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A Study on Blended Inlet Body Design for a High Supersonic Unmanned Aerial Vehicle

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Abstract

The design process of blended inlet body (BIB) for the preliminary design of a near-space high supersonic unmanned aerial vehicle (HSUAV) is presented. The mass flow rate and cowl area of inlet at a design point are obtained according to the cruise condition of the HSUAV. A mixed-compression axisymmetric supersonic inlet section with a fixed geometry reasonably matching the high supersonic cruise state is created by using the inviscid theory of aerodynamics. The inlet section is optimized and used as a baseline section for the BIB design. Three BIB concepts for the HSUAV are proposed, and their internal aerodynamic characteristics of inlet are evaluated using Euler computational fluid dynamics (Euler CFD) solver. The preferred concept is identified, in which the straight leading edge of the baseline HSUAV configuration is modified into the convex leading edge to accommodate the inlet and meet the requirements of the cowl area to capture the sufficient air flow. The total recovery of inlet for the preferred BIB concept and the aerodynamic characteristics of the modified HSUAV configuration are verified using Navier-Stokes computational fluid dynamics (NS CFD) solver. The validation indicates that the preferred BIB concept can meet both the requirements of the inlet and aerodynamic performance of the HSUAV.

Key words: near-space unmanned aerial vehicle, supersonic inlet, aerodynamic configuration, integrated design, numerical simulation

1. Introduction

The high supersonic unmanned aerial vehicle (HSUAV) is an unmanned flight vehicle that can cruise at a higher supersonic speed (3.0 < Mach < 5.0) [1]. The HSUAV generally uses Rocket Based Combined Cycle (RBCC) or Turbine Based Combined Cycle (TBCC) [2] as a primary propulsion system, and is superior to most of current subsonic and supersonic unmanned aerial vehicles (UAV) in terms of penetration ability and survivability. In the view of technology readiness, the concept of HSUAV powered by RBCC or TBCC is more realistic compared to that of hypersonic unmanned aerial vehicles powered by scramjet. For instances, the aircraft such as D-21B [3], SR-71 [4] and XB-70 [5] powered by RBCC, TBCC and afterburner turbojet respectively were able to cruise at Mach number 3.0 or higher.

One challenge in the HSUAV preliminary design is how to design a supersonic inlet that can meet the TBCC operating requirements as well as be blended with the aerodynamic configuration. This issue is referred as the blended inlet body (BIB) design in the HSUAV preliminary design. The reference [6] presents a systematic review on various supersonic inlets for military aircraft, and their evolution and development. The fundamentals, aerodynamic characteristics and operating performance of the supersonic inlet have been investigated theoretically and experimentally in references [7-9]. But the systematic design process for the blended inlet body (BIB) for

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the HSUAV preliminary design has not been fully reported in publications.

This paper aims to develop the design process to cope with the BIB design issue in the HSUAV preliminary design, and is organized as follows. The concept of HSUAV is briefly described in section 2, and design process how the inlet is blended with the fuselage is detailed in section 3, and the preferred BIB design concept is evaluated in section 4 followed by the conclusions in section 5.

2. Concept of HSUAV

The HSUAV is a notional UAV powered by a tandem TBCC combining turbojet with ramjet. Its typical mission is reconnaissance with cruise speed at Mach 3.5 and operating radius of 1500km at the altitude of 25000m. The HSUAV is able to take off and land autonomously, and its maximum takeoff weight is around 4300kg.

The baseline aerodynamic configuration of the HSUAV is quasi-rhombus platform with aspect ratio less than 1.0, as shown in Fig. 1. The HSUAV aerodynamic configuration features are: 1) the wing is blended with the body (fuselage); 2) the aerodynamic configuration is designed such that the leading edges is subsonic, and trailing edges is supersonic at cruise Mach number M=3.5; 3) the V tail is located in the aft-body to provide the suitable controllability and stability at both subsonic and supersonic speed; and 4) the inlet and nozzle are located at the upper body to enhance the stealth performance of the HSUAV.

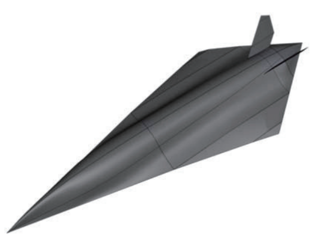


Fig. 1. Aerodynamic Configuration of HSUAV without Inlet Layout

The task of this research is to design a suitable supersonic inlet and blend it into the upper body of the HSUAV.

