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FULL LENGTH ARTICLE

Shock/shock interactions between bodies and wings

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Abstract This paper examines the Shock/Shock Interactions (SSI) between the body and wing of aircraft in supersonic flows. The body is simplified to a flat wedge and the wing is assumed to be a sharp wing. The theoretical spatial dimension reduction method, which transforms the 3D problem into a 2D one, is used to analyze the SSI between the body and wing. The temperature and pressure behind the Mach stem induced by the wing and body are obtained, and the wave configurations in the corner are determined. Numerical validations are conducted by solving the inviscid Euler equations in 3D with a Non-oscillatory and Non-free-parameters Dissipative (NND) finite difference scheme. Good agreements between the theoretical and numerical results are obtained. Additionally, the effects of the wedge angle and sweep angle on wave configurations and flow field are considered numerically and theoretically. The influences of wedge angle are significant, whereas the effects of sweep angle on wave configurations are negligible. This paper provides useful information for the design and thermal protection of aircraft in supersonic and hypersonic flows.

1. Introduction

In aerospace engineering, the prediction of aerodynamic heating is very important for the design of supersonic or hypersonic aircraft. There are two approaches to estimate aerodynamic heating in protective engineering. The first method is to use correlations between pressure and heating to predict the aerodynamic heating, which assumes that the aerodynamic heating is positively related to the pressure or density.[1] This approach is applied to the simple geometric shapes well; however, it could not predict the aerodynamic heating well for the complex geometric shape. The second method considers the location of Shock/Shock Interaction (SSI) or the interactive wave configuration as the key factors of aerodynamic heating [2], but the mechanism has not been well established. Thus, the problem of SSI is very important to the prediction of aerodynamic heating.

Regarding the SSI induced by the body and wing of aircraft, many researchers have conducted numerous experimental and numerical studies.[3–7] Zheltovodov and Schulein[3–5] conducted experimental and theoretical (computational) investigations on a model of one fin mounted on a flat plate at Mach number 3, and the technology of surface oil flow and flow visualization by Planar Laser Scattering (PLS) was used in his experiments. He also considered the effects of the

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deflection angle of the fin on surface pressure and wave configuration. Horstman and Hung[6] used the Reynolds-Averaged Navier–Stokes (RANS) simulation with a simple algebraic eddy-viscosity turbulence model to compute streamline trajectory. Schülein[7] performed experiments to study the surface pressure and skin-friction distributions at Mach number 5. Other researchers also study the SSI by using different models.[8–15] In the above research, the plate was flat and only the Shock wave-Boundary-Layer Interactions (SBLIs) were taken into consideration. In the design of hypersonic aircraft, the high heat flux may be caused by SSI and SBLIs. Therefore, the interactions between incident waves induced by the plate and the fin are very important for the prediction of heat flux in these regions.

Compared to the experimental and numerical researches, the theoretical research is seldom conducted. The earliest theories about 2D Regular Reflection (RR) and Mach Reflection (MR) were proposed by von Neumann,[16,17] who termed them as the two-shock theory and three-shock theory. Based on these theories, Kawamura and Saito[18] developed the (p, θ)-polar method, where p denotes the flow static pressure and θ is the flow deflection angles, to describe the shock reflection and SSI problems. Ben-Dor[19] used the (p, θ)-polar method to analyze various shock reflection and interaction wave configurations. However, the above theories are 2D, and in fact, there is no theory for the 3D cases. Recently, Yang and Xiang et al. developed a spatial dimension reduction approach to analyze the 3D SSI.[20–24] Through the use of the new theoretical method, the 3D steady SSI problem can be treated as a 2D unsteady one, and then, the flow structures could be solved by shock dynamic.

In this paper, the SSIs induced by bodies and wings were studied numerically and theoretically. The spatial dimension reduction method is used to analyze the flow parameter and the results are compared with the numerical results. In Section 2, the procedures and numerical methods are simply presented. Numerical results and theoretical analysis are given and discussed in detail in Section 3. Finally, the conclusions are drawn in Section 4.

