LONGITUDINAL STABILITY DESIGN CRITERIA FOR HYPERSONIC GLIDERS

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Abstract

Hypersonic gliders with high lift-to-drag ratio, including waveriders, are one of the major interests on hypersonic vehicles development. Longitudinal stability characteristics analysis and design is crucial for the design of a hypersonic glider. However, longitudinal stability design criteria have yet been developed for this type of aircrafts. In this work, longitudinal stability criterion is derived based on a simplified hypersonic glider model and the Newton theory. The critical geometric parameter determining the longitudinal stability of the glider is identified from the criterion. Qualitative and quantitative correlations between the geometric parameters and the longitudinal stability are analyzed using a series of simplified hypersonic glider examples. The analysis results are verified using a CFD method for the simplified glider models. Then the longitudinal design criteria are applied to design a longitudinal stable self-trimmed waverider. In order to meet the criteria, the waverider is generated using a waverider design method based on shock-fitting technique. The CFD simulation results show that the waverider is longitudinally stable self-trimmed at the designed angle of attack, as the longitudinal design criteria expects.

1 INTRODUCTION

Hypersonic gliders with high lift-to-drag ratio, including waveriders, are one of the major interests on hypersonic vehicles development. Longitudinal stability characteristics analysis and design is crucial for the design of a hypersonic glider. For a hypersonic glider, longitudinal self-trimmed at cruise angle of attack with static stable characteristics is preferable. However, longitudinal stability design criteria have yet been developed for this type of aircrafts. And waverider configurations created with traditional planar shock or conical shock methods are usually longitudinally unstable when trimmed at the design angle of attack.

In this work, longitudinal stability criterion is derived based on a simplified hypersonic glider model and the Newton theory. Critical geometric parameter determining the longitudinal stability of the glider is identified from the criterion. Qualitative and quantitative correlation between the geometric parameter and the longitudinal stability is analyzed using a series of simplified hypersonic glider examples. The analysis results are verified using a CFD method for the simplified glider models. Then the longitudinal design criteria are applied to design a longitudinal stable self-trimmed waverider. In order to meet the criteria, the waverider is generated using a new waverider design method with shock-fitting technique. With this new method, the design space of a waverider is extended to general 3D flow field with shock wave. By choosing an appropriate Shock Generating Body configuration, a waverider configuration with negative cambered windward profile is created. The CFD simulation results show that the waverider is longitudinally stable self-trimmed at the designed angle of attack, as the longitudinal design criteria expects.

2 LONGITUDINAL STABILITY DESIGN CRITERIA

2.1 Longitudinal stability definition

Definition of aerodynamic forces and moments for a hypersonic glider under body axes systemis shown in Fig. 1. *Vx*, *Vy* and *Vz* represent flow field velocities in the *x*, *y* and *z* direction, respectively.

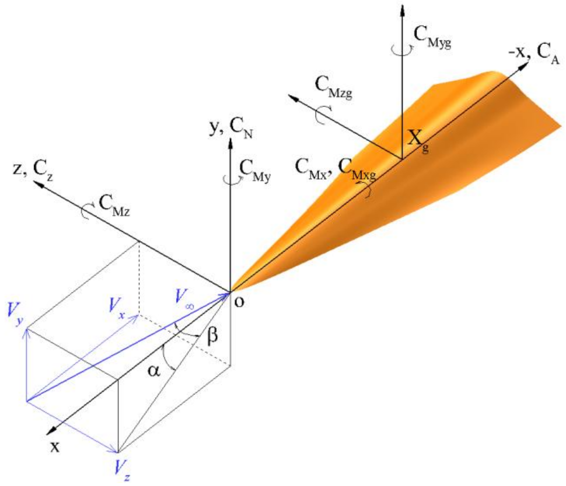

Fig. 1: Definition of aerodynamic forces and moments for a hypersonic glider underbody axes system.

Key conditions for longitudinally static stable at trimmed angle of attack α_T are:

$$C_{Mzg}\Big|_{\alpha=\alpha_T}=0,\qquad C_{Mzg}^{\alpha}<0$$

or,

$$X_g=X_{cp}\Big|_{\alpha=\alpha_T},\qquad X_{cp}^{\alpha}>0$$

2.2 Longitudinal stability criterion

Fig. 2 shows the geometricfeature of a simplified hypersonic glider model.The aerodynamic forces and moments of the leeward surface are neglected under hypersonic flight condition. The windward surface simplified as two plane with different shape and incline angle (θ_1 and θ_2). The aerodynamic forces and moments of the windward surface are calculated using the Newton law.

