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Engineering Notes

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Wing Planform Design Optimization for Reusable Launch Vehicle

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Nomenclature

C_m	=	pitching moment coefficient
$f(x)$	=	polynomial function
i, j	=	index
L/D	=	lift to drag ratio
V_{TD}	=	touch-down velocity, m/s
W	=	wing weight, kg
X^T	=	transpose of design matrix
X^{-1}	=	inverse of design matrix
$x_1, x_2, \ldots, x_k$	=	input variables
y	=	column vector
$\hat{y}$	=	predicted response
$y(x)$	=	unknown function
α	=	angle of attack, deg
β	=	parameter of polynomial
ε	=	random error
Λ_{LE}	=	wing leading-edge sweep angle, deg
σ^2	=	variance

I. Introduction

WING planform design plays a fundamental role in the wing-body configuration design. The complexity of wing planform design increases for a winged reusable launch vehicle (RLV), where apart from aerodynamic and performance constraints, a configuration has to be designed to reduce the aerodynamic heating during reentry. In this study, two separate approaches for wing planform design fulfilling the aerodynamic and performance constraints with minimum weight as an objective have been attempted using the same constraints, objective, and input data. The first approach is using a graphical procedure and the second approach is using the Response Surface Methodology (RSM) [1,2].

II. Design Criteria

The guidelines/analysis criteria used in the present study for RLV wing planform design are given as follows:

1) Subsonic maximum landing speed is ≤ 85 m/s, at an angle of attack of 14 deg.

2) Maximum subsonic untrimmed $L/D \geq 4.5$.

3) The leading-edge sweep angle of the wing must be ≥ 45 deg to minimize aerodynamic heating.

4) The minimum pitching moment coefficient is required at typical subsonic, supersonic, hypersonic Mach numbers (0.3, 2.0, and 6.0) at corresponding angles of attack (14, 14, and 30 deg, respectively).

5) The vehicle has to be stable/near neutrally stable at complete trajectory Mach numbers and angles of attack.

6) The vehicle must be trimmable/controllable at complete trajectory Mach numbers and angles of attack.

III. Design Space Creation

A wing-body configuration consisting of an ogive nosed fuselage, a single aft swept vertical tail, and a small aspect ratio delta wing with NACA 0010 airfoil section is selected as the baseline configuration. A leading-edge strake is added ahead of the delta wing in proportion to the basic wing planform. Elevons placed at the trailing edge of the wing act as both longitudinal and lateral control devices. The shape, volume, and weight of the fuselage and vertical tail are unaltered in this study.

Figure 1 shows the matrix of nine wing planform configurations generated by perturbing the exposed root chord, tip chord, and exposed semispan of the baseline configuration (XSF = YSF = 1.0) using the X-scale factor (XSF) and Y-scale factor (YSF). The XSF and YSF are varied by 0.8, 1.0, and 1.2 to arrive at nine different configurations. All the configurations have a 10-deg trailing-edge sweep angle. The leading-edge strake for all nine configurations is arrived at based on the exposed basic wing planform. The trailing edge of the exposed wing root chord for all the configurations is flushed with a fuselage base.

IV. Aerodynamic Analysis Tools

1) WINGAERS [3] is an in-house developed code based on DATCOM [4]. The code is capable of estimation of longitudinal aerodynamic coefficients at Mach numbers from low subsonic to hypersonic ($M = 0.25$ to 10.0) and angles of attack (−10 to 50 deg) for the reentry class of wing-body configurations. The results of the code are validated against space shuttle data [5].

2) WTAP [6] is an in-house developed database code based on the Space Shuttle Orbiter database [5]. The code is capable of estimation of trimmed longitudinal aerodynamic coefficients at Mach numbers from low subsonic to hypersonic ($M = 0.25$ to 8.0) and angles of attack (−10 to 50 deg) for the reentry class of wing-body configurations. The code computes the incremental longitudinal aerodynamic parameters due to control surface deflection and the control surface (elevon/body flap) deflection required to trim the vehicle. The code is validated against wind-tunnel data available for the NASA Earth-to-orbit configuration and a typical winged RLV data.

