Computation and analysis of aero-optic imaging deviation of a blunt nosed aircraft with Mach number 0.5—3*

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Aero-optic imaging is a kind of optical effect, which describes the imaging deviation on the imaging plane. In this paper, the effect of the change of Mach number of blunt aircraft on the aero-optic imaging deviation is studied. The imaging deviations of Mach number 0.5—3 are analyzed systematically. The results show that with the increase of Mach number, imaging deviation increases gradually, and the increase rate is gradually slow. Imaging deviation slope decreases gradually with the increase of Mach number, and gradually tends to be zero, suggesting that imaging deviation is not sensitive to the change of the larger Mach number. In other words, the Mach number of smaller changes can lead to larger imaging deviation. As the Mach number of the aircraft increases, the slope of the imaging offset tends to be closer and closer to 0. When the Mach number of the aircraft increases to a certain extent, the change of the imaging offset will not have much influence. Therefore, in order to reduce the impact of flight speed on imaging migration, the aircraft should fly at a higher Mach number.

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When the infrared guided aircraft moves at a high speed in the atmosphere, the gas at the head of the aircraft is violently compressed, resulting in a gas flow field with non-uniform density and refractive index. Both the beam generation and the beam absorption system will be adversely affected by the flow field[1-4]. Aero-optic effect involves multi-disciplinary fields such as optics, fluid mechanics and engineering physics, so its research diversity is also very obvious. The main research angle of this paper is the comprehensive theoretical calculation angle[5-9].

Most experiments show that aerodynamic imaging deviation has an important relationship with the flight height, Mach number, angle of attack and sight angle of the aircraft. Through the two-dimensional analysis of infrared guided aircraft published by XU Liang[10], the effects of different flight altitudes, Mach numbers and angles of attack on aero-optical imaging deviation are analyzed. Based on the paper published by YAO Yuan[11], the effect of line-of-sight angle on aero-optical imaging deviation of infrared guided aircraft is analyzed. On the basis of three dimensions, CHEN Xi[12] proposed new factors - roll angle of view for the influence of pneumatic optical imaging deviation, and ZHANG Ziye[13] analyzed the three-dimensional model under the influence of different heights for pneumatic optical imaging excursion to Lenovo, thoroughly discussed within the Mach number scope of 0.5—3, whether the change of Mach number had the same influence on imaging deviation[10-18].

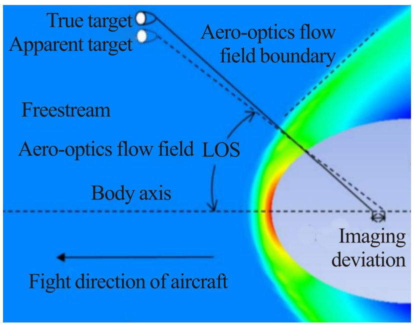

Fig.1 Schematic diagram of aero-optic effect

When the aircraft moves at high speed in the atmosphere, the head gas of the aircraft is violently compressed, forming a gas flow field with uneven density and refractive index. As the gas flow field generated is uneven, the refractive index of the flow field will become irregular. As Fig.1 shows, the light emitted from the target enters the aero optical flow field through a uniform free air

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flow. After passing through the aero optical flow field, it reaches the optical window. Under the action of non-uniform aero optical flow field, the incident position of light on the outer surface of the window will be different from that of the window without aero optical flow field, and there is a difference between the two incident positions, which is called aero-optical imaging deviation[19].

Flow field analysis is the prerequisite for studying aero-optics. The two bases of aero-optics are flow field density and optical refractive index. First, we need to analyze flow field density, and then we need to deduce the relationship between flow field density and optical refractive index. Density is one of the important dynamic parameters of gas medium. In the study of aero-optics, optical distortion occurs in the gas flow field surrounding the aircraft, so we need to analyze and study the density distribution of this flow field[20].

Computational fluid dynamics (CFD) provides three flow field calculation methods, direct numerical simulation (DNS), large eddy simulation (LES) and Reynolds average Navier-Stockes (RANS). In the study of aero-optics, we mainly consider the changes of average flow field caused by turbulence, and the imaging offset and imaging blur of aero-optical effect are the results of the action of average flow field. There are many kinds of turbulence models. In this paper, the k-ε two-equation model of RANS is adopted, which is briefly introduced below.

