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Multi-Objective and Multidisciplinary Design Optimization of Supersonic Fighter Wing

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An aerodynamic/structural multidisciplinary design with multiple objectives was carried out for the supersonic fighter wing using response surface methodology. Through a series of static aeroelastic analyses of a variety of candidate wings, the aerodynamic performance and structural strength were calculated. Nine wing and airfoil parameters were chosen for the aerodynamic design variables, and four structural variables were added to determine the wing skin thickness. To consider various flight conditions, multipoint design optimization was performed on the three representative design points. As expected, the single-point design shows the most improved performance on its own design point, but it produces inferior results by not satisfying some constraints on other design points. To improve the performances evenly and moderately at all design points, a multipoint optimal design was conducted. A genetic algorithm was also introduced to control the weight of the multiple objectives. The multipoint designed wing features improved performance and satisfies whole constraints at all design points. It is similar to the real supersonic fighter wing that was developed through numerous wind-tunnel tests and tradeoff studies. The proposed multidisciplinary design optimization framework could be adopted as an efficient practical design tool for the supersonic fighter wing to fix the basic geometry at a conceptual design stage.

Nomenclature

b	=	wingspan
c_i, c_{ij}	=	regression coefficient
eff	=	performance increase ratio of each objective
F	=	cumulative distribution function or objective function
f	=	response surface model or probability density function
L/D	=	lift-to-drag ratio
M	=	Mach number
nc	=	number of objectives
n_s	=	number of sample data points
n_v	=	number of design variables
S	=	wing area
w	=	weighting factor
$\bar{X}$	=	vector of design variables or matrix of datapoint set or random variable
x, y, z	=	Cartesian coordinates
$x_{ij}^{(p)}$	=	design variables
y	=	observed response
α	=	angle of attack
ε	=	strain or error
θ	=	linear twist angle of a wing
Λ	=	leading-edge sweep angle

Subscript

$dp1, dp2, dp3$	=	design points 1, 2, and 3, respectively

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I. Introduction

As numerical optimization techniques have rapidly developed over the past several decades, they have gradually replaced traditional design techniques. Since the early stages, of development a great number of design methods have been successfully applied to airfoil and simple three-dimensional wing design problems. The inverse design method has been widely used as an efficient design method to guarantee the existing inverse solution. Inverse design studies on the aerodynamic configurations of the transonic airfoil and wing were also implemented in conformity with various governing equations and algorithms.[1–5] However, distributions of the target pressure must be described before beginning the design procedure, which can be very difficult for each designer. To specify the optimal target distribution automatically, some numerical optimization methods were adopted.[6–8] Then direct numerical optimization methods based on the mathematical steepest descent method quickly replaced inverse design methods with the aerodynamic shape optimization method. Among numerous direct numerical optimization methods, gradient-based optimization algorithms have been widely utilized for conventional direct numerical optimization.[9–12] Hicks and Henne[9] first introduced this type of design procedure in the design of a three-dimensional configuration. Jameson et al.[11] applied a direct optimization method with an adjoint variable method for sensitivity analysis to a transonic wing–body configuration. Reuther et al.[12] extended this research to the multipoint aerodynamic wing design of a business jet configuration by introducing the parallel computation. Although the gradient-based optimization algorithm is one of the most efficient optimization algorithms, it cannot ensure the global optimum. Hence, global optimum search algorithms such as genetic algorithms (GAs)[13,14] and the response surface methodology (RSM)[15,16] have been used for direct numerical optimization.

The improvement of the numerical analysis and optimization techniques indicates that interest in the application of multidisciplinary analysis and design optimization to the complex three-dimensional wing and aircraft configuration has grown in recent years.[17–22] Chen et al.[17] developed an interface method to bridge the gap between the aerodynamic and structural models to transform the loads and displacements during the aeroelastic analysis. This approach was successfully applied to the aeroelastic analyses of the MD-90 wing. Samareh[20] proposed a new multidisciplinary shape parameterization approach applied to the multidisciplinary design optimization (MDO) of a simple wing and a high-speed civil transport configuration. Of late, on the basis of the global sensitivity equation for a coupled system, the coupled sensitivity analysis method was applied to evaluate aeroelastic sensitivity. Maute et al.[23] carried out a coupled sensitivity analysis and optimization of a three-dimensional nonlinear aeroelastic wing with high-fidelity analysis code, and aerostructural optimization of a supersonic business jet was implemented by Martins et al.[24] based on a coupled sensitivity analysis method. In addition to previous research on multidisciplinary analysis and optimization, multipoint analysis and optimization studies on the aerodynamic shape and configuration were conducted in terms of multiple objectives.[25,26]

Despite existing research on the MDO of aircraft, research on multipoint and multi-objective design optimization are insufficient to embrace whole-flight conditions, especially in the case of the supersonic fighter; flight conditions and required performance are dramatically changed with respect to the mission. Hence, more detailed studies concerning various flight conditions are required to design practical and realistic supersonic fighter wings.

In preliminary work, Kim et al.[27,28] carried out the multidisciplinary aerodynamic-structural optimal design for the wing of the T/A-50, which is a supersonic trainer/fighter developed in the Republic of Korea.[29] They considered more realistic design parameters pertaining to airfoil shapes of the supersonic wing sections in that work. Moreover, to consider various flight conditions of the supersonic fighter, a modified weighted-sum method was suggested for the optimization of multipoint and multi-objective design, harnessing a GA to automatically determine the weighting factors. In this paper, multipoint and multi-objective aerostructural MDO results of the supersonic fighter wing under various flight conditions will be demonstrated and will be compared with aerodynamic single disciplinary and multidisciplinary single-point design results to explore the suggested design method.

