Study on the Effects of Atmospheric Parameters on Space Vehicle Design

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Study on the Effects of Atmospheric Parameters on Space Vehicle Design

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Abstract. For the space vehicle flying in the airspace and near-space, the structure safety and attitude control ability are related to the surrounding atmosphere. The distribution characteristics of atmospheric parameters, including temperature, pressure, density and wind field should be studied based on the data statistics. In this article, the spatiotemporal distribution characteristics and measurement methods of atmospheric parameters are summarized, and the effects of atmospheric parameters on the engineering design of ballistic trajectory, propulsion system, aero-thermal heating, and attitude control system are provided. These results have considerable significance in the space vehicle general design.

Keywords: Atmospheric Parameters; Space vehicle; Atmospheric measurements

1. Introduction

Driven by the strong demands for military operations and civil space transportation, research and development of new type spacecraft has been conducted extensively in the space field world-widely [1]. Recently, many new aerospace vehicles, such as reusable rockets, high-speed cruise vehicles of the United States and European space reentry vehicles, have been developed and carried out flight tests successively. More and more researchers and institutions have already begun studies relevant to space and near-space from the earth's surface to orbital space.

Traditional launch vehicles, missile weapons and space reentry spacecraft always pass through atmosphere for a short time (usually at the speed of above Mach 10). However, the new type of aerospace vehicles fly for a long time (usually at the speed of Mach 3-6) and perform specific maneuvering flight tasks in the 0-30km airspace and 30-80km near-space, where the temperature, pressure, density, wind field and other characteristic parameters of earth atmosphere change sharply along with time and space. Especially, after NASA (National Aeronautics and Space Administration) found that the variability of atmospheric density using the real flight telemetry data of the Space Shuttle, the research on the characteristics of earth atmosphere has attracted extensive attention [2]. Therefore, it is necessary to pay attention to the distribution characteristics and variability range of atmospheric parameters in the design of space vehicle to ensure sufficient control ability and safety margin for the flight process of an aerospace vehicle in the near-space and airspace.

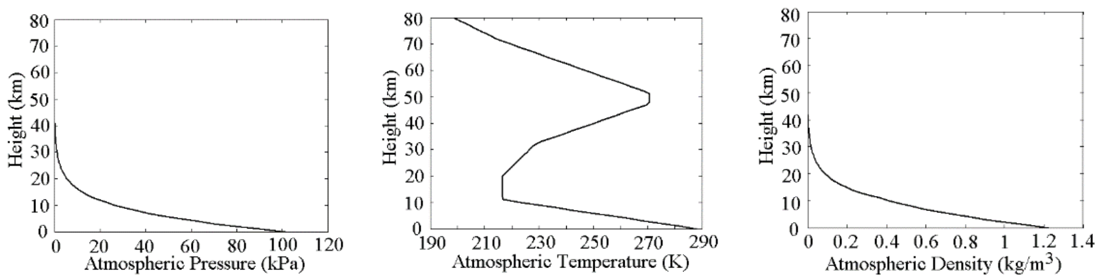
2. Atmospheric parameters and measurement methods

The atmosphere studied in this paper refers to the Earth's atmosphere from the launch site ground to a height of 80km, where the new type spacecrafts usually fly. Among them, atmosphere under 15km is the troposphere, and contains 75% of the total mass of the Earth's atmosphere. The convective movement in the vertical direction is intense and the parameters such as density and temperature change rapidly with height; atmosphere between 15km and 50km is the stratosphere, where the motion of the air is dominated by the meridional wind component and temperature is fairly well-distributed; atmosphere between 50km and 80km belongs to the mesosphere, where the air is thin, vertical movement of the air is intense and temperature decreases rapidly with increasing altitude; atmosphere above 80km is extremely thin, and is mainly composed of ionized and neutral particles. For aerospace vehicles performing space reentry, high-speed cruising and maneuvering missions, the atmospheric parameters, including temperature, pressure, density, wind field, and other characteristics, have important impact on many aspects of the vehicle including the trajectory design, power system performance and attitude control capability [3].