The governing equation of turbulence includes the equation of turbulent kinetic energy k and the equation of dissipation rate ε, shown as follows

$$k=\frac{\overline{u_i u_j'}}{2}=\frac{1}{2}\left(\overline{u'^2}+\overline{v'^2}+\overline{w'^2}\right), \tag{1}$$

$$\varepsilon=\frac{\mu}{\rho}\left(\frac{\partial \mu_i'}{\partial x_k}\right)\left(\frac{\partial \mu_j'}{\partial x_k}\right), \tag{2}$$

where u, v and w are the time-mean components of the fluid velocity vector in the x, y and z directions, respectively. ρ is the fluid density, and μ is vortex viscosity coefficient of laminar flow.

Gladstone-dale (G-D) formula connects the density of the flow field with the refractive index to obtain the discrete refractive index field, shown as follows

$$n=1+K_{\mathrm{GD}}\rho, \tag{3}$$

$$K_{\mathrm{GD}}=2.23\times10^{-4}\left(1+\frac{7.52\times10^{-15}}{\lambda^2}\right), \tag{4}$$

where n is the refractive index of gas, ρ is the density of gas, and λ is wavelength.

For standard air, different wavelengths have different G-D coefficients. As the wavelength increases, the G-D coefficient becomes smaller, and the G-D coefficient changes more when the wavelength is smaller, that is, the shorter the wavelength is, the faster the refractive index changes.

The basic equations of turbulence and the basic model for calculating turbulence have been given above, so the aircraft will be modeled and analyzed below. The preliminary work of calculating aero-optical imaging migration mainly includes geometric modeling, meshing, defining fluid properties, setting boundary conditions, etc. The following paper mainly uses GAMBIT software for geometric modeling of the aircraft. After the initial processing of the aircraft, the aircraft modeling is imported into FULENT for calculation. After the calculation, the flow field density data generated by FLUENT is imported into CFD-POST to export the density data. Fig.2 shows aircraft modeling after grid division by GAMBIT software.

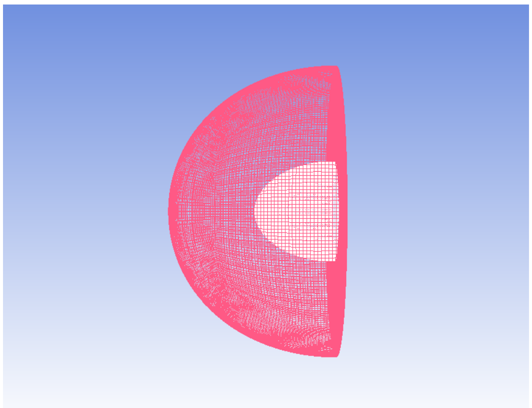

Fig.2 Aircraft modeling

Since there are many flight states of the aircraft, all CFD calculation results cannot be presented in this paper. Tab.1 only shows the calculation results of flow field density and imaging offset at different Mach numbers.

Tab.1 Aircraft condition

Example	Altitude (km)	Angle of attack (°)	Line-of-sight angle (°)	Roll angle (°)
1	15	0	35	0
2	15	30	45	30
3	15	45	55	60
4	20	0	45	60
5	20	30	55	0
6	25	45	45	0

Because the flight of the aircraft has different states, the imaging system of the aircraft will receive the reflected light of the target in different paths, and thus different aerodynamic imaging deviations will appear. In this paper, when the sight angle of the target (the included angle between the light and the aircraft axis) is different, the light reflected by the target will have different propagation paths in the aero-optical flow field, thus the aerodynamic imaging deviation will be different. In this paper, the Mach number is in the range of 0.5—3, and the concept of imaging deviation rate is introduced.

The imaging deviation rate is defined as the slight change of the imaging deviation divided by the slight change of the correlation variable, reflecting the sensitivity of the imaging deviation to the correlation variable. In this paper, the finite difference method was used to calculate the imaging deviation rate[10].

The density distributions of flow field under example 4 are shown in Figs.3—8.

