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A design review on hypersonic aerodynamics configurations and applicability to hypersonic transports

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Abstract. As the world of commercial aviation recovers from the global recession after the pandemic, demands for faster and more reliable air transportation are on the rise. Research in Hypersonic Transports, led by both government and private sectors, aims to revolutionize the industry with its high time efficiency and customizability for various needs. This paper reviews the design principle and challenges of HST from a technical standpoint, while overviewing high-speed gas dynamics, analyzing the waverider configurations, and addressing the technical intricacies of designing a hypersonic vehicle. It shows that the waverider configuration is a suitable HST candidate for its large fuel storage and high inlet compatibility for an airframe-propulsion integrated design. This paper aims to provide holistic context for the advantages and challenges associated with HST, while providing insights into the compatibility of a waverider configuration that can be optimized for civilian transport applications.

Keywords: hypersonic transport, design review, waveriders, compressible aerodynamics.

1. Introduction

1.1. Hypersonic research & technologies

Striving for greater speed has been the signature of the development of aviation since its dawn, thanks to the continuous perfection of aerodynamic theories and manufacturing technologies. More powerful and efficient engines paired with the ever advancing and robust airframes and wings has made modern aircrafts completely unrecognizable to a contemporary of the Wright Brothers'. At the same time, growing engineering capabilities of aircrafts were also essential contributors to the rapid development of the world during the 20th century, from the popularization of transonic aerial transport to the complete transformation of military combats via supersonic jets and missiles, which all, for better or worse, impacted billions and accelerated the world into the age of high-speed aviation.

Decades of scientific research in the field of high-speed aerodynamics, based on existing low-speed subsonic fluid mechanics, has been integral to supersonic flights. Researchers such as Busemann, Ackeret, von Kármán, Lees, and Jones had developed a multitude of closed form expressions, approximations and similarity laws for analyzing subsonic and supersonic flight [1]. Tsien first developed similarity laws for hypersonic flights [2] which laid foundations for all subsequent hypersonic research. Their work was integral to the expansion of compressible aerodynamic theories, which in turn prompted rapid growth of high-speed aviation as an industry.

Building upon the above theories, engineers strive to develop various tools and technologies for bringing supersonic/hypersonic vehicles into realization. Hypersonic flows are flow fields where fluid velocity is much larger (typically larger than five times) than the velocity of propagation of small disturbances, the speed of sound [2]. As a result of this unique property, the realization of hypersonic vehicles requires intricate design and integration of airframe, propulsion, avionics systems and much more. Engineering challenges associated with hypersonic flow will be discussed in the following sections.

1.2. *Hypersonic transport*

Air travel volume worldwide has in general recovered from the pandemic. In the US alone, air travel volume in 2022 increased by 30% from 2021, by 194 million passengers [3]. Figure 1 shows the monthly passengers on a US scheduled flight from Dec. 2019 to Dec. 2022.

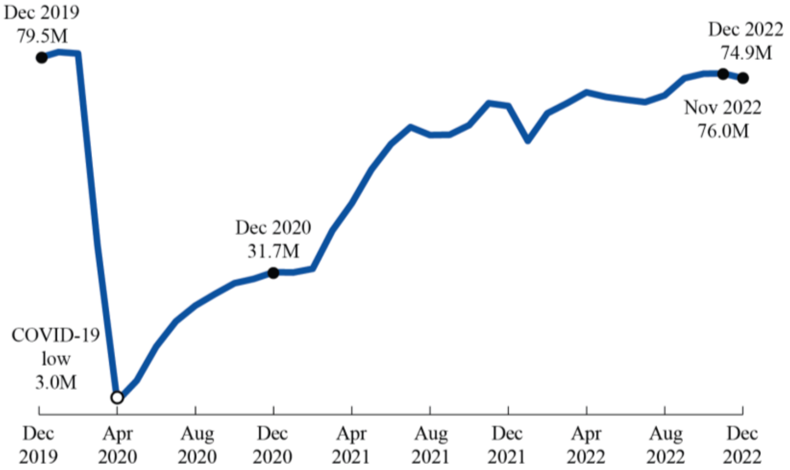

Figure 1. Monthly passenger on U.S. scheduled Airlines (Domestic + International), Seasonally adjusted, Dec. 2019--Dec. 2022 [3].