Since the 1960s, some international organizations and countries have formulated and published a series of atmospheric parameter models, such as CIRA [4], GRAM [5], NASA TM-100697 [6], USSA-1976 [7], and China-GJB366 [8] as shown in Table 1. These atmospheric parameters models focus on different geographical area and altitude range and show the atmospheric variability in month, season or solar activity in the form of graph or program. Among these, the USSA-1976 model of the US standard atmosphere is most widely used. In this model, atmospheric temperature, pressure, meridional wind and zonal wind in different seasons are provided for five latitudes (15,30,45,60,75) in the northern hemisphere. As shown in Figure 1, the atmospheric pressure and density decreases with increasing altitude, but the atmospheric temperature decreases from the ground surface to 10km, and then increases from 10km to 50km, after that, decreases with increasing altitude. In USSA-1976 atmosphere model, the atmospheric density is determined by ideal gas equation using its temperature and pressure according to latitude, longitude and height. Namely, $\rho = P/RT$ where R is the specific gas constant of air and R=287.05287J/(K*kg).

Table 1. Partial typical atmospheric model

Atmospheric Model	Geographical Area	Altitude Range	Variables	Data Form
CIRA [4]	Global	130-2000km	Season Solar Activity	Graph Program
GRAM [5]	Global	0-2500km	Month	Program
NASA TM-100697 [6]	Global	0-120km	Month	Graph
USSA -1976 [7]	Mid-latitude region	-5-1000km	Season Solar Cycle	Graph
China-GJB 366 [8]	China	0-80km	Season	Graph



(a) Atmospheric pressure (b) Atmospheric temperature (c) Atmospheric density

Figure 1. The USSA-1976 atmospheric model [7]

The measurement methods for obtaining atmospheric characteristic data mainly include meteorological balloons, sounding rockets, falling spheres, lidars, meteorological radars and meteorological satellites. The meteorological balloon is a latex balloon carrying radio detector to an altitude of 30km, which transmits the observed temperature, humidity, pressure and wind field data along the way to the ground observatory. The sounding rockets and falling spheres are the field detection tools above 30km, which can detect the atmospheric structure, composition and other characteristic parameters. Near-space Rayleigh scattering lidar mainly uses the principle that the scattering intensity of atmospheric molecules is proportional to the atmospheric density. By measuring and analyzing the intensity of the scattered signal, the atmospheric density, pressure and temperature at altitudes of 30-70 km can be obtained. The meteor radar uses the reflection signal of the meteor trails on the ultra-high frequency radio waves to detect the atmospheric horizontal wind field and meteor flux in the height range of 70-110km. Meteorological satellites operate at low Earth orbit (LEO) and geostationary orbit (GEO) and obtain different locations and altitude atmospheric parameters by electronic and electromagnetic detection.

In addition, some aerospace vehicles carry the Flush Air Data System to measure and calculate more accurate flight states and atmospheric parameters in real time such as angle of attack, sideslip angle, Mach number, dynamic pressure and so on. For example, the GRAM-1999 model of the United States uses the atmospheric measurements from 32 actual flights of Space Shuttle as the reference.

3. The effects of atmospheric parameters on design of aerospace vehicles

The changes of the atmosphere are complex, because it is influenced by many factors such as longitude, latitude, altitude, season, day and night, irregularity of gravity waves, solar activity, cosmic rays and geomagnetism [8]. Figure 2 shows the wind speed data of 72-80km in the Yinchuan Airport in West China measured by the all-sky meteor radar (belonging to the China National Space Science Center). It can be seen the wind speed varies with day, night and altitude.

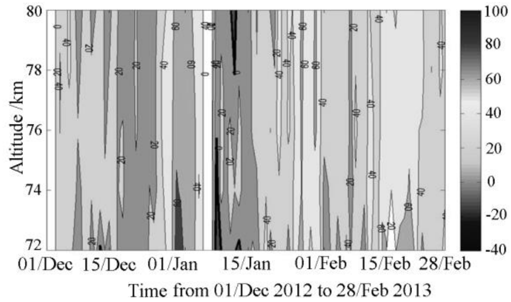


Figure 2. Wind speed data of 72-80km height in the Yinchuan Airport in West China

For aerospace vehicles which mainly carry out missions in 0-80km altitude airspace and near-space, it is necessary to pay more attention to the influence of characteristic parameters including atmospheric temperature, pressure, density and wind field on the design of the aircraft system, and determination of the deviation range of the main parameters so as to ensure that the aircraft has sufficient attitude control ability and flight safety.

