

A RAPID AERODYNAMIC ASSESSMENT METHOD FOR BATTLE-DAMAGED CRUISE MISSILES

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Abstract

Damage to the wings of a cruise missile alters its aerodynamic characteristics, causing a significant decrease in the lift coefficient, which severely affects the missile's impact point and strike effectiveness. This study establishes a damaged cruise missile model with wing breakage after being struck, based on a typical cruise missile model. The lift coefficient curves under different speeds and damage severities were calculated and analyzed using the Computational Fluid Dynamics (CFD) method. The results show that after truncating part of the wing area, the change in the linear portion of the lift coefficient curve is primarily related to the lost wing area, the airfoil's zero-lift angle of attack, and the flight speed. A method for obtaining the lift coefficient of a cruise missile with damaged wings by deriving a function that linearly superimposes the degree of damage and velocity based on the lift coefficient of an undamaged missile. Based on the variation law of the lift coefficient of cruise missiles with damage degree, a rapid calculation method of "rough calculation-law prediction-error prediction correction" was constructed by combining the vortex lattice method (VLM) and neural network (BP). For cruise missiles with damages at flight speeds of 0.4 to 0.7 Mach, the rapid prediction results of the lift coefficient show a maximum error of approximately 17% and a minimum error of about -0.08% compared to CFD.

Keywords: Cruise missile; Lift coefficient; Computational Fluid Dynamics; Vortex Lattice Method; Neural network

1. Introduction

Cruise missiles are a type of winged missile, and during their cruise phase, their aerodynamic characteristics are similar to those of aircraft targets. Therefore, in the rapid evaluation of cruise missile aerodynamic performance, research on aerodynamic disturbance damage to aircraft-like targets can be referenced. Damage to the missile's wings affects its aerodynamic characteristics during flight, thereby impacting the missile's strike accuracy. Thus, the study and rapid assessment of the aerodynamic performance of damaged aircraft hold significant engineering importance for researching weapon combat effectiveness.

In the study of aerodynamic characteristics under damage, Yikun Wang from Nanjing University of Science and Technology employed numerical simulation methods to comparatively investigate the impact of common damage on the three main components of a supersonic cruise missile on its operational performance[1]. Bowen Zhao and others, based on numerical simulation and wind tunnel tests, analyzed the influence patterns of component damage, control surface jamming, engine failure, and icing on aircraft aerodynamic characteristics[2]. Yang Pei and Zhiwei Chen used CFD simulations to study the effects of circular hole damage caused by projectile strikes on wing aerodynamic characteristics[3]. Fei Cen and others established an aerodynamic force calculation method for structurally damaged aircraft models based on the vortex lattice method and corrected the aerodynamic force calculation data for structurally damaged aircraft using wind tunnel test data from undamaged aircraft[4]. Baigang Mi from Northwestern Polytechnical University, based on computational fluid dynamics and rigid dynamic grid technology, calculated

the improved longitudinal and lateral coupling forces and moments of the SACCON aircraft, as well as the dynamic derivatives of two fragment structure damage models and two continuous rod damage models[5]. Render and others conducted extensive wind tunnel tests on wings with circular hole damage based on the NASA LS(1)-0417MOD airfoil, proposing a technique for predicting the impact of battle damage on aircraft wing aerodynamic performance[6]. John developed a mathematical model and guidance algorithm for anti-tank missiles, and through Monte Carlo simulations, obtained damage scenarios for different types and locations of the missile body and wings, with results showing that the missile's damage response performance is extremely sensitive to the radial position of the damage[7]. Djellal conducted preliminary research on the effects of artillery fire damage on the aerodynamic performance of a typical aircraft model with different sizes and locations of damage on the wing, with results indicating that damage leads to a significant reduction in aerodynamic coefficients related to the diameter and position of the holes, and that patch repairs can largely restore aerodynamic losses[8].

For rapid aerodynamic calculation methods of missiles, there is MissileDatcom, primarily based on the vortex lattice method, developed by the U.S. Air Force Flight Mechanics Laboratory[9]; NASA has developed the open-source aircraft modeling and analysis tool NASA OpenVSP, which employs various low-fidelity aerodynamic evaluation methods such as the vortex lattice method and panel method, and is applied in research institutions and aircraft design departments both domestically and internationally[10]~[11]. Domestically, Lin Liu et al. proposed a K-nearest neighbor large-margin loss function based on deep metric learning, using missile aerodynamic shapes and operating conditions as inputs to output a rapid estimation method for missile aerodynamic coefficients[12]. Pengzhen Fu et al. introduced a hybrid adaptive sampling method based on max-min scaling distance and cross-validation error, building a surrogate model with a small number of CFD numerical results to predict missile aerodynamic data[13].

2. Typical Damage Modes and Parametric Characterization of Cruise Missiles

This study focuses on cruise missiles with straight wings and cruciform tail configurations. In actual combat, cruise missiles face threats from anti-aircraft missiles, close-in weapon systems (CIWS), laser weapons, and others. Due to the compact arrangement of internal equipment within the missile body, any damage to the structure is highly likely to cause immediate loss of control or disintegration. Such cruise missiles typically employ all-movable tail surfaces as control surfaces, but the area of the tail wings is significantly smaller than that of the main wings. Therefore, among non-disabling hits, the probability of striking the main wings is noticeably higher than hitting the tail wings[14].



(a) Anti-missile missile



(b) Close-in weapon system



(c) Laser weapon

Figure 1 – Common anti-missile weapons.

