Computer Simulation of Infrared Characteristics of Hypersonic Vehicle X43A

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Abstract. The simulation of aircraft infrared physical field mainly focuses on the changes of infrared characteristics during the flight process, which is also an important component of flight simulation. It plays a significant role in improving the operational capability of aircraft as a reliable verification method of infrared resistance performance. In this paper, we mainly focused on the generation and transformation process of flow field data in the infrared simulation process, and we realized the rendering of X43A infrared characteristics under standard sparse grid based on heterogeneous mapping method.

1. Introduction

Infrared simulations have typically high efficiency and cost-effectiveness[1], and are able to render infrared scene under different environments and meteorological conditions. Infrared simulation tools can be extensively applied in military and civilian fields such as equipment development and training. The simulation of infrared physical field involves both target simulation and background simulation. The former refers to objects of interest in the simulation scene, such as vehicles, ships, and buildings; the latter includes the infrared background fields, such as oceans and terrains. Aircraft is treated as exceedingly typical target simulation object, whose infrared antagonism performance plays an important role in overall design.

The research on infrared simulation technology of aircraft has been widely developed along with the improvement of computing power. Yanzhi Li[2] established a theoretical calculation model for infrared radiation intensity of an aircraft based on theory of infrared radiation correlation. Dong Wang[3] demonstrated the infrared radiation luminance attenuation model for sky background. Liang Zhang[4] modeled the aircraft infrared radiation model and atmospheric transmittance calculation model, and verified the model by the simulation test. These research improve the accuracy of the infrared simulation of aircraft, and increase the scope of application of infrared simulation.

For the solution of infrared characteristics, the method of CFD (Computational Fluid Dynamics) is extensively applied. X Gu[5] proposed an automated CFD-based analysis process for applications at the early aircraft development stages. Y Xie[6] introduces the application of high performance parallel computing in CFD numerical simulation. The method of generation of Tetrahedral Layer for Off-Body Pressure Calculation For CFD-based sonic boom analysis was proposed by AIAA[7]. These researches improved the reliability of simulation in the field of modeling, mesh generation.
During the CFD process, dense mesh is needed for finite element solution. In order to ensure the correctness of the solution, the mesh is often too dense for iteration and rendering. During the infrared simulation of aircraft, a mass of infrared field data will be generated in these massive meshes which is not necessary for rendering and hinder the effective use of data significantly. We presented the method of heterogeneous mapping from dense mesh to sparse mesh to promote the using of flow data getting from CFD process.

In this paper, we use the hypersonic vehicle X43A as a research model and study the distribution of infrared data on the surface of the aircraft at 7 Mach and 30000 meters. Through grid alignment and heterogeneous interpolation algorithm, the dense polygon mesh flow field data generated by CFD was transformed into sparse standardized triangular mesh number flow field data. The distribution of infrared characteristics was calculated and rendered based on infrared radiation model. The real-time simulation of hypersonic aircraft flight is a difficult problem in the current research field, and multi-modal real-time interpolation based on the standard grid flow field data set is a reliable solution[8]. The contribution of this paper is to propose how to map the CFD flow field data to the standard sparse grid through the method of heterogeneous interpolation, reduce the redundant data without reducing the accuracy of the data, and provide support for building the multi-case flow field data set.

The remainder of the paper is organized as follows: In Section 2, we mainly explain the preparation process of the flow field data and the corresponding engineering method. In Section 3, we introduced the implementation of flow field data processing functions, including reading and writing of geometry and flow field data, heterogeneous interpolation algorithm and solving infrared characteristics of sparse mesh surface. In Section 4, the rendering effect of the interpolated data is demonstrated.

2. Data preparation

According to the basic idea of "geometric structure determines physical properties", geometric data is the basic data of modeling while the infrared data are attached to geometric data points or geometric surfaces. The distribution of geometric structure and the form of geometric structure determine the data structure of infrared physical field during simulation. For the subject of simulation, geometric structure is generally divided into two types: structured geometry and unstructured geometry. The interior points of the former all have the same number of adjacent units, while the latter has different adjacent units by different interior points. The time consumption in artificial design grows rapidly when structure becomes complex. As for the complex aircraft shape, the unstructured mesh is usually used to describe the surface of aircraft, which is conducive to mesh adaptation and control of mesh density.

