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Design of shape morphing hypersonic inward-turning inlet using multistage optimization

Jifei Wang[a], Jinsheng Cai[a,*], Yanhui Duan[b], Yuan Tian[c]

[a] School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, PR China
[b] Computational Aerodynamics Institute, China Aerodynamics Research and Development Center, Mianyang 621000, PR China
[c] The 41st Institute of No. 6 Academy, China Aerospace Science and Technology Corp., Hohhot 010010, PR China

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ABSTRACT

To make a compromise between compression efficiency and aerodynamic performance, a novel multistage optimization approach is proposed to improve the design of the shape morphing hypersonic inward-turning inlet. In the first stage, a parent flow inside an internal cone shaped from a special dual-inflection-point generatrix is optimized for the improvements of total pressure recovery and flow uniformity. The second stage is established to design the inlet lip shape via a single-objective optimization aiming to minimize the inviscid drag of the inlet. For rapidly predicting the inlet inviscid drag, we propose a streamline integral method characterized by high levels of computational efficiency and accuracy. The last stage is auxiliary to improve the practicability, mainly including an algebraic shape transition to regulate the inlet exit shape. Numerical results demonstrate that both the flow non-uniformity and the total pressure loss of the optimized parent flow are decreased significantly compared with the baseline parent flow. With the optimized lip shape, the inlet inviscid drag per unit mass flow rate is decreased as well. A simple quadratic function is the best choice to achieve the shape transition, which is beneficial to improve the inlet practicability with a less performance loss. With the multistage optimization framework, the improvements of the compression efficiency and the aerodynamic performance are both achieved and the balance between them is carefully manipulated as well. All the above demonstrates that the proposed optimization approach for the design of the shape morphing hypersonic inward-turning inlet is practical and efficient.

1. Introduction

For the hypersonic vehicles powered by airbreathing engines, the inlet is the core element to provide efficient gas compression, and hence it is the essence to hypersonic vehicles. Considering the severe flight conditions of hypersonic aircraft, the inlet should be well designed to achieve a high level of compression efficiency and to reduce the negative influence on the overall aerodynamic performance. So far numerical and experimental studies [1] have been carried out extensively to study three conventional types of hypersonic inlets, namely, the two-dimensional planar inlet, the two-dimensional axisymmetric inlet and the sidewall-compression inlet. The two-dimensional planar inlet has been used on X-43A [2] and X-51 [3] hypersonic testing vehicles.

In addition to the aforementioned three typical kinds of hypersonic inlets, another promising type is an inward-turning inlet. A representative configuration of this type is the Busemann inlet [4]. It has a relatively higher total pressure recovery, a less wet area and a wider adaptive capability compared with the other kinds. The original Busemann inlet compresses the air isentropically everywhere except across the incident and reflected shock waves, and the flow field behind the reflected shock wave is perfectly uniform. However, the flow path of the complete Busemann inlet is too long. Therefore, the practical use of the Busemann inlet is greatly limited when the viscous effect has to be considered. The truncated Busemann inlet may overcome this drawback partially, but the quantity of the outflow is not as high as that of the complete Busemann flow. To overcome the shortcomings of the Busemann inlet, Vanwie [5] created a modular Busemann inlet using a streamline tracing technique and defined the Busemann flow field as a parent flow. Smart [6] from NASA created a Rectangular to Elliptical Shape Transition (REST) inlet using a similar strategy but the flow in a reversed axisymmetric expansion nozzle was chosen as the parent flow. Chinese researchers from NUAA

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* Corresponding author.
E-mail addresses: jifeiwangnwpu@163.com (J. Wang), caijsh@nwpu.edu.cn (J. Cai), duanyanhui@foxmail.com (Y. Duan).

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performed studies on the hypersonic inward-turning inlet as well. You [7,8] designed an internal waverider hypersonic inlet using the parent flow inside an internal cone shaped by a straight generatrix; Zhang [9,10] generated the parent flows whose the pressure or Mach number distributions were controllable to create the inward-turning inlet and investigated their influences on the inlet performance. He [11] from CARC proposed a conceptual design of osculating internal waverider to realize the inward-turning inlet/airframe integration.

How to improve the compression characteristics is undoubtedly the major design concern of hypersonic inlets. Ref. [12] pointed out that one percent increase of the inlet compression efficiency would result in about four percent increase of the specific impulse of the propulsion system for vehicles flying at $Ma = 5 \sim 7$. Moreover, because of the uncertainty of combustion time scales and the possible desire of using multiple engine modules on a single forebody, an uniform flow downstream the inlet exit is highly desirable [13]. Besides, the hypersonic inlet should be well integrated with the airframe to minimize the aerodynamic performance loss. Consequently, the prime challenge in the design of inward-turning inlet is to balance the compression efficiency and the aerodynamic performance.