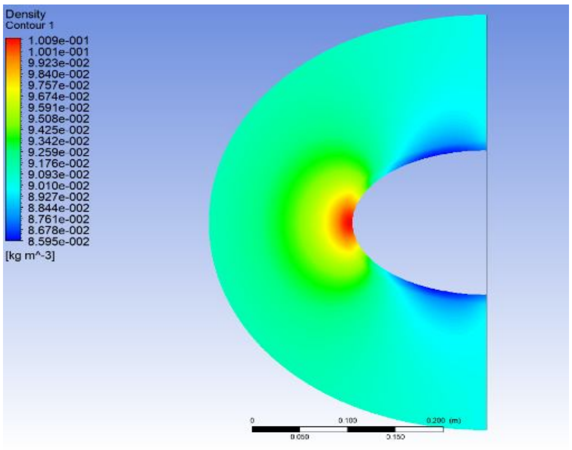

Fig.3 Flow density diagram at Mach number 0.5

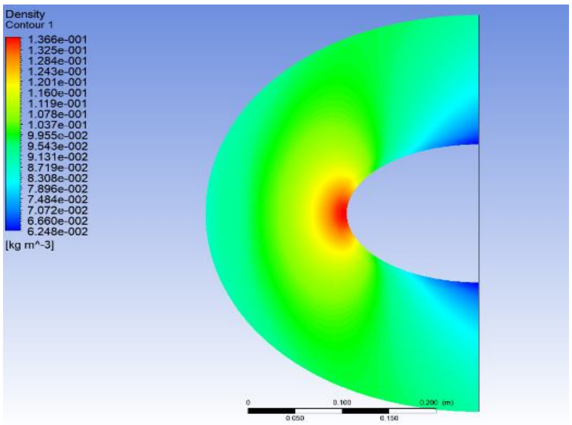

Fig.4 Flow density diagram at Mach number 1

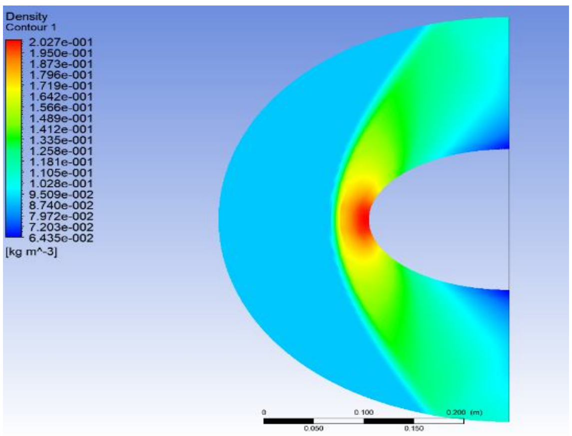

Fig.5 Flow density diagram at Mach number 1.5

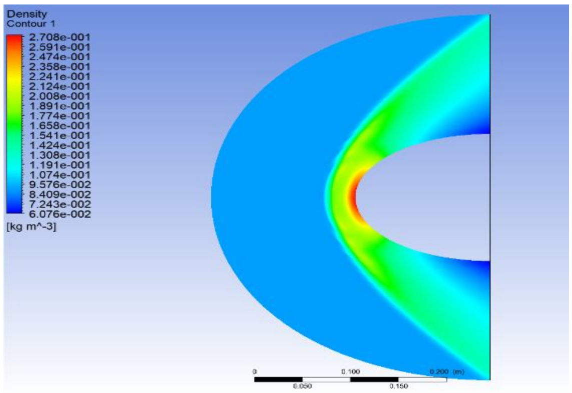

Fig.6 Flow density diagram at Mach number 2

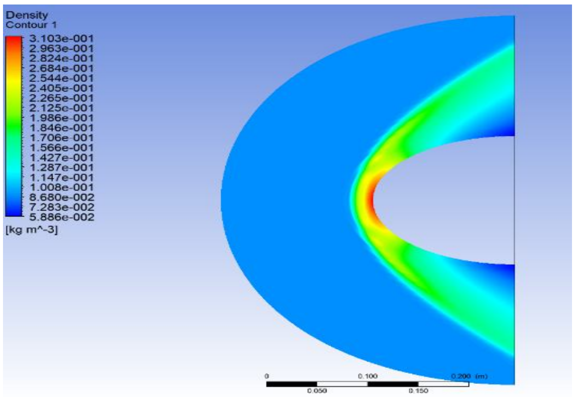

Fig.7 Flow density diagram at Mach number 2.5

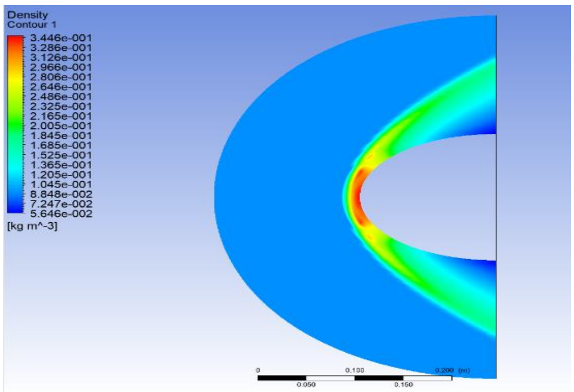

Fig.8 Flow density diagram at Mach number 3

As there are many flight conditions of aircraft, only some parts are selected for display. In this paper, the flow field density distribution diagram of example 4 is selected for display.