This paper simplifies and parameterizes the characteristics of damage based on typical forms of destruction resulting from the partial fracture of cruise missile wings after being struck in combat. To reduce interference from complex damage, the study focuses solely on unilateral damage scenarios where only one side of the wing is impaired, disregarding the coupled effects of bilateral damage.

Let the exposed span length of a single wing be $b_{1/2,exp}$, the damaged length along the span

direction be b_{damage}, and b_e be the percentage of wing loss. For the case of unilateral wing damage, the percentage of the damaged length relative to the exposed span length of a single wing can be used to describe it:

$$b_e = \frac{b_{damage}}{b_{1/2,exp}} \tag{1}$$

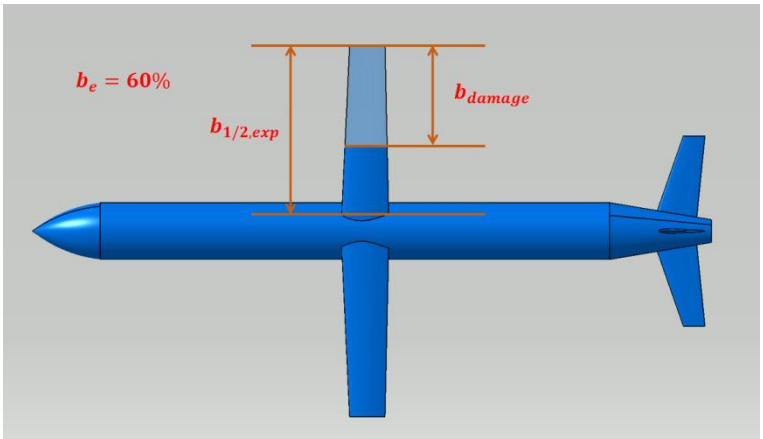
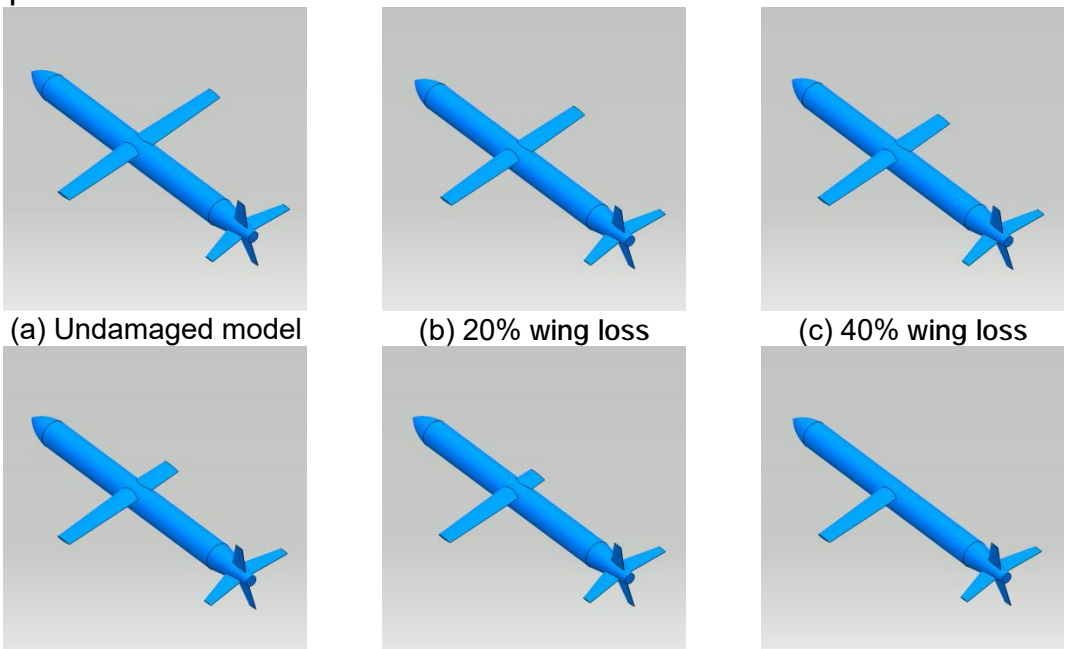


Figure 2 – Damage parameterization schematic diagram.

Establish aerodynamic configuration models with unilateral wing loss of 20%, 40%, 60%, 80%, and 100% of the wingspan, respectively, for studying the aerodynamic variation patterns under damage in this paper. The constructed models are as follows.



(a) Undamaged model (b) 20% wing loss (c) 40% wing loss

(d) 60% wing loss (e) 80% wing loss (f) 100% wing loss

Figure 3 – Damaged wing models.

3. Construction of an Aerodynamic Rapid Evaluation Method for Damaged Cruise Missiles

3.1 Analysis of Aerodynamic Coefficient Variation Patterns for Damaged Cruise Missiles Based on CFD

This section investigates the solution using a steady RANS approach based on the k-ω SST turbulence model.For CFD calculation, the governing equations are based on continuity equation[15], momentum equation and energy equation. The three-dimensional compressible N-S

equations are as follows:
continuity equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u_j)}{\partial x_j} \tag{2}$$

momentum equation

$$\frac{\partial(\rho u_j)}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_i u_j) =-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j} \tag{3}$$

energy equation

$$\frac{\partial(\rho E)}{\partial t}+\frac{\partial}{\partial x_j}(\rho E u_j) =-\frac{\partial}{\partial x_j}(p)-\frac{\partial q_j}{\partial x_j}+\frac{\partial}{\partial x_j}(u_j \tau_{ij}) \tag{4}$$

Based on Ansys-Fluent, the cases in this paper were solved under flight conditions at an altitude of 150 meters with Mach numbers of 0.4Ma, 0.5Ma, and 0.7Ma, with the variation of the lift coefficient as the main research focus. The calculated lift coefficient results are as follows. For the damaged wing, the geometric parameters of the intact missile were still used as the dimensionless reference values.