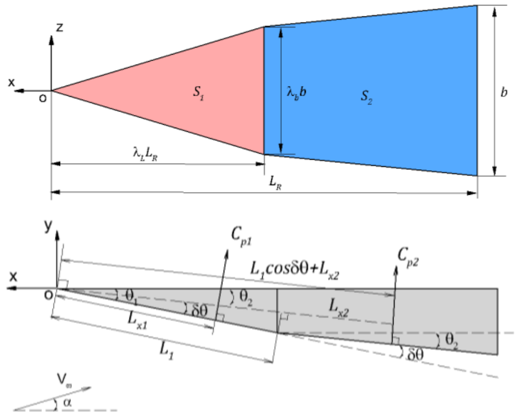

Fig. 2: Geometry of simplified hypersonic glider model.

Longitudinal stability criterion can be derived as follows:

- Longitudinal unstable: $\delta\theta<0$, or $\theta>\theta_c$
- Longitudinal neutral stable: $\delta\theta=0$, or $\delta\theta=\theta_c$
- Longitudinal unstable: $0<\delta\theta<\theta_c$

where,

$$\theta_c=\cos^{-1}\left(\sqrt{\frac{\lambda_2^2}{4}+\lambda_1}-\frac{\lambda_2}{2}\right),\ \lambda_1=\frac{L_{x1}}{L_1},\ \lambda_2=\frac{L_{x2}}{L_1}$$

2.3 Correlation between geometric parameters and longitudinal stabilities

For the simplified hypersonic glider model,the variations of the longitudinal static stable margin, X_F-X_{cp}, with deflection angle, $\delta\theta$, under different conditions are shown in Fig. 3.

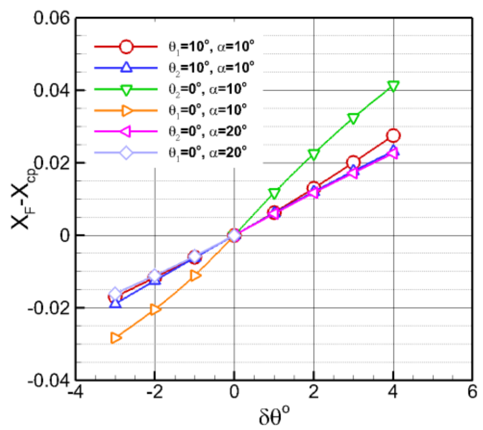

Fig. 3:Variation of static stable margin with $\delta\theta$.

The variations of the longitudinal static stable margin, X_F-X_{cp}, and center of pressure,X_{cp}, with front body width ratio, λ_b, under different angle of attack are shown inFig. 4.

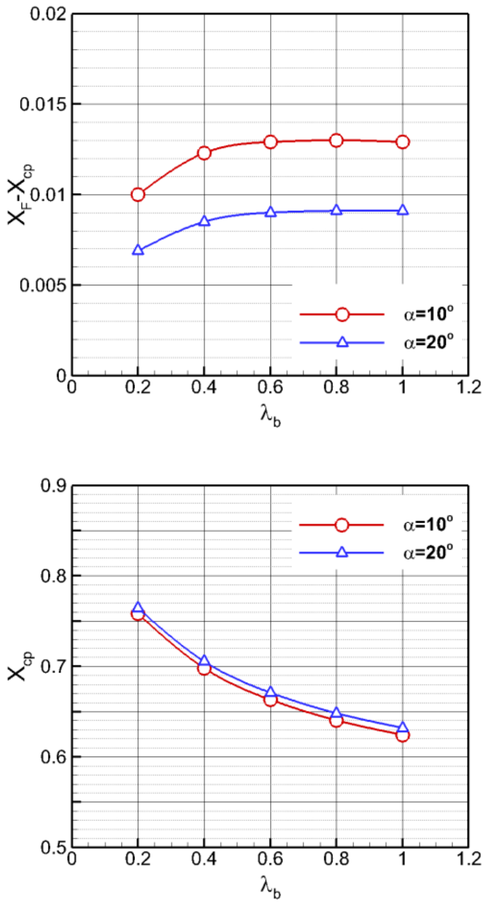

Fig. 4:Variation of static stable margin and center of pressure with λ_b.

