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Short communication

Inverse design of shock wave distortion for a direct-connect facility

Kaikai Yu, Jinglei Xu *, Xiaofei Zhang, Shun Liu

Jiangsu Province Key Laboratory of Aerospace Power System, Nanjing University of Aeronautics and Astronautics, Nanjing 21006, People's Republic of China

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A B S T R A C T

Direct-connect facilities are very important experimental equipment for studying scramjets that have become the primary focus of research on hypersonic aircraft. Because of its short research cycle, minimal investment, and high revenue, this type of facility is used to conduct measurements in isolator/combustor studies. The principal function of the facility is to reproduce the distortions generated by the scramjet inlet during free jet experiments or flight tests. Many researches consider that the shock wave is the crucial factor influencing distortion. In this study, which is based on the Method of Characteristics (MOC), direct simulation of the shock wave distortion is presented. After specification of the parameters of the target line across the shock wave, the shock wave and flow path of the facility can be generated using the code based on MOC. The details of the design philosophy are described and the robustness and accuracy of the proposed method are verified in two cases with the aid of computational fluid dynamics. Finally, a specific facility is designed according to the proposed method. The relative errors of the Mach number and pressure are small enough to satisfy the requirements of the experiments. The facility also utilizes the expansion concept proposed by the authors in a previous study to address the starting problem successfully.

1. Introduction

The scramjet, which is made up of four crucial elements (i.e., the inlet, isolator, combustor, and nozzle), is the most important component of hypersonic air-breathing propulsion systems. Numerous experimental efforts have been carried out over the last few decades to gain a better understanding of the complex phenomena in scramjets [1,2]. Ensuring stable performance of the isolator/combustor is the major consideration in scramjet design, and the main research methods in this area can be classified as either numerical simulations or experimental studies. In the experimental studies, the direct-connect facility (for nozzle–isolator–combustor components) presents substantial advantages over the free-jet facility (for inlet–isolator–combustor components) in terms of experimental cost, test duration, steady-state and experimental complexity. In the early direct-connect experiments, the isolator/combustor studies are conducted using a facility nozzle to establish the flow conditions which are uniform and match the conditions at the engine throat (the entrance of the isolator). Because of the advantages of the direct-connect facility, the facility has been most often adopted in experimental studies on scramjets [3–5].

Several researchers have sought to optimize the design method of direct-connect facilities. In some ways, the direct-connect facility plays a role of the inlet, which produces the distortions generated by the boundary layer and shock waves that will develop and propagate downstream of the scramjet inner flowfield. This concept also indicates that the key consideration in a direct-connect facility is the design of the inlet distortion. Because the distortions generated by shock waves produce the most crucial flowfield structure and dominate the performance of the isolator/combustor, Gruber [6] and Hagenmaier [7] used a portion of the original inlet ramp to generate shock waves. In this method, a shock reflection point is first selected in the inlet as the start of the distortion generator. Then, the portion of the ramp before the selected reflection point is substituted by a facility nozzle designed according to the flow parameters of the selected position. The method is both universal and simple, and has higher accuracy than the earliest method which only utilizes a facility nozzle directly. However, the method is also seriously flawed in the sense that a contraction configuration is adopted in the supersonic flow. When the contraction area ratio is too large, the facility can't establish supersonic flow in the isolator and suffers the starting problem. The phenomena and mechanisms of the starting problem were introduced in the work of Yu et al. [8]. Another method proposed by Tam [9] used ramps, injection slots, and ports to design direct-connect facility with the help of computational fluid dynamics (CFD) tools. Previous research found that an optimal combination of these fea-

* Corresponding author.
E-mail address: xujl@nuaa.edu.cn (J. Xu).

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tures can effectively replace the distortion generator, and the experiments conducted in a supersonic wind-tunnel facility by Tam [10] validated these results. The method was confirmed to be useful and reliable once the numerical simulations were completed. However, different configurations of the inlets require numerous simulations that must be performed to design the distortion facilities. Yu et al. [8] proposed a universal method to generate the flow parameters before the shock waves based on the Method of Characteristics (MOC). In this work, a proper distribution of the flow parameters is selected. The contour line of the distortion generator can then be obtained using the inverse MOC. The main advantage of this method is that the design of the inlet distortion may be directed via the code based on inverse MOC. Thus, the method is very convenient, efficient, and accurate. As well, the starting problem is solved completely by adopting the expansion concept rather than contraction.

