An Engineering Method for Computing the Aerodynamics Performance of Hypersonic Vehicle

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Abstract: For fast and automatic calculation of aerodynamic in conceptual design of hypersonic vehicles, an aerodynamic fast calculation program based on C/C++ is compiled in this paper. In this paper, the HL-20 lift body and the double radial ball model are selected for the example verification, and the calculation results are compared with the wind tunnel experimental data, it is shown the calculation results is highly consistent with the experiment. The program not only can accurately predict the aerodynamic characteristics of hypersonic vehicles, but also be linked to the optimization program as a C++ library file to realize the shape optimization design.

1. Introduction
Near space hypersonic vehicle has the advantages of fast speed, moderate height, fast military response and strong penetration resistance. It has attracted the attention of major powers in the world and become the research frontier in aerospace field. Different from traditional supersonic and subsonic vehicles, the aerodynamic shape design of hypersonic vehicles is highly integrated. The aerodynamic shape designed during the conceptual design phase largely determines the aerodynamic performance of the hypersonic vehicle. Therefore, to obtain a suitable aerodynamic shape, large number of aerodynamic performance calculations are required, but the conventional CFD calculation method and wind experiments are inefficient in the conceptual design stage. Comprehensive considerations, engineering estimates are more suitable for this stage. Many scholars concentrated on the aerodynamic engineering calculation of hypersonic vehicle and put forward many engineering estimation methods, such as Newton formula, Dahlem-Buck formula, tangent cone formula, expansion wave [1-4] formula and so on. Based on the above estimation formula, we can use the panel method to implement the aerodynamic estimation program for a hypersonic vehicle. In order to realize the fast calculation of aerodynamics of aerodynamic in conceptual design and optimization design of hypersonic vehicles, an aerodynamic fast calculation program based on C/C++ is compiled in this paper. The program can quickly and accurately predict the aerodynamics of hypersonic vehicles, and the results can be visualized in Tecplot.

2. Program Framework of Aerodynamic Engineering Calculation for Hypersonic Vehicle
The aerodynamic engineering program of hypersonic vehicle consists of four parts: grid reading, grid correction, aerodynamic calculation and result output.
2.1 Read the mesh model data

The STL triangle mesh generated directly by preprocessing software. In the modeling ontology coordinate system, each triangle element is represented by three vertex coordinates one normal vector, which are $\text{A} (X_A, Y_A, Z_A), \text{B} (X_B, Y_B, Z_B), \text{C} (X_C, Y_C, Z_C)$ and $\mathbf{N}$. Taking $\text{A}$ as the starting point and ending with $\text{B}$ and $\text{C}$ respectively, two vectors can be obtained as $\mathbf{T}_1$ and $\mathbf{T}_2$.

$$\mathbf{N} = \mathbf{T}_1 \times \mathbf{T}_2$$  \hspace{1cm} (1)

By cross multiplication of vectors $\mathbf{T}_1$ and $\mathbf{T}_2$, the normal vector $\mathbf{N}$ of the plane element can be obtained. The data of each element is stored in a structure, and the structure is managed by using an alternating number tree (ADT) to realize fast storage and management of each element.

2.2 Correct the vector direction of the element

The normal vectors $\mathbf{N}$ calculated during the grid reading process are not all pointing to the outside of the model. But the calculation of the impact angle requires that the vector $\mathbf{N}$ be directed outside the model. Therefore, it is necessary to check and correct the normal vector of each plane element, which is an important prerequisite to improve the calculation accuracy. In reference [5], a fast method of modifying the vector outside the grid is presented. The ray casting algorithm is used to modify the normal vector of each plane element quickly and accurately.

2.3 Calculation of impact angle

By solving the geometric relationship of the velocity vector in the plane coordinate system, the impact angle $\delta$ between the free flow and the aircraft surface can be calculated. The calculation formula of impact angle $\delta$ is as follows:

$$\delta = \frac{\pi}{2} - \cos^{-1}\left(\frac{-N \mathbf{V}}{|N| |\mathbf{V}|}\right)$$  \hspace{1cm} (2)

The value range of $\delta$ is $-\frac{\pi}{2}$ to $\frac{\pi}{2}$.