3) The weight of the wing is computed using empirical relation [7].

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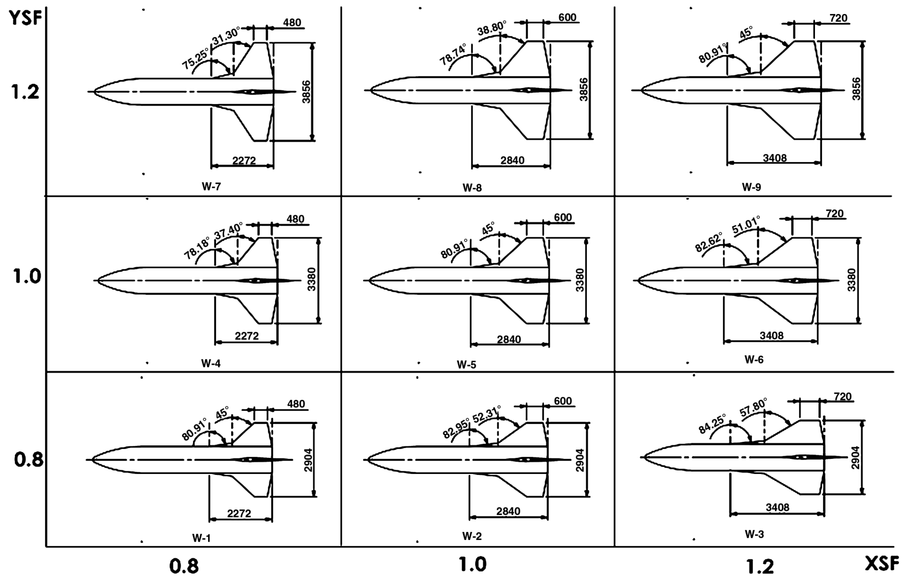

Fig. 1 Matrix of wing-body configurations studied.

V. Design Process

Longitudinal aerodynamic characteristics of all nine configurations at Mach numbers 0.3, 2.0, and 6.0 are computed using the WINGAERS code. The parameters such as touch-down velocity and landing distance are computed using the standard relations. The wing weight [7] is computed using the wing structural span. These parameters have been computed before the wing planform optimization process. In this study, two separate approaches for wing planform design have been attempted using the same constraints, objective, and input data. The first approach is using a graphical procedure and the second approach is using RSM. The details of the wing planform design procedures using these two different methods are explained next.

A. Wing Planform Optimization Through Graphical Procedure

Figure 2 indicates the graphical method of obtaining a design configuration with the relevant constraints. A wing planform satisfying the required constraints for a wing-body reentry vehicle with minimum weight is available at XSF of 1.054 and YSF of 1.054. The aerodynamic analysis of the designed configuration is carried out and the aerodynamic, performance, and weight characteristics are as predicted.

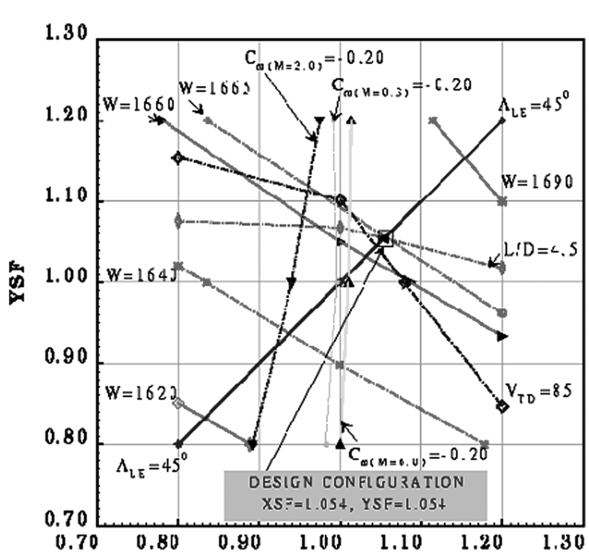

Fig. 2 Isolines of V_{TD}, Λ_{LE}, $L/D_{(M=0.3)}$, W, $C_{m(M=0.3)}$, $C_{m(M=2.0)}$, and $C_{m(M=6.0)}$ (graphical technique).