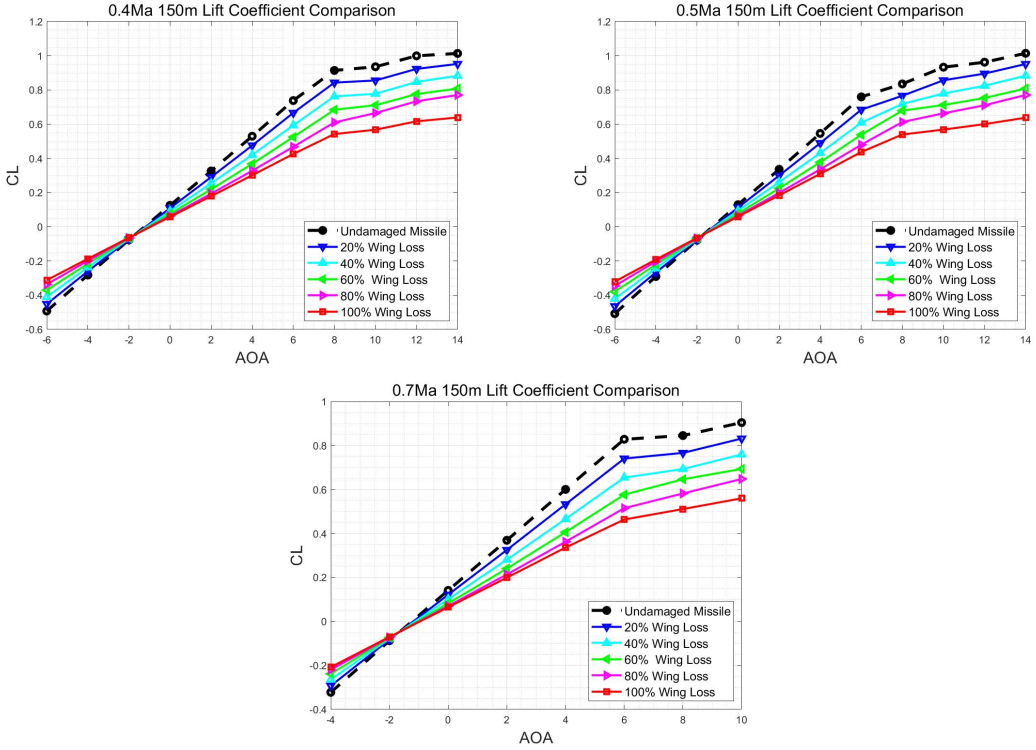


Figure 4 – The results of lift coefficient under different Mach numbers and damage levels.

It is evident that for the damage form of truncated wings, the lift coefficient curves intersect at an angle of attack of -1.7° across different speeds. We refer to this pivot point as the 'rotation point of CL'. When the missile's angle of attack does not reach the stall angle, the lift coefficient curve rotates around this pivot point as wing loss increases, accompanied by a reduction in slope.
When the right wing of the missile is severed, the wing's area and aspect ratio both undergo changes. A three-dimensional wing surface inevitably experiences transverse airflow, and when the loss ratio of the right wing approaches 100%, assuming no interference occurs between the two wing halves due to the missile body's separation, the aspect ratio of the right wing approaches zero. Under these conditions, the transverse airflow must become extremely severe. Based on the facts described above, to further analyze the origin of the lift line's pivot point, we assume the absence of transverse airflow on the wing surface. In this assumption, the lift coefficient can be simplified to the integration of the airfoil lift coefficient along the spanwise direction relative to the chord length. Therefore, the airfoil of this cruise missile is extracted for two-dimensional aerodynamic computational analysis.

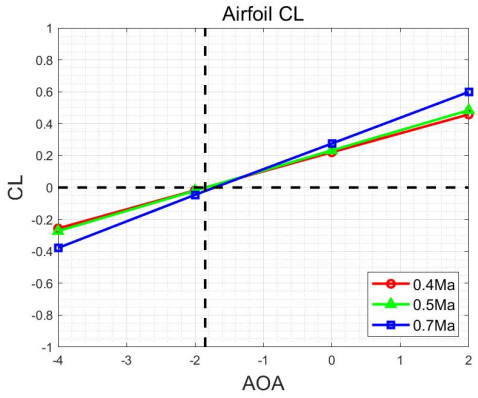


Figure 5 – CL curve of the airfoil.

Based on these results, it can be observed that the zero-lift angle of attack of the airfoil is extremely close to the rotation point of CL, with the small difference between the two attributed to the influence of the tail. Since the tail employs a symmetric airfoil with a smaller lift curve slope and its area is significantly smaller than that of the wing, the difference between the zero-lift angle of attack of the airfoil and the aerodynamic center is very minor in this case. For such a missile configuration, it is reasonable to consider the rotation point of CL as equivalent to the zero-lift angle of attack of the wing airfoil.

Based on this pattern, we calculated the variation in the lift coefficient of the damaged wing compared to that of the undamaged wing, obtaining the results shown in the figure 6.