3. Design Process

In order to find a suitable inlet which can be blended into the body of the HSUAV, a design process is developed as shown Fig. 2. The 'Sizing' portion of the design flowchart presents the previous finished work to size HSUAV before the BIB design. The 'BIB Design' portion of the design flowchart is the BIB design process that this paper will focus on.

The BIB design process consists of the following steps:

1) The mass flow rate $\dot{m}_{in}$ of the inlet at design point is predicted according to the mission analysis of the HSUAV.

2) The two dimensional section of the inlet is created by using one-dimensional isentropic flow theory [10] and optimized through iSIGHT-FD software [11].

3) Based on the above optimized section of the inlet, several design concepts for the BIB are proposed.

4) The aerodynamic characteristics of the supersonic inlet at design point for each BIB design concept are evaluated by using Euler CFD solver, and a preferred BIB concept is then identified.

5) The total pressure recovery of the supersonic inlet at design point for the preferred BIB concept is evaluated by a higher fidelity code, i.e. the CFD code based upon the Navier-Stokes (NS) equations to verify the total pressure recovery of the inlet, and also aerodynamic performance of the HSUAV configuration is evaluated to verify that lift-to-drag ratio and maximum lift is reasonably satisfied.

The following subsections will present the details for each step in the design flowchart.

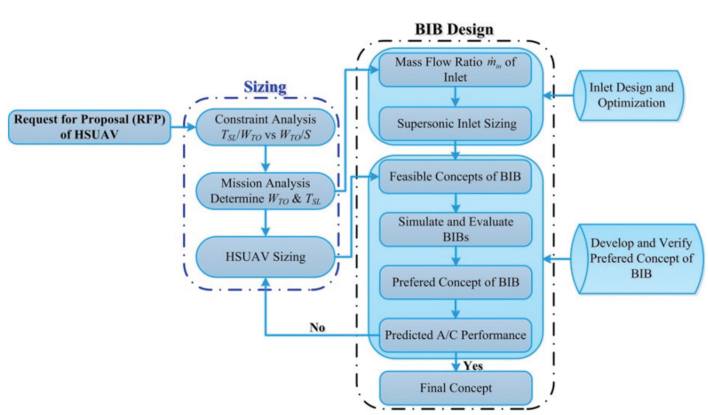


Fig. 2. Design Flowcharts of Blended Inlet Body (BIB)

3.1 Determination of mass flow rate of the inlet

The cruise state is usually taken as the design point of propulsion system of aircraft. The dynamic equilibrium equation at design point is written as

$$\left(\frac{T}{W}\right)_{cruise}=\frac{1}{\left(L/D\right)_{cruise}} \tag{1}$$

where T is the installed thrust, W is the instantaneous weight, L is the lift, D is the drag and the subscript cruise means the cruise state. The parametric cycle analysis of ideal ramjet is given in reference [12]. Once the flight conditions (the ambient pressure, temperature and Mach number) and exit total temperature T_{t7} of combustion chamber exit of ramjet are known, the specific thrust $F/\dot{m}$ of ramjet can be estimated, where F is the uninstalled thrust and $\dot{m}$ is the mass flow rate. Also, installed thrust T and instantaneous weight W at the start point of cruise flight and $(L/D)_{cruise}$ are already known. Considering that F may exceed to T by 0 to 10% depending on the situation and distance from the final point [13], the uninstalled thrust is finally selected as F=(1+10%)T at the stage of aircraft preliminary design.

Based on the above calculations, the mass flow rate $\dot{m}_{in}$ of the supersonic inlet at design point can be calculated and its value equals to 17.22kg/s.

3.2 Design and Optimization of the Inlet

3.2.1 The design requirements of the inlet

According to the mission of the HSUAV, the design requirements of the inlet are as follows:

1) Design height: H_D=25000m

2) Design Mach number: M_D=3.5

3) Total pressure recovery at design point: $\sigma > 0.5$

4) Captured mass flow rate at design point: $\dot{m}_{in}$ =17.22kg/s

Ignoring the spillage of external compression three-dimensional inlet, the inlet at design point should attain the maximum total pressure recovery.

3.2.2 The baseline section of the inlet

The HSUAV is designed to fly most of the time at Mach number M=3.5 over the whole mission profile. Therefore, a fixed mixed-compression axisymmetric supersonic inlet is selected for the HSUAV. The two-dimensional section profile of the inlet is depicted in Fig. 3, where l_7 is the inlet total length, l_{th} is the throat section length of inlet, δ_1 is the first conical half-angle, δ_t is the total inclined angle to the freestream flow direction, $ABCDEFG$ and $HIJK$ are the internal and cowl conical curves of inlet respectively. At design point the first oblique shock wave produced by AB and second isentropic compression shock wave [14] produced by BC intersects at point H of the cowl lip. The third quasi-isentropic compression reflected shock wave produced by HI intersects at point E of starting point of the throat section.

