

## Research Article

# A New Aerodynamic Optimization Method with the Consideration of Dynamic Stability

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Dynamic stability is significantly important for flying quality evaluation and control system design of the advanced aircraft, and it should be considered in the initial aerodynamic design process. However, most of the conventional aerodynamic optimizations only focus on static performances and the dynamic motion has never been included. In this study, a new optimization method considering both dynamic stability and general lift-to-drag ratio performance has been developed. First, the longitudinal combined dynamic derivative based on the small amplitude oscillation method is calculated. Then, combined with the PSO (particle swarm optimization) algorithm, a dynamic stability derivative that must not be decreased is added to the constraints of optimization and the lift-drag ratio is chosen as the optimization objective. Finally, a new aerodynamic optimization method can be built. We take NACA0012 as an example to validate this method. The results show that the dynamic derivative calculation method is effective and conventional optimization design can significantly improve the lift-drag ratio. However, the dynamic stability is enormously changed at the same time. By contrast, the new optimization method can improve the lift-drag performance while maintaining the dynamic stability.

## 1. Introduction

As one type of the advanced transport systems, high-performance airfoil and aircraft configurations are increasingly important for the whole design cycle of advanced aircrafts. Therefore, the development of an aerodynamic optimization method combined with CFD technology, which can determine the best aerodynamic shape and maximize the aircraft performance and flight quality under given constraints, can greatly promote aerodynamic design. In recent years, domestic and foreign research institutions have developed a variety of effective aerodynamic optimization methods and made great progress. The single-objective and single-point optimization problem of the optimization design model has become a multiobjective, multipoint optimization, and multidisciplinary optimization problem [1–4]. The simple wing surface representation method of the parametric model has been developed into the spline function method of a complex shape and the free surface defor-

mation method [5–8]. Euler and NS methods have been developed into surrogate model-based CFD methods. Moreover, optimization search has evolved from gradient-based and evolutionary methods to current artificial intelligence optimization methods. The developments mentioned above all provide a powerful reference for aerodynamic design.

At present, with the improvement of aircraft performance requirements, the scope of attention of aerodynamic design extends to a wider area. One is a multidisciplinary comprehensive design combined with structural stress and reliability [9–13]. The other is an unsteady aerodynamic design considering dynamic aerodynamic characteristics. The combination of the former and optimization becomes multidisciplinary optimization, which is one of the hot spots of current research, especially in recent years. Zhu et al. [9] investigated the integrated aerodynamic thermal structure design optimization method of lifting surfaces. He combined the heating transfer and unsteady aerodynamic to present a coupled optimization process. This excellent study related

the unsteady aerodynamics to the optimization; however, the dynamic motion or stability is not considered, which limits the application of the method. Benaouali [14] developed a multidisciplinary design optimization framework by considering the aerodynamics and structure characteristics. He used several commercial software to achieve the calculation results. This work studies the coupling process between the different analysis tools and provides a practical method for aircraft design. Li et al. [8] used machine learning techniques to reduce the abnormality of both initial and infill samples in aerodynamic performance optimization of the airfoil and wing; similar work had been proposed by Yan et al. [7]; he applied the AI method to improve the aerodynamic performance of the aircraft. The new optimization concept with AI grows fast and leads to various new algorithms. Champasak et al. [15] developed a many-objective optimization problem for an unmanned aerial vehicle (UAV) with 6 objective functions. This method presented good efficiency in aerospace design. Yildiz and Erda [16] proposed a new hybrid Taguchi salp swarm algorithm (HTSSA) to speed up the optimization processes of structural design problems in the industry and to approach a global optimum solution; this work can also be referenced in an aerodynamic design process. Panagant et al. [17] investigated the comparative performance of fourteen new and established multiobjective metaheuristics when solving truss optimization problems, which gave us a brief introduction and comparison of the generally used algorithms. These previous studies indicate that the various improved optimization algorithms have been widely used on the aerodynamic design; however, these jobs only focus on the static aerodynamic performance; the aerodynamic optimization design combined with dynamic characteristics is rare.