II. Numerical Analysis

A. Aerodynamic Analysis

The three-dimensional Euler equation is used to calculate the transonic and supersonic aerodynamic properties of the supersonic fighter wing. In this study, Van Leer's flux vector splitting is used to calculate the Jacobian matrix and Roe's flux difference splitting to solve the flux vector. To increase the order of spatial accuracy, flux vectors on the cell interface are computed via the MUSCL extrapolation scheme. To avoid the unexpected oscillation of the solution around the discontinuous flowfield, the MUSCL scheme is tapped with a Van Albada limiter.

In this regard, Beam and Warming's approximate factorization-alternating direction implicit (AF-ADI) scheme is used as the time integration method. To accelerate the convergence of the numerical analysis and reduce the computational time, the local time step, the sawtooth cycle multigrid method, and implicit residual smoothing are also adopted. An O-H type grid is used as the wing mesh for computational fluid dynamics (CFD) calculation. More detailed aerodynamic analysis of this study is described in Refs. 27 and 28.

B. Structural Analysis

For the structural analysis of the wing, a nine-node shell mixed finite element is utilized. The element has three translational degrees of freedom (DOF) and two rotational DOF per node as shown in Fig. 1; therefore, each element has 45 DOF.

Because the rotational deformation of a discontinuous surface cannot be expressed with only two rotational DOF per node, "drilling degrees of freedom" are adopted for the elements.[30] To combine CFD with computational structural mechanics (CSM), the nonuniform bicubic spline composite surface method is applied to transform CFD mesh to CSM mesh (see Fig. 2).

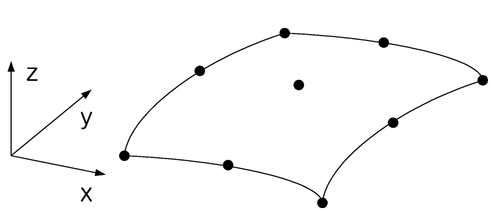

Fig. 1 Nine-node shell mixed element.

Table 1 Aeroelastic displacement of wing tip calculated by each coupling method

Aeroelastic analysis method	Displacement, in.
Loose coupling	2.1670 (5.5042 cm)
Tight coupling	2.1677 (5.5060 cm)

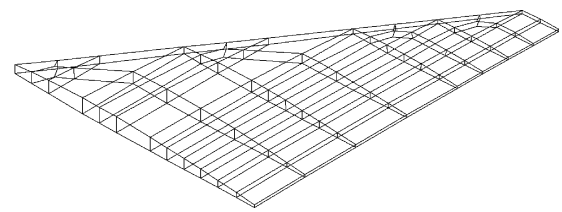

Fig. 2 CSM model of the wing.

Because of the inconsistency between CFD mesh and CSM mesh, the "VMT" method (V-shear force, M-moment, T-torque) is adopted to transform aerodynamic forces into structural nodal forces maintaining the shear force, moment, and torque equilibriums. The wing is divided into several parts for the multi-VMT method.

To determine the minimum structural size of the wing components, the durability and damage tolerance (DADT) allowable method is used for spar, rib, and lower skin subjected to tension forces. This method is based on the constraint that the maximum principal stress of each element must not exceed the DADT allowable stress. Also, the minimum size of the upper skin thickness is determined to withstand the buckling, whose load is acquired by the analysis of an idealized equivalent rectangular panel. In the process of the multidisciplinary design, the minimum size of the structural component calculated by the afore mentioned methods is used as a structural constraint.[27,28]

C. Aeroelastic Analysis

The developed CFD code is coupled with the CSM code for static aeroelastic analysis of a supersonic fighter wing. The traditional way of coupling those two analysis codes is as follows. First, aerodynamic analysis is performed and the converged aerodynamic force distribution is transformed into the structural nodal force and then transferred to the finite element method (FEM) analysis. After the wing deformation is calculated by FEM, the CFD mesh for the deformed wing is regenerated and the aerodynamic analysis is conducted again for the renewed mesh. This method is defined as the loose coupling method. To achieve the converged wing deformation using this method, about four to seven iterations of repeated full-cycle aerodynamic/structural analysis is needed, which is very time-consuming and inefficient.

To deal with this problem, another coupling method is introduced, defined as the tight coupling method. During the iteration of the flow solver, the FEM solver is called and executed per every specified number of CFD iteration. The aeroelastic deformation is calculated under the nonconverged aerodynamic load and transferred to the wing mesh, whereas the static aeroelastic analysis is performed until the flow solver is converged. This procedure is well summarized in Fig. 3. This method requires only 30 to 50% additional time for the CFD calculation. Furthermore, it is very efficient compared with the loose coupling method.

To validate the adequacy of the tight coupling method, the displacement of the wing tip is calculated by both methods and compared in Table 1. The main wing of the T-50, the baseline wing of the optimization, is used for this calculation. The freestream Mach number is 0.9. The leading-edge flap is rotated downward by 10 deg and the angle of attack is also 10 deg. It is obvious in Table 1 that the displacements of the wing tip exhibit no significant discrepancy; from this fact, it can be inferred that the tight coupling method is very efficient and appropriate. Therefore, all of the aeroelastic analyses from this point are performed via the tight coupling method.

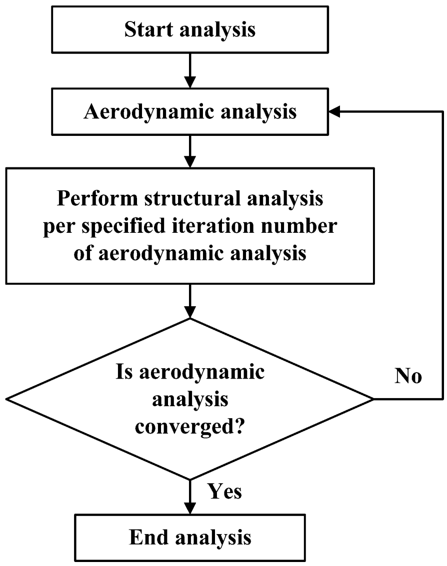

Fig. 3 Tight coupling method for the static aeroelastic analysis.

