The Flow Control Technology for Hypersonic Flights

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Abstract. The hypersonic aircraft has important implications for society. This technology helps military operations proceed more smoothly and easily. It also opens up new possibilities for scientific exploration, such as exploring space and meteorological observation. In this essay, the perspective of s specific system on the hypersonic aircraft, the flow control, is used to illustrate the feasibility of adapting to high-altitude aerodynamic phenomena, including turbulence, vortexes and boundary layers. The advantages and effectiveness of the flow control technology are shown clearly by introducing two cases. Through analyzing the design aerodynamic characteristics of the typical vehicle, X-51A, the passive flow control is demonstrated as a good way to improve flow stability and overall efficiency due to the streamlined shape and the wave rider design. The HAWC successfully utilizes the active and MHD flow control system. It adjusts the velocity of fluid flow by changing the direction and strength of the magnetic field. Thus, not only can the precise control be guaranteed, but also the fuel consumption is reduced. Despite current benefits, for future research, the scientist should focus more on the new materials and the combination and optimization of several flow control technologies.

Keywords: hypersonic aircraft, flow control technology, case analysis, history.

1. Introduction

Due to the growing demand for national security and the individual's well-being, the immediate development of machines that combine two functions gradually comes to be the consensus of the majority. Among these machines, hypersonic flights have become a focus. Hypersonic flights are defined as a type of aircraft that can soar with a speed of over Mach 5(5 times the speed of sound). The notion of hypersonic was suggested by a Chinese scientist, Qian, Xuesen in 1945. Unexpectedly, only after one-decade, huge progress has been made in this area. The design of long-range ballistic missiles, the success of launching manned spacecraft and the remarkable improvements in the velocity of the X-15 airplane all marked that hypersonic objects were no longer fantasies [1]. Till now, in terms of countries, they have kept their passion to invest in this technology.

Also, the potential of hypersonic technology in the aerospace field has gradually been exploited. The current hypersonic flights combine several advanced technologies. First, to withstand extreme conditions, some high-temperature-resistant materials must be applied. Traditionally, ceramics are frequently employed in various types of aircraft [2]. However, in the hypersonic conditions, particular phenomena often occur. Compression waves and shock waves are formed, leading to a local rise in pressure and temperature. The ceramic materials are too brittle to experience intense heat. After making a lot of material tests, the thermal protection system finally uses metallic structures --ARMOR to ensure safety. The alloys used are mainly a combination of Inconel 718 and Inconel 617.

One important parameter that all modern aircraft are monitored is the aerodynamic characteristic. Basically, the aerodynamic characteristics are defined as the certified summaries of data for forces, heat and sounds. The corresponding technology applied to improve the performance of the flight in terms of aerodynamic characteristics is the flow control technology. One phenomenon that severely influences performance can be alleviated by flow control technology. When the air is flowing over the surface of an aircraft, the speed in different positions is unequal. The speed of the thin layer of fluid adhering to the surface is close to 0 because of the normal viscous forces, forming the boundary layer. The layer may encounter an adverse pressure gradient where the air further decelerates. Therefore, insufficient kinetic energy can be utilized to ensure sustainable flow, producing boundary layer separation. This phenomenon can lead to lift loss, increased drag and instability. An example of flow control technology to reduce impact is the pneumatic actuators. They can adjust the angles of wings to ensure the aircraft fly stably by reacting to immediate changes in pressure. The actuators can also produce local pressure fluctuations to offset the influence of the separation.

Overall, this essay is structured into three core parts, including some existing advantages together with some challenges that may be encountered, a review of the flow control technology and case analysis. To ensure the comprehensiveness of the review, a worldwide scale will be applied in the dissertation. It is expected that the findings can provide a theoretical basis and reference value for future better design.

2. Flow Control Technology

As the researcher mentioned above, the flow control technology improves the performance of the aircraft and paves the way for future aerospace technology development. Therefore, a comprehensive classification and explanation will be made in this part.

2.1. Passive Flow Control

Compared with other types of flow control technology, passive flow control technology manages the flow by the geometrical changes instead of using active mechanisms. Due to no extra energy consumption, it is relatively easy to apply. Regardless of the types of passive flow control, throttling devices, diffusers and constrictors all follow the principle that by designing specific shapes, the flow area changes, causing corresponding changes in flow speed.

An example of this technology is the winglets. The winglet refers to a small, vertical extension attached to the wingtip. It was designed in the 1970s by an engineer at NASA, R.T. Whitcomb to cope with the oil crisis at that time [3]. During the flight, the high-pressure airflow on the lower surface of the wing can flow around to the upper surface, forming the vortex which can spread to wide areas. The winglets can block the flow, weakening the strength of the vortex. In addition, the winglets provide a tip vortex which has an opposite direction to that of the main wing, which offsets the impact on the aircraft.

Another important function is to prevent premature separation of the wingtip flow. Therefore, the stalling angle of attack can increase, reducing the risks of stalling. However, improper installations of the winglets increase the bending moment which influences the structural strength. The designers need to consider seriously on the winglets.