To meet the required total pressure recovery at design point and the self-start of the inlet at lower supersonic speed, the two-dimensional baseline section of the fixed mixed-compression axisymmetric supersonic inlet is optimized under Kantrowitz limit [15] that confirms the throat area A_{th}. The cowl and diffuser exit areas A_c and A_e are determined by mass flow rates and Mach numbers at their corresponding sections [16].

3.2.3 Optimization of the Inlet Section

To maximize the total pressure recovery at design point, the inlet section geometry needs to be optimized. The inlet section optimization problem is stated as follows:

Find: δ_1, M_2, l_1

Maximize: σ

Subject to: $\delta_1 \in [7.5°,12.0°]$

$M_2 \in [1.8,2.6]$

$l_1 \in [1.5,2.2]$

$\delta_t \in [0.0°,30.0°]$

$\beta_3 \in [0.0°,90.0°]$

$M_3 \in [1.1,1.8]$

$\sigma \in [0.7276,1.0]$

where l_1 is the length between cowl lip and the nose of internal cone (or fuselage), M_2 and M_3 are the Mach numbers vertical to area A_1 and normal shock wave respectively, and β_3 is the inclined angle of deflected oblique shock wave in front of normal shock wave.

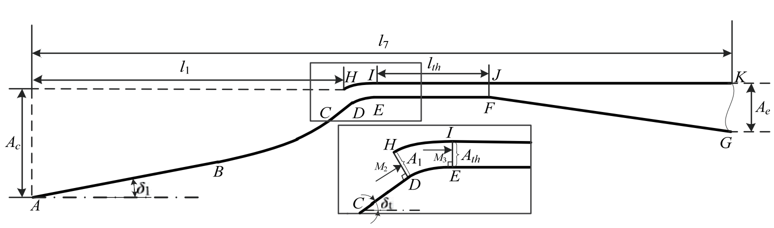


Fig. 3. Baseline Section Profile of the Inlet

The Genetic Algorithm [17, 18] is applied to solve the optimization problem. The optimal solution is obtained and listed in Table 1. The parameter values in Table 1 are used to size the section of the inlet.

3.3 Concept of Blending Inlet into Body

The purpose of this section is to find a preferred design concept blending the inlet section obtained in Sec. 3.2 into body (or fuselage) of the HSUAV shown in Fig 1. Three concepts of the blended inlet body (BIB) will be proposed and evaluated. The preferred one will be identified based on the evaluations and comparisons for three BIB concepts.

3.3.1 Three Design Concepts for BIB

On the basis of the inlet section in Sec. 3.2 and known captured air flow ratio $\dot{m}_{in}$ =17.22kg/s in Sec. 3.1, a one-third round axisymmetric inlet is deployed in the front of the body of the HSUAV. The one-third conical surface in front of the cowl lip is a part of the body and also served as the supersonic diffuser of the inlet.

The difficulties of the BIB design come from a conflict between the large leading edge sweep of the HSUAV configuration and the required cowl area A_c of the inlet when the inlet is utilized to suck the air in the front of the body. In this design study, three concepts of BIB are proposed as shown in Fig. 4, where l_1 is the length between the cowl lip and the nose of the body (also see l_1 in Fig. 3), l_2 is the length between the farthest beveling point of inlet entrance and the nose of the body, D is the width of the inlet that all external compression waves are attached to the cowl lip, and W is the width at the position of the inlet entrance.

Table 1. Parameter Values of Optimized Inlet Section

Design Variables			Constraints			Objectives
δ_1 (°)	M_2	l_1 (m)	δ_t (°)	M_3	β_3 (°)	σ
8.04	2.353	1.924	28.97	1.568	42.73	0.8124

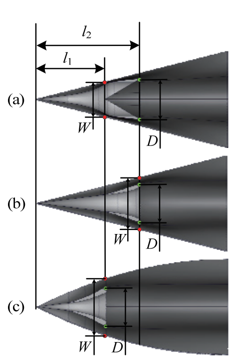


Fig. 4. Three Concepts Blending Inlet into Body

In concept I, the cowl lip is placed away from the nose of body with the distance l_1. To avoid the conflict between the required inlet entrance width and large sweep of the leading edge of the HSUAV configuration, the cowl lip is cut through backward 60-degree beveling along with symmetric plane, and the cowl lip is swept backward, as shown in Fig. 4(a). In this way, the inlet external compression part and cowl lip are compatible with the baseline aerodynamic configuration.

