Chapter

Introductory Chapter: Hypersonic Vehicles - Past, Present, and Future Insights

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1. Introduction

In the aviation field, great interest is growing in high-speed vehicle design. The increase in manned and unmanned space operations in low earth orbit (LEO) demands an evolution in the vehicle for payloads transportation up to and from LEO to improve the levels of flexibility, affordability and safety of routine access-to-space missions. Today this need is utmost stringent in the light of the NASA Space Shuttle retirement.

On the other hand, in the last few years, the attention to hypersonic travels for civilian application has also increased dramatically. Many start-up industries are focusing attention on hypersonic aircrafts able to fly, e.g., from New York to Sydney in less than 2–3 hours, thus providing a lot of insights on the oncoming market of hypersonic flights.

As a result, over the decades the potential benefit of an operational hypersonic vehicle (HV) has driven continued researches in basic and applied technologies. Indeed, several high-speed aircraft concepts (i.e., lifting and winged vehicles) have been conceived or developed in the USA, Russia (former USSR), Europe, France, Germany, Italy, and Japan to simplify access to LEO and sustained high-speed flight routinely and in a safe way. Most of these projects, however, were just prototypes or developed at the conceptual design stage and linked to flight testing focused mainly on some technologies rather than assessing the effectiveness and the advantages of a cutting-edge design.

A look on the HV research programs developed so far is hereinafter described for each country.

2. Past developments

US research on HVs lies on the X-plane (XP) programs. They are a series of experimental aircrafts to test and evaluate innovative technologies and aerodynamic concepts. Most of the XP have been operated by the National Advisory Committee for Aeronautics (NACA) or, later, the National Aeronautics and Space Administration (NASA), often in conjunction with the United States Air Force (USAF). The manned Bell X-1 and the North American X-15 were the most famous [1]. The former was the first aircraft to break the sound barrier in level flight in 1947. The latter was a hypersonic rocket-powered aircraft that achieved the world record for the highest speed ever recorded by a manned vehicle at the time [1].

Later XPs which supported important research in a multitude of aerodynamic and technical fields were unmanned (some were remotely flown, some were partially or fully autonomous) such as the X-20 Dyna-Soar, X-23A, X-24, X-30, X-33, X-34, X-37, X-38, X-43, X-51, and Dream Chaser [1]. The X-20 was a USAF program to develop a spaceplane for several military missions, including satellite maintenance or sabotage and aerial reconnaissance. The vehicle configuration was innovative and more like the much later Space Shuttle. It was designed to glide to Earth like an aircraft under the pilot's control and land on runway, rather than simply falling to Earth and landing with a parachute. The program started on October 24, 1957, but was cancelled in 1963 just after spacecraft construction. The X-23A was a small lifting body tested by the USAF to study the effects of maneuvering during reentry, including cross-range maneuvers. The X-24 was developed from a joint USAF-NASA program. It was designed and built to test lifting body concepts, experimenting with the concept of unpowered reentry and landing, later used by the Space Shuttle [2]. The X-30 was an advanced technology demonstrator for the National Aero-Space Plane (NASP) program to create a single-stage-to-orbit (SSTO) spacecraft and passenger spaceliner. It started with the aim to advance and demonstrate hypersonic technologies for scramjet-powered vehicles. The X-30 was cancelled in the early 1990s before a prototype was completed, although much development work in advanced materials and aerospace design was completed [3, 4]. The X-33 was an unmanned, subscale technology demonstrator for the VentureStar orbital spaceplane, which was planned to be a next-generation reusable launch vehicle (RLV) [5, 6]. The X-33 would flight-test a range of technologies that NASA deemed critical for SSTO RLVs, such as the aerospike engine, metallic thermal protection system (TPS), and its lifting body aerodynamics. The X-34 was intended to be a low-cost testbed for demonstrating RLV key technologies [7]. It was conceived to be an autonomous pilotless craft capable of reaching Mach 8 and performing 25 test flights per year. The X-37 is a reusable HV developed as orbital test vehicle (OTV) [8, 9]. An early goal for the program was in-orbit operations for the spacecraft to rendezvous with satellites and perform repairs. The technologies demonstrated in the X-37 include an improved TPS, enhanced avionics, an autonomous guidance navigation, and control system. The X-38 was an experimental reentry vehicle designed by NASA to research a possible emergency crew return vehicle (CRV) for the International Space Station (ISS) [10].