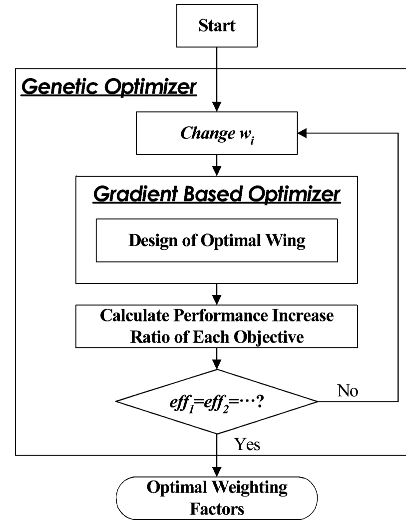

Fig. 4 Design process for optimal weighting factors using genetic algorithm.

III. Design Methodology

A. Multidisciplinary Design Optimization Using Response Surface Methodology

Because of interactions and couplings of the disciplines, it is not an easy task to predict the behavior of the multidisciplinary system accurately, and what is worse is that it requires tremendous analysis time and computing power. In addition, numerous multidisciplinary analyses are needed during the iterative design process. Hence, efficient design method is the core focus of MDO. For reasons stated earlier, RSM has been selected for the multidisciplinary design of the supersonic fighter wing.

RSM is one of the representative approximation techniques. To construct the response surfaces that approximate the objective functions and constraints with respect to the design variables, RSM uses design-of-experiments techniques, regression analysis, and analysis of variance, collectively.[31,32] The response surface model usually assumes a simple mathematical model such as a second-order polynomial, which can be written for nv design variables as follows:

$$y^{(p)} = c_0 + \sum_{1 \le i \le n_v} c_i x_i^{(p)} + \sum_{1 \le i \le j \le n_v} c_{ij} x_i^{(p)} x_j^{(p)} + \varepsilon \qquad p = 1, \ldots, n \tag{1}$$

In this study, as a selection technique of data points, the D-optimality condition is used, and the candidate points are three-level factorial designs. The D-optimality criterion states that the n_s points to be chosen are those that maximize the determinant $|\bar{X}^T \bar{X}|$.

B. Multi-Objective Optimization Method

The optimization problem dealt with in this research is essentially a multidisciplinary and multipoint design problem. Hence, multiple objectives which often conflict across a high-dimensional problem space, should be optimized concurrently. Some kinds of multi-objective optimization methods include weighted-sum method, the ε-constraint method, and the distance metric method.[33,34] In this study, the weighted-sum method is adopted. F^s is simply defined as a composite of each objective:

$$F^s = \sum_{i=1}^{nc} w_i f_i(\bar{X}), \qquad \sum_{i=1}^{nc} w_i = 1 \qquad 0 \le w_i \le 1 \tag{2}$$

Where $\bar{X}$ is the vector of design variables, nc is the number of objectives, and w_i is the weighting factor multiplied by the ith objective. Perturbing the weighting factor makes each optimization process produce a different Pareto optimum.

When the weighted-sum method is used to construct the objective function, the determination of appropriate weighting factors to yield satisfactory optimization results is very hard and depends on the designer's intuition or trial and errors. To overcome this difficulty, the automatic design method for finding appropriate weighting factors is developed and adopted by introducing the genetic algorithm (see Fig. 4).[35,36] By using this method, even performance increases can be obtained at all design points.

In this work, the weighting factors are decided for the purpose of improving the aerodynamic and structural performance of the wing evenly at all design points. For this, the genetic optimizer is incorporated in the wing design system, and the objective function of the weighting factor design problem is defined as follows. Minimize

$$F_o = \sqrt{\frac{\sum_{i=1}^{nc} (eff_i - \overline{eff})^2}{nc - 1}}, \qquad eff_i = \frac{(f_i(\bar{X}_{\text{Baseline}}) - f_i(\bar{X}))}{f_i(\bar{X}_{\text{Baseline}})}$$

$$\overline{eff} = \frac{\sum_{i=1}^{nc} eff_i}{nc} \tag{3}$$

subject to

$$eff_i > 0 \qquad i = 1, 2, \ldots, nc \tag{4}$$

where eff_i indicates the performance increase ratio of each objective. The defined objective function F_o denotes the standard deviation of the performance increase ratios. If the standard deviation is reduced, the difference between the performance increase ratios is also decreased. By designing weighting factors that minimize this objective function, the performance of the wing is enhanced evenly at all design points and disciplines.

IV. Formulation of Design Problem

A. Selection of Design Variables

The design space dealt with in this study consists of parameters related to the planform, the airfoil shapes, and the structural skin thickness of the wing, as summarized in Table 2. The sweep angle (Λ), the aspect ratio (AR), the linear twist angle (θ), the area (S), and the taper ratio (tr) of wing are chosen as the design variables that uniquely determine the wing planform. Its design variables are well depicted in Fig. 5.

To reflect the effect of the geometric airfoil shape in the optimization process, four design variables linked to the airfoil shapes are added: the thickness ratio (t_root) and the maximum camber (c_root) of the airfoil at the wing root, and the thickness ratio (t_tip) and the maximum camber (c_tip) of airfoil at the wing tip.