The variations of the longitudinal static stable margin, X_F-X_{cp}, with front body length ratio, λ_L, under different angle of attack are shown in Fig. 5.

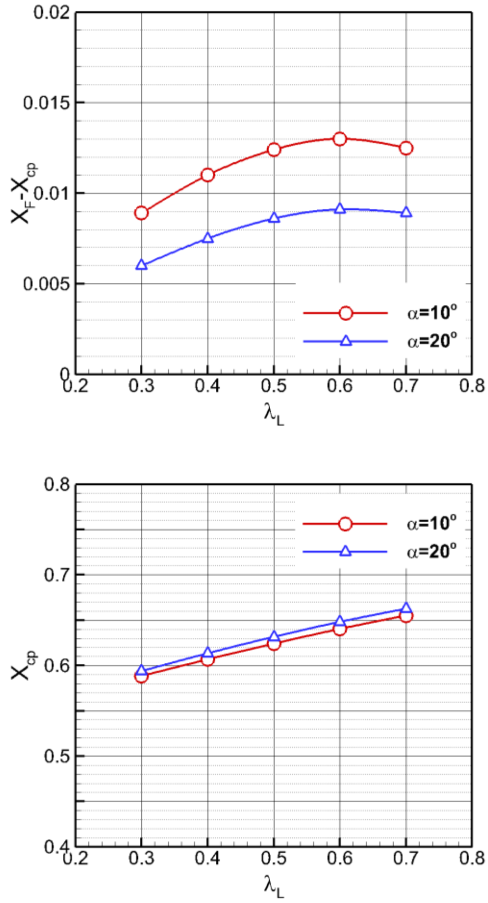

Fig. 5:Variation of static stable margin and center of pressure with λ_L.

3 LONGITUDINAL STABLE WAVERIDER DESIGN

3.1 Waverider design method

Most commonly,a waverider is defined as an aerodynamic configuration that is inversely created from aprescribed hypersonic flow field based on a planar or conical shock wave. As a result, the design space of waverider configurations is greatly restricted based on these traditional design methods.To expand the waverider design space, we developed a new waverider design methodology based on shock-fitting numerical simulation technique. Using this technique, 3D shock wave generated from various types of configurations can be obtained with high accuracy.Many computations of flows with shocks are designed to have the shock waves appear naturally within the computational space as a direct result of the overall flow-field solution, without any special treatment to take care of the shocks themselves. Such approaches are called shock-capturing methods. This is contrast to the alternate approach, where shock waves are explicitly introduced into the flow-field solution, the exact Rankine-Hugoniot relations for changes across a shock are used to relate the flow immediately ahead of and behind the shock. This approach is called the shock-fitting method. These two different approaches are illustrated in Fig. 6.

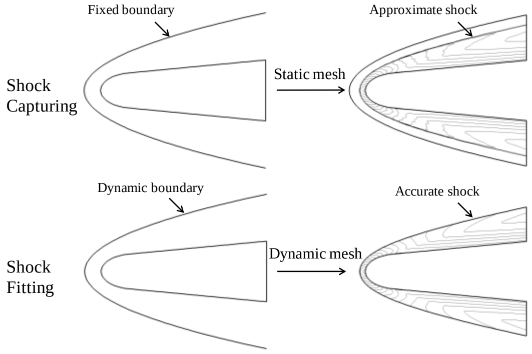

Fig. 6: Comparison between shock-capturing method and shock-fitting method.

The disadvantage of the shock-capturing method is that the shocks are generally smeared over a finite number of grid points in the computational mesh, and hence the precise location of the shock discontinuity is uncertain within a few mesh sizes. In contrast, the advantage of the shock-fitting method is that the shock is always treated as a discontinuity, and its location is well-defined numerically. This advantage of the shock-fitting approach makes it an ideal method to numerically obtain the shock waves generated by arbitrary configurations.

The configuration that is used to generate shock wave and hypersonic flow field for waverider design is called the Shock Generating Body (SGB). The shock wave or expansion wave generated from the aft-body of double-cone of a SGB can effectively alter the distribution characteristics of the SGB flow field velocity along longitudinal direction. Waverider configurations with different type of longitudinal feature can be design using these SGB flow field features.