Following NASP, in the 2000s, NASA concern was National Aerospace Initiative (NAI) where a large use of multidisciplinary design was undertaken. The NAI's mission was to ensure the USA's aerospace leadership with an integrated, capability-focused, national approach that enables high-speed/hypersonic flight; safe, responsive, affordable, reliable access to and from space; and in-space operation by developing, maturing, demonstrating, and transitioning transformational aerospace technologies. In the framework of NAI, NASA performed several in-flight validations of hypersonic technologies and evaluation of new concepts, such as X-43 and X-51 vehicles [11, 12]. The X-43 program set out to demonstrate hydrogen-fueled scramjet operations in a fully integrated aircraft system at Mach numbers of 7 and 10. The X-43 vehicle was a 4-m-long lifting body design, weighing about 1500 kg, with a fully integrated scramjet engine. The two flights of the X-43A vehicles were successful in achieving all research objectives. Comparisons to ground test in shock-heated tunnels confirm the ability of these facilities to measure engine performance consistent with flight.

The recently successful X-51 flight program went even further in technology development and mission objectives. After release from the B-52 carrier, the waverider-derived vehicle is accelerated by an ATACMS booster to Mach 4.5, whereas the scramjet engine further accelerated the vehicle up to about Mach 6. Furthermore, the engine flowpath is cooled using fuel in a cooled loop to both maintain tolerable flowpath temperatures and crack the fuel to facilitate ignition once it is injected into the combustion region of the scramjet engine. The external vehicle configuration utilizes a waverider-type aerodynamic mold line as forebody to maximize hypersonic L/D ratios. After three (partial) failures, the final flight of the X-51A Waverider test program has accomplished a breakthrough in the development of flight reaching Mach 5.1 over the Pacific Ocean on May 1. The cruiser travelled over 250 km in just over 6 minutes. It was the longest of the four X-51A test flights and the longest air-breathing hypersonic flight ever.

The Dream Chaser is a reusable lifting-body spaceplane being developed by Sierra Nevada Corporation (SNC) [13].

Russia (former USSR) involvements in developing high-speed vehicles and their related propulsion units refer to various Mach numbers. Russia was and still is very active in high-speed vehicle and propulsion design for various Mach numbers. However, limited information is available. The most important was the OK-1K1 spaceplane, referred to as Buran [14]. It was the first spaceplane to be produced as part of the Soviet/Russian RLV program and is the only Soviet RLV to be launched into space.

In Europe, in the last years, a whole range of space transportation concepts under various research and development programs have been investigated. During the 1980s and 1990s, there was significant interest in designing a RLV. National space agencies such as the Centre National d'Études Spatiales (CNES) of France and the German Aerospace Centre (DLR) worked on their own designs, the most prominent of these to emerge being the Hermes spaceplane of CNES [15]. It is very similar to the X-20 and the Space Shuttle. As intended, the Hermes was an RLV to transport both astronauts and moderate-size payloads into LEO and back again. In comparison to the Shuttle, Hermes is a substantially smaller vehicle and does not share the ogival platform of the Orbiter. But, it was designed with a highly swept delta wing with wingtips, close to the X-20. Then, Hermes was later further developed by the European Space Agency (ESA) for several years but was ultimately terminated in 1992 prior to any flights due to numerous delays for unachievable performance goals and funding issues. After the abandonment of the Hermes program, ESA, however, decided to maintain the strategic long-term objective to develop a RLV. It was started the Future European Space Transportation Investigations Programme (FESTIP). In the framework of FESTIP, the Hopper concept was envisioned by the ESA as RLV. It was one of the several concepts to function as a European RLV for the inexpensive delivery of payloads into orbit [16]. A prototype of Hopper, namely, Phoenix, was tested within the wider ASTRA program of the DLR [17, 18]. After that, ESA started the Future Launchers Preparatory Programme (FLPP) [19]. Under FLPP, Europe has undertaken detailed investigations of several partially reusable launch concepts with the aim to develop a next-generation launcher [19]. A total of four concepts were investigated, namely, the horizontal take-off (HTO) Hopper, the vertical take-off (VTO) Hopper, the reusable first stage, and the liquid fly-back booster [20]. Each of these concepts consisted of a reusable winged booster, able to carry an expendable upper stage, to deliver a payload in geostationary transfer orbit [21]. The HTO Hopper featured a relatively conventional wing-body configuration, investigated yet within the ASTRA program [17]. The VTO-Hopper was designed with a traditional slender missile-like body but with a small delta wing and a central vertical stabilizer arrangement [21]. To test and further develop the technologies and concepts produced by these studies, there was a clear need to accumulate practical flight experience. To this end, ESA has undertaken the design of the intermediate experimental vehicle (IXV) also promoted within the FLPP framework [22]. It was derived by the Pre-X concept investigated early by CNES [23]. The IXV holds the distinction of being the first ever lifting body to perform full atmospheric reentry.

