Design and Realization of Numerical Simulation System for Aero-Optical Effects

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ABSTRACT

In order to study the influence of aero-optical effects on the detection system of hypersonic vehicles, a set of numerical simulation system is developed for simulating the whole process of aero-optical effects. With the design scheme of “system platform plus simulation function module plus data storage”, the development work for the platform and function modules are accomplished in Qt5 development environment. Users can create simulation tasks and complete simulations according to their needs. The system has good scalability and supports users to develop new functional modules according to the interface specifications. The simulation results of this system can provide theoretical basis for theoretical research and engineering application of aero-optical effects.

KEYWORDS
Aero-Optical Effect, Numerical Simulation, Software Development, Scalability.

INTRODUCTION

When vehicles with an imaging guidance system fly at a hypersonic speed in the atmosphere, the severe friction between the optical window and the atmosphere results in a large amount of kinetic energy being converted into heat energy, and producing a complex turbulent flow field between optical window and the incoming flow. This will lead to changes in air temperature, density, component, and even gas molecular ionization, which can interfere with optical imaging detection systems and signal transmission, causing distortion, offset, jitter, and blurring of the target image. This effect is called aero-optical effect, which is a problem that must be solved in the optical imaging of hypersonic vehicles. The schematic diagram of aero-optical effects is shown in Figure 1.
At present, there are a large number of researches on aero-optical effects, including numerical simulation algorithms\(^1\), wind tunnel tests and verification\(^2,3\), fluid-solid coupling analysis algorithms\(^4,5\) and so on. Based on the existing research foundation, the simulation of aero-optical effects has been developed in the engineering direction. For example, the AOQ Code and the DNAOS aero-optical effect simulation software developed by the US HIPEC Evaluation Center can be used for simulation analysis and detection performance prediction\(^6\).

The related research on aero-optical effects involves aerodynamic optical transmission effects, aerodynamic thermal radiation effects, aerodynamic thermal effects\(^7\), and degraded image correction\(^8\). However, most of the research is based on a specific effect, and there are few comprehensive simulations of all the aero-optical effects for the whole process.

Based on the current research, this paper designs and develops a numerical simulation system for aero-optical effects, which can simulate and analyze fluid-structure interaction, flow field and window aerodynamic heat radiation, aerodynamic light transmission of flow field and window, imaging simulation and evaluation, degraded image correction. The results can provide a data basis for the study of aero-optical effects.

**SYSTEM DESIGN**

**Analysis of Functional Requirements**

In order to simulate the aero-optical effect, the system is required to have the function of establishing CFD model and solving fluid-solid coupling problem. The system should also have the ability to calculate ray tracing and thermal radiation through numerical calculation results. Based on the above results, imaging simulation and degraded image correction are performed, so the system needs to have the function related to image processing.

It can be seen that the whole process simulation of aero-optical effect involves many functions and the system structure is complex. In order to facilitate the
management and operation of simulation tasks, the system adopts the mode of "system platform plus simulation function module plus data storage". The system platform is the core part, through which the simulation task is created and managed; the functional modules are developed according to requirements and unified standards, which is the execution part of the numerical simulation. The system data is stored and verified using XML documents.

According to the functions, the system is divided into five modules: modeling and fluid-structure coupling simulation module, flow field simulation module, optical window simulation module, imaging simulation and correction module, and system platform module. Each functional module is subdivided into multiple units, as shown in Figure 2.

**Design of System Framework**

Based on the requirements of function modules, the system is divided into three parts: “data storage”, “simulation parameters” and “numerical simulation”. Each part is connected through the system platform. The overall design scheme is shown in Figure 3.

The “data storage” part is based on XML document, which stores parameters information, data source setup information, function module setup information, interface connection information, file path and system configuration information. When reading the data, the system will check the XSD document to determine whether the data format meets the requirements of the system.

Users can input all simulation parameters through the “simulation parameters” part. According to the type of parameters, it mainly includes:

1. Window parameters: including the constraint parameters of the window structure and the physical parameters of the window material;
2. Hull parameters: physical properties of the hull material;
3. Flight parameters: including atmospheric model, flight speed, altitude and trajectory parameters;
4. Optical system parameters: including parameters of the optical system and detectors;
5. Target image: The result of the aero-optical effect will act on target image to obtain the simulated degradation image.
User can access the data storage file to complete the selection, modification, and deletion of historical simulation parameters, and the addition and storage of new data.

The “numerical simulation” completes the calculation process of aero-optical effect simulation. According to the order of the solution, this part is mainly divided into the following modules:

1. **Modeling**: Automatic mesh modeling based on window and parameters and shell parameters, and saved to DTF files;

2. **Fluid-solid coupling numerical simulation**: According to the corresponding parameters, the fluid-solid coupling field simulation calculation is carried out to obtain the pressure, density, temperature distribution of the flow field and the temperature distribution of the optical window;

3. **Ray tracing of the window**: Calculating the wavefront distortion of the emitted light due to the uneven refractive index segmentation according to the reticle refractive index distribution data;

4. **Calculation heat radiation of the window**: According to the temperature distribution data of the window, the heat radiation distribution of the window is obtained by solving the radiation transfer equation;

5. **Ray tracing of the flow field**: According to the gas field density distribution data of the flow field, the refractive index change is calculated, and the transmission process of the light in the flow field is simulated to obtain the wavefront distortion of the emitted light;

6. **Calculation heat radiation of the flow field**: Calculation of gas radiation based on flow field temperature distribution data and gas molecular spectral radiation theory;

7. **Imaging simulation**: Superimposing the optical transmission effect and thermal radiation effect of the flow field and the hood on the target image to obtain a simulated degraded image;

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**Figure 3. Overall design of the system.**

| Simulation parameters | Numerical simulation |
|-----------------------|----------------------|
| Window parameters     | Modeling             |
| Hull parameters       | Fluid-solid coupling numerical simulation |
| Flight parameters     | Ray tracing of the optical window |
| Optical system parameters | Ray tracing of the flow field |
| Target image          | Calculation heat radiation of the optical window |
|                       | Calculation heat radiation of the flow field |
|                       | Imaging simulation |
|                       | Image of optical transmission effect |
|                       | Image of thermal radiation effect |
|                       | Degraded image correction |
|                       | Image-quality evaluation |

| Data storage |
|--------------|
| Verification |
| Data Files   |
8. Degraded image evaluation: The degradation image is evaluated using indicators such as peak signal to noise ratio, Strehl ratio, and correlation measure;
9. Degraded image correction: The degraded images are corrected by Wiener filtering or blind deconvolution to obtain restored images.