The dynamic aerodynamic characteristics of an aircraft originate from the motion of the aircraft affected by various factors. One of the most important concepts is dynamic stability [18–24], which refers to the damping moment during the movement of the aircraft after disturbance and finally makes the object return to the original equilibrium state. It studies the time response history of the disturbed movement of the object. In the linear range, the dynamic stability can be characterized by dynamic stability derivatives. These derivatives are the derivatives of unsteady aerodynamic relative motion parameters ( $\bar{q}$ ,  $\bar{p}$ ,  $\bar{r}$ ,  $\bar{\alpha}$ , and  $\bar{\beta}$ ), which are of great significance for the control system design and quality analysis of aircrafts. In addition, these dynamic derivatives can now be identified by the CFD method.

In this paper, an aerodynamic optimization method considering dynamic stability is proposed and studied. The concept of a dynamic stability derivative is introduced into the optimization design process. Based on the CFD calculation method, the dynamic derivative is identified in real time by using the small-amplitude forced vibration process, and combined with the particle swarm optimization (PSO) algorithm, the new optimization method considering both static and dynamic aerodynamic characteristics can be much more practical during the aerodynamic design of the advanced aircraft.

## 2. Aerodynamic Optimization Methods

**2.1. Regular Optimization Methods.** The conventional aerodynamic optimization design is based on the feed-in optimization algorithm. The basic idea is to combine the flow field analysis with the optimization algorithm, take the aerodynamic characteristics as the objective function, such as the drag or lift-drag ratio, and apply aerodynamic constraints or geometric constraints to optimize the objective function directly. The commonly used optimization algorithms include genetic algorithms, particle swarm optimization, and neural network algorithms. The example used to illustrate the conventional optimization method in this paper is the aerodynamic optimization design of the particle swarm algorithm.

The particle swarm optimization (PSO) algorithm [25] completes the whole search process by iteration. In each iteration step, the velocity and position update formula of the  $i$ th particle in the population of  $N$  in the  $n$ -dimensional search space is as follows:

The particle swarm optimization algorithm simulates the flight foraging behavior of a bird swarm. The design variables in the solution space are regarded as a group of birds without volume and mass (also known as particles), and the optimal solution of the problem is regarded as the food sought by the bird swarm. All particles continuously change their flight direction and distance and guide themselves to adjust the flight state by  $p_{\text{best}}$  and  $g_{\text{best}}$ , and their speed and position are updated to tend to the optimal solution of the problem.

$$\begin{aligned} v_{ij}^{t+1} &= wv_{ij}^t + c_1 r_1 (p_{\text{best}ij}^t - x_{ij}^t) + c_2 r_2 (g_{\text{best}ij}^t - x_{ij}^t), \\ x_{ij}^{t+1} &= x_{ij}^t + v_{ij}^{t+1}, \end{aligned} \quad (1)$$

where  $x$  represents the current position of the particle and  $v$  represents the velocity of the particles.  $w$  represents the inertia weight factor, which is one of the important parameters affecting the performance of the algorithm. Its size determines how much the particle inherits from the current velocity. The value range is usually defined between [0.4, 0.9], and the linear decreasing strategy is adopted in the evolution process. In addition, learning factors  $c_1$  and  $c_2$  are used to adjust the step length of particles flying to  $p_{\text{best}}$  and  $g_{\text{best}}$ ,  $r_1$  and  $r_2$  are random numbers generated between (0, 1), subscripts  $i$  and  $j$  represent  $i$  particles and  $j$  dimensions, and superscript  $t$  is an evolutionary generation.

$$\begin{aligned} v_{ij}(t+1) &= wv_{ij}(t) + c_1 r_1 (p_{ij}(t) - x_{ij}(t)) + c_2 r_2 (p_{gj}(t) - x_{ij}(t)), \\ x_{ij}(t+1) &= x_{ij}(t) + v_{ij}(t+1), \end{aligned} \quad (2)$$

where  $i = 1, 2, \dots, N$ ,  $j = 1, 2, \dots, n$ ,  $w$  represents inertia weight,  $c_1$  and  $c_2$  represent cognitive parameters and social parameters, and  $r_1$  and  $r_2$  represent two completely independent random parameters in (0, 1). The best position