As can be seen from the figures above, the flow field density at the head of the aircraft is relatively large, while the flow field density at the surface of the aircraft is relatively small. At the same height, angle of attack, sight angle and sight roll angle, the maximum flow field density increases gradually with the increase of the Mach number of the aircraft. As can be seen from the figures above, the maximum density of flow field is 0.100 0, 0.136 6, 0.202 7, 0.270 8, 0.310 3 and 0.344 6, respectively.

In order to study and analyze the influence of Mach number on imaging migration, six flight conditions are given for analysis. The results of the imaging deviation and the slope of the imaging deviation are shown in Figs.9—14.

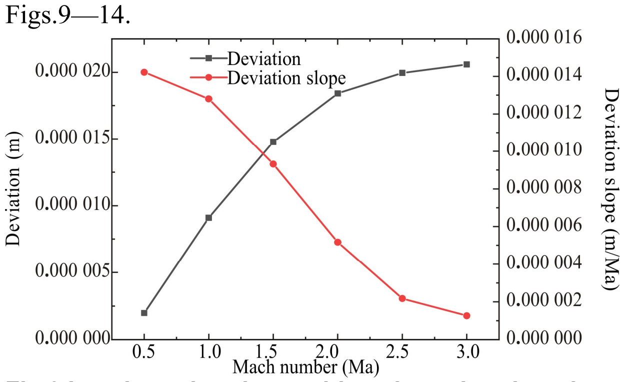

Fig.9 Imaging migration and imaging migration slope of example 1

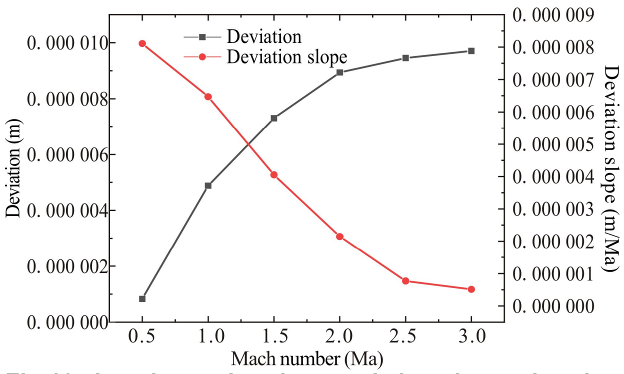

Fig.10 Imaging migration and imaging migration slope of example 2

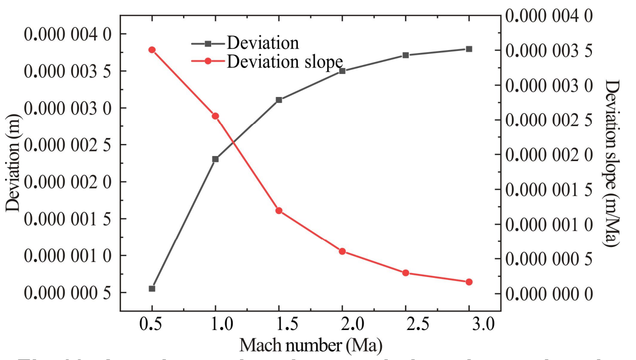

Fig.11 Imaging migration and imaging migration slope of example 3

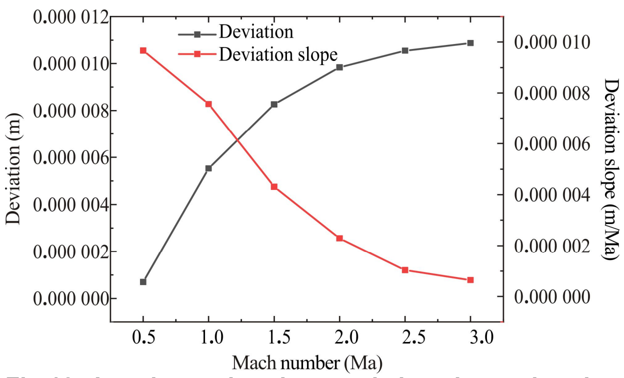

Fig.12 Imaging migration and imaging migration slope of example 4

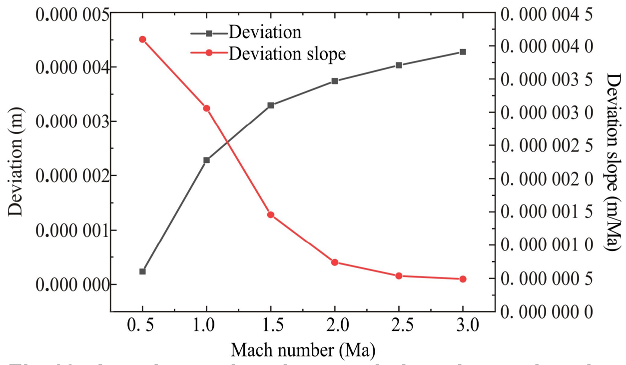

Fig.13 Imaging migration and imaging migration slope of example 5

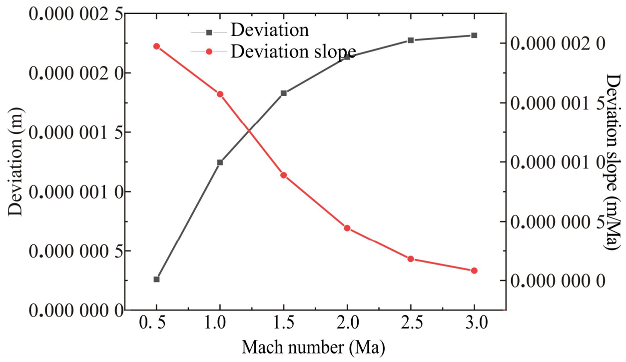

Fig.14 Imaging migration and imaging migration slope of example 6

With the increase of Mach number, the imaging deviation increases gradually, and the increase rate is gradually slow. The slope of the imaging deviation gradually decreases, and with the gradual increase of Mach number, the slope of the imaging deviation gradually approaches 0, indicating that the imaging offset is not sensitive to the change of larger Mach number. In other words, when the Mach number is small, the change of the Mach number will cause a relatively large imaging deviation.

As there are many flight conditions of aircraft, only six examples of flight conditions are given above. When the aircraft is flying, the system will calculate the current flight altitude, flight speed, angle of attack and other factors, and then the system will carry out a lot of calculation, according to the current flight conditions to calculate different imaging migration results, and then according to the current calculation results.