B. Wing Planform Design Through Response Surface Methodology

RSM is a collection of mathematical and statistical techniques that are useful for modeling and analysis in applications where a response of interest is influenced by several variables and the objective is to optimize the response [1,2].

The main steps in RSM are as follows:

1) Aerodynamic computations are carried out at the points in the design space, selected using design of experiments.

2) Regression analysis is carried out to build the approximation model/surrogate for the objective and constraint functions.

3) Optimization of the independent variables is carried out for the given objective and constraint functions.

4) Verification of the optimal values is carried out.

C. Design of Experiments

The candidate points/combinations of input variables chosen for this study are the points, which have already been used in the graphical procedure. The candidate points neatly form a design called the "face centered central composite" design in two variables and is shown in Fig. 3.

The vertices of the square represent the combination (XSF, YSF) = (0.8, 0.8), (0.8, 1.2), (1.2, 1.2), and (1.2, 0.8). The center point represents (XSF, YSF) = (1.0, 1.0). The values of the response/output variables are available at the nine factor/input

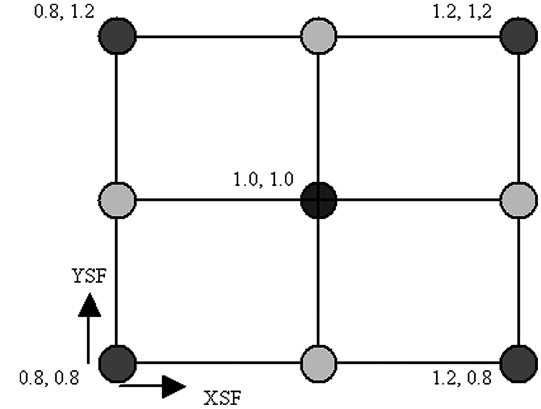

Fig. 3 Face centered central composite design.

Table 1 Input variables and output responses

XSF	YSF	$\Lambda_{LE}(^0)$	L/D ($M = 0.3$)	V_{TD}, m/s	W, kg	C_m ($M = 0.3$)	C_m ($M = 2$)	C_m ($M = 6$)
1.0	1.0	45.0	4.29	87.1	1652.9	−0.197	−0.165	−0.20
1.2	0.8	57.8	3.96	86.0	1641.4	−0.099	−0.076	−0.12
0.8	0.8	45.0	3.56	99.6	1614.0	−0.335	−0.251	−0.34
1.2	1.2	45.0	4.96	77.3	1697.8	−0.102	−0.106	−0.12
0.8	1.0	37.4	4.21	93.7	1637.3	−0.348	−0.280	−0.35
0.8	1.2	31.3	4.97	82.4	1661.8	−0.410	−0.291	−0.35
1.0	0.8	52.3	3.8	92.8	1627.5	−0.187	−0.139	−0.20
1.2	1.0	51.0	4.45	81.8	1669.1	−0.102	−0.094	−0.12
1.0	1.2	38.8	4.97	83.0	1679.5	−0.192	−0.187	−0.20

combinations illustrated in Fig. 3 and the values are provided in Table 1.

D. Regression Analysis for Building Approximation Models

Response surface modeling postulates a model of the form

$$y(x) = f(x) + \varepsilon \tag{1}$$

where $y(x)$ is the unknown function of interest, $f(x)$ is the polynomial approximation of x, and ε is the random error that is assumed to be normally distributed with mean zero and variance σ^2. The error ε at each observation is assumed to be independent and identically distributed. The polynomial function $f(x)$ used to approximate $y(x)$ is typically a low order polynomial, which is assumed to be either linear, or quadratic. The function $f(x)$ can also be represented by radial basis functions, splines, etc.