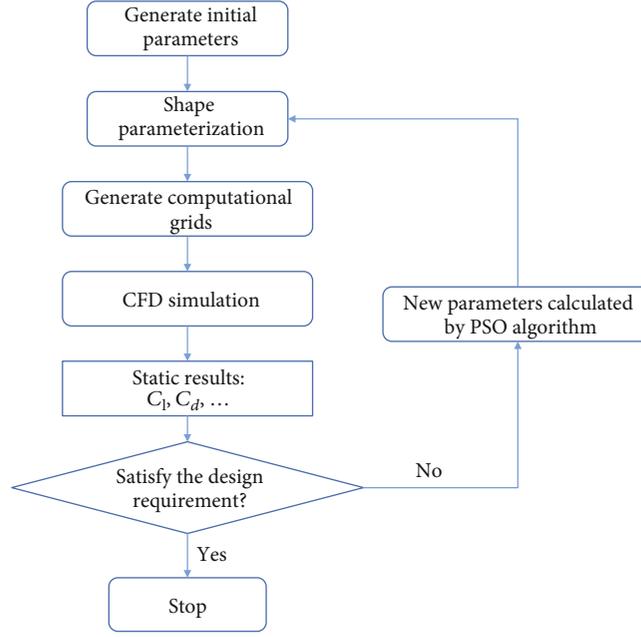


FIGURE 1: Traditional pneumatic optimization design process.

update formula for each particle can be expressed as equation (3) as follows:

$$p_i(t+1) = x_i(t+1), \quad \text{if } f(x_i) < f(p_i). \quad (3)$$

Therefore, the aerodynamic optimization process based on the particle swarm optimization algorithm can be described in Figure 1.

**2.2. New Aerodynamic Optimization Method considering Dynamic Stability.** Dynamic stability plays an important role in the evaluation of aircraft handling and stability characteristics and the design of flight control laws. In the design of aircrafts, the dynamic stability derivative (dynamic derivative) is usually used to characterize the dynamic stability. Therefore, the design value of the dynamic derivative should be reasonable. An increase in the absolute value of the dynamic derivative leads to an increase in dynamic damping, which limits the performance of fighters with high maneuverability. However, for configurations with small dynamic damping in the longitudinal and lateral-directional directions, such as flying wing vehicles, it is necessary to increase the absolute value of the dynamic derivative to reduce the cost of the control system design.

In aerodynamic optimization design, the influence of aerodynamic shape change on subsequent handling and stability characteristics and flight control systems is usually not considered, which will not only result in poor practicability of optimization results but also does not conform to the current rapid development of aircraft design ideas and concepts. Thus, we comprehensively consider the static and dynamic aerodynamic characteristics and establish a more practical integrated optimization design method.

**2.2.1. Numerical Calculation Method of Dynamic Derivative.** Firstly, we take the longitudinal direction as an example to introduce the method of CFD identification of dynamic derivatives [26, 27]. When the aircraft is forced to make a small amplitude of harmonic vibration around its center of gravity, the unsteady aerodynamic forces can be expressed with the Taylor expansion method. Taking the pitching moment coefficient as an example, its expansion form can be expressed as equation (4) as follows:

$$M_z = M_{z0} + M_z^\alpha \Delta\alpha + M_z^{\dot{\alpha}} \Delta\dot{\alpha} + M_z^\omega \omega_z + M_z^{\dot{\omega}} \dot{\omega} + \widehat{\Delta}(\Delta\alpha, \omega_z), \quad (4)$$

where  $M_z^\alpha$  represents the static derivative of aerodynamic torque,  $M_z^{\dot{\alpha}}$  represents the first-order dynamic derivative of aerodynamic torque to the angle of attack,  $M_z^\omega$  represents the zero-order dynamic derivative of aerodynamic torque to the pitching angular velocity,  $M_z^{\dot{\omega}}$  represents the first-order dynamic derivative of aerodynamic torque to the pitching angular velocity, and  $\widehat{\Delta}$  represents higher-order derivative terms.