As an example, consider three axisymmetric SGB configurations: a 8.5 °sharp cone A04, a double-cone with contracted aft-body A01, and a double-cone with expanded aft-body A02, as shown in Fig. 7.From these shock wave flow field, waveriders with different types of longitudinal profile can be generated. Fig. 8 shows three waverider configurations, i.e., W-A04, W-A01, and W-A02, created from the flow field correlated to SGB A04, A01, and A02, respectively.

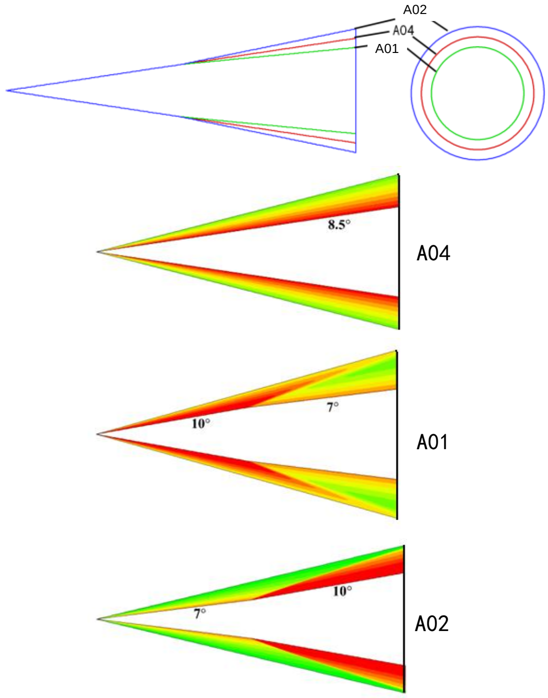

Fig. 7: Three SGBs with different longitudinal profile.

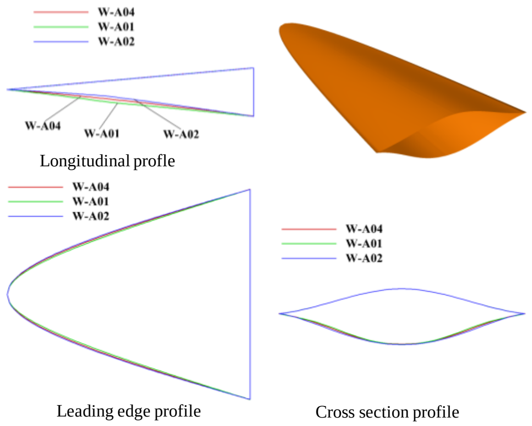

Fig. 8: Three waveriderscreated fromA04, A01, and A02.

3.2 SGB design and basic flow field calculation

In order to generate a shock wave flow field for longitudinal stable waverider design, streamlines with positive deflection angle, i.e. $\delta\theta>0$, are needed. Fig. 9 shows the SGB configuration used for shock wave flow field generation.The SGB is a double elliptic cone. The half-cone angles are 3.2 °and1.6 °. The ratio of long-axis to short-axis of the ellipse is 2.5.

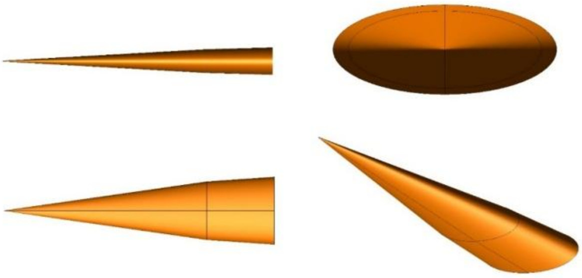

Fig. 9: SGB configuration for longitudinal stable waverider design.

The shock wave flow field generated from the SGB at the waverider design condition (Ma=15, α=10 °) is calculated using the shock-fitting method. Fig. 10 shows the calculatedshock wave flow field characteristics.

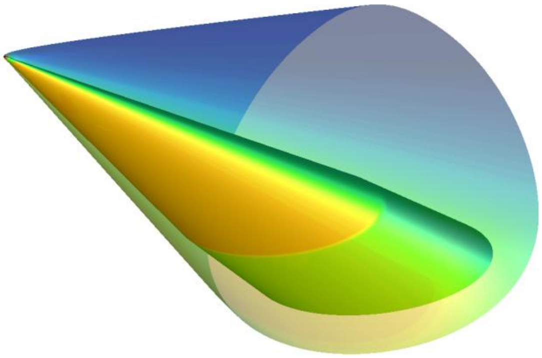

Fig. 10: Calculated shock wave flow field using shock-fitting method.