The unstructured mesh usually consists of triangulation or polygon to describe the structure. Compared to triangulation, the using of polygon format reduces the mesh number while maintaining mesh quality. The comparison of quantity and quality of meshes of X43A is shown in figure 1, the quality referred to is on the standard of skewness[9]. The use of the polygon mesh reduces the skewness coefficient of the mesh and the amount of mesh data, which means it is able to express more accurate aircraft structures with less data volume (see table 1). However, the triangulation is the most widely used format in CAD, mesh generation, post-processing and so on. In comparison, the triangulation format is comparatively easy to evaluate, express and adjust. So we selected the polygon mesh in the calculation phase and prepared a sparse triangular mesh for rendering infrared characteristics.

| NAME      | NUMBER OF MESHES | DEVIATION DEGREE |
|-----------|------------------|------------------|
| POLYGON   | 391910           | 0.874            |
| TRIANGLE  | 1852665          | 0.996            |

In this paper, we considered the disparity between the dense mesh used in CFD process and the common triangular mesh. For the simulation of infrared field of aircraft, the dense mesh for calculating flow field and sparse mesh for rendering were both adopted. The data mapping between these meshes
whose structure, density and spatial relationship differ from one another was realized by heterogeneous interpolation (see Section 3).

And the distribution of dense polygon meshes is shown in figure 1:

![Figure 1. The distribution of meshes](image)

(a) head  (b) engine  (c) tail

It is seen from the figure 1 that the mesh distribution is uniform in flat and subtler deformation area and dense in connection of different structures (wings, fuselage, engine, etc.) This is due to the high precision demand for flow field calculation. Infrared radiation characteristics are closely related to temperature, material properties, and atmospheric propagation. In this paper, we consider the simulation of zero-line-range infrared physics distribution of X43A hypersonic vehicle under single working condition. Therefore, the temperature field distribution after CFD solution is an important data foundation. We obtain the temperature distribution by CFD solution for the dense polygon mesh mentioned above (see figure 2).

![Figure 2. The distribution of temperature](image)

After the CFD process, we can get the distribution of temperature in the dense polygon mesh. Then, we obtained the infrared characteristics by some important methods mentioned in Section 3.

3. Data processing

3.1 Interpolation processing

The fineness of the meshes directly determines the accuracy of the flow field calculation. Generally, the meshes used for solving the flow field are relatively fine and dense. By the application of polygon format, the meshes has a significant decline in quantity, but it still has the local overcrowding problem. In this paper, X43A’s dense polygon meshes are generated based on sparse triangle meshes, and have approximately the same geometric features. So we can map dense mesh data to the sparse mesh for later
calling and rendering. After the implementing mesh data mapping, the distribution of infrared characteristic should be generated based on infrared calculation model. The entire data processing, including flow field data extraction, formatting and heterogeneous mapping, which is able to construct the spatial distribution of objects under the various parameter dimensions. In this paper, the temperature field with the highest correlation with infrared characteristics is selected as the research physics field and the work flow is shown in figure 3.

![Diagram](image)

Figure 3. The distribution of temperature

The flow field data is stored in the format of CFD-POST, which stores coordinates and various flow field data according to the distribution of each point (see figure 4a). The STL format can express closed surfaces or bodies with triangular meshes, and is widely used in various CAD tools due to its simplicity. The detailed format of binary STL is shown in Fig .4b.

![Diagram](image)

Figure 4. The distribution of temperature

Compared to ASCII format, STL's binary format takes up less space and is more integrated. We built a data processing program to load data from binary STL file, and store it in memory based on distribution of each point. The coordinates, connected relations, flow field data on each point is loaded.

Then, interpolation algorithm is adopted to interpolating the flow data of polygonal meshes into sparse triangular meshes. Considering the need for robustness and performance, we choose the n-simplex interpolation algorithm which can be described in formula 1.

$$K_s = \omega_1 K_1 + \omega_2 K_2 + \ldots + \omega_n K_n$$

In formula 1, the $K_s$ is the data of target point, the $K_n$ is the data for the N reference point and the $\omega_n$ is the weight for the N reference. The $\omega_n$ is decided by the volume ration of simplex[10](see formula 2). The $K_n$ and $K_s$ should be chosen according to the actual demand. In this paper, the distribution of temperature is the foundation for solving the infrared characteristics of the X43A.
The n-simplex interpolation selects fewer points and reduces the number of table accesses. The method is efficient and high in robustness when applied to grid interpolation. A n-simplex is a n-dimensional polytope which is the convex hull of its k+1 vertices. For example, 2-dimensional simplex corresponds to triangle and 3-dimensional simplex corresponds to tetrahedron. The volume of an n-simplex in n-dimensional space with vertices \((v_0, v_1, ..., v_n)\) is:

\[
\frac{1}{n!} \det(v_1 - v_0, v_2 - v_0, ..., v_n - v_0)
\]

On the basis of the implementation of the interpolation algorithm, two problems of isomeric interpolation still need to be solved:

3.1.1 Mesh Alignment
In general, data mapping of heterogeneous grids is very complicated. But as mentioned above, the selected sparse grid and polygonal mesh are different descriptions of the same geometric structure (see figure 5). We applied the adjustment of size, position and angle to make dense mesh and sparse mesh roughly in the same space state. As can be seen from the figure, the blue polygon mesh is basically aligned with the black triangle mesh.