When the rigid vehicle oscillates at a small amplitude with low frequency  $\omega$ , its model motion equation can be simplified as equation (5) as follows:

$$\begin{aligned} \theta &= \theta_0 \sin(\omega t), \\ \dot{\theta} &= \omega \theta_0 \cos(\omega t) = \omega_z, \\ \ddot{\theta} &= -\omega^2 \theta_0 \sin(\omega t) = \dot{\omega}_z, \\ \Delta\alpha &= \theta = \theta_0 \sin(\omega t), \\ \Delta\dot{\alpha} &= \dot{\theta} = \omega \theta_0 \cos(\omega t), \end{aligned} \quad (5)$$

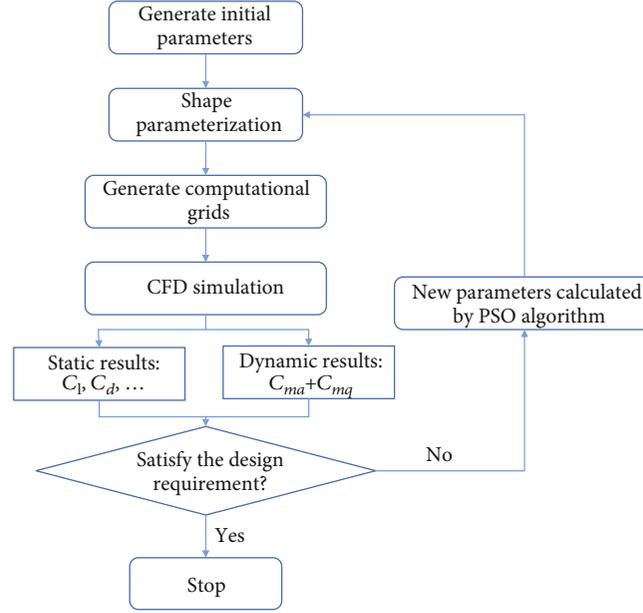


FIGURE 2: A new aerodynamic optimization design method considering the influence of dynamic derivative.

where  $\theta$  represents an instantaneous elevation angle,  $\theta_0$  represents the amplitude of the pitch angle variation, and  $\omega_z$  represents the pitching angular velocity.

We expand equation (4), omit the higher harmonic components, substitute into equation (5), and omit the high-order component  $\hat{\Delta}$ . Then, equation (6) can be used to obtain the same kind of items.

$$M_z = M_{z0} + \left( M_z^\alpha - \omega^2 M_z^{\dot{\omega}} \right) \theta_0 \sin \omega t + \left( M_z^{\ddot{\alpha}} + M_z^{\omega_z} \right) \omega \theta_0 \cos \omega t. \quad (6)$$

When the unsteady problem is calculated long enough and you let  $\omega t = 2n\pi$ , the effect of the initial effect will be erased and the aerodynamic moment reaches a periodic steady-state value, where equation (6) can be written as equation (7) as follows:

$$M_z^{\ddot{\alpha}} + M_z^{\omega_z} = \frac{M_{\omega t=2n\pi} - M_{z0}}{\omega \theta_0}. \quad (7)$$

The reduced frequency pair  $k = \omega l / 2V_*$  is introduced as a dimensionless size, where  $l$  is the reference length and  $V_*$  is the free-flow velocity in the far field. Finally, the formula for calculating the dynamic derivative is equation (8) as follows:

$$C_{m\ddot{\alpha}} + C_{m\omega_z} = \frac{C_{M_{\omega t=2n\pi}} - C_{M_{z0}}}{k\theta_0}. \quad (8)$$

The velocity of the pitching angle  $q$  and the change rate of the angle of attack  $\dot{\alpha}$  have the same expression when the free flow is constant, so the dynamic derivative calculated here is a combination form. We need more precise calculation methods if the two are to be calculated separately. In general,

the combined dynamic derivatives can basically meet the requirements of subsequent flight quality analysis [15].

**2.2.2. A New Aerodynamic Optimization Design Method considering the Influence of the Dynamic Derivative.** Different from the traditional optimization method, when considering the influence of the dynamic derivative, each optimization cycle not only needs to calculate the lift and drag of the static condition but also needs to further evaluate the dynamic derivative characteristics of the optimization scheme. Then, dynamic and static results are combined to determine whether the best solution is available. Its optimization process is shown in Figure 2.