The double-cone characteristics of the SGB create deflection characteristics for the streamlines in the shock wave flow field. To illustrate this deflection characteristics, streamlines at the symmetry plane of the shock wave flow field are shown in Fig. 11. The figure is scaled 5 times in y direction in order to evidently show the deflection characteristics.

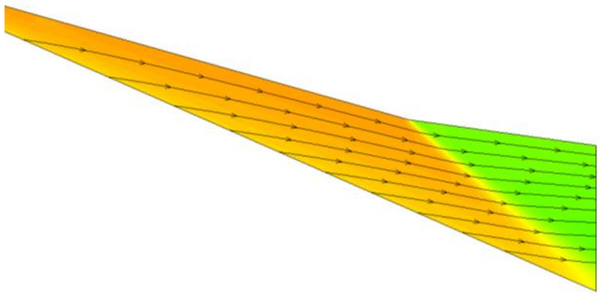

Fig. 11: Deflection characteristics of streamlines at symmetry plane of the shock wave flow field.

3.3 Waverider generation

With given exit curve, windward surface of the waverider can be generated through inverse streamline tracing, as shown in Fig. 12. Leeward surface of the waverider can be generated by free stream tracing or modified with respect to specific design requirements.

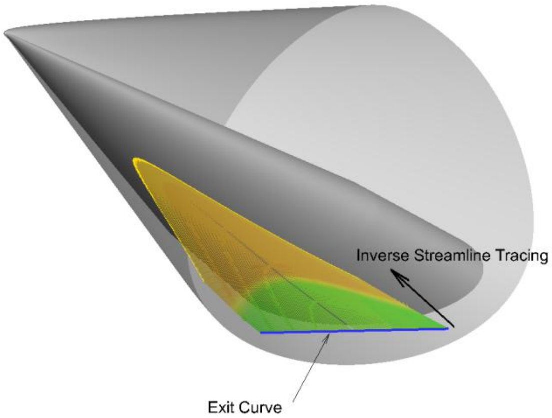

Fig. 12:Windward surface generation through streamline tracing for waverider design.

The geometric characteristicsof the generated waverider windward surface are shown in Fig. 13. It should be noted that the side view, upper part of the figure, of the surface is scaled in y direction to make the positive deflection characteristic more obvious. The actual values of the θ_1, θ_2, and $\delta\theta$ are also shown in the figure.The top view ofthe surface is shown in the lower part of the figure. This configuration can be approximated by the simplified model discussed above. From the longitudinal stability design criteria, this waverider should be longitudinally stable and has a static stable margin at around 0.01.

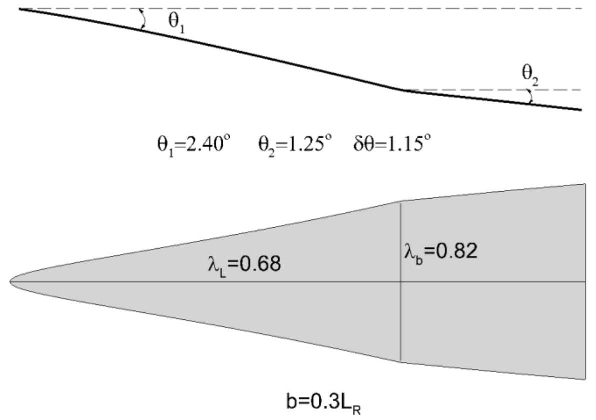

Fig. 13:Waverider windward surface geometry characteristics.

Longitudinal stability characteristics of the waverider are calculated using four approaches, i.e., the simplified model method, Newton law, Euler equations and N-S equations. The computation results are shown in Fig. 14. It can be seen from the figure that the waverider is longitudinal stable over the calculated angle of attack range from 5 °~30 °, as expected from the longitudinal design criteria. The static stable margin values predicted by the four methods are all around 0.01 at the waverider design point (10 °angle of attack).The pitching moment coefficient predicted by the four methods are close. The values of the pressure center coefficient predicted by two CFD methods are almost the same (except 5 °angle of attack). These results indicate that the longitudinal stability design criteria developed from simplified model are valid and useful for waverider longitudinal stability design. The waverider design method using shock-fitting technique is effective in designing a longitudinal stable waverider.With 0.01 static stable margin and center of pressure around 0.60~0.61 at 10 °angle of attack, the longitudinal stability characteristics of this waverider are preferable for a hypersonic vehicle design.