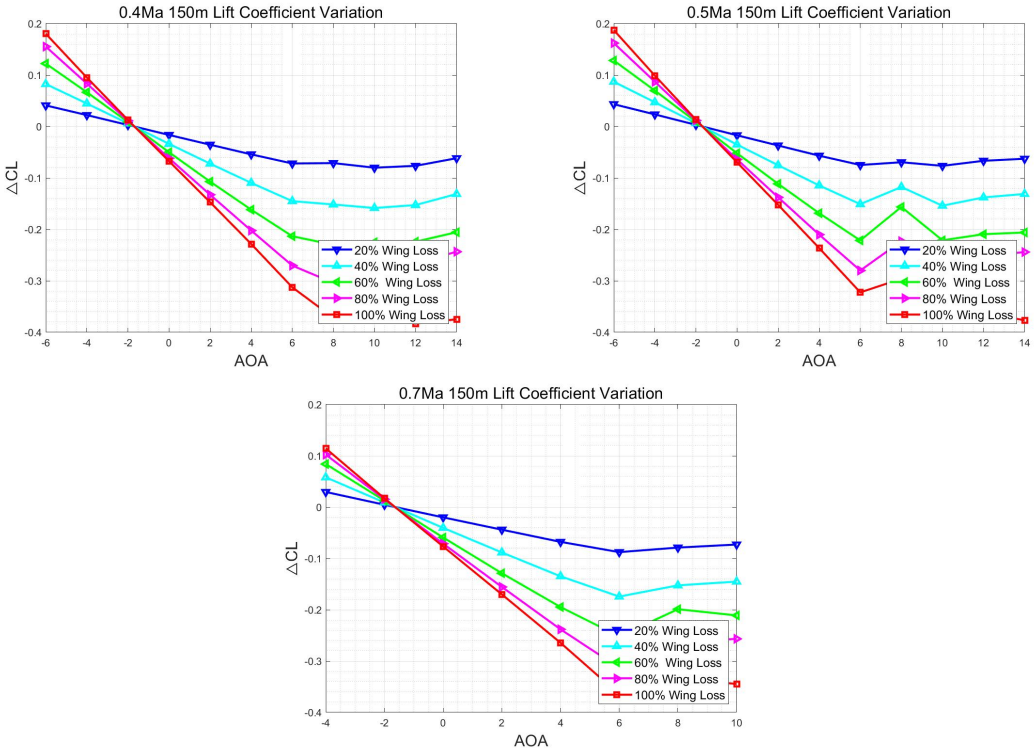


Figure 6 – CL Variation.

The lift coefficient curve in Figure 6 clearly intersects at the point (-1.7, 0). Based on this characteristic, the variation of the lift coefficient ΔCL after wing damage can be expressed as:

$$\Delta CL = \Delta CL_{\alpha}(\alpha - \alpha_{foil,\ 0}) \tag{5}$$

where $\alpha_{foil,\ 0}$ is the zero-lift angle of attack of the airfoil, here taken as $\alpha_{foil,\ 0} = -1.8°$, and ΔCL_{α} is the slope of the lift coefficient variation. The damaged lift coefficient $CL_{Damaged}$ can be expressed as:

$$CL_{Damaged} = CL_{Undamaged} + \Delta CL_{\alpha}(\alpha - \alpha_{foil,\ 0}) \tag{6}$$

where $CL_{Undamaged}$ is the lift coefficient of the undamaged missile.

Based on this pattern, an analysis of the variation law of ΔCL_α is conducted. Because the lift coefficient results indicate that the variation of the missile's lift coefficient at high angles of attack exhibits fluctuations, which are caused by the numerical errors arising from the unstable airflow at high angles of attack in both the missile's aerodynamic performance and CFD calculations, the pattern in this study is only applicable to the linear segment of the lift coefficient.

This paper extracts damage parameters as the percentage of exposed spanwise loss length, a setting designed to make damage representation more intuitive. However, when studying the linear segment of ΔCL_α, it is necessary to consider the chord length distribution along the wingspan. Therefore, in analyzing the variation of ΔCL_α, we now convert the percentage of exposed spanwise loss length b_e into the percentage of wing area loss on one side for analysis. The changes in ΔCL_α with area loss at different speeds are illustrated in the figure below.

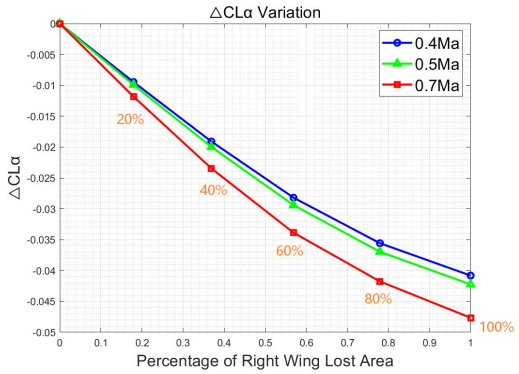
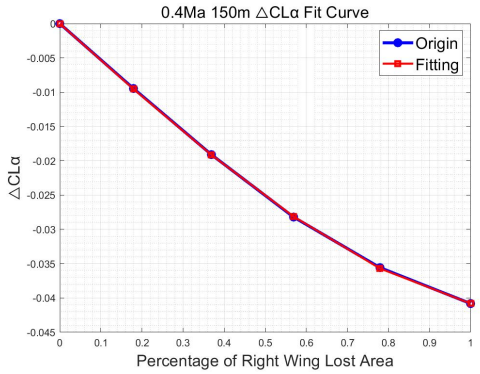
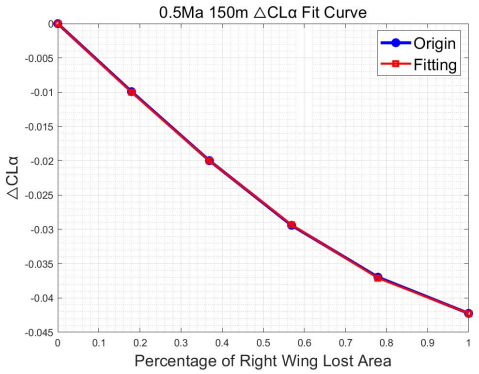


Figure 7 – ΔCL_α Variation with area loss and Mach number.