Similar to the traditional method, the new aerodynamic optimization method is still set as a single objective, which takes the dynamic derivative effect as a constraint to join the optimization model. In the design of the aircraft, the dynamic derivative is different from the resistance characteristics and its value has no obvious limit range. The dynamic derivative balances the dynamic maneuverability and stability, so the ideal constraint condition is that the dynamic derivative characteristics of the optimized configuration are basically consistent with the original configuration. For this reason, when the dynamic derivative is added to the constraint in this paper, it is expressed as the absolute value that does not decrease.

### 3. Calculation and Validation

**3.1. Verification of the Dynamic Derivative Calculation Method.** The model used to verify the dynamic derivative calculation method in this paper is the international standard model basic Finner missile [28], and its basic shape is shown in Figure 3. The structured grids were generated using the ANSYS ICEM CFD code. The grid height of the first layer of the boundary layer is approximately  $y+ \approx 1.1$ , and the

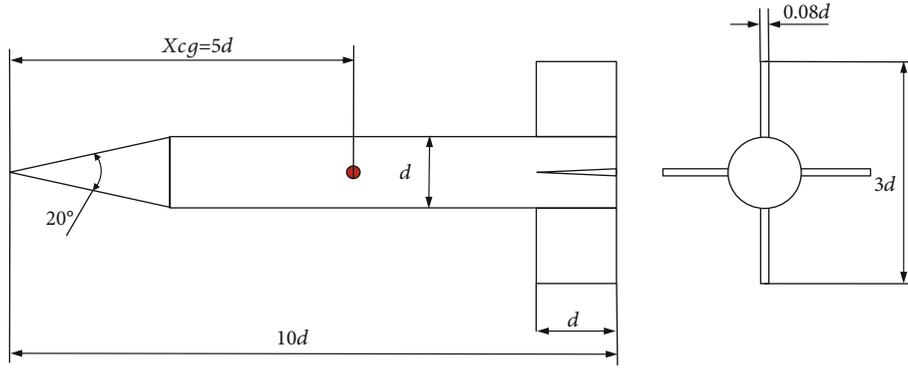
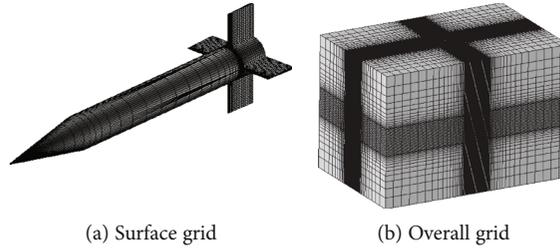


FIGURE 3: Finner missile configuration.



(a) Surface grid (b) Overall grid

FIGURE 4: Computational grid.

growth rate is 1.1. The total grid number is 5 million. Figure 4 shows the simulating mesh of the model.

We calculated the longitudinal combined dynamic derivatives of the model at supersonic speed. The Mach number is  $Ma = 1.58$ , and the model performs unsteady motion around the center of gravity ( $Xcg = 5d$ ) during the calculation. The initial angle of attack is  $\alpha_0 = 0^\circ$ , the vibration law is  $\alpha = \alpha_0 + \alpha_m \sin(\omega t) = 0^\circ + 1^\circ \sin(17t)$ , and the reduction frequency is  $k = \omega d / 2V_* = 0.0158226$ , which means the diameter  $d$  is the reference length of the missile.

To realize the movement of the object surface, this paper adopts rigid dynamic grid technology, which makes the whole grid perform a rigid movement. Compared with previous mesh deformation and unstructured mesh reconstruction methods, this method is simpler in form and more practical for single-degree-of-freedom small-amplitude vibration. To accurately capture the dynamic aerodynamic performance, we use the  $k-\omega$  SST model to solve the unsteady RANS equations. This turbulence model has good adaptability on various static and dynamic cases of aircraft in small and medium angles of attack. Further dynamic calculations in this paper also use the same method.