The equation for a quadratic polynomial response surface is given as

$$\hat{y} = \beta_0 + \sum_i \beta_i x_i + \sum_i \beta_{ii} x_i^2 + \sum_{i<j} \beta_{ij} x_i x_{ij} \tag{2}$$

The parameters of the polynomials in the equation, β_0, β_i, β_{ii}, and β_{ij}, are determined through least-squares regression, which minimizes the sum of squares of the deviations of the predicted values $\hat{y}$ from the actual values $y(x)$. The coefficients of the equations can be found using the equation

$$\beta = [X^T X]^{-1} X^T y \tag{3}$$

where X is the design matrix of sample data points, X^T is its transpose, and y is a column vector that contains the values of the response at each sample point.

Multiple linear regression analysis using the data given in the table provides the *best estimates* for the coefficients in the polynomial equations. Equations have been computed for the variation of all the responses in the design space. The equation for the variation of the wing leading-edge sweep angle in terms of the independent variables, XSF and YSF, is given next along with the statistical details regarding the fit:

$$\Lambda_{LE} = \beta_1 * \text{XSF} + \beta_2 * \text{YSF} + \beta_3 * \text{XSF}^2 + \beta_4 * \text{YSF}^2 + \beta_5 * \text{YSF} * \text{XSF} \tag{4}$$

The constants β_0 to β^5 have been estimated using the "Design Expert" [8] and the relevant statistical details are given as follows: R squared = 0.9999, adjusted R squared = 0.9997, and predicted R squared = 0.9986. The values of R squared, adjusted R squared, and predicted R squared near to 1 indicate that the model is good and can be used for design space exploration. Similar equations for the variation of subsonic lift-to-drag ratio, touch-down velocity, pitching moment coefficient at $M = 0.3$, 2.0, and 6.0, and weight in terms of the independent variables, XSF and YSF, are computed using multiple linear regression.

Figures 4 and 5 show the variation of the wing leading-edge sweep angle, lift-to-drag ratio at $M = 0.3$, and $\alpha = 14$ deg with XSF and YSF.

E. Optimization to Find the Best Settings of Input Variables

The constraints used in the present studies for wing planform design are as follows:

1) Subsonic maximum landing speed is ≤ 85 m/s, at an angle of attack of 14 deg.

2) Maximum subsonic untrimmed $L/D \geq 4.5$.

3) Leading-edge sweep angle of the wing must be ≥ 45 deg.

4) The maximum pitch-down moment coefficient at $M = 0.3$, $\alpha = 14$ deg, $M = 2.0$, $\alpha = 14$ deg, $M = 6.0$, and $\alpha = 30$ deg is ≤ 0.2 and the objective is the *minimum wing weight*.

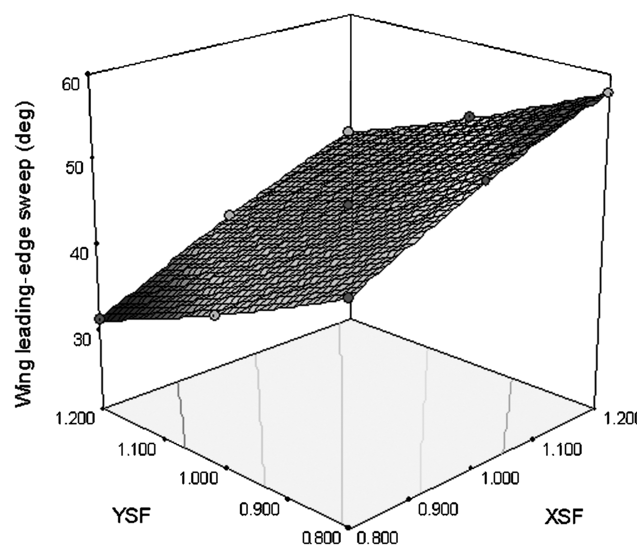

Fig. 4 Wing leading-edge sweep angle.