Four structural design variables are added to determine the upper and lower wing skin thickness. From the minimum thickness determined by the structural ultimate loading conditions, the skin

Table 2 Ranges of design variables

Design variable	Minimum	Baseline	Maximum
Λ, deg	30	35	40
AR	3	3.5	4
θ, deg	−4	−3	−2
S, ft^2	229.5	255	280.5
tr	0.2162	0.2402	0.2642
t_root	0.04	0.05	0.06
c_root	0.005	0.011	0.015
t_tip	0.04	0.05	0.06
c_tip	0.005	0.011	0.015
Δt1, in.	0	0.1	0.2
Δt2, in.	0	0.1	0.2
Δt3, in.	0	0.1	0.2
Δt4, in.	0	0.1	0.2

Table 3 Design points and design objectives for multipoint design

Variables	Maximum speed (dp1)	Cruise speed (dp2)	High angle of attack(dp3)
Mach number	1.5	0.87	0.9
α, deg	2	2	10
Flap angle, deg	2	2	−10
Design altitude, ft	35,000	40,000	8,000
Aerodynamic design objective	Minimize drag	Maximize L/D	Maximize L/D
Structural design objective	Minimize weight	Minimize weight	Minimize weight

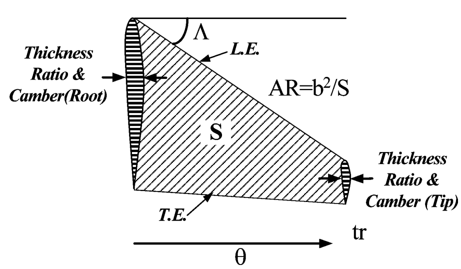

Fig. 5 Aerodynamic design variables of the supersonic wing.

thickness of wing lower surface is increased by the amount of linearly interpolated value between Δt1 at the wing root and Δt2 at the wing tip. The skin thickness of the wing upper surface is also increased by the amount of linearly interpolated value between Δt3 at the wing root and Δt4 at the wing tip. The skin thickness ranges in Table 2 indicate the thickness increment for each minimum skin thickness.

The total number of design variables is 13, and the range of design variables is summarized in Table 2. The main wing of the T-50 is selected as the baseline wing for the optimization.

B. Design Points and Design Objectives

A supersonic fighter is generally maneuvered at various flight conditions. Because the single-point design of the wing, which considers only one flight condition such as the cruise, has no significant meaning, the multipoint design should be carried out by taking into account various flight conditions. In this study, three representative flight conditions for a supersonic fighter wing and the required design objectives at each flight condition are carefully selected and determined as follows. First, to boost the maximum speed of the fighter, the drag should be minimized at the maximum flight-speed condition. Second, the higher L/D at the cruise flight-speed condition is favorable to extend the flying range. Third, to improve the maneuverability at the transonic flight condition, L/D should be maximized at a high-angle-of-attack flight condition.

The specified design points and the aerodynamic design objectives are well listed in Table 3. The flap angle defined in Table 3 represents the leading-edge flap angle. If positive, 15% of the leading edge is rotated upward. The structural design objective is to minimize the wing weight.

V. Design Results

A. Multidisciplinary Design Optimization

Based on the static aeroelastic analysis coupling CFD and CSM, single-point and multipoint multidisciplinary designs are performed. The design results of the multidisciplinary aerodynamic/structural optimization are thoroughly compared with those of the aerodynamic design in later sections.

B. Objective Function and Constraints

The single-point design is conducted at each design point by considering the aerodynamic and structural performances at that point. After this, the multipoint design is investigated to improve the performance at all three design points. The multi-objective function and constraints used for the multidisciplinary aerodynamic/structural design optimization are defined as follows.

For a single-point design at maximum-speed design point (Single-Point Design 1), minimize

$$F = w_1 \cdot \mathrm{Drag}_{\mathrm{dp1}} + w_2 \cdot \mathrm{Weight} \tag{5}$$

subject to

$$\mathrm{Lift}_{\mathrm{dp1}} > \mathrm{Lift}_{\mathrm{dp1}}^{\mathrm{baseline}}$$

$$\text{Tip Displacement}_{\mathrm{dp1}} < \text{Tip Displacement}_{\mathrm{dp1}}^{\mathrm{baseline}} \tag{6}$$

For a single-point design at cruise-speed design point (single-point design 2), minimize

$$F = w_1 \cdot D/L_{\mathrm{dp2}} + w_2 \cdot \mathrm{Weight} \tag{7}$$

subject to

$$\mathrm{Lift}_{\mathrm{dp2}} > \mathrm{Lift}_{\mathrm{dp2}}^{\mathrm{baseline}}, \qquad \mathrm{Drag}_{\mathrm{dp2}} < \mathrm{Drag}_{\mathrm{dp2}}^{\mathrm{baseline}}$$

$$\text{Tip Displacement}_{\mathrm{dp2}} < \text{Tip Displacement}_{\mathrm{dp2}}^{\mathrm{baseline}} \tag{8}$$

For a single-point design at high-angle-of-attack design point (single-point design 3), minimize

$$F = w_1 \cdot D/L_{\mathrm{dp3}} + w_2 \cdot \mathrm{Weight} \tag{9}$$

subject to

$$\mathrm{Lift}_{\mathrm{dp3}} > \mathrm{Lift}_{\mathrm{dp3}}^{\mathrm{baseline}}, \qquad \mathrm{Drag}_{\mathrm{dp3}} < \mathrm{Drag}_{\mathrm{dp3}}^{\mathrm{baseline}}$$

$$\text{Tip Displacement}_{\mathrm{dp3}} < \text{Tip Displacement}_{\mathrm{dp3}}^{\mathrm{baseline}} \tag{10}$$