The hysteresis loop of the unsteady pitching moment coefficient calculated by the small amplitude forced sinusoidal vibration method in this paper is shown in Figure 5.

According to the calculation method in this paper, the longitudinal combined dynamic derivatives can be calculated as shown in Table 1.

The dynamic derivative test results in reference [10] are  $-506$ , and the error is 3.62%. Thus, the calculation method of the dynamic derivative in this paper is relatively accurate.

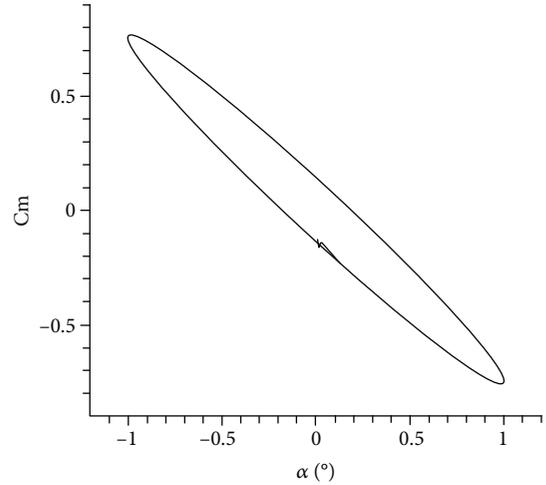


FIGURE 5: Hysteresis loop of pitching moment coefficient.

TABLE 1: Longitudinal combined dynamic derivative.

Initial angle of attack $\alpha_0$ (degree)	$C_{M_{z0}}$	$C_{M_{z\omega t=2\pi}}$	$C_{m\dot{\alpha}} + C_{mq}$
0	0.004852	-0.136386	-511.48

3.2. *Conventional Airfoil Optimization.* The optimization design model includes three elements: objective function, constraint conditions, and design variables. For the conventional aerodynamic optimization design of an airfoil, after the design point is generally determined, the aerodynamic

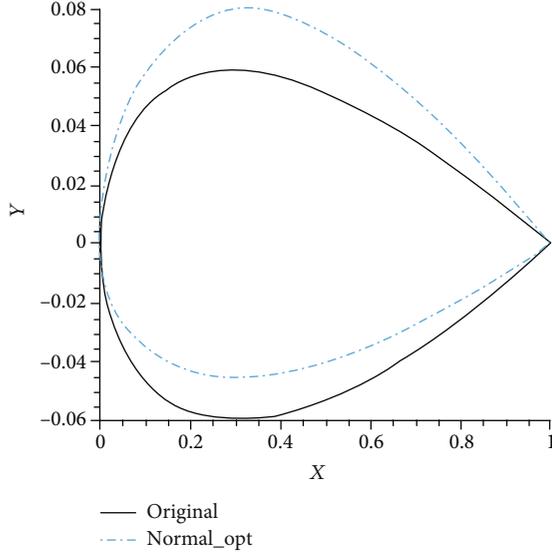


FIGURE 6: Geometric shape after conventional optimization.

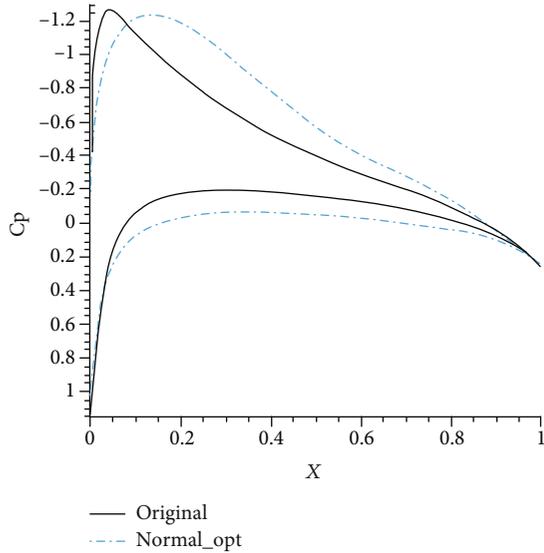


FIGURE 7: Pressure coefficient distribution of airfoil after conventional optimization.

coefficient that represents the lift-to-drag is selected as the objective function, the thickness is taken as constraints, and the geometric shape of the airfoil is taken as the design variable.