2. Analytical approach and numerical methods

As depicted in Fig. 1, the numerical model is a simplified symmetrical model of a wing and body, where the body is replaced by a wedge and the wing is assumed to be a sharp wing. The wedge angle of the body is θ, and the body is L in length, d in width and h in height. The distance from the front point of the wing O to the leading edge of the body is l_1, A is the top point of the wing. λ_2 is the sweep angle of the wing, and is formed by the leading edge of the wing and the horizontal line. Half angle of the wedge is defined as θ_1, and the height of the wing is h_1.

For the free inviscid inflow Ma_0, the incident wave CBF is induced by the body, the incident wave APR is induced by the wing, and they interact with each other in the corner as shown in Fig. 2. Two reflected waves, OPR and PRG, occur due to the intersection of the two incident waves. The computational zone is selected as half of the model, which is divided by the symmetry plane. The intersecting line of the two incident waves, PR, is defined as the characteristic direction, and the plane NMD perpendicular to it is defined as the characteristic plane. Q is the intersecting point of line PR and the plane NMD. In the interactive zone, the wave configuration is self-similar in the direction of the characteristic line, and thus, the 3D steady SSI could be regarded as a 2D SSI in the characteristic plane moving in the direction of the characteristic line PR.

The decomposed Mach number projected on PR is $Ma_{\rm n}$. The decomposed Mach numbers $Ma_{\rm s1}$ and $Ma_{\rm s2}$ on the characteristic plane are given by

$$Ma_{\rm s1} = Ma_0 \sin\beta_1, \quad Ma_{\rm s2} = Ma_0 \sin\beta_{2n} \cos\lambda_2 \tag{1}$$

where β_1 is the shock angle in the direction of the incoming flow, and β_{2n} is the shock angle perpendicular to the leading edge of the wing.

When the above geometrical relationships between 3D steady problem and 2D unsteady problem are determined, the problem of 3D could be regarded as the interaction of two incident waves $Ma_{\rm s1}$ and $Ma_{\rm s2}$ moving on the characteristic plane, which can be treated as the characteristic plane moving in the direction of the characteristic line PR.

The determination of the wave configurations could be achieved by shock polar analysis of the 2D unsteady problem.[18,19]

$$\tan\theta = \frac{\xi - 1}{\gamma Ma^2 - (\xi - 1)}\sqrt{\frac{\frac{2\gamma}{\gamma+1}(Ma^2 - 1) - (\xi - 1)}{\xi + \frac{\gamma-1}{\gamma+1}}} \tag{2}$$

where Ma is the decomposed Mach number in the direction of the reflection point, γ is 1.4 for an ideal gas, and ξ is the ratio of the pressure behind the waves.

If the wave configuration is Mach interaction, a Mach stem is formed between $Ma_{\rm s1}$ and $Ma_{\rm s2}$. The Mach number behind

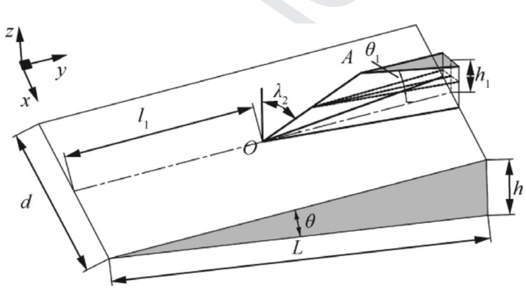

Fig. 1 Schematic illustration of a simplified model for wing and body.

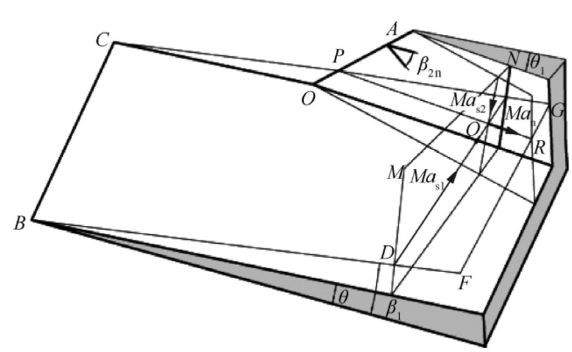

Fig. 2 Schematic of "spatial-dimension reduction" approach.

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