3.1. Impacts on flight trajectory design

For a long-time cruising aerospace vehicle in high altitude atmosphere, the effects of atmospheric temperature, density, pressure and wind field and their deviations should be considered in the flight trajectory design.

The variations of atmospheric pressure and temperature change the engine thrust and further affect the flight overload and trajectory; the deviation of atmospheric density change the aerodynamic drag value of the aircraft, which affect the flight speed and the track inclination, and reduce the accuracy of the drop point; the change of atmospheric wind field cause the change of flying attack angle and sideslip angle, which affect the flight attitude and direction; changes in atmospheric temperature cause changes in the flight Mach number, leading to the difference of the interpolation results of aerodynamic forces and aerodynamic moments coefficients and affecting flight overload; the emergence of the gust cause a sharp change in the angle of attack and the side slip angle, which shift the flight path.

During the actual flight of the spacecraft, there is a certain degree of difference between standard atmospheric model and actual the atmospheric parameters values including temperature, density, pressure and wind field. However, the deviation of observations from the standard atmosphere mode can be obtained by the probability distributions of the parameters in different seasons and altitudes. Then the envelope range of flight trajectory can be obtained by deviation trajectory design and trajectory model correction considering the effect of various factors, and the accuracy of flight and landing point prediction can be improved. In order to ensure the smooth execution of key flight actions, the effects of atmospheric parameters on the state parameters of key design points, including the angle of attack, sideslip angle, Mach number and dynamic pressure of aircraft, need special attention and evaluation, especially for those critical trajectory points of abrupt movements, such as space reentry, stage separation, fairing abandoning, engine restart, and maneuvering steering.

3.2. Impacts on power system design

For traditional solid or liquid rockets, the thrust needs to be corrected for high altitude conditions (especially vacuum) in the design of the power system, because the oxidant and fuel used are self-contained and the thrust performance is mainly affected by the jet state under high atmospheric pressure environment.

However, for an aerospace vehicle with a new type of inspiratory power system, which only carries fuel and needs oxygen combustion in the atmosphere to provide thrust, the characteristic parameters such as pressure, temperature, density and wind field of the atmosphere have a great impact on its intake effect, fuel supply calculation, judgment of ignition status and stable working boundary. Therefore, the atmospheric parameter model needs to be pre-bound or solved in real time by the atmospheric measurement system.

Figure 3 shows the deviations of the atmospheric temperature (compared with the USSA-1976 standard atmospheric model, the same as Figures 4 and 6 based on the data of TIMED/SABER satellite [9] for 13 years from January 2002 to January 2015 in the Yinchuan Airport in West China. In Figure 3, the same lines (2 lines) with the same legend show the maximum and minimum parameter values in the same season, that is similar to Figures 4 and 6. For high dynamic suction aerospace vehicle with high-speed and low-altitude, the fuel control needs to pay special attention to the atmospheric temperature and its deviation range at different altitudes to improve the cruise distance.

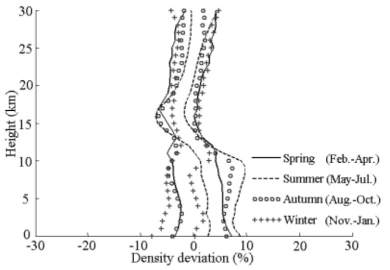


Figure 3. Deviation distributions of the four seasons atmospheric temperature in the Yinchuan Airport in West China

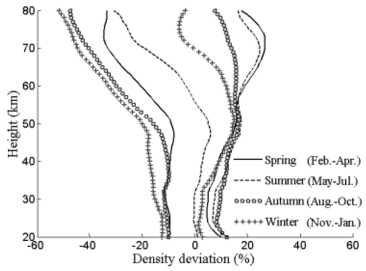


Figure 4. Deviation distributions of the four seasons atmospheric density data in the Yinchuan Airport in West China