In Figure 7, it is clearly observed that when the lost single-side wingspan is less than 60%, the variation in ΔCL_α exhibits a highly linear trend. This is because the change in lateral flow patterns due to the reduction in aspect ratio is minimal, resulting in a negligible impact on the overall lift coefficient variation. However, when the lost single-side wingspan exceeds 60%, the lateral flow caused by the reduced aspect ratio leads to ΔCL_α no longer changing linearly with the decrease in wing area.

Below, the functional form $\Delta CL_\alpha(s) = as^3 + bs^2 + cs + d$ is used to fit ΔCL_α, where s represents the percentage of wing area lost on one side relative to the exposed wing area on that side. According to the figure 7, it is enforced that $d = 0$ in $\Delta CL_\alpha(s)$. Furthermore, the coefficients a, b, and c of $\Delta CL_\alpha(s)$ at different speeds are plotted against speed and fitted again, obtaining functions for coefficients a, b, and c as functions of Mach number.





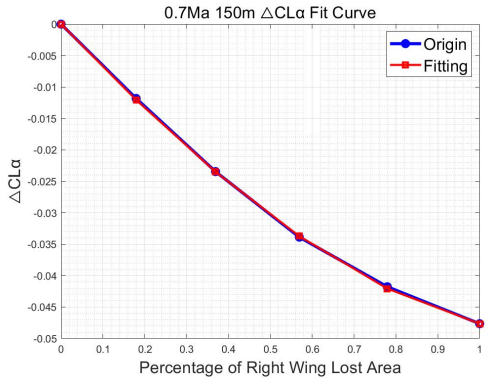


Figure 8 – Fitting of ΔCL_α.

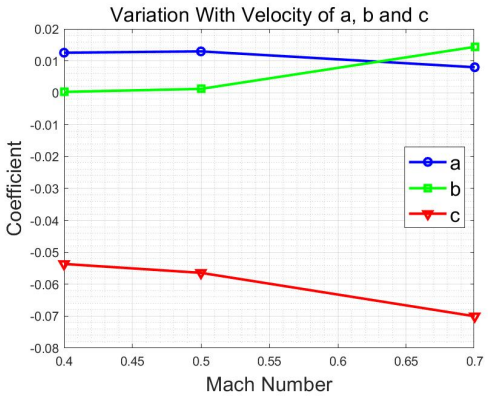


Figure 9 – Variation with Mach number of a,b and c.

Since the three coefficients of the polynomial $\Delta CL_\alpha(s)$ vary monotonically with the Mach number, a second-order polynomial fit for the Mach number is applied to the three coefficients of $\Delta CL_\alpha(s)$. The fitting results and relationships are as follows.

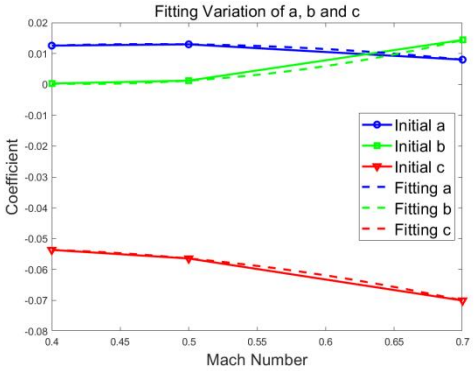


Figure 10 – Fitting variation with Mach number of a,b and c.

$$a(m) = -0.0964m^2 + 0.0909m - 0.0084 \quad (7)$$

$$b(m) = 0.1883m^2 - 0.1601m + 0.3402 \quad (8)$$

$$c(m) = -0.1342m^2 + 0.093m - 0.0694 \quad (9)$$

3.2 Rapid Aerodynamic Calculation Based on VLM

In the previous section, we obtained the relationship as shown in (5)~(9) and quickly derived the variation of the lift coefficient in the linear segment. However, in practical applications, we also need to obtain the undamaged lift coefficient to complete the rapid calculation of the damaged missile's lift coefficient. If we use the CFD method to obtain the inviscid lift coefficient, it will consume a significant amount of time and computational resources, unable to meet the demand for rapid calculations. Therefore, in this section, the vortex lattice method (VLM) is employed to

conduct fast computations for inviscid configurations[16].

VLM is a numerical solution for lifting surface theory, whose mathematical essence is the superposition of two simple potential flows—uniform flow and three-dimensional vortex filaments—under the steady linearized small perturbation assumption. The inviscid aerodynamic calculation method is conducted using NASA OpenVSP. NASA OpenVSP is an open-source parametric aircraft design and analysis tool that can rapidly generate aircraft geometries by inputting geometric parameters. In its solver module, VSPAERO, an improved VLM is employed for low-fidelity aerodynamic characteristic calculations. Unlike the classical VLM, VSPAERO places a vortex ring on each panel of the wing, with the vortex ring's center point serving as a singularity (similar to the control point of a horseshoe vortex). The vortex strength determines its induced velocity at the singularity, and its direction is tangent to the lifting surface. Additionally, VSPAERO incorporates compressibility corrections for air during the solution process, allowing the VLM's computational accuracy to extend beyond the incompressible air assumption of the classical VLM.