The existing research on the hypersonic inward-turning inlet design focuses on the improvement of the compression characteristics, but suffers from insufficient consideration of the flow uniformity. More importantly, the lip shape of the inlet has not earned sufficient concerns although it has a great influence on the inlet aerodynamic performance. Furthermore, the practicability of the inlet would be impaired if all above factors are taken into consideration during the design process. Obviously, the existing design methods are only able to improve the performance of a single aspect, but not the entire system. In order to comprehensively improve the inlet performance, a multistage design system is a potential choice. As the whole design process is divided into several stages, different aspects of performance can be improved individually by different stages, and the compromise among all the aspects is able to be manipulated as well. Therefore, a multistage optimization approach is proposed to design the hypersonic inward-turning inlet in this paper. In the first stage, a parent flow is determined by a multi-objective optimization, which provides a preferred fundamental flow field with improvements of compression and flow uniformity. The second stage aims to improve the inlet aerodynamic performance continuously, and the major objective is to minimize the inviscid drag by a lip shape optimization. Since the lip shape variation may lead to an irregular inlet exit, the inlet practicability will be impaired. Therefore, the next stage is set up to improve the inlet practicability, mainly including an algebraic shape transition to regulate the inlet exit shape. A boundary layer correction is also involved in this stage, which aims to make the inlet work better in the viscous gas environment. As the inward-turning inlet is determined by this multistage design approach, the performances of compression and aerodynamic are easily improved at the same time, and the prime challenge to balance several performance aspects can be addressed as well.

We organize the paper as follows: the first stage of the proposed approach to design the parent flow is introduced in section 2; section 3 illustrates the second stage of the approach, which improves the aerodynamic performance by a lip shape design optimization; the stage for the practicability improvement is introduced in section 4; in section 5, numerical simulations are demonstrated and the design results are assessed comprehensively; the conclusion is drawn in section 6.

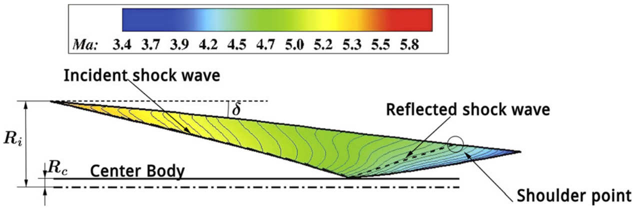

Fig. 1. Mach number contours of the parent flow solved by the MOC.

2. Parent flow design optimization

2.1. Parent flow solving methodology

The primitive configuration of an inward-turning inlet is the envelope of streamlines traced in the parent flow, and hence the parent flow is the essence to an inward-turning inlet. The word "parent" also indicates that the inlet inherits the major properties of the parent flow. In this paper, the parent flow is the flow inside an internal cone, and it is perfectly supersonic at the hypersonic design point. Therefore, a two-dimensional axisymmetric rotational method of characteristics (MOC [14]) can be used to solve the inviscid parent flow, and its accuracy has been validated in ref. [7]. The MOC has an excellent property of space marching to improve the computational efficiency by avoiding the whole field iteration. Besides, the accurate position of the incident shock wave can be captured by the MOC, which is convenient for the subsequent streamline tracing. The MOC needs an initial flow field prior to the rest calculations. In this paper, a combination of the incident shock wave at the leading point and the flow field immediately behind it is defined as the initial flow field, which is a quasi-ICFA [15] derived by integrating the Taylor–Maccoll equation. This treatment is more precise than the oblique shock wave relationship.

If the incident shock wave directly points at the axis of symmetry, a steady normal shock wave reflection cannot exist due to the singularity, and thus a Mach disk may appear and destroy the parent flow. Fortunately, ref. [16] proposed a method to avoid this unfavorable phenomenon by installing a cylinder center body at the position of the symmetric axis. In our work, the center body is installed by aligning it co-axially with the parent flow. The proper installation of the cylinder can induce a normal shock wave reflection, which makes the flow behind the reflected shock wave parallel to the freestream. Making full use of the property of the normal shock wave reflection and assuming the reflected shock wave just pointing at the shoulder point, the parent flow solving methodology can be simplified. According to the oblique shock wave relationship, the parent flow is solved by searching the flow direction behind the reflected shock wave iteratively until the flow becomes parallel to the freestream, and then the position of the reflected shock wave can be obtained simultaneously.

The main design parameters of the parent flow are the freestream Mach number $Ma_\infty = 6$, the freestream static pressure $P_\infty = 1185$ Pa, the leading compression angle $\delta = 6°$, the radius of the parent flow inlet $R_i = 1m$ and the radius ratio of the inlet to the center body $R_c/R_i = 0.1$. According to the studies presented in ref. [9] and ref. [10], 0.1 is a reasonable value of R_c/R_i since it helps to balance all the aspects of the performances. The Mach number contours of the parent flow solved by the MOC are illustrated in Fig. 1. The dash line in Fig. 1 shows the position of the reflected shock wave while the actual flow field behind the reflected shock wave is not the same as that shown in the figure. This part is just presented to get the flow information in front of the reflected shock wave for searching the position of the reflected shock wave.