The rapid increase of air travel demands during the past 2 years signifies the increasing demand for fast, reliable and efficient modes of air travel, whilst, as Szirozak and Smith points out, most large airframe manufacturers are focusing on developing more efficient, cheaper, greener, aircraft designs [4]. Hypersonic transport thus emerges as an aspiring candidate which could transform the future of the aviation industry. Traveling from Tokyo to Los Angeles in under 2 hours is a great example which justifies the existence of Hypersonic Transport for applications such as emergency response, time critical business trips and numerous military applications [4]. Commercialization of hypersonic transport is currently being spearheaded by start-ups such as the Houston-based Venus Aerospace, the Atlanta-based Hermeus and the Beijing-based Space Transportation [5], while governmental agencies such as NASA are also studying the fundamental physics and technologies to support the development of hypersonic aircrafts [6].

This paper aims to provide broad yet comprehensive context for the current situation, advantages and challenges associated with hypersonic transport, while providing insights to a new, integrated design which optimizes for civilian transport applications based on previous design approaches. A summary of past literature on the challenges of hypersonic vehicle design and commercialization of hypersonic transport, as well as reviews of existing hypersonic transport designs (focusing on waveriders) are presented.

2. Hypersonic aerodynamics design

2.1. *Hypersonic gas dynamics*

The hypersonic flow regime poses theoretical aerodynamics challenges to the design process of hypersonic transportations. As mentioned above, the free stream velocity in the hypersonic flow regime is at least five times the speed of propagation of perturbations in the flow, in other words, the free stream Mach number (M_∞) is larger or equal to 5. The conventional compressible gas dynamic theories needed to be expanded for accurate modeling of this flow regime. Generally high-temperature gas effect when $M > 5$ must be taken into considerations during the design process. The atmospheric composition in front and behind a normal shock of a hypersonic vehicle differs greatly, which results in the excitations of the various degrees of freedom of gas molecules, partial dissociations and even ionization of gas molecules [7]. In addition, failure of the assumption of local thermodynamic equilibrium which in turn makes thermodynamic and force analysis on the airframe challenging. For a given gas molecule, certain modes of excitations in translational or vibrational degrees of freedom may have longer relaxation time to the equilibrium state than others. Hence during rapid compression and expansion such as rear of the normal shock formed in front of a hypersonic vehicle, the specific heat capacity $\gamma = c_p/c_v$ is no longer constant but becomes highly dependent on temperature (gas no longer calorically perfect), which further complicates analysis and optimization of aerodynamic forces and moments upon the hypersonic aircraft [7, 8]. Thermodynamic analysis also becomes crucial as strong shock waves accumulate in the vicinity of the surface of hypersonic vehicles, which results in steep temperature gradients across the shocks. A summary of the above effects is illustrated below in Figure 2.

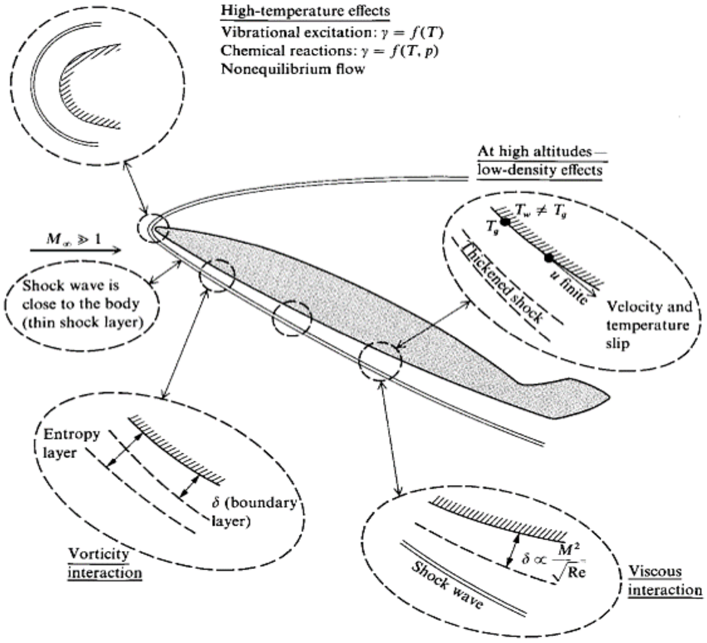

Figure 2. Physical Effect Characteristics of Hypersonic Flow [9].