Modeling and calculation of the given lossless configuration condition were performed using OpenVSP. The influence of the projectile body was ignored during modeling, and Mach number correction was introduced in the calculations. The comparison between VLM calculation results and CFD calculation results show in Figure 11 and Table 1.

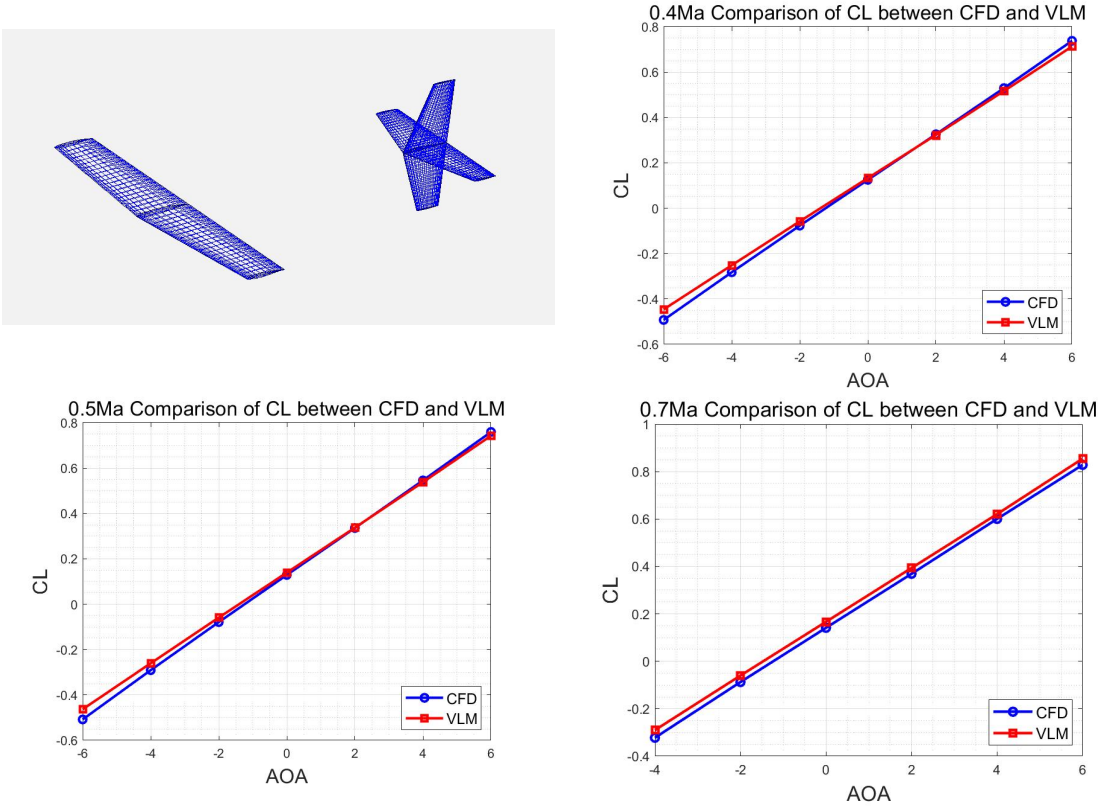


Figure 11 – Comparison of CL between CFD and VLM in differrent Mach number

Table 1 - Comparison of CL between CFD and VLM in differrent Mach number

Ma	0.4Ma		0.5Ma		0.7Ma	
AOA	△	e_r	△	e_r	△	e_r
-6.0	0.04646	9.43 %	0.04484	8.83 %	\	\
-4.0	0.03082	10.92 %	0.03051	10.49 %	0.03211	9.96 %
-2.0	0.01882	24.52 %	0.01980	25.13 %	0.02732	31.22 %
0.0	0.00766	6.12 %	0.01034	8.01 %	0.02537	17.96 %
2.0	-0.00289	-0.89 %	0.00151	0.45 %	0.02457	6.66 %
4.0	-0.01274	-2.41 %	-0.00772	-1.41 %	0.02026	3.37 %
6.0	-0.02491	-3.38 %	-0.01659	-2.18 %	0.02635	3.18 %

From the above data, it can be observed that there is a certain error between the lift coefficient curve obtained by the VLM method and that obtained by CFD in compressible flow. Additionally, since the influence of the fuselage was not considered in the calculations, the lift slope differs somewhat from that of the CFD method. Moreover, the wing sections shielded by the fuselage still generate lift in the VLM method, causing the overall lift coefficient obtained by VLM to be higher than that of the CFD method.

The VLM method here is only a quick estimation method for the coefficient $CL_{Undamaged}$, and the errors it produces, along with those from the damaged wing lift coefficient estimation formula, will be corrected in later chapters.

3.3 Summary of VLM based Rapid Lift Coefficient Calculation Method for Damaged Cruise Missile

For the calculation results of the intact missile model obtained by the VLM method, using formulas (5) to (9), the rapid estimation results of the CL for the damaged cruise missile, represented by the dashed line in Figure xx, can be obtained. These results are compared with those obtained through CFD calculations, as shown in Figure xx.