2.2. Active Flow Control and Hybrid Flow Control

As a supplement to passive flow control technology, instead of pre-calculation of several parameters, the active flow control technology mainly operates continuously during the flight. As a feedback control system, the components of it must contain two functions, receiving electrical signal and adjusting electric actuator movement. It is flexible to meet the urgent challenges, such as controlling turbulence production in the boundary layers to reduce friction and drag [4].

To help engineers get the key data for the aircraft in real time and decide for further improvements, sensors are needed to install. According to the parameters that the sensors measure, the sensors can be classified into several types, including temperature sensors, pressure sensors, accelerometer and so on. In terms of flow control, the parameters, pressure and acceleration are often emphasized. First, the hypersonic vehicles are subjected to intense fluctuating pressure. Therefore, the internal components vibrate, causing the structural fatigue [5]. The sensors are quite necessary to achieve the balance of safety, durability and efficiency, especially the strain gauge pressure sensors. They can monitor the amount of stress the surface can handle. The sensors contain several resistance strain gauges which are made up of three layers. From top to bottom, there is a protective laminate, a metallic sensing element and a plastic film base. This structure allows the distortion of gauges in unison with the surface. Therefore, the resistance change can be detected to measure the pressure around.

From the above description, the researcher can conclude that both flow control technologies have their own advantages and drawbacks. Accordingly, the combination of these two technologies is gradually considered as a better way to deal with some common airflow problems. In the aspect of throttling control, while the traditional flow control changes shapes to increase the resistance for flowing, the hybrid method can manipulate the hand tools and intelligent system, which ensures that the flow is not only precise in its amount and stable on the flight. For instance, integrating pulsed jets and variable geometry nozzle technology can guarantee the safety and improve the efficiency of the engine. The pulsed jets or the synthetic jets can adjust the flow speed and the pressure distribution. The problems such as intake non-starting can be avoided since it provides sufficient air at any time. The nozzle technology can increase the aircraft's power and improve fuel efficiency.

2.3. Electromagnetic Flow Control

Electromagnetic flow control is based on some basic principles of electromagnetism. In 1820, the Denmark scientist, Oersted discovered the phenomenon of the magnetic effect of electric current during an experiment. This laid a solid foundation for future development in this area including the discovery of the Lorentz force. Because of this force, the charged particles in a magnetic field will change their flow velocity, direction and some turbulence characteristics. When this technology applies to the aerodynamic area, its functions are like the above two technologies. However, the operating principles are quite different and harder to directly apply due to insufficient knowledge of computational fluid dynamics. It is difficult for scientists to obtain high enthalpy and conductivity streams. Therefore, the effective date for this technology is limited. The research aimed at this field may be done using numerical modelling [6]. Additionally, another drawback is that it may lead to interference when using a magnetic field. Some other devices are more likely to be damaged because of the influence. The solenoid valves still have their benefits. The response speed and the precision of controlling is higher. No contacts occur during the operation. The erosion or abrasion caused by the flow can be avoided. In general, more scientific progress must be made to further apply electromagnetic technology.

3. Case Study

3.1. X-51A

Currently, the hypersonic aircraft is under development. A lot of countries have invested resources like talent, money and machines in this area to satisfy the potential economic demand and military requirements. In China, The Starry Sky II can handle foreign interference and missile interception. In Germany, the EuroHawk unmanned aerial vehicle performs well in the aspect of reconnaissance. Among these advanced applications, one aircraft contains the previous functions made by others and develops new technology, which has epoch-making significance, showing the capabilities and promise of the hypersonic aircraft. The X-51 A is a perfect representation of the series of aircraft designed by NASA (National Aeronautics and Space Administration). Apart from learning from the innovations from other countries, the X-51A highly relies on the technology applied in the X-43A, which is another type in the series. In 2004, the X-43A succeeded in the test flight, demonstrating that it was reasonable for airplanes to have features including streamlined shape, ramjet engines and canards. In the same year, a 10-minute high-speed motorized gliding was performed to get more pneumatic data. Consequently, the X-51A kept applying the streamline shape which is considered as a type of passive flow control to minimize the friction caused by the high-speed flow. The ramjet engines witnessed an improvement. The engines directly absorbed the oxygen during the flight instead of taking oxidizers. In this way, the total weight decreased, leading to more stability and a greater amount of air intake. While the engines better controlled and used the flow, the wing of the X-51A changed. The canards applied in the X-43A had advantages including a better lift force when experiencing a greater angle of attack and a wide range of maneuvering torque at supersonic speed. However, after about twenty years of research on the pneumatic data, an advanced alternative was proposed. It chose to simplify the wing design but modified some small parts to make the aircraft work as a wave rider which means a special design on the fuselage, specifically to the nose of the plane and the rear air intakes. This shape design can generate a shock wave on the lifting surface. The leading-edge plane of the shock wave generated by the supersonic flight of the vehicle coincides with the upper surface of the wing. This mechanism produces compressed lifting force. To better show the effectiveness of the application, an important concept to illustrate the aerodynamic phenomenon is the lift-drag ratio. It is calculated by the lift coefficient divided by the drag coefficient. The relationship between the ratio and the pneumatic efficiency is that when the ratio reaches its maximum, the aircraft can perform perfectly. The wave rider, due to its characteristics mentioned above, has a higher lift-drag ratio compared with that of the X-43A. The X-51A can address more urgent issues during the flight, especially in the aspect of the force change exerted by the flow.