3.1.2 Confirm Reference Points
In this article, the vast majority of data is stored on a per-point basis. In the process of data mapping from dense points to sparse points, the problem of how to find the interpolation reference point is involved. We selected neighbor points from dense mesh for sparse mesh based on XYZ coordinate distance, by using the search algorithm.

Generally speaking, there are many means to implement fast approximate nearest neighbors matching: classic k-d tree, randomized k-d tree, k-means tree, hierarchical tree and so on. The FLANN method contains a collection of these basic algorithms and can choose the best algorithm automatically. Fast matching for reference point was achieved by this algorithm. The process is shown below in figure 6.

Figure 5. The distribution mesh
We used the dense points form CFD-post file to build index and the spares from STL file to build query. Then, the FLANN is adopted to choose the appropriate algorithm to implement fast approximate nearest neighbors matching. Through the above steps, we obtained the reference point necessary for interpolation.

After we solved the above two problems, we can implement the simplex volume interpolation, and got the distribution of temperature field on sparse mesh.

### 3.2 Surface infrared
Infrared radiation is the thermal radiation in the infrared band. When infrared radiation is propagated in the atmosphere, the radiation of some wavelengths gradually attenuates in the course of transmission due to the absorption and scattering of gases, vapor, solid particles and dust in the atmosphere. The infrared transmittance of three bands is dominant: $1\sim3\mu m$, $3\sim5\mu m$ and $8\sim14\mu m$. Infrared detection generally works in the atmosphere window of these three bands.

During the flight of hypersonic vehicle, aerodynamic heating is the main cause of infrared radiation. In cruising state, the wall boundary of the aircraft reaches the equilibrium temperature, that means the heat transfer vanishes.

According to the reference[11], the infrared calculation formula for the surface of the aircraft is as follows:

At the $8\sim14\mu m$ infrared detection band, the formula is shown below:

$$I_{sclp}(\varepsilon_{s}, T_{w}) = \frac{E}{\pi} \left( f(\lambda_{2}T_{w}) - f(\lambda_{1}T_{w}) \right) \cdot \sigma T_{w}^{4}$$  \hspace{1cm} (3)

The $f(\lambda T)$ represent the black radiation function, which represents the percentage of the blackbody radiation energy from the wavelength to the total radiation force of the blackbody. The infrared radiation of this band is remarkable, and we took this band as the main concern.

### 4. Rendering Results
After the data parsing process in step 3, the distribution of infrared data under the standard sparse mesh is obtained. The compare of distribution of infrared data under dense mesh and sparse mesh is shown in figure 6.
Figure 7. Infrared data under dense mesh and sparse mesh

figure 7(a) is the dense polygon-format mesh, figure 7(b) is the flow field data obtained from CFD calculation. figure 7(c) is the target sparse mesh, figure 7(d) is the data distribution obtained by interpolation. The dense meshes mentioned are composed of 390 thousand polygons, while the sparse meshes are composed of 52728 triangles.

The dense meshes are designed to meet the needs in CFD calculations and actually contain a large amount of duplicate information. Under the premise of ensuring that the grid can accurately express the geometric information, a standardized sparse grid structure is generated based on the same geometry as the dense grid, and the flow field data is heterogeneously mapped to the sparse grid by interpolation algorithm. The data rejection process is implemented.

This article uses a cross-validation method to verify the accuracy of the interpolation method: First, we assume that the data for each measurement point is unknown, and use the value of the surrounding samples to make an estimate. Then calculate the error between the actual observation and the interpolation. The average relative error is 9.8% and the data distribution before and after interpolation is shown in the figure 8.
5. Conclusions
A simulation process of the infrared characteristics of X43A was presented that integrated data loading, data processing and rendering. We realized the interpolation from dense polygon mesh to sparse triangle mesh by n-simplex interpolation. We also reorganized coordinate and flow data, then output it to realize the rendering process. We manage a significant decline in quantity, but still guaranteed the rendering effect.

For future work, we will consider the use of new technical means such as Ť spline to redraw the geometry of the aircraft, reducing the over-tight mesh of the edge areas such as the wing, leading edge and other parts.

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