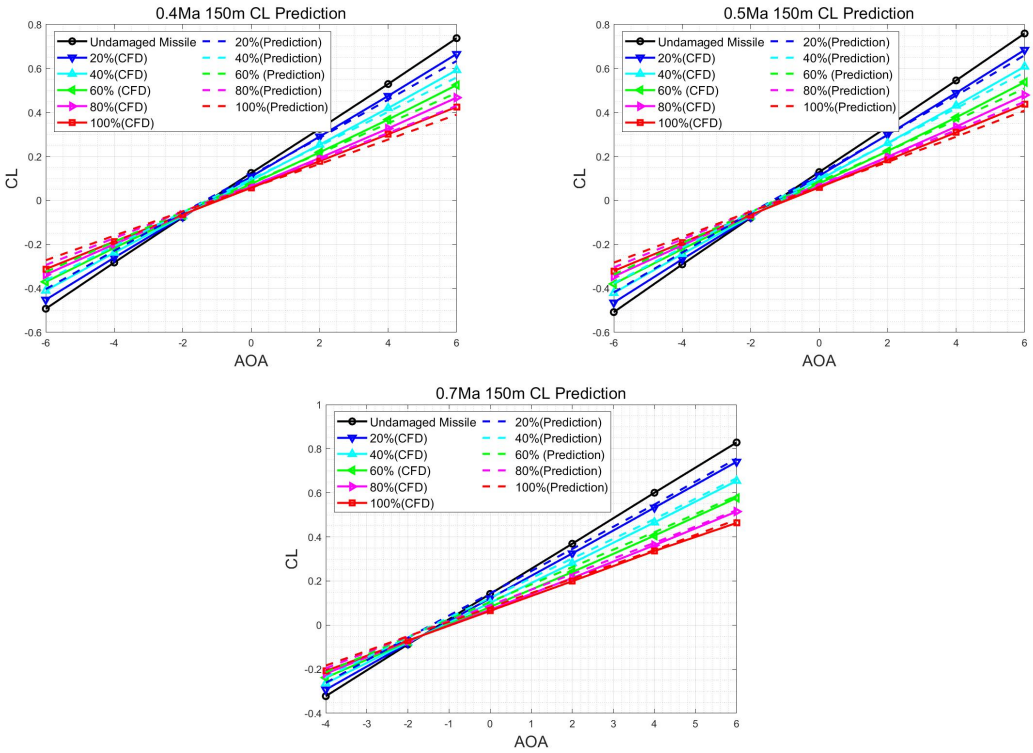


Figure 12 – Comparison of CL between CFD and preliminary prediction

To further validate the method and study the accuracy of the aforementioned approaches, we selected the working conditions from the table below to conduct CFD calculations. In the table 2, we also performed calculations for the undamaged model. This was done to use the CFD results of the undamaged model as $CL_{Undamaged}$, comparing them with the VLM predictions to determine whether the primary source of error lies in the VLM calculations or the fitting formula derived earlier. A comparison between the calculation results and the rapid estimation results is shown in Figure 13.

Table 2 - CFD verification condition list

Mach Number	AOA	Wing Loss b_e
0.6	-4,0,6	40%
0.6	-4,0,6	80%
0.6	-4,0,6	0

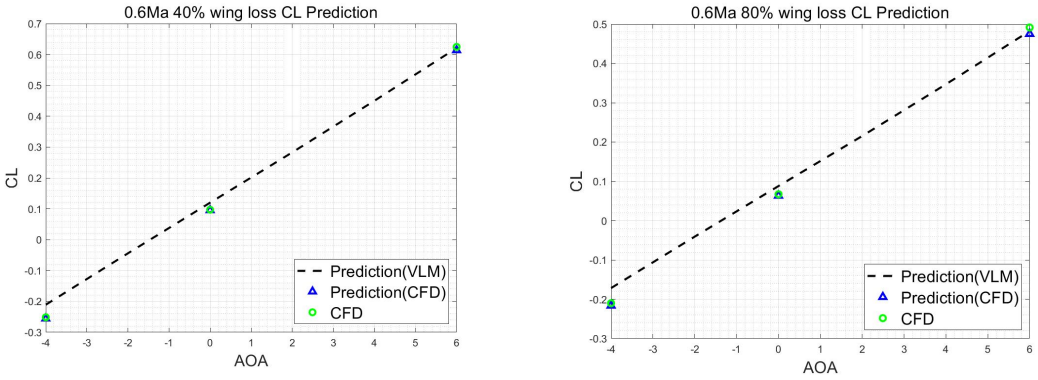


Figure 13 – Comparison of CL during CFD, VLM prediction and CFD based prediction

From the above figure, it can be observed that using the undamaged missile lift coefficient obtained from CFD calculations to predict the damaged lift coefficient can yield results with minimal error compared to the CFD method by analyzing the variation pattern of lift coefficient damage. This result indicates that the primary source of error in this method stems from the VLM process.

4. Neural Network-based Error Correction

To further refine the rapid calculation method for the damaged lift coefficient, this paper employs neural network fitting to predict the errors generated by the aforementioned VLM prediction of the damaged lift coefficient.

Figure xx illustrates the neural network model used for lift coefficient prediction. This neural network model takes as input the Mach number, angle of attack, percentage of damage relative to wingspan, and the lift coefficient obtained from VLM. The output is the error between the VLM-based predicted lift coefficient and the CFD-calculated lift coefficient, which comprehensively considers the influence of flight conditions and damage parameters on the prediction error variation of the lift coefficient, thereby enhancing the model's physical interpretability. The network structure consists of one hidden layer with 10 neurons and is trained using the Levenberg-Marquardt algorithm.