2.2. Hypersonic vehicle design principles & methods

From the above analysis of the hypersonic flow regime it is evident that the design of hypersonic vehicles requires intricate design approaches and comprehensive considerations of a variety of aerodynamic theories. One should focus not only on the general aerodynamic performance of the vehicle, but also consider the efficient use of compression lift, stability and control of the vehicle, propulsion integration and heat transfer phenomena [9]. A few common design methods for the integration of the above factors are introduced below.

Though no general, closed form solutions exist for the hypersonic flow regime, one can often solve the governing equations numerically [10]. Computational Fluid Dynamics (CFD) has been a field of constant development for the past half century which can provides accurate results for almost all arbitrary aerodynamic configurations. In fact, given the difficulties of analytical designs, CFD dominates the analysis of modern hypersonic problems [10]. Various high-resolution numerical schemes developed by MacCormack, Van Leer, Godunov, etc. [1] are promising candidates for providing accurate and stable solutions in the analytical process.

A surprising finding is the high applicability of the Newtonian flow theories in hypersonic analysis. The simplicity and accuracy of this method in inviscid hypersonic problems made it favorable for providing important analytical insights. Newton initially proposed that the resultant force upon a solid body is due entirely to the momentum transfer in the normal direction from the impact of fluid streams, which assumes that fluid particles have no knowledge of the solid body until impact. Though inaccurate for general low-speed flow, the Newtonian flow theory is relatively accurate for hypersonic flows because the body moves so quickly that the fluid "cannot see it" before it passes [9].

In addition, for accurate simulations of the complex physics experienced by high-speed vehicles, ground testing facilities such as shock tubes and wind tunnels are usually employed. Experimental methods can recover the aero and thermodynamic loads exerted by the incoming flow upon target vehicle with high fidelity in a controlled setting. However, the high manufacturing and maintenance costs, as well as the sizing constraints of the facility associated with above experimental methods remain as roadblocks to an efficient and reproducible design method. In addition, a large number of experimental testing are still required to understand the relationship between actual flight data and data from measurements in test facilities [7], as experimental calibrations are integral to accurate analysis.

2.3. Hypersonic vehicle design example

The maximum lift-to-drag ratio $\mathrm{L/D_{max}}$ for a flight vehicle is a measure of its aerodynamic efficiency and crucial for large-scale transporting flights. However, for hypersonic flow, $\mathrm{L/D_{max}}$ reduces dramatically as $\mathrm{M_\infty}$ increases [10]. A class of configurations which retains relatively high $\mathrm{L/D_{max}}$ in hypersonic speeds is the waveriders, a supersonic/hypersonic configuration which has an attached shock along its leading edge. Waveriders form an attached shock on the bottom surface to sever communications between the top and bottom surface and preserve high pressures exclusively on the bottom surface, hence maintaining high lift. The advantage of the caret wing waveriders is that the body appears to be riding on top of the attached shock wave at design Mach number, as illustrated below in Figure 3 [9]. Figure 4 compares lift (L) and $\mathrm{L/D_{max}}$ of a waverider configuration to a generic vehicle. It is evident from Figure 4 that waveriders provide significantly higher lift for a given angle of attack compared to conventional vehicles.

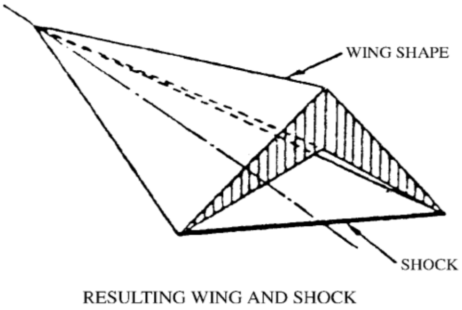

Figure 3. Caret Wing Waverider and attached planar shock on bottom surface [10].

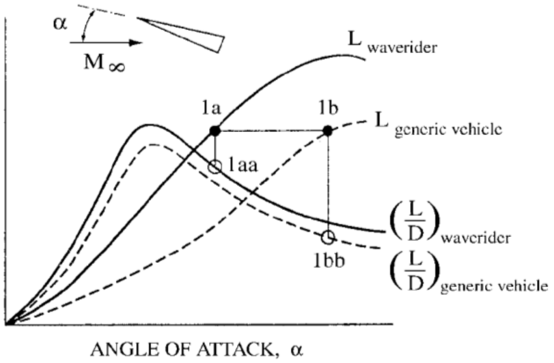

Figure 4. Comparison of Lift and $\boldsymbol{L/D}$ curves between a waverider and a generic vehicle [10].