In concept II, the cowl lip is moved directly backward to the position where the second isentropic compression waves can be attached to the cowl lip, as shown in Fig. 4(b). This BIB concept is also compatible with the baseline aerodynamic configuration, but less air flow is captured due to the impact of the first oblique shock wave unattached to the cowl lip.

In concept III, the baseline HSUAV configuration is slightly modified by enlarging the width of the front body. The straight leading edge of the baseline HSUAV configuration is modified into the convex leading edge [18]. This concept results in minor change of the baseline aerodynamic configuration, as shown in Fig. 4(c). The modified platform shape with the convex leading edge enlarges the body width at the position of the cowl lip, which ensures that the all external compression waves are attached to the cowl lip without changing the shape or moving the position of the cowl lip like Concept I or II.

The geometric parameter values of three BIB concepts are listed in Table 2.

3.3.2 Evaluations of Three BIB Concepts

Euler CFD solver is applied to evaluate the inlet performance for above three design-point concepts whose specific inlet sections are meshed through using a 2-D structured grid. The TVD scheme is used for spatial discretization, and implicit LU-SGS scheme is implemented for time integration. To validate the Euler CFD analysis process in this study, the example of a dual mode scramjet inlet from the reference [20] is used to test the analysis process. The result by the Euler CFD analysis in this study is in agreement with the experimental data [20].

The compression wave structures and mass flow ratio are used to investigate the inlet behaviors [10]. The mass flow ratio is given by

Table 2. Geometric Parameters of Supersonic Inlet of Three Concepts

Concept	δ_1 (°)	l_1 (m)	D (m)	W (m)	l_2 (m)
I	8.04	1.926	1.114	0.96	2.9
II	8.04	—	1.114	1.446	2.9
III	8.04	1.926	1.114	1.575	—

$$\varphi = \frac{A_0}{A_c} \tag{2}$$

where A_0 is the cross-sectional area of the free stream tube captured by the inlet.

For Concept I, the cowl lip edge is not in the same plane, therefore the flow characteristics of two typical sections - the axial sections at symmetric plane and outermost side plane of the inlet are chosen to be simulated. The flow fields of two external supersonic compression sections of the inlet are shown in Fig. 5. The flow field of the axial section at symmetric plane of the inlet in Fig. 5(a) shows that all external compression waves are perfectly attached to the cowl lip. However, when we investigate the static pressure contour lines of the axial section at outermost side plane, there exists plenty of overflow which disobeys the inlet design-point requirements that all external compression waves are expected to attach to the cowl lip. Meanwhile, the flow of axial section at outermost side plane of the inlet accelerates when the air flow passes the top of inner cone. Flow accelerating results in unexpected supersonic flow before coming into subsonic diffuser. This situation should be avoided in view of inlet operating at design point.

For Concept II, the cowl lip edge is in the same plane. The flow characteristics of the axial section only at symmetric plane of the inlet are simulated. The flow field of external supersonic compression section of the inlet is shown in Fig. 6, where the first oblique shock wave is not attached to the cowl lip, but the second isentropic compression waves are attached to the cowl lip. However, the mass flow ratio of the inlet is far less than 1.0 due to the first oblique shock wave away from the cowl lip. The lower mass flow ratio means that the inlet cannot capture the required mass flow rate. A way to sustain the required mass flow rate $\dot{m}_{in}$ =17.22kg/s in Concept II is that the cowl area would be enlarged, but it would lead to an encounter with the baseline configuration of HSUAV.

For Concept III, the cowl lip edge is still in the same plane. The flow characteristics of the axial section at symmetric plane of the inlet are simulated. The simulating results of external supersonic compression section of the inlet are shown in Fig. 7. The pressure contour lines of Fig. 7 reflect that the mass flow ratio is closely equal to one. That means the concept III for the BIB design can meet the need of all external compression waves attached to the cowl lip.

After the investigation of the simulation results for three BIB concepts, the comparisons of features for three BIB concepts are listed in Table 3 in terms of maximum mass flow rate, the spillage, the flow uniform and compatibility with baseline configuration of the HSUAV. From the comparisons, the concept III is certainly the preferred one among three concepts. Therefore the concept III is selected for the BIB design. The overall HSUAV configuration with the BIB of the concept III is depicted in Fig. 8.