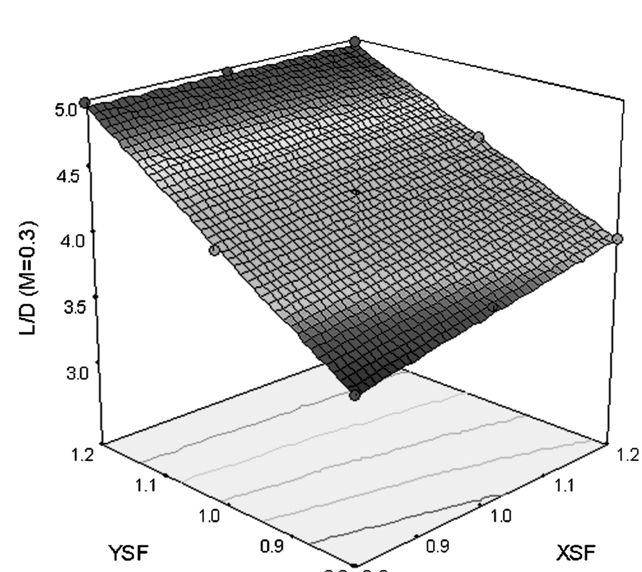

Fig. 5 Lift-to-drag ratio at $M = 0.3$, $\alpha = 14$ deg.

The constraints and objective translated into numbers are given as follows:

1) $45 \le \Lambda_{LE} \le 60$ deg.
2) $4.5 \le L/D_{(M=0.3)} \le 4.97$.
3) $77.3 \le V_{TD} \le 85.0$.
4) Minimum weight within the range 1614–1697.8 kg.
5) $-0.2 \le C_{m(M=0.3)} \le -0.099$.
6) $-0.2 \le C_{m(M=2.0)} \le -0.076$.
7) $-0.2 \le C_{m(M=6.0)} \le -0.117$.

All the constraints are plotted in the overlay plot which shows the feasible design space (Fig. 6). The configuration which satisfies all the constraints with the objective of minimum weight is found out to be XSF, YSF equals 1.063, 1.052, respectively. The optimization was carried out using the Design Expert.

VI. Results

Wing planform design has been carried out using graphical technique and RSM for winged RLV. The graphical technique results in a wing planform design of XSF = 1.054, and YSF = 1.054 for the objective of minimum wing weight. The RSM results in a wing planform design of XSF = 1.063, and YSF = 1.052 for the objective of minimum wing weight.

The designs using the two methods match well (XSF = 1.054, and YSF = 1.054 for the graphical method), (XSF = 1.063, and YSF = 1.052 for RSM). This small deviation is mainly due to the approximation of the touch-down velocity curve as straight-line segments in the graphical optimization (Fig. 2).

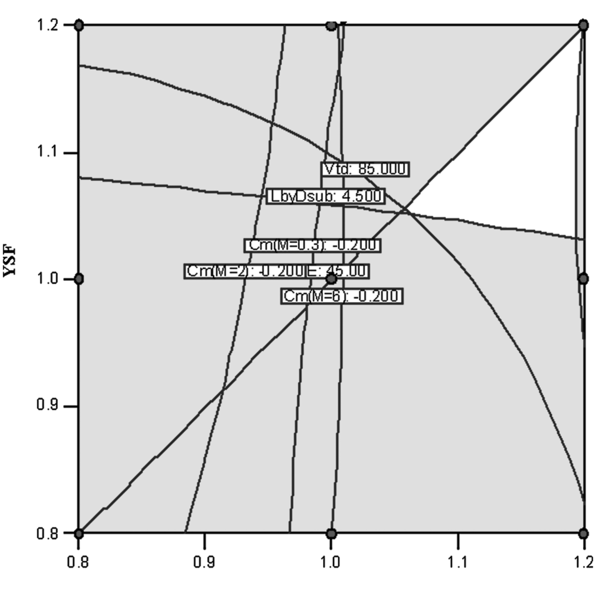

Fig. 6 Overlay plot indicating feasible design space (response surface methodology).

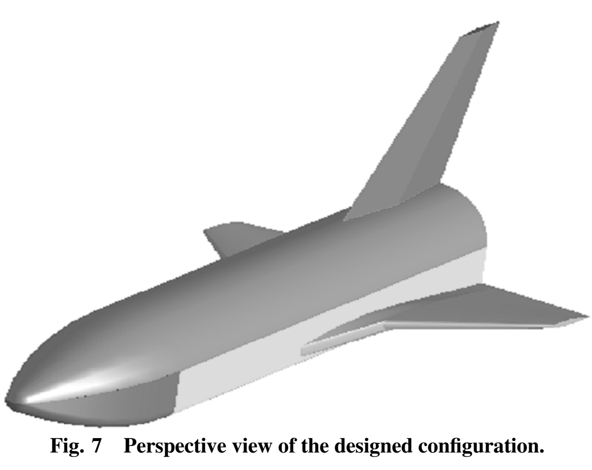

Fig. 7 Perspective view of the designed configuration.