For multipoint design, minimize

$$F = w_1 \cdot \mathrm{Drag}_{\mathrm{dp1}} + w_2 \cdot D/L_{\mathrm{dp2}} + w_3 \cdot D/L_{\mathrm{dp3}} + w_4 \cdot \mathrm{Weight} \tag{11}$$

subject to

$$\mathrm{Lift}_{\mathrm{dp1}} > \mathrm{Lift}_{\mathrm{dp1}}^{\mathrm{baseline}}, \qquad \mathrm{Drag}_{\mathrm{dp1}} < \mathrm{Drag}_{\mathrm{dp1}}^{\mathrm{baseline}}$$

$$\mathrm{Lift}_{\mathrm{dp2}} > \mathrm{Lift}_{\mathrm{dp2}}^{\mathrm{baseline}}, \qquad \mathrm{Drag}_{\mathrm{dp2}} < \mathrm{Drag}_{\mathrm{dp2}}^{\mathrm{baseline}}$$

$$\mathrm{Lift}_{\mathrm{dp3}} > \mathrm{Lift}_{\mathrm{dp3}}^{\mathrm{baseline}}, \qquad \mathrm{Drag}_{\mathrm{dp3}} < \mathrm{Drag}_{\mathrm{dp3}}^{\mathrm{baseline}}$$

$$\text{Tip Displacement}_{\mathrm{dp1}} < \text{Tip Displacement}_{\mathrm{dp1}}^{\mathrm{baseline}}$$

$$\text{Tip Displacement}_{\mathrm{dp2}} < \text{Tip Displacement}_{\mathrm{dp2}}^{\mathrm{baseline}}$$

$$\text{Tip Displacement}_{\mathrm{dp3}} < \text{Tip Displacement}_{\mathrm{dp3}}^{\mathrm{baseline}} \tag{12}$$

The subscripts dp1, dp2, and dp3 mean that the aerodynamic and structural values are calculated at the maximum-speed design point, that is, the cruise-speed design point and the high-angle-of-attack design point, respectively. The superscript "baseline" means that the values are the calculated result for the baseline wing. The weight and the deformation of the wing, such as wing-tip displacement, are measured through the structural FEM code.

The aerodynamic constraints are imposed on the lift, drag, and moment coefficients to meet the goal that the aerodynamic performance of a designed wing should be at least as good as that of a baseline wing. The structural constraint means that the wing-tip displacement of the optimized wing must be less than that of the baseline wing, and this plays a key role in the structural stability of the wing. The designed wing is made structurally more stable and stiff than the baseline wing by imposing this structural constraint. The wing-tip displacement used for the structural constraint is measured at the trailing edge.

C. Construction of Response Surface Models and Regression Analysis

The total number of design variables is 13, and approximately 160 calculations are sufficient to produce accurate response surface (RS) models. One hundred and sixty experimental points are chosen through the D-optimal experimental design, and static aeroelastic analyses are performed to construct the RS models for the lift, the drag, the L/D, the wing-tip displacement, and the weight. R^2_{adj} and the root-mean-square (rms) error are summarized in Table 4. R^2_{adj} is more than 0.98 for all RS models, which guarantees the reliable prediction capability of the RS models.

Table 4 Results of regression analysis for RS models

Head	R^2	R^2_{adj}	RMS error
$\mathrm{Lift}_{\mathrm{dp1}}$	0.99987	0.999625	0.005894
$\mathrm{Drag}_{\mathrm{dp1}}$	0.999961	0.999887	0.002499
Tip $\mathrm{Displacement}_{\mathrm{dp1}}$	0.995435	0.986803	0.126194
$\mathrm{Lift}_{\mathrm{dp2}}$	0.999609	0.998869	0.009969
$\mathrm{Drag}_{\mathrm{dp2}}$	0.997728	0.993433	0.039733
L/D_{dp2}	0.995913	0.988186	0.024671
Tip $\mathrm{Displacement}_{\mathrm{dp2}}$	0.99664	0.990287	0.061954
$\mathrm{Lift}_{\mathrm{dp3}}$	0.999517	0.998604	0.00405
$\mathrm{Drag}_{\mathrm{dp3}}$	0.999207	0.997708	0.006881
L/D_{dp3}	0.998905	0.996834	0.005261
Tip $\mathrm{Displacement}_{\mathrm{dp3}}$	0.999038	0.99722	0.022159
Weight	0.999999	0.999997	0.000235

D. Optimization Results of the Supersonic Fighter Wing

Figure 6 demonstrates the comparison of aerodynamic optimized wing and aerostructural multidisciplinary optimized wing planforms. Aerodynamic constraints and objectives are the same as in the multidisciplinary optimization except for structural properties like wing-tip displacement and weight. The single-point design is performed at each design point by considering the aerodynamic and structural performance at that point. After this, the multipoint design is investigated to improve the performance at all the three design points. The multi-objective functions are optimized under given constraints.

As seen in Fig. 6a, most aerodynamically designed wings have maximum sweepback angle and maximum span to reduce drag and to increase lift-to-drag ratio. The span of single-point design 1 becomes shorter than the baseline wing to minimize the drag under supersonic flight condition, and those of single-point designs 2 and 3 become longer to increase L/D. The area of single-point design 1 is smaller than that of the baseline wing to minimize the drag, and the other single-point designed wings have larger area than the baseline wing, to maximize L/D. Because structural performance is not considered, aerodynamically designed wings have unrealistic and unpractical planforms in contrast with an MDO wing.

