
# number of row == number dvs within MASSOUD,
# number of col == final number dvs
#(row) (col) (# of nonzero rows)
52 2 4
#(row #) (row)
1 1 0
2 0 1
10 1 0
11 0 1

#Example 6: this is input sd file for MASSOUD
# number of row == number dvs within MASSOUD,
# number of col == final number dvs
#(row) (col) (# of nonzero rows)
52 3 4
#(row #) (row)
1 1 0 1
2 0 1 0
10 1 0 0
11 0 1 0
```

Fig. 13 Sample input file for user-defined design variables.

Users must provide the nonzero rows of matrix in Eq. (2) in an ASCII format and the file name should appear at line 11 of `massoudInputFile` as shown in Fig. 12. Figure 13 shows six example input files, and the following section describes the file format.

- lines 1–4: comments
- line 5: number of rows (number of P_i 's), (number of columns (number of V_j 's), (number of nonzero rows)
- line 6: comments
- line 7–last: nonzero row number followed by the entire row

The following section provides a description of the examples shown in Fig. 13.

- Example 1 has one design variable — the wing-tip trailing edge x -coordinate
- Example 2 has one design variable — the values for camber have been linked to create a single camber design variable for the entire wing trailing edge
- Example 3 has one design variable — the values for camber and thickness have been linked to create a single design variable for the entire wing lower surface
- Example 4 has one design variable — the values for camber have been linked to create a single camber design variable for the entire wing surface
- Example 5 has two design variables — wing-tip x - and y -coordinates
- Example 6 has three design variables— the wing-tip trailing edge x -coordinate and the wing-tip x - and y -coordinates

References

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⁸Walatka, P. P., Buning, P. G., Pierce, L., and Elson, P. A., "PLOT3D User's Manual," Tech. Rep. NASA-TM-1990-101067, Mar. 1990.