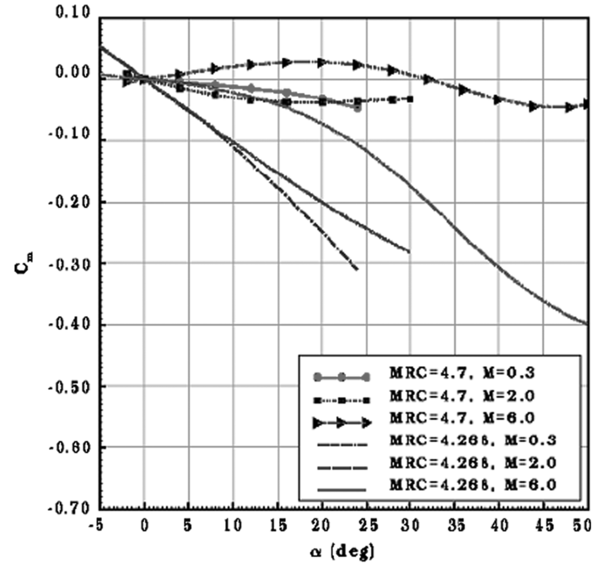

Fig. 8 Variation of pitching moment coefficient at $M = 0.3, 2.0,$ and 6.0 with MRC.

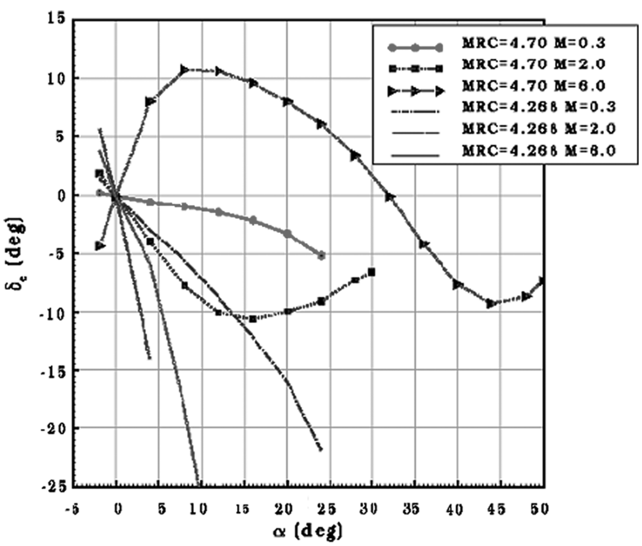

Fig. 9 Variation of elevon deflection for trim at $M = 0.3, 2.0,$ and 6.0 with MRC.

The configuration designed through RSM is given in Fig. 7. The pitching moment coefficient is plotted in Fig. 8 and this shows that the vehicle is stable at the forward center of gravity location (4.268 m from nose) at the selected subsonic, supersonic, and hypersonic Mach numbers. Figure 9 shows that the vehicle is not trimmable at this moment reference center (MRC). So, the MRC is shifted aft (4.7 m from nose) to decrease the stability and improve the controllability of the vehicle. Thereby the maximum elevon deflection needed for trim is within 11 deg.

VII. Conclusions

A wing planform design for a RLV has been successfully carried out using a graphical optimization and numerical optimization technique, response surface methodology. The designs using the two methods match well (XSF = 1.054, and YSF = 1.054 for the graphical method), (XSF = 1.063, and YSF = 1.052 for the RSM). This small deviation is mainly due to the approximation of the touch-down velocity curve as straight-line segments in the graphical optimization technique. The designed configuration is stable at the selected subsonic, supersonic, and hypersonic Mach numbers. The center of gravity location is selected for trimming the vehicle within small/allowable elevon deflections.

Acknowledgments

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