A large number of previous papers have studied the influence of altitude, line-of-sight angle and roll angle on aero-optical imaging deviation. This paper mainly studies the influence of Mach number on aero-optical imaging deviation through a large number of simulation experiments and data analysis.

It can be seen from the flow field density distribution diagram that the flow density distributions of different Mach numbers are similar. The flow field density value of the head of the aircraft is relatively large, while the flow field density value of the surface of the aircraft is relatively small. And it is obvious from the figures that with the increase of Mach number, namely the increase of velocity, the flow field at the head of the aircraft will be gradually compressed, resulting in the non-uniform gas flow field being compressed closer to the wall of the aircraft. At the same height, angle of attack, line-of-sight angle and roll angle, the maximum flow field density increases gradually with the increase of the Mach number of the aircraft.

The curves of the examples all show the same trend, that is, with the increase of Mach number, the imaging deviation gradually increases, and the increasing speed gradually slows down. The results are consistent with the objective law. According to the density distribution diagram of the flow field, with the increase of Mach number, the air density will increase due to the increase of velocity, which will make the compressed non-uniform flow field become compact, resulting in more deflections of the light emitted by the target object through the flow field and the imaging deviation increasing. In the Mach number range of 0.5—2, the changes of imaging deviation and imaging deviation slope are obvious, while in the Mach number range of 2—3, the changes of imaging deviation and imaging deviation slope are relatively flat. With the gradual increase of Mach number, the imaging deflection slope gradually tends to be 0, indicating that the imaging excursion to larger Mach number of the response is not sensitive to change. When the Mach number increases to a certain speed, the non-uniform flow field has been compressed to the point where it will not change. At this time, the increase of Mach number has little effect on imaging deviation.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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