According to the impact angle $\delta$, the flow field of the panel element can be divided into windward ($\delta > 0$) or leeward ($\delta < 0$). For these two cases, different calculation formulas are used to calculate the surface pressure coefficient.

2.4 Calculation formula of pressure coefficient

In this procedure, the calculation of the windward side is the Schaaf and Chambre formula of M. C. Fadgyas [6], and the pressure coefficient of the leeward side is calculated using the ACM empirical formula [7]. The calculation formula is as follows:

2.4.1 Schaaf and Chambre formula

$$C_p = \frac{1}{\pi^2} \left[ \frac{\left(2 - \sigma_N \sin(\theta) \right) + \left(2 \sigma_T \sin(\theta) \right)}{\sqrt{\pi} \sqrt{T}} e^{-\frac{(s \sin(\theta))^2}{2}} \right]$$  \hspace{1cm} (3)

$$C_r = \frac{\sigma_T \cos \theta}{\sqrt{s \pi}} \left[ e^{-\left(s \sin(\theta)^2 \right)} + \sqrt{\pi} \frac{s}{\sin(\theta)} \left[1 + \textnormal{erf}(s \sin(\theta))\right]\right]$$  \hspace{1cm} (4)

$$s = \frac{\sqrt{2RT}}{\sqrt{\bar{V}}}$$  \hspace{1cm} (5)

where $\sigma_N$ and $\sigma_T$ are normal and tangential momentum accommodation coefficients. Specular reflection simplifies to $\sigma_N = \sigma_T = 0$ while the diffusive reflection $\sigma_N = \sigma_T = 1$.

2.4.2 ACM empirical formula

$$C_p = \max \left[ -\frac{(\delta - 15)}{15} \left(1/Ma^2\right), - \left(1/Ma^2\right) \right]$$  \hspace{1cm} (6)

The pressure coefficient of each panel is calculated by the above equation, and the $C_p$ of the calculation result is stored in each structure.
2.5 Aerodynamic coefficient calculation and result output

According to the impact angle $\delta$ and free flow conditions, the aerodynamic parameters can be calculated:

$$C_L = - \sum C_p n_x \Delta A / S_{ref} \sin \alpha + C_z \cos \alpha$$

$$C_D = \sum C_p n_x \Delta A / S_{ref} \cos \alpha + \sum C_p n_z \Delta A / S_{ref} \sin \alpha \cos \beta$$

$$C_m = \left[ \sum C_p (x - x_{CG}) n_z \Delta A - \sum C_p (x - x_{CG}) n_z \Delta A \right] / \left( S_{ref} b_{ref} \right)$$

Where $b_{ref}$ is the characteristic length of the aircraft, $x_{CG}$ is the position of the center of gravity, $\Delta A$ is the element area and $S_{ref}$ is the reference area.

The output of the calculation result is divided into two parts: the output of the aerodynamic calculation result and the DAT file output for post processing.

3. Program Verification

In order to verify the accuracy of the calculation program, the following two models are selected to verify the calculation program: the high lift body (HL20) model designed by NASA Langley center [7] and the double ellipsoid model [8] for hypersonic atmospheric reentry.

3.1 Verification of HL-20 example

The HL-20 lift body model is derived from the laser-based HL-20 model provided by NASA. The geometric model file output by OpenVSP is shown in Figure 1. The model is imported into the pre-processing software to generate the STL grid file as shown in Figure 2:

In this paper, we choose the experiment of Mach 6 to verify the program. The Surface pressure coefficient distribution map of HL-20 is shown in Figure 3. And the calculation results are compared with the wind tunnel test data, as shown in Figure 4.