SOFTWARE IMPLEMENTATION OF THE SYSTEM

Implementation Solution

Modeling and fluid-solid coupling simulation functions of the system are calculated by the ESI-CFD software package (including GEOM, Fastran, ACE, VIEW), while secondary development was carried out according to actual needs. Other function modules are developed independently based on Qt5. The implementation solution is as shown in Figure 4.

Figure 4. Implementation solution of the software.

Class Modeling of the System Platform

As the core part of the software, the function of system platform includes: data source management, function module management, simulation task management, task creation and execution, and system environment configuration. The whole process of numerical simulation of aero-optical effects is realized by creating and executing simulation tasks. A simulation task consists of multiple data sources, function modules, and data interface connections. The creation and execution are implemented through system platform operations.

The system platform is composed of platform, interface and user operation window. According to the requirements, the system platform class is divided into the platform foundation class, the window class and the dialog class, wherein the
platform foundation class is the core part. The design of the platform foundation class is shown in Figure 5. And the classes and their functions are shown in Table I.

**TABLE I. THE DESCRIPTION OF THE PLATFORM FOUNDATION CLASS.**

| Class name      | Class function                                  |
|-----------------|-------------------------------------------------|
| Task            | Read and store simulation tasks                 |
| TaskItem        | Read and store basic information about the tasks |
| ModuleFrame     | Handling the display, setting, etc. of modules  |
| DataSrcFrame    | Handling the display, settings, etc. of sources  |
| FuncModuleFrame | Handling the display, settings, etc. of modules  |
| Port            | Process and store interface information         |
| DataPort        | Read and store source module interface information |
| ModulePort      | Read and store function module information      |
| DataSrcItem     | Read and store definition information for sources |
| FuncModuleItem  | Read and store definition information for modules |
| Link            | Read and store information between data interfaces |
| Aoes            | Platform system class, read and store information |
| SystemInfo      | Storage system information                      |

Figure 5. Design of platform foundation class.

In addition to the platform base class, the window class includes the MainWindow class that creates the main window of the user interaction interface, the ToolBox class that generates the tool list, etc. The dialog class includes a TypeEdit class that edits data interface information, a FilePathEdit class that stores file paths, etc.
**Implementation of Functional Modules**

The function modules are developed according to specific requirements. In order to improve the usability of the software, all function modules in the system can run independently in the form of exe files and have an operating interface. User can set input parameters according to their actual demand, to complete a step-by-step simulation without the system.

Each functional module can also be embedded in the system platform through the unified interface. If the process of aero-optical effect simulation is carried out, the function modules will run in the background operation model and users can manage them through the system platform.

**Simulated Examples**

The numerical simulation system of aero-optical effect is developed by the above method. Users can create different simulation tasks according to their needs and complete sub-process simulation or whole process simulation. Firstly, choosing the data source modules and function modules according to demand, and connecting corresponding modules through the link function. After that, setting the simulation parameters and configuring the function modules or data source modules operating parameters. Once the simulation starts, the CFD model will be built automatically according to the parameters. Then the fluid-solid coupling calculation and so on will be run. Finally, the calculation results will be stored in the set path.

**Sub-process Simulation Fluid-Solid Coupling Calculation**

The classical experiment of flow around a circular tube\(^{[2]}\) is selected for simulation verification. Detailed parameters can be found in references.

The simulation value of the stagnation point temperature of the circular tube at 2s is 388.05K, which is very close to the experimental value of 388.72K, and the error is 0.17%. The simulation results show that the temperature distribution of the tube and flow field is very close to that of the wind tunnel test. The simulation result is shown in Figure 6.
Figure 6. Simulation result of flow around a circular tube.

**Whole Process Simulation of Aero-Optical Effect**

The aero-optical effects numerical simulation with flight speed of 3Ma, flight duration of 0.4s and 0 degrees of attack angle are simulated.

In the simulation process, the ray tracing calculation is carried out by calculating the refractive index changes of the flow field and the optical window. The equivalent PSF is convoluted with the target image as the effect of optical transmission on imaging system. The it is superimposed with the heat radiation results of the flow field and the optical window.

The simulation results are shown in Figure 7, which (a) is the target image, (b) is the degraded image under aero-optical effect.

Between the degraded image and the original target image, the maximum mean square error is 0.678, the peak signal-to-noise ratio (PSNR) is 10.292, and the correlation measure is 0.861. It can be seen that the aero-optical effect makes the imaging quality of the detection system decline, and the target image will be blurred and offset obviously.

In the simulation of higher flight speed and longer flight time, it is found that the effects of aero-optical effects on imaging are more severe. When flying for more than 5 Ma for a long time, the quality of the target image presented by the imaging system drops sharply and will not meet the requirements of guidance. At this point,
it is necessary to take corresponding measures to overcome the impact of image degradation. For example, using cryogenic jet to cool the optical window, using a series of blind deconvolution algorithms to correct the degraded images and so on.

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