Design of a configuration which has an attached shock can be done with few numerical calculations and experimental simulations. By employing an imaginary cone body in the incoming hypersonic flow, the 3D shock layer also takes the shape of a cone. By simply dissecting a region of this shock cone one obtains the airframe of a waverider which encloses a shock surface below its surface.

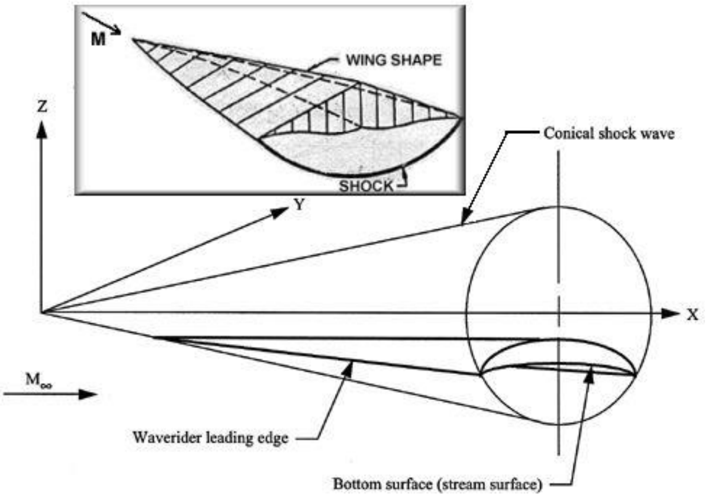

Figure 5. Construction of conical shock and waverider airframe [9].

In Figure 5, an imaginary conical shock was constructed, a waverider body is obtained by dissecting a region of this shock cone. The upper surface of the body is usually designed assuming it is a freestream surface or an expansion surface [9]. Similarly, the caret wing configuration can be obtained by constructing an imaginary wedge which produces 2D planar shocks. Analysis of planar and conical shocks are relatively simple compared to arbitrary compressible flow fields. 2D compressible flow relations can be employed for planar shocks as the flow conditions are identical across the span-wise direction of the caret wing. While conical shocks are quasi-3D, which have identical flow properties across the azimuthal direction. Exact numerical solutions of conical flow were first obtained by Taylor and Maccoll in 1932 and were intensively studied in the following decades [11]. The employment of known 2D and quasi-3D flow properties provides more flexibility in the generation of waverider shapes [9] – a desirable attribute in practical engineering design where shorter design cycles allows for more optimization iterations of the vehicle.

3. Applicability of commercial hypersonic transportations

3.1. Characteristics of hypersonic commercial transport

Hypersonic commercial transport (HST), as envisioned by Kirkham and Hunt in 1976, pertains to a 200-passenger, Mach 6 aircraft with a range of 9200 km, with a gross take-off weight similar to modern wide-body subsonic aircraft. Though much of this vision has yet to be realized, research efforts led by government agencies, universities and private sectors have made numerous advances towards bringing HST to the commercial aviation market. Currently, ten high-speed aircrafts cruising at exceeding Mach 4 have been introduced in recent years, with more than 300 city-pairs equipped with infrastructures to support high-speed commercial and general aviation [12]. A study by BryceTech on the marketing future of HST also found that the commercial high-speed transportation industry will justify the significant investments in research and development in excess of 20-billion dollars [12]. The introduction of a fleet of fast and reliable HST is thus the key to further developing the billion-dollar commercial aviation industry. The following section aims to analyze the compatibility of HST with the present from a technical standpoint.

3.2. HST compatibility analysis

A high-performance and reliable HST vehicle requires a combination of intricate technical considerations and strategies across multiple design aspects including fuel selection, modes of propulsion, airframe-propulsion integration, active cooling, fail-proof systems, etc. A successful HST design thus need combinatory efforts from all above fronts, which are applicable to different extents to current engineering capabilities and configurations mentioned above.

As noted by Kirkham and Hunt, liquid hydrogen fuel (LH_2) is integral to high-performance HST [13]. Its unique light-weight, energy-dense and heat-sinking capabilities provides HST vehicles tremendous advantages over conventional fuels. Compared with conventional jet fuel, hydrogen has almost 3 times the energy content and 30 times the heat sink capacity [13]. These chemical properties grant hypersonic vehicles superior range, payload capacity, and engine cooling capabilities over conventional transporting aircrafts. Configurations such as the caret and conical wing waveriders above can also provide large spaces for fuel storage, sufficient for large payloads over continental flights. Liquid hydrogen fuels, however, face challenges such as safety and ground storage [13]. Similar to rocketry applications, liquid hydrogen fuels would need to be injected right before take-off to prevent evaporation, which requires ground storage in all airports that are projected to support HST. The small size of hydrogen molecules poses additional challenges to the airframe materials and structures, which have to be designed to sustain heat loads and prevent leakage.