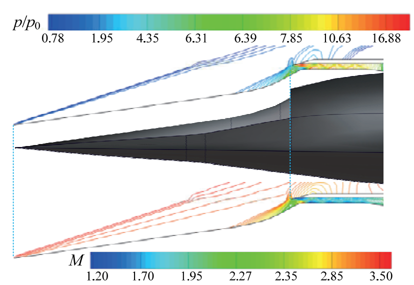


Fig. 6. Flow Field Simulation of External Compression Section for Concept II at Design Point

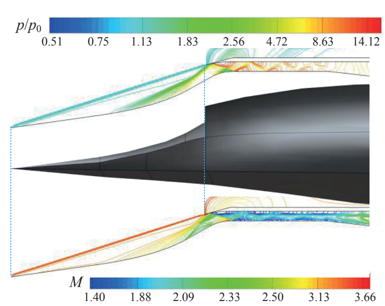
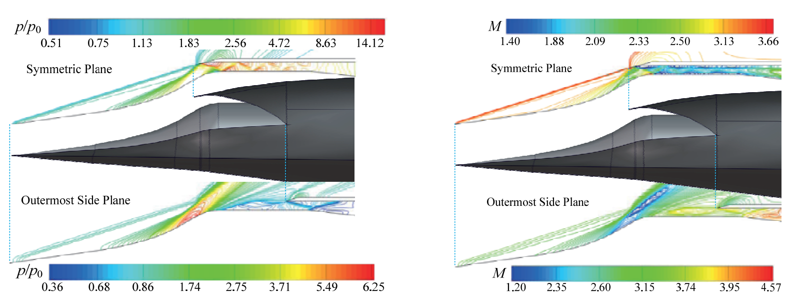


Fig. 7. Flow Field Simulation of External Compression Section for Concept III at Design Point



(a) Static Pressure Contour (b) Mach Number Contour

Fig. 5. Flow Field Simulation of External Compression Section for Concept I at Design Point

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4. Further Evaluation of the Preferred Concept

4.1 Total Pressure Recovery of Inlet at Design Point

A higher fidelity code (NS CFD solver) is used to evaluate the total pressure recovery of the axial section at symmetric plane of the inlet for the concept III. The 2-D structured grid is meshed for the axial section of the inlet. The k-ω turbulence model and the Reynolds-averaged NS (RANS) equations are employed in the simulation. The AUSM scheme is used for spatial discretization, and implicit MUSCL scheme is implemented for time integration. The method of NS CFD analysis in this paper was validated by the example of the 2D supersonic inlet with the simulation and experiment results provided by the reference [21].

The flow fields are depicted in Fig. 9. It shows that the shock wave is pushed to outside of the inlet entrance when the back pressure of diffuser exit is 38 times ambient pressure. That means the inlet is operating at subcritical state. But when the back pressure of diffuser exit is 37 times ambient pressure, all external compression waves are attached to the cowl lip and the shock train is terminated over the half throat length. The inlet is very close to operating at design point. The area-weighted average Mach number at diffuser exit is M_5=0.2262 and the total pressure recovery is σ=0.5072.

Table 3. Comparisons of BIB Concepts at Design Point

Concept	Mass Flow Rate	Spillage	Uniform	Compatibility
I	0.220	Larger	Bad	Hard
II	0.652	Large	Good	Easy
III	0.996	Small	Good	Easy

Fig. 8. The HSUAV Configuration with BIB of Concept III

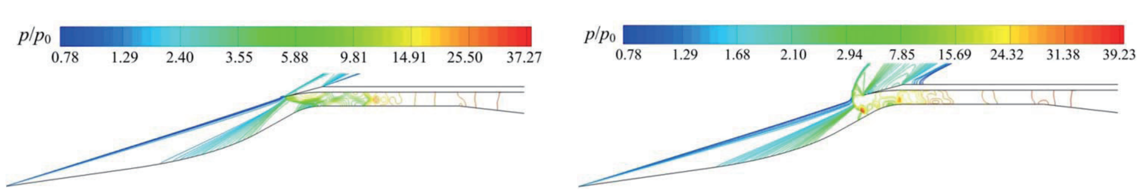
The value of total pressure recovery predicted by NS CFD is much lower than that from one-dimensional isentropic theory. The reason is that the effects of viscosity, separation of boundary layer, shock/boundary-layer interaction are not considered when the initial baseline section of the inlet is created (see in Fig. 3.). However, the baseline section of the inlet at design point has been established to satisfy the requirements of blending the inlet into body of HSUAV at the stage of preliminary design.