Figure 3 shows the surface pressure coefficient distribution of HL-20 lift body model at 30 ° angle of attack, which is consistent with the pressure distribution at high angle of attack. It can be seen from the figure that the results obtained by the calculation program are basically consistent with the basic change trend of the experimental data of the wind tunnel, and the values are also basically consistent, with the maximum error within 10%. The accuracy of the program is verified, which can meet the accuracy requirements of the preliminary aerodynamic shape optimization design stage of the hypersonic vehicle. Compare the results of the modified Newton formula and the Prand-Meyer expansion wave formula under the same conditions in the literature[5], as shown in Figure 5. The comparison shows that the
calculation results in this paper are in good agreement with the wind tunnel experimental data. This also shows that the evolving estimation method provides an improvement in the accuracy of the aerodynamic estimation of hypersonic vehicles, which greatly improves the reliability of the calculation results.

3.2 Verification of Double ellipsoid model example

The double ellipsoid case is one of the standard cases to study hypersonic vehicle, which has a lot of wind tunnel experimental data. Its geometric model can be accurately constructed by formula. We choose this model to verify the accuracy of the calculation of the surface pressure coefficient $C_p$. The geometry diagram of the double ellipsoid model [8] is shown in Figure 6. The modelling of the completed double ellipsoid model is shown in Figure 7:

The shape of the double ellipsoid model can be modelled by the following formula:

\[
\text{Horizontal ellipsoid } \quad \left( \frac{x}{157.9} \right)^2 + \left( \frac{y}{39.47} \right)^2 + \left( \frac{z}{65.79} \right)^2 = 1 \quad (10)
\]

\[
\text{Vertical ellipsoid } \quad \left( \frac{x}{92.11} \right)^2 + \left( \frac{y}{65.79} \right)^2 + \left( \frac{z}{46.05} \right)^2 = 1 \quad (11)
\]

\[
\text{Upper half cylinder } \quad \left( \frac{y}{39.47} \right)^2 + \left( \frac{z}{65.79} \right)^2 = 1 \quad (12)
\]

\[
\text{Lower half cylinder } \quad \left( \frac{y}{65.79} \right)^2 + \left( \frac{z}{46.05} \right)^2 = 1 \quad (13)
\]

In this paper, we select the experimental data of the surface pressure distribution of the double ellipsoid (cannon wind tunnel) for comparison. The free-flow Mach number is 7.79 Ma, the Reynolds number per unit length is $1.04 \times 10^7$/m, the angle between the airflow and the long axis of the double ellipsoid is $0^\circ$. Compare the distribution of surface pressure coefficients on the center line. The comparison of wind tunnel test data of calculation results is shown in Figure 8 and Figure 9:

![Figure 8. comparison of partial pressure coefficient of the upper surface of the center line](image1)

![Figure 9. comparison of partial pressure coefficient of the lower surface of the center line](image2)
Figures 8 and 9 show a comparison between the wind tunnel experimental data and the calculation results of the program. Figure 10 shows the surface pressure coefficient distribution of the double ellipsoid model at an angle of attack of 0°. The calculation data in Figs. 8 and 9 is extracted by the post-processing software in the program-generated DAT file. It can be seen from the comparison chart that the calculation results of the pressure coefficient of the lower surface are in good agreement with the experiment. On the upper surface, the calculation results are basically consistent with the experimental data, and the numerical values are basically the same, but there are some deviations in the -80mm to -50mm part. Comparing Figure 8 and Figure 9, the range of -80mm to -50mm belongs to the intersection of the upper ellipsoid and the lower ellipsoid. In this range, the pressure coefficient changes greatly with the change of the x position, and there are some differences between the position of the experiment and the position of the calculated result, which leads to the deviations. In general, the accuracy of the calculation of the surface pressure coefficient $C_p$ fully meets the engineering calculation requirements.

4. Conclusion

Two examples of HL-20 and double ellipsoid model are calculated, and the results are compared with the experimental data of wind tunnel. The following conclusions can be drawn:

1. The program designed in this paper can quickly and accurately estimate the aerodynamic force of hypersonic vehicle. And the results can be visualized in the post-processing software Tecplot.
2. Compared with the experimental data and other literature results, the estimation formula used in this paper (the combination of Schaaf and Chambre formula and ACM empirical formula) has higher calculation accuracy, which can fully meet the accuracy requirements of engineering calculation.

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