The aerostructural multidisciplinary optimized wing planforms of single-point and multi-point designs are illustrated in Fig. 6b. The multidisciplinary optimized design variables are summarized in Table 5. As shown in Fig. 6b, the span of single-point design 1

Table 5 Multidisciplinary optimized design variables of each single-point design and multipoint design

Design variable	Single-point design 1	Single-point design 2	Single-point design 3	Multipoint design
Λ, deg	32.93852	35.97654	40.00000	40.00000
AR	3.00000	3.86333	3.00000	3.34540
θ, deg	−2.52748	−2.93405	−4.00000	−3.18290
S, ft^2	229.50000	260.36025	279.20970	260.72730
tr	0.21685	0.21618	0.22764	0.21618
t_root	0.04221	0.06000	0.05816	0.05865
c_root	0.01500	0.01005	0.01284	0.01073
t_tip	0.04000	0.04000	0.04000	0.04000
c_tip	0.00500	0.00962	0.01113	0.01343
Δt1, in.	0.00000	0.00000	0.00000	0.00000
Δt2, in.	0.15586	0.20000	0.07885	0.20000
Δt3, in.	0.00000	0.00000	0.00000	0.00000
Δt4, in.	0.00000	0.20000	0.05655	0.19990

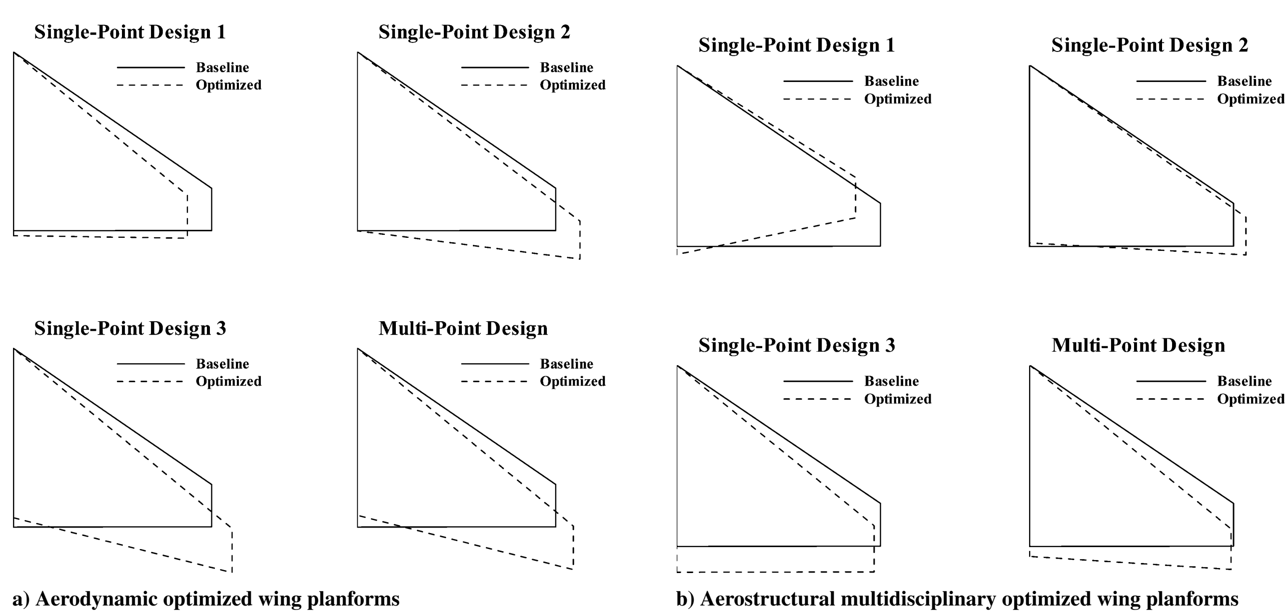

Fig. 6 Optimized wing planforms of each single-point design and multipoint design.

becomes shorter than the baseline wing to decrease the drag at supersonic flight conditions, but those of the other designs are not significantly changed from the baseline. The long span is effective to increase L/D but makes the wing bend easily and generates excessive structural deformation. Compared with the aerodynamic design, the wingspan does not get excessively long to meet the structural constraints. At a glance, the multipoint designed wing looks like the average planform of the single-point designed wings.

The aerodynamic optimized airfoil shapes and the multidisciplinary optimized airfoil shapes are also shown in Figs. 7 and 8. Within the transonic and supersonic flow regimes, a thin wing is proper to minimize drag and to increase L/D. As a result, the aerodynamically designed wings become thinner than the baseline wing in Fig. 7. However, the root airfoil of the multidisciplinary optimized wing tends to be thicker than the baseline wing, but the wing-tip airfoil is thinner than the baseline wing. The multidisciplinary designed wing should satisfy the structural constraint and has enough stiffness to resist wing bending. Therefore, the root airfoil becomes thicker to maintain the structural strength.

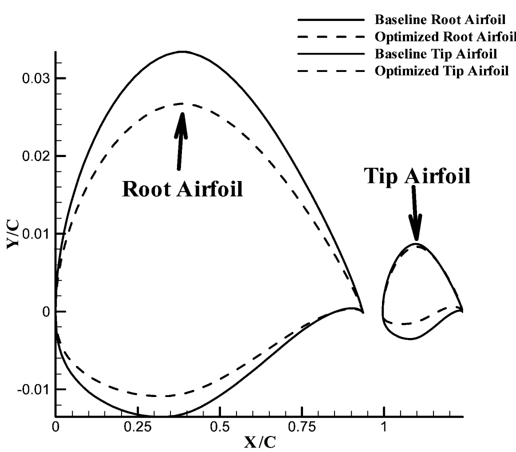

Fig. 7 Optimized airfoil shapes of multipoint design (aerodynamic design).

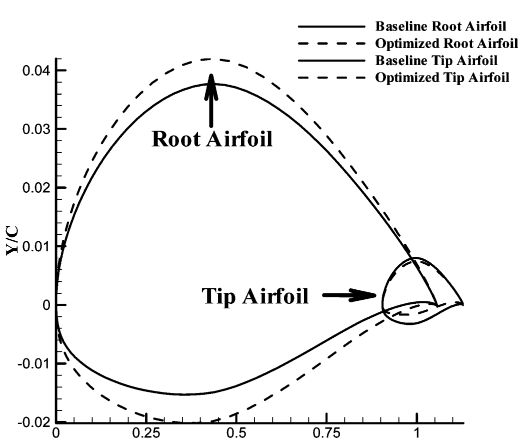

Fig. 8 Optimized airfoil shapes of multipoint design (MDO).