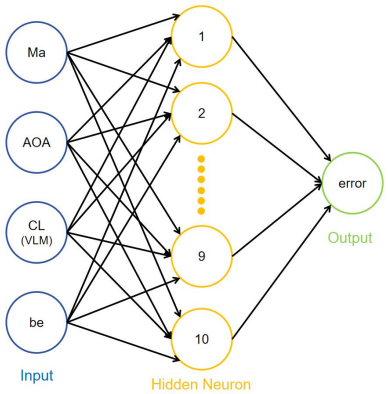


Figure 14 – Neural network model.

Based on the neural network model, we obtained the error model for lift coefficient prediction. By recording the fitting error of the lift coefficient estimation as e_{bp}, the fast calculation formula for $CL_{Damaged}$ can be revised as:

$$CL_{Damaged} = CL_{Undamaged} + \Delta CL_{\alpha}(\alpha - \alpha_{foil,\ 0}) - e_{bp} \tag{10}$$

Using this method to verify the calculation results of the working conditions in Table 2 again, the following results can be obtained. After incorporating the error correction model, it is found that the maximum relative error in the verification decreased from 31.2% to 16.99%. This is because the lift

coefficient at this angle of attack is numerically very small, leading to an inevitably larger error compared to the reference value. The minimum relative error decreased from -0.57% to -0.08%, and the rapid calculation error was significantly reduced.

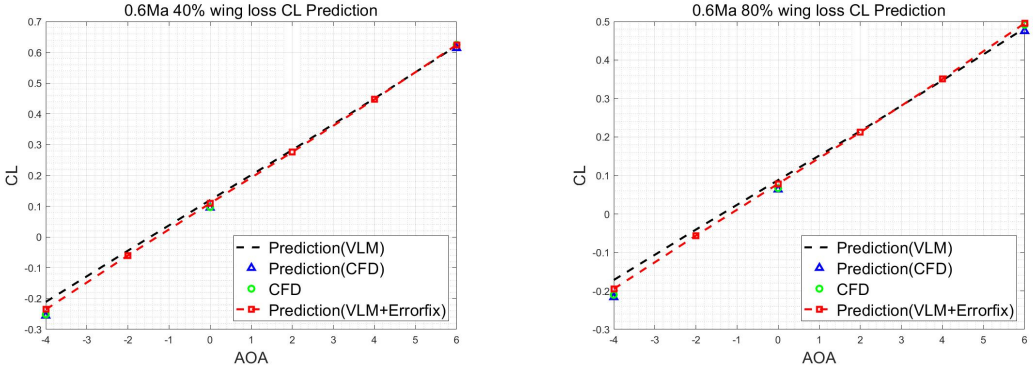


Figure 15 – Comparison of corrected prediction results.

Table 3 - Comparison of rapid prediction results before and after BP correction.

		VLM+Predict		VLM+Predict+error correction	
b_e	aoa	△	e_r	△	e_r
40%	-4	0.0407	16.18 %	0.0161	6.40 %
	0	0.0229	23.66 %	0.0124	12.83 %
	6	-0.0036	-0.57 %	-0.0005	-0.08 %
80%	-4	0.0385	18.30 %	0.0154	7.32 %
	0	0.0209	31.20 %	0.0114	16.99 %
	6	-0.0090	-1.84 %	0.0037	0.76 %

5. conclusion

This study addresses the problem of rapid aerodynamic evaluation of battle-damaged cruise missiles. Based on computational fluid dynamics (CFD) analysis, vortex lattice method (VLM), and backpropagation (BP) neural network technology, a rapid aerodynamic evaluation method chain of "rough calculation-pattern prediction-error prediction and correction" is proposed. The main research achievements are as follows:

(1) A systematic study was conducted using CFD numerical simulations to investigate the influence of wing damage on the lift coefficient of cruise missiles at different Mach numbers (0.4Ma, 0.5Ma, and 0.7Ma). The research revealed that after wing damage, the linear segment of the lift coefficient rotates around a characteristic point, which was determined through analysis to be closely related to the airfoil's zero-lift angle of attack—approximately -1.8° in this study. This finding provides an important theoretical basis for modeling the lift characteristics of combat-damaged aircraft.

(2) A quantitative relationship model was established between wing damage extent and the variation in lift coefficient. Through systematic analysis of different damage extents (20%, 40%, 60%, 80%, 100%) on a single wing, it was found that when the damaged area is less than 60%, the change in lift coefficient ΔCl exhibits a highly linear relationship with the damaged area. However, when the damage exceeds 60%, the relationship becomes nonlinear due to the enhanced lateral flow effect caused by a sharp decrease in aspect ratio. Based on this, a polynomial model was developed for the variation in lift coefficient slope with respect to damaged area and Mach number.

(3) Based on the vortex lattice method module in NASA OpenVSP, a rapid calculation method for the lift coefficient of undamaged configurations was established. Building upon this, combined with the variation patterns of the lift coefficient under wing damage, an initial rapid prediction model for the lift coefficient of damaged missile wings was derived. Although the VLM method exhibits significant errors compared to CFD due to neglecting fuselage effects and fully linear assumptions,

its computational efficiency is notably advantageous, making it suitable as a foundational method for rapid evaluation.

(4) A neural network-based error prediction and correction module was constructed. To address the discrepancy between the rapid calculation results of the VLM joint rule prediction and the CFD benchmark data, a single-hidden-layer BP network with 10 neurons was established. The inputs to this network were the Mach number, angle of attack, damage severity, and the VLM joint rule prediction values, while the output was the predicted error magnitude. After applying this correction model, the maximum relative error decreased from 31.2% to 17%, and the minimum relative error improved from -0.57% to -0.08%, significantly enhancing the accuracy of the rapid assessment.

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