3.3. Impacts on pneumatic thermal environment design

When the aerospace vehicle performs high-speed cruising or space re-entry at a height of 0-80km, its head stagnation point and wing leading edge position need to withstand up to MW/m^2-level pneumatic heating, and the maximum temperature can reach above 1500^{o}C. Therefore, the aircraft's nose, windward side, leeward side, tail end, wing and moving control parts must be protected with high temperature resistant materials or covered with thermal protection system. The maximum heat flow and maximum heat load conditions need to be evaluated according to the flight trajectory in the design of pneumatic thermal environment. The atmospheric density has the most direct effect on pneumatic heat. Figure 4 shows the distribution of the deviations of the atmospheric density calculated from the atmospheric density data of TIMED/SABER satellite in the Yinchuan Airport in West China. It can be seen from Figure 4 that the summer atmospheric density is obviously higher than other seasons, which is unfavorable for aircraft reentry and long-time cruise flight. This is consistent with the US Space Shuttle's ban that does not allow summer reentry and return from the Arctic. Moreover, during the US Space Shuttle flight, there have been many dramatic changes in aerodynamic drag caused by fluctuations in atmospheric density, resulting in frequent fluctuations in flight angle of attack [10-11].

3.4. Impacts on attitude control system design

The attitude control system design of aerospace vehicle needs to reasonably control the engine swing angle and the movable rudder angle to ensure the stability and controllability of the aircraft attitude during the whole flight process. The irregular distribution of the atmosphere in space and time and the effect of gust [12] cause the overall sudden change of aircraft's aerodynamic drag and rudder surface control force, which affect the important flight state parameters such as angle of attack, sideslip angle, Mach number and dynamic pressure, even cause the aircraft to become unstable and the mission failure.

When the attitude control system carries out attitude balance and six-degree-of-freedom flight simulation, it is necessary to evaluate the control capability of the active rudder and engine swing. The distribution of wind field with height has an important influence on its anti-interference ability. Figure 5 shows the distribution of 95% probability of the maximum wind speed with altitude based on the four seasons wind field data of TIMED/SABER satellite in the Yinchuan Airport in West China, which was calculated by the integrated vector wind profile method [13]. It is demonstrated by Figure 5 that within the height range of 0-30km, the maximum wind speed gradually increases to the maximum value from the ground to the height of about 11km, then the maximum wind speed decreases gradually until the height of about 18km, and then increases with the height again. Among them, the winter wind field is more severe than other seasons, so the attitude control design of the aircraft is the most severe in winter. This is the main reason why the spacecraft attitude control system usually adopts the winter wind field as the design condition.

3.5. Impacts on design of structural and institutional system

In aerodynamic calculation, the influence of dynamic pressure on aerodynamic system design is avoided by using aerodynamic coefficients, so the influence of atmospheric parameters on aerodynamic system design is small. However, in the design of the structure and mechanism system, the aerodynamic coefficient needs to be converted into the load condition of the structure, and the influence of the atmospheric parameters cannot be ignored.

The airframe structure and active control components need to bear larger aerodynamic pressure in high-speed flight, while the cabin pressure is closer to the atmospheric static pressure at its altitude [14]. In the design of the aircraft structure and mechanism system, it is necessary to consider the load changes caused by atmospheric fluctuations in the flight state, to ensure the structural strength and safety, and the activity control mechanism has sufficient actuation capability. Therefore, in addition to obtaining the external aerodynamic pressure through wind tunnel test and numerical simulation, it is also crucial for the structure and mechanism system design to accurately grasp the atmospheric environment of the space vehicle flight area. Figure 6 shows the deviation of the atmospheric pressure calculated from TIMED/SABER satellite data for four seasons in the Yinchuan Airport in West China. The results show that the atmospheric pressure in summer is higher than that in winter. In addition, considering the influence of day and night changes and geographical location, the structure and mechanism system design of space vehicle should retain enough safety margin to ensure flight safety.