In this paper, the PSO algorithm is used to optimize the aerodynamic performance of the NACA0012 airfoil. The parameterization of the airfoil adopts the CST method [11]. Seven design variables are selected for each upper and lower wing surface to determine the airfoil.

The Mach number is  $Ma = 0.6$ . The Reynolds number based on the chord length  $Re_{ref} = 4.80 \times 10^6$ . The single-objective optimization design of the airfoil is carried out. The optimization objective is the lift-to-drag ratio of the airfoil, and the constraint conditions are the maximum thickness of the airfoil ( $t$ ) and its lift ( $C_l$ ) and drag ( $C_d$ ) coefficients.

TABLE 2: Aerodynamic parameters after conventional optimization.

Parameters	Original airfoil	Conventional optimization
$C_l$	0.406184	0.6082
$C_d$	0.01240452	0.012
Lift-to-drag ratio	32.74	50.68
$t$	12%c	12.6%c
$C_{m\dot{\alpha}} + C_{mq}$	-2.11	16.32

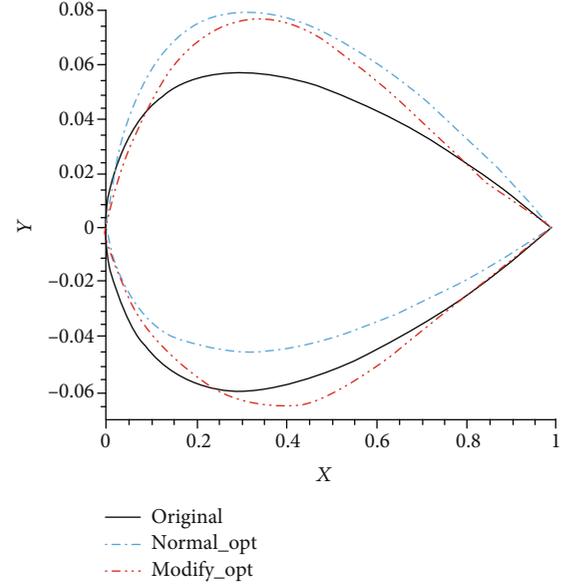


FIGURE 8: Geometric shape after conventional optimization.

The design objectives and constraints are as follows:

$$\begin{aligned}
 \max f &= \frac{C_l}{C_d}, \\
 g_1(x) &= C_l \geq C_{l0}, \\
 \text{s.t. } g_2(x) &= t_{\max} \geq t_0, \\
 g_3(x) &= C_d \leq C_{d0}.
 \end{aligned} \tag{9}$$

The results of the optimization design are presented in Figures 6 and 7 and Table 2.

Table 2 shows that the lift-to-drag ratio of the conventional optimized airfoil is greatly improved compared with that of the original airfoil, and the lift-to-drag ratio increases by 54.8%. The dynamic derivative of the original airfoil is  $-2.11$ , indicating that the original airfoil has good dynamic stability at this design point. However, the dynamic derivative of the airfoil after conventional optimization has been countersigned, showing dynamic instability. This result is unfavorable for the optimization of the overall aerodynamic characteristics of the aircraft. Therefore, it is necessary to further consider the constraint of the dynamic derivative to improve the optimization.

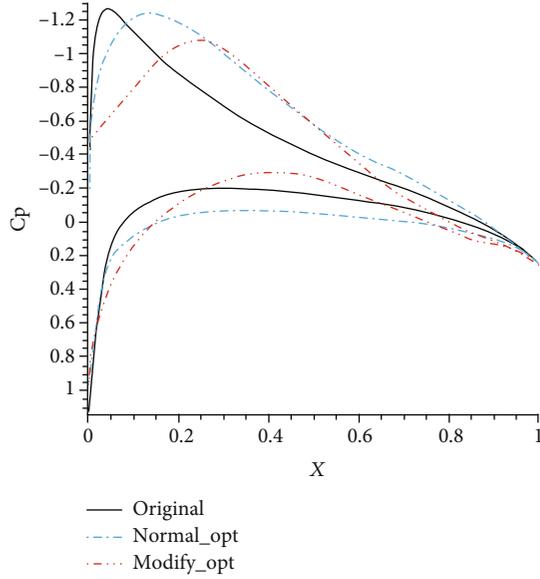


FIGURE 9: Pressure coefficient distribution of airfoil after conventional optimization.