Unlike rockets, HST vehicles has the option for air-breathing propulsion systems to obtain oxidizers straightly from the atmosphere, which can dramatically decrease take-off weight and increase range. The propulsion system is tasked to sustain Mach 5+ speeds in rarified atmosphere while capable of low-speed operations [12]. However, both hypersonic air-breathing propulsion and airframe-engine integrations remain as challenges. Ramjets and scramjets technologies were both studied and tested extensively, where the testing programs in the U.S. Navy, Air Force and NASA provided general confirmation of predicted internal performance level in speed range of Mach 4-7 [12]. However, problems such as uncomplete combustion, undesired inlet vibrations and ingestion of boundary layer can all degrade engine performance [14]. In addition, the inlet design of hypersonic air-breathing propulsion must be completed with care, for the shock formed by the vehicle itself plays large roles in compressing the inlet fluids for scramjets. A uniform inlet flow produced by forebodies of the HST vehicle can maximize the engine efficiency and minimize fuel consumption. The caret wing waverider design, as mentioned above, generates a planar shock which can retain flow uniformity at the engine inlet, thus shown to be a promising candidate for HST propulsion integration. An illustration of airframe-propulsion integration is shown in Figure 6 below. Continuing efforts for airframe-propulsion integration applied on hypersonic vehicles are led by both numerical and experimental methods [13] and remain as active fields of research.

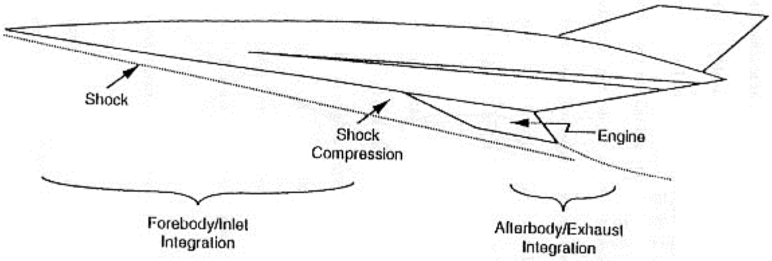

Figure 6. Body-induced shock compression of scramjet/ramjet engine in hypersonic flow [9].

As mentioned above, thermos effects are crucial to hypersonic vehicle design, for the extreme compression associated with the shock comes with high heat loads. Passive conduction via ablative materials needs to be supplemented with active cooling systems to prevent the airframe from melting or disintegrating. A sharp leading edge minimizes drag but intensifies heat conduction into the airframe, thus blunt shapes are needed to spread heat flux over a larger area and to provide volume for the application of heat-absorbing materials [9] and cryogenic cooling systems. For vehicles with moderate life requirement under Mach 6, heat shields would suffice as a passive cooling system, such as the Concorde. An actively cooled HST structure appears most attractive for hypersonic transport with long life requirements [13]. A liquid hydrogen propelled HST can circulate its liquid hydrogen along the nose and leading edge to cryogenically cool the airframe. A caret or conical wing waverider, with its large fuel capacity for liquid hydrogen, thus need not to carry additional coolant. Both passive cooling materials and active circulation cooling are crucial to a breakthrough of HST research.

4. Conclusion

This paper provides a holistic review of the present and future of hypersonic transport. The hypersonic flow field is prone to analytical difficulties such as thermochemical, gas association and other high-temperature effects. Common design principles of hypersonic vehicles and exemplar aerodynamic configurations such as the caret and conical waveriders and their properties are presented and explored. Liquid nitrogen (LH_2) is shown to be a favorable choice for HST fuel, while several active research fields related to airframe-propulsion integration and cooling system which are crucial to a successful commercial HST are presented. The caret wing shows unique properties of large fuel capacity, uniform engine inlet compression and supports for a cryogenic active cooling system. Future areas of research that fully explore the potential of caret wing waverider as HST include holistic aerodynamic analysis of integrated scramjet/ramjet engines via numerical methods, thermos analysis of integrated cryogenic LH_2 cooling systems, and ablative airframe materials.

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