The static aeroelastic analyses are performed at three design points to compare the aerodynamic and structural performances of the designed wings, and the results are summarized in Table 6.

All of the values listed in Table 6 are calculated, not predicted by RS models and normalized by the baseline values. At each design point, the result of the single-point design performed at its own design point and the result of the multipoint design are shown in bold. The tip displacement constraints are violated somewhat because the RS model accuracy of the tip displacements is inferior to that of the other RS models, and some prediction error is, therefore, inevitable. The prediction capability of the RS models, however, could be improved by increasing the number of numerical experiments.

The optimized wings feature better performance than the baseline wing; the aerodynamic performance is improved, whereas the structural weight is decreased. As shown clearly in Table 6, each single-point designed wing posts better performances than that of the multipoint design at its own design point. However, taking a careful look at the results, we see that no single-point designed wing satisfies constraints at the other design points. The multipoint designed wing, on the other hand, shows better performance at those design points. From these facts, it is noted that the multipoint design should be performed to consider the multiple flight conditions because it enhances the aerodynamic and structural performance evenly and moderately at all design points.

Taking an observation of the analysis results for the single-point design at the cruise-speed design point, L/D is increased by about 7.23% compared with the baseline value, and the decrement of the structural weight amounts to 6.52%. The aerodynamic/structural performances are improved almost equally and, from this result, it is clearly shown that the weighting design method has the capability of improving each performance evenly and moderately.

Figures 9–14 compare the performance increments and constraint violation ratios of each designed wing at the maximum-speed

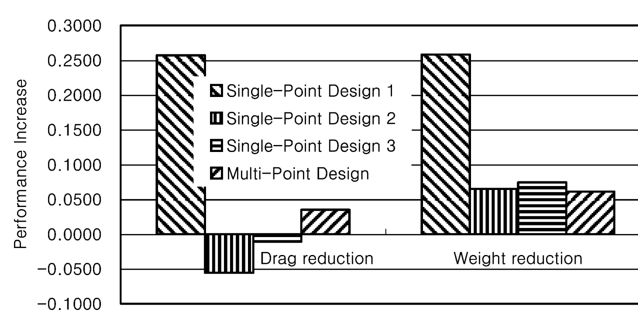

Fig. 9 Performance increments of optimized wings at design point 1.

Table 6 Performance of multidisciplinary designed wing

Optimization Condition	**Head**	Lift	Drag	L/D	Tip displacement	Weight
Maximum speed (dp1)	**Single-point design 1**	**1.0048**	**0.7429**	**1.3526**	**1.0890**	**0.7418**
	Single-point design 2	1.0362	1.0556	0.9817	1.1592	0.9348
	Single-point design 3	0.7896	1.0107	0.7812	0.3362	0.9257
	Multipoint design	**0.9880**	**0.9650**	**1.0238**	**1.1063**	**0.9390**
Cruise speed (dp2)	Single-point design 1	0.8176	0.8922	0.9164	0.7620	0.7418
	Single-point design 2	**1.0034**	**0.9357**	**1.0723**	**1.1374**	**0.9348**
	Single-point design 3	0.9193	0.9372	0.9809	0.8821	0.9257
	Multipoint design	**1.0050**	**0.9772**	**1.0285**	**1.0595**	**0.9390**
High angle of attack (dp3)	Single-point design 1	0.8386	0.8328	1.0069	0.8440	0.7418
	Single-point design 2	1.0251	0.9963	1.0289	1.1753	0.9348
	Single-point design 3	**1.0032**	**0.9331**	**1.0751**	**0.9950**	**0.9257**
	Multipoint design	**0.9972**	**0.9509**	**1.0487**	**1.0105**	**0.9390**

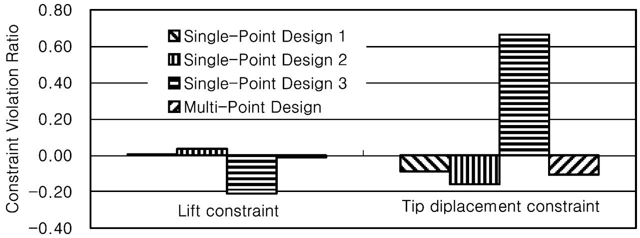

Fig. 10 Constraint violation ratios of optimized wings at design point 1.

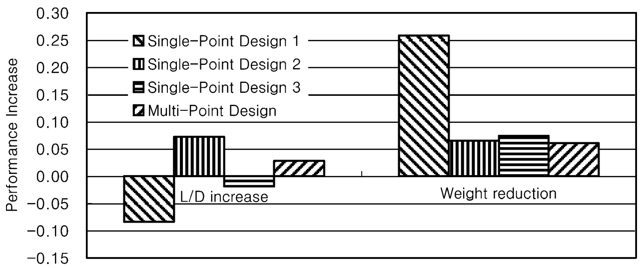

Fig. 11 Performance increments of optimized wings at design point 2.

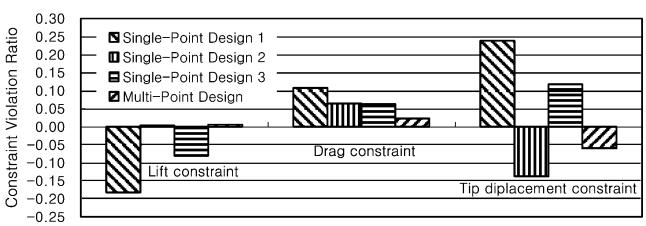

Fig. 12 Constraint violation ratios of optimized wings at design point 2.