3.2. The Hypersonic Air-breathing Weapon Concept(HAWC)

The hypersonic air-breathing weapon concept (HAWC) is a futuristic air-to-air combat missile concept. In 2022, the HAWC finished its second test successfully, passing across 556km at an above 5-mach cruise speed. A key aspect of promoting the development of the HAWC, performed as a hypersonic cruise vehicle was the comprehensive applications of magnetohydrodynamics (MHD) flow control system. The design of the MHD system at that time broke the stereotype that the new aircraft must counteract the effect caused by the flow in a high-altitude environment. Instead, this system utilized the environment that had an adverse influence on the flight and made the environmental influence to become the main advantage for maintaining flying [7]. The system did not employ the conventional way to ionize in advance. The fluid that was preconized was easily affected by the external magnetic field. Therefore, the active flow control was used by controlling the current. During the flight, the MHD generators keep adjusting the magnetic field to decrease the mass flow rate, generating the suitable current. In terms of the mass flow rate, a shock system is applied to capture the mass air to move to the intake. However, due to this special design, the shock system is configured to direct the flow to the cowl lip [8]. In this way, some technical support is needed. The current types of shock structures that can satisfy the requirements are shock out of or into the intake. In a critical operating condition, because of sufficient data, no significant differences occur between the two types. More scientific research is needed to make in this area to further improve the quality of the MHD system and promote the development of HAWC.

4. Conclusion

As a remarkable advancement in the aerospace area, the hypersonic aircraft now plays a significant role in future technology development. This essay illustrates the history, and the current technology applied to hypersonic aircraft, especially in the aspect of flow control. Different types of sensors, generators, materials and geometrical shapes are all mentioned in the essay. According to all the above writing work, the aims of this essay have been largely achieved. The goals are to examine hypersonic aircraft by analyzing the benefits, then concerning challenges and evaluating the potential for that. The case study is used as the researcher's main methodology. According to the introduction of X-51A, the evolution of hypersonic aircraft can be shown. From X-43A to X-51A, there existed obvious progress in the flow control technology, offering valuable inspiration for future aircraft. In addition, both cases provide practical evidence and data for the theories and innovations proposed in this essay. The streamlined shape and wave rider design of the X-51A demonstrates the effectiveness of passive flow control techniques. The successful outcome of the second test of the HAWC highlights the importance of the MHD flow control system in harnessing the high-altitude environment. The concept of different types of flow control technologies can be easily understood. One drawback of this essay is that it involves insufficient quantitative research. To find solutions to optimize the configuration and calculate the exact drag/lift coefficient, computational fluid dynamics (CFD) should have been used. Cart3D also can be used to generate a three-dimensional geometrical model of the aircraft for the next time. Under this circumstance, the case can be more persuasive and useful for future researchers.

References

[1] Wang, J., Han, C., Huang, Y., Liu, J., & He, Y. (2024). A review of international hypersonic technology developments in 2023. Journal of Tactical Missile Technology, 01, 7-19. doi: 10.16358/j.issn.1009-1300.20240503.

[2] Yang, Y. Z., Yang, J. L., & Fang, D. N. (2008). Research progress on thermal protection materials and structures of hypersonic vehicles. Applied Mathematics and Mechanics, 29, 51-60.

[3] Guerrero, J., Sanguineti, M., & Wittkowski, K. (2018). CFD study of the impact of variable cant angle winglets on total drag reduction. Aerospace, 5(4), 126.

[4] Robinson, S. T. E. P. H. E. N. K. (1991). Coherent motions in the turbulent boundary layer. Annual review of fluid mechanics, 23(1), 601-639.

[5] Casper, K., Beresh, S., Henfling, J., Spillers, R., Pruett, B., & Schneider, S. (2009, June). Hypersonic wind-tunnel measurements of boundary-layer pressure fluctuations. In 39th AIAA fluid dynamics conference (p. 4054).

[6] Teng, Z., Zhou, Z., Zhang, Z., Xu, K., & Gao, Z. (2024). Numerical simulation study on MHD flow control at hypersonic speeds. Aerodynamic Research and Experimentation, 01, 86-99. doi: 10.20118/j.issn2097-258X.2024.01.007.

[7] Kuranov, A. L., & Sheikin, E. G. (2003). Magnetohydrodynamic Control on hypersonic Aircraft under" AJAX" concept. Journal of Spacecraft and Rockets, 40(2), 174-182.

[8] Yi, W., Wang, Y., Pang, L., Xiao, L., Ding, Z., & Duan, P. (2019). Progress in plasma/MHD flow control research of air intakes. Acta Mechanica Sinica, 51(2), 311-321.