In summary, the main goal of the research works described above is to simulate the distortion generated by shock waves in the inlet during free jet experiments or flight tests. In the previous study, we proposed the expansion concept to eliminate the starting problem encountered in the traditional direct-connect facilities [8]. For the simulation of the shock wave distortion, the flow parameters before the specified shock wave were extracted to be the target. So in essence, the generator in Ref. [8] produced the deflection flow instead of the shock wave. Thus, reflection points of the shock waves must be recognized, which may inconvenience designers. And we also found that the flow parameters cannot be easily obtained under the two-dimensional effect and need to be optimized for simulating the specified shock wave accurately. Even if optimal parameters have been decided, the shock wave obtained does not completely coincide with that generated in the inlet. So the idea that the generator should produce the shock wave distortion directly comes to mind. So based on the previous work [8], the focus of the present research is to develop a code based on MOC through which the shock waves can be simulated directly. In other words, once the physical parameters of the target line across the shock waves are specified, the contour line of the distortion generator can be generated directly using MOC. So the proposed method is one step method which can generate the shock wave directly instead of the parameters before the shock wave. Besides that, this design method still adopts the expansion concept to eliminate the starting problem encountered in traditional direct-connect facilities. First, the details of the contour line design method are introduced. And the process of the shock wave in inverse MOC is introduced in detail, which is the key point of the proposed method. Then, verification cases are performed and computed by CFD tools with inviscid and viscous flows. Finally, a generic inlet is selected and a specific direct-connect facility is developed to confirm the universality and reliability of the proposed method. In summary, the facility designed by the proposed method can generate shock waves directly and mimic the flow distortion of the scramjet inlet without undergoing any starting problem.

2. Proposed methodology

To illustrate the problem more clearly, essential design theory on the direct-connect facility is introduced in this section. Fig. 1 shows the flow pattern of a generic supersonic inlet; here, the shock waves (red dashed line) and expansion waves (blue dotted line) can be observed. Under the influence of the boundary layers, the combination of these waves causes complex flow phenomena, such as shock wave/boundary interactions, shock wave/expansion wave interactions, and so on. To save on experimental costs and increase the test duration, the direct-connect facility is used to produce flow distortion generated by the inlet in the free-jet experiments. Gruber et al. [6] and Hagenmaier et al. [7] proposed

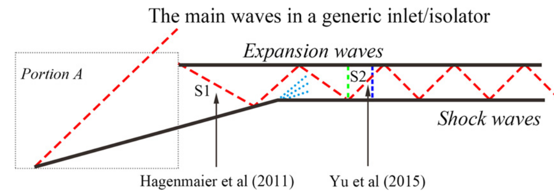

Fig. 1. The flow structures of the generic inlet. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

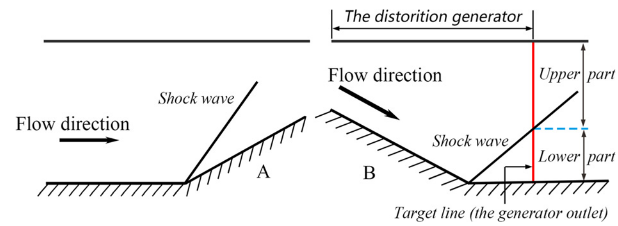

Fig. 2. Different configurations of the direct-connect facility.

a commonly adopted method of flow distortion production. These researchers simulated shock waves labeled S1 by "removing" portion A of the inlet and "adding" the corresponding facility nozzle. This design works efficiently when the contraction area ratio is lower enough. To solve the starting problem and improve the ability of the system to work with high back pressures, the shock wave labeled S2 was selected by Yu et al. [8]. In this work, the supersonic flow deflects to a specified angle distribution. Afterward, the flow comes into contact with the horizontal wall and forms a corresponding shock wave (i.e. shock wave labeled S2). Thus, the distributions of the flow angle are the most important target parameters. Once decided, the contour line of the distortion generator can be inverse designed using MOC. And we studied the influence of angle distributions and concluded that an optimal distribution is difficult to determine in Yu et al. [8]. In the present study, the inverse design method will start from the parameters of the shock wave directly, rather than the parameters before the shock wave. The new method will overcome the disadvantage of the original method that a shock reflection point must be recognized to extract and the target parameters need to be optimized. Besides that, a direct inverse design method can simulate the corresponding shock wave more accurately.

Fig. 2 illustrates the different configurations of the direct-connect facility. Fig. 2A shows the traditional configuration, while Fig. 2B shows the configuration that can solve the starting problem absolutely. The final purpose of these configurations is to form shock waves. Thus, we can reasonably believe that direct simulation of shocks will become more reliable and efficient. Under this condition, the flow parameters on the target line across the shock wave (target line in Fig. 2) may be assumed to be known; these parameters can be obtained by CFD simulation of the inlet. The conditions of the line before the shock wave are denoted by the subscript 1, and those of the line after the shock wave are denoted by the subscript 2. The conditions of the line after the shock wave should include the distributions of the Mach number (Ma_2), stagnation pressure (P_2), stagnation temperature (T_2), and the flow deflection angle (θ_2). By contrast, the line before the shock wave only requires information on the distributions of Ma_1.

Now that we know the distributions of the essential parameters of the line (the blue line in Fig. 1, pre-simulated), MOC can be used to solve the upstream flow and design the contour line inversely. MOC is a numerical tool for solving hyperbolic equations based on characteristics of theory. This method is a major aerodynamic tool for computing supersonic flow field, designing nozzles and obtaining upstream flow conditions [11]. MOC is discussed in various aerodynamic textbooks. With emphasis on a steady,