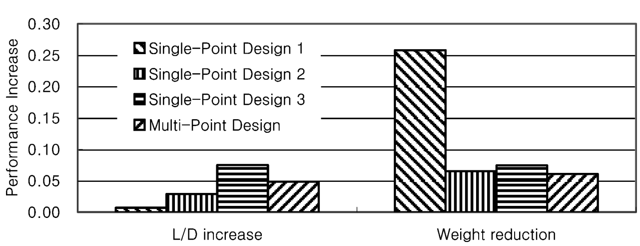

Fig. 13 Performance increments of optimized wings at design point 3.

design point, the cruise-speed design point, and the high-angle-of-attack design point, respectively. As is clearly seen in Fig. 9, the single-point designed wing at the maximum-speed design point and the multipoint designed wing show better performance than the baseline wing and satisfy all constraints. The drag reduction and the weight decrement for single-point design 1 have nearly the same magnitude, demonstrating the validity of the weighting design method in multi-objective design.

E. Structural Stability Comparison Between Aerodynamic Design and MDO

For the comparison between structural stability of the aerodynamic design and that of the multidisciplinary aerodynamic/structural design optimization, the static aeroelastic analyses are conducted for the aerodynamic multipoint designed wing at three design points, and the calculated wing-tip displacements are compared with those of the multidisciplinary multipoint designed wing in Fig. 15. To accord the best stiffness to the aerodynamic designed wing, the design variables related to the wing skin thickness are set to a maximum during the aeroelastic analysis for the aerodynamic multipoint designed wing. As shown clearly in this figure, the aerodynamically designed wing shows an excessive deformation at all design points and seriously violates the wing-tip displacement constraint, although the weight of the wing is increased by 22.6% compared with the baseline wing. This is caused by not considering the structural property of the wing during the design process. This excessive deformation can cause wing destruction and distortion of the flowfield around the wing, which exerts a bad influence on the aerodynamic performance of the wing. In view of the preceding results, it can be concluded that the multidisciplinary aerodynamic/structural design is more desirable and practical because it enhances aerodynamic and structural performance simultaneously and maintains a moderate structural wing stability.

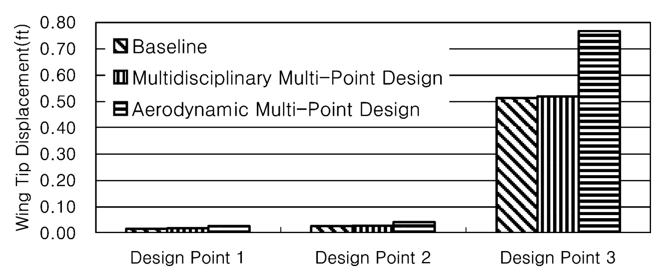

Fig. 15 Comparison of wing-tip displacements between aerodynamic multipoint designed wing and multidisciplinary multipoint designed wing.

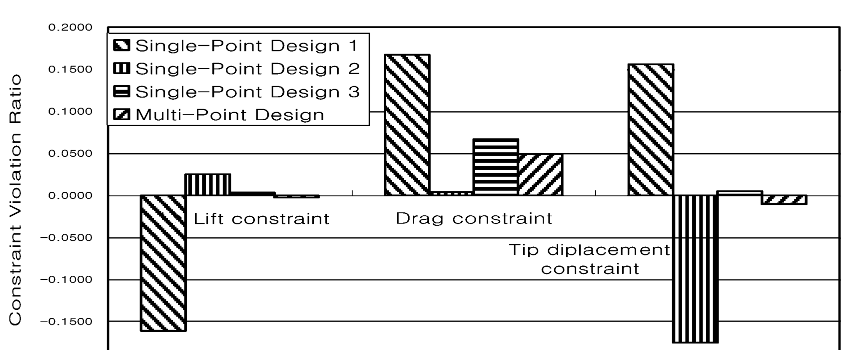

Fig. 14 Constraint violation ratios of optimized wings at design point 3.

VI. Conclusions

In this study, an aerodynamic/structural MDO of the supersonic fighter wing was exploited with a multi-objective approach using RSM.

In consideration of the aerodynamic/structural interaction of the supersonic fighter wing, high-fidelity multidisciplinary analysis was implemented, and a tightly coupled analysis method was also proposed to improve analysis efficiency. Through multidisciplinary analysis and optimization, the wing-tip displacement constraint plays a dominant role. Although aerodynamic single-disciplinary design produces long wingspan, the aerodynamic/structural multidisciplinary design keeps the wing from having an excessively long span and makes the wing structurally stable. Hence, it is confirmed that the aerodynamic/structural multidisciplinary design is more desirable, realistic and practical in that it enhances aerodynamic and structural performance concurrently and moderately maintains the structural wing strength.

In addition, three representative design points are selected for use in considering various flight missions and conditions of the supersonic fighter. The weighted-sum method is introduced to consider multiple objectives, and the weighting factors were designed to improve the performance evenly and moderately by using genetic algorithms. As expected, the single-point design shows the most improved performance at its own design point, but it produces inferior performance and does not satisfy some constraints at the other design points. However, the multipoint designed wing shows improved performance over the baseline wing, meeting entire constraints at all design points; lift-to-drag ratio increases by at least about 2.4% and weight reduces by about 6.1%.

Consequently, multipoint and multidisciplinary design optimization must be considered to design a realistic supersonic fighter wing. Compared with the traditional design procedure, which requires numerous wind-tunnel tests and tradeoff studies, the proposed MDO framework for the supersonic fighter wing can produce substantial multidisciplinary optimized wing shape more efficiently and successfully in the conceptual design stage.

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