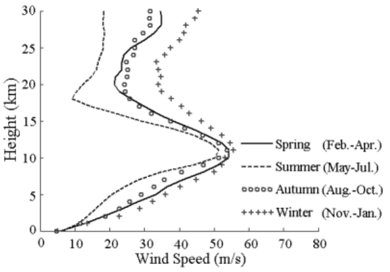


Figure 5. Maximum wind speed distribution in the Yinchuan Airport in West China

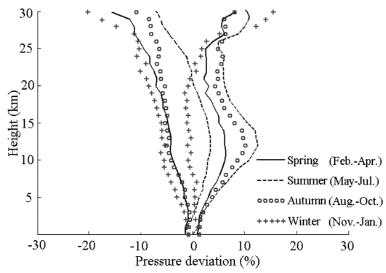


Figure 6. Deviation distributions of the four seasons atmospheric pressure data in the Yinchuan Airport in West China

3.6. Impacts on the Design of Thermal Control System

The thermal control system of aerospace vehicle is designed to protect the temperature of important single aircraft and equipment which are sensitive to temperature in the cabin by using active and passive temperature control method. In order to reduce the spacecraft structure's load caused by the pressure difference between the interior and exterior during cruise flight at high speed and high dynamic pressure, the passive flushing and exhausting system is often used to enable the surrounding atmosphere to enter and exit the spacecraft cabin structure [14]. The atmospheric temperature gradually decreases with increasing altitude under 10km. For example, the atmospheric temperature at the height of 10km is reduced by about 60^{o}C compared to the ground as shown in Figure 1. During the return of the aircraft to the ground, the cold air gradually enters the aircraft cabin under pressure, which results in the temperature drop in the cabin. In the design of the thermal control system, it is necessary to evaluate the effects of atmospheric temperature, density and intake and exhaust volume at different altitudes on the cabin temperature, especially on the temperature sensitive equipment.

3.7. Impacts on measurement system design

The measurement antennas and windows of the flight measurement system are usually arranged on the side and back of the aerospace vehicle to avoid the influence of intense aerodynamic heating. However, the drastic changes of atmospheric temperature, density, pressure and other parameters lead to frost phenomenon in the measurement module. It is necessary to reduce the influence of atmospheric moisture by blowing, heating or dehumidifying. And for high-precision optical measurement and imaging equipment, the temperature gradient caused by the combination of atmospheric temperature and aerodynamic heating changes the curvature of the optical lens, which affects the imaging effect. It is necessary to design its temperature control system separately or to correct the deviation of the imaging results. In addition, the deviation of atmospheric temperature and pressure affects the atmospheric refraction factor, and the propagation speed of electromagnetic wave in the atmosphere will change, leading to the deviation of radar detection distance, angle and height.

4. Conclusions

Compared with traditional spacecraft represented by launch vehicles and missile weapons, and low-altitude aircraft represented by passenger and military fighters, aerospace vehicles should be capable of long-term cruising and maneuvering at a high speed at altitudes of 0-80km. The temperature, density, pressure and distribution of the surround atmosphere in space and time have a great influence on the design of various systems of aerospace vehicles, which is one of the important causes of aerospace accidents.

This article dedicates to the study on the effects of atmosphere parameters on the engineering design of ballistic trajectory, propulsion system, aero-thermal heating, and attitude control system of the new type spacecrafts, which usually fly in the 0-30km airspace and 30-80km near-space. Based on the temperature, pressure and density data analysis from TIMED/SABER satellite, and wind speed from the all-sky meteor radar, the distribution characteristics of atmospheric parameters at different times are provided. These results have significance in the space vehicle general design.

For the safety of the structure and the success of the flight mission, the distribution and deviation of atmospheric parameters should be considered in the design of each system on the one hand. On the other hand, it is necessary to obtain the atmospheric parameter data of launch site, landing field and mission execution area by various ways such as radio, electromagnetic, laser, sounding rocket, satellite, etc. and to enrich and improve the atmospheric model continuously by using the telemetry data in flight test so as to accurately determine the deviation range of each parameter.

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