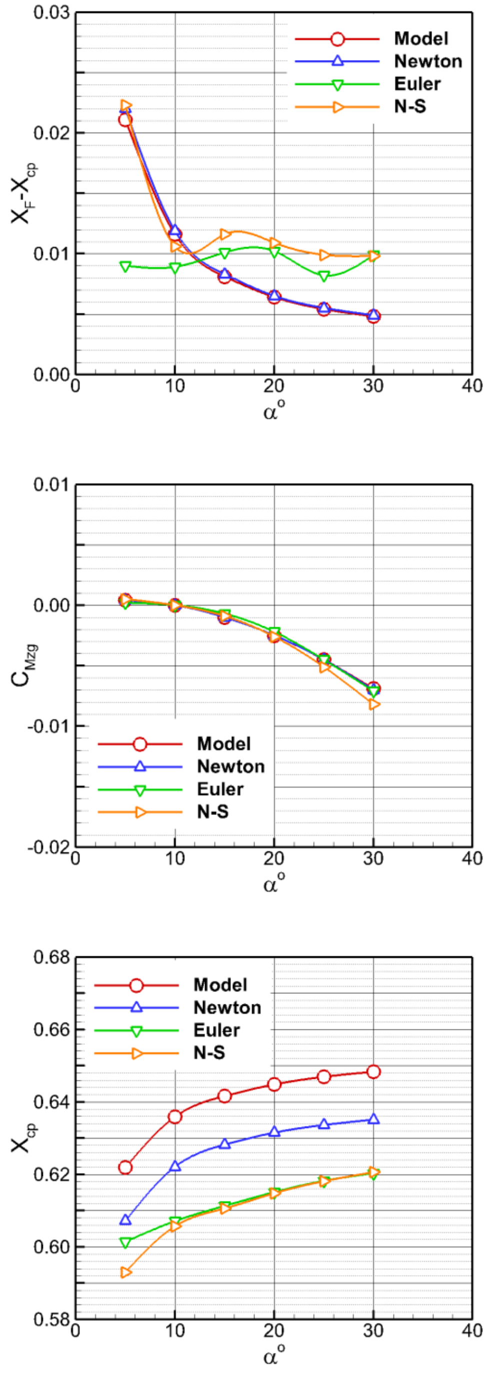

Fig. 14:Longitudinal stability characteristics of the waverider.

Fig. 15 shows the inviscid CFD simulation of the waverider flow field at design condition (Ma=15, α=10 °). The “shock wave riding” of the waverider can be clearly seen from the figure.

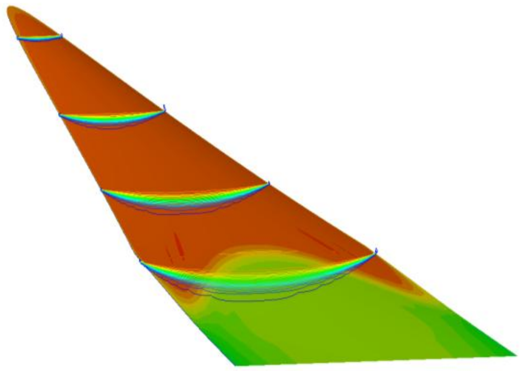

Fig. 15:CFD simulation of the waverider flow field at design condition.

4 SUMMARIES

Longitudinal stability criterion is derived based on a simplified hypersonic glider model and the Newton theory. Critical geometric parameter determining the longitudinal stability of the glider is identified from the criterion. Qualitative and quantitative correlation between the geometric parameter and the longitudinal stability is analyzed using a series of simplified hypersonic glider examples. The analysis results are verified using a CFD method for the simplified glider models. Then the longitudinal design criteria are applied to design a longitudinal stable self-trimmed waverider. In order to meet the criteria, the waverider is generated using a new waverider design method with shock-fitting technique. With this new method, the design space of a waverider is extended to general 3D flow field with shock wave. By choosing an appropriate Shock Generating Body configuration, a waverider configuration with negative cambered windward profile is created. The CFD simulation results show that the waverider is longitudinally stable self-trimmed at the designed angle of attack, as the longitudinal design criteria expects.

These results indicate that the longitudinal stability design criteria developed from simplified model are valid and useful for waverider longitudinal stability design. The waverider design method using shock-fitting technique is effective in designing a longitudinal stable waverider.

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