4.2 Aerodynamic Characteristics of Overall Configuration

Since the straight leading edge of the baseline configuration is modified into the convex leading edge in the preferred concept (see Fig. 8), it is necessary to evaluate the effect of the modification on aerodynamic characteristics of the overall configuration of the HSUAV. NS CFD solver is applied to evaluate impact of the modification on the aerodynamic characteristics. The 3-D unstructured grid is meshed for the modified configuration. The k-ω turbulence model and the RANS equations are used in the simulation. The AUSM scheme is used for spatial discretization, and implicit First-Order Upwind scheme is implemented for time integration. The NS CFD analysis process of the aerodynamic simulation in this study was validated by the example of the AFRL 1303 UCAV model from the reference [22]. The result from the NS CFD analysis in this study is reasonably consistent with the experimental data in the reference [22].

Figure 10 shows the lift-drag ratio L/D with angle of attack α at cruise speed M=3.5 for the baseline and modified configuration. The lift-drag ratio of the modified configuration is 6.25% reduction than that of baseline one. The main reasons are: 1) the wave drag is increased due to the convex leading edge in the front body of the modified configuration; 2) the increased exposed surface area due to convex leading edge of the modified configuration results in larger friction drag.

One of the aerodynamic requirements in "Sizing" of the design process as shown in Fig 2 is that the maximum lift to drag ratio of the HSUAV should be larger than 4.3. The NS



(a) 37 Times Back Pressure

(b) 38 Times Back Pressure

Fig. 9. Static Pressure Contour Lines at Mach 3.5 and Diffuser Exit Back Pressure with 37 and 38 Times to Ambient Pressure

CFD analysis shows that the maximum lift to drag ratio of the modified configuration is larger than 4.3 even though there is 6.25% reduction compared to the baseline configuration, which means the modified configuration is acceptable from the viewpoint of the aerodynamic requirement. Actually, the modified configuration is a compromise between the aerodynamic performance and the inlet design requirements.

Figure 11 depicts the lift coefficient C_L of the HSUAV with angle of attack α at low speed M=0.3 by the numerical simulation. The lift curves of the baseline and modified configurations are very similar, and the value of maximum lift coefficient of the modified one is slightly higher than that of the baseline one.

5. Conclusions

Blending an inlet into the body is a crucial issue in the preliminary design of the HSUAV. A method for the blended inlet body (BIB) design was established to solve the issue in this paper. Three BIB design concepts were proposed and evaluated. The preferred BIB concept was identified, in which the straight leading edge of the baseline configuration was modified into the convex leading edge to accommodate the inlet and meet the requirement of inlet entrance area to capture sufficient mass flow rate at design point.

The preferred BIB concept was further verified by the more elaborate simulations (NS CFD). The results indicate that the value of the total pressure recovery for the preferred BIB concept is 0.5072, and should be enhanced in subsequent detail design. It is suggested that the techniques such as boundary layer suction and effect of changes in throat length relative to shock train length should be applied if the total pressure recovery for the preferred BIB concept is expected to be further improved. The simulations also show that the lift-drag ratio of the modified configuration at the cruise speed is slightly decreased compared to the baseline configuration, however its maximum lift coefficient at the low speed are slightly better than that of the baseline one.

In conclusion, the preferred concept is a promising BIB design of the HSUAV, and is worth to be further investigated in subsequent detail design stage.

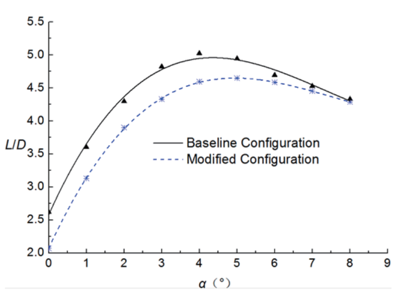


Fig. 10. Lift-to-drag (L/D) vs Angle of Attack (α) at Cruise Speed M=3.5

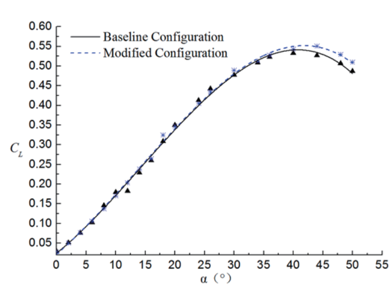


Fig. 11. Lift Coefficient (C_L) with Angle of Attack (α) at Low Speed M=0.3

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