TABLE 3: Comparison of optimization results.

Parameter	Original airfoil	Conventional optimization	Considering dynamic derivative optimization
$C_l$	0.406184	0.6082	0.45586
$C_d$	0.012404	0.012	0.011
Lift-to-drag ratio	32.74	50.68	41.44
$C_{m\dot{\alpha}} + C_{mq}$	-2.11	16.32	-2.38
$t$	12% $c$	12.6% $c$	14.5%

**3.3. Airfoil Optimization considering the Dynamic Derivative.** Conventional airfoil optimization design does not consider the dynamic characteristics of airfoils. In this section, the dynamic derivative of the airfoil in the optimization is calculated in real time using the above dynamic derivative calculation method. The value is introduced into the optimization design of the airfoil as a constraint, and the absolute value of the dynamic derivative ( $\bar{C}_{mq} = C_{m\dot{\alpha}} + C_{mq}$ ) is kept unchanged, while the other constraints remain unchanged.

The design objectives and constraints are as follows:

$$\begin{aligned}
 \max f &= \frac{C_l}{C_d}, \\
 g_1(x) &= C_l \geq C_{l0}, \\
 g_2(x) &= |\bar{C}_{mq}| \geq |\bar{C}_{mq0}|, \\
 g_3(x) &= t_{\max} \geq t_0, \\
 g_4(x) &= C_d \leq C_{d0}.
 \end{aligned} \tag{10}$$

The geometric and pressure distributions of the final

optimization results are shown in Figures 8 and 9. The lift-drag coefficient and dynamic derivative are shown in Table 3.

Table 3 shows the comparison of the optimization results after considering the dynamic derivative with the original airfoil and the conventional optimization results. After considering the dynamic stability constraint, the lift-drag ratio increases by 26.6% compared with the original airfoil, which is approximately half of the increase effect of the conventional optimization lift-drag ratio. By comparing the results of the dynamic derivative, it can be seen that the optimization of the dynamic derivative can better maintain the longitudinal dynamic stability of the airfoil. This method considering both dynamic stability and lift-drag performance is more practical for the design of the aerodynamic performance of the aircraft.

The new optimization method considers both the static and dynamic aerodynamic performances of the airfoil; thus, it should calculate the unsteady aerodynamics of the dynamic motion in every iteration. The time-cost can be much more higher than the original optimization. In this study, a convergent conventional optimization costs only 10 hours, while the new optimization using the same algorithm needs more than 80 hours. Therefore, how to reduce the time cost of the unsteady optimization should be further investigated.

## 4. Conclusions

In this study, the PSO algorithm is used for the conventional optimization of a two-dimensional airfoil and the optimization calculation considering the dynamic stability characteristics. The conclusions are as follows:

- (1) Dynamic stability plays an important role in the dynamic performance of aircrafts. The calculation method based on small amplitude forced vibration in this paper has high accuracy in calculating the longitudinal dynamic stability derivative. In addition, this method can be extended to the calculation of the dynamic derivative of the lateral direction
- (2) Conventional optimization methods can greatly improve the lift and drag characteristics of the NACA0012 airfoil. However, few constraints lead to dramatic changes in the dynamic characteristics of optimized airfoils. The dynamic stability is enormously changed at the same time
- (3) The optimization design considering the influence of dynamic stability fully considers the constraint of the dynamic derivative, which can improve the lift-drag performance while maintaining dynamic stability

The new optimization method developed by combining the dynamic stability analysis process can improve the static and dynamic performances of an aircraft, which has strong practicability in advanced aircraft design.

## Data Availability

The data will be provided if anyone needed.

## Conflicts of Interest

The authors declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work; there is no professional or other personal interest of any nature or kind in any products, service, and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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