German studies refer to the SHarp Edge Flight EXperiment (SHEFEX) program of DLR for the development of future reentry and hypersonic technologies [24]. The goal is to set up a flying laboratory to gain knowledge of the physics of hypersonic flow, complemented by numerical analysis and ground-based testing. SHEFEX flight experiments were an excellent laboratory to test new technological concepts and in-flight experimental sensors.

In Italy there was the unmanned space vehicle (USV) program [25]. Within the ongoing USV project, CIRA conceived a family of flying test beds (FTB's) for in-flight experiments in the fields of aerodynamics, aerothermodynamics, flight mechanics, control, and aeroelasticity. The first phase of the USV Program consisted of the design and realization of two laboratories (i.e., FTB-1). The FTB-1 concept was based on a winged slender-body vehicle able to address in-flight experiments and low atmosphere maneuvered flights at supersonic, transonic, and low subsonic Mach numbers, referred to as dropped transonic flight test (DTFT) missions. The flight test success demonstrated the ability of designing and implementing robust guidance and control laws up to low subsonic Mach numbers.

Japan contributions to unmanned RLVs' design refer to programs of National Space Development Agency of Japan (NASDA) and, later, by the Japan Aerospace eXploration Agency (JAXA). Hypersonic Flight Experiment (HYFLEX) was a NASDA unmanned reentry demonstrator which was launched in 1996 from the Tanegashima Space Center by a J-I expendable rocket. It was a successor of OREX and was a precursor for the HOPE-X concept [26]. HYFLEX was a lifting body laboratory to gather data on aerodynamic heating and pressure loads.

3. Present developments

To date there are only two servicing HVs, namely, the X-37 and the Soyuz spacecrafts. As discussed before, the former is a US unmanned reentry spacecraft (winged-body) close to the Space Shuttle, while the latter is the only human-rated capsule operated by Russian Federation [9, 27, 28].

The X-37's aerodynamic design was derived from the Shuttle Orbiter, and hence the X-37 has a similar lift-to-drag ratio (L/D). The X-37 is the smallest and lightest lifting winged vehicle flown to date. It features a forwarded double delta wing and a butterfly tail [9]. The X-37 re-enters Earth's atmosphere and lands automatically. It is the second reusable spacecraft to have such a capability, after the Buran shuttle [14]. The X-37 is now operated by the USAF being transferred to the Defense Advanced Research Projects Agency (DARPA).

The Soyuz spacecraft was designed for the Soviet space program by the Korolev Design Bureau in the 1960s, and it is still in service today. It is currently the only manned space vehicle in the world to support flight to and from the ISS. The spacecraft consists of three parts, namely, orbital module (OM), service module (SM), and reentry module (RM). The OM is a spheroid spacecraft's segment which provides accommodation for the crew during mission. The cylindrical spacecraft's segment is the SM. It features solar panels attached and contains the instruments and engines. Finally, the RM is a small capsule which returns the crew to Earth [27, 28].

4. Future developments

As future developments in HVs, there are Dream Chaser and Space RIDER (both lifting bodies) concepts. They are being developed by the USA and Europe, respectively [13, 29, 30].

The Dream Chaser is a reusable lifting-body spaceplane that can fly autonomously to resupply the ISS with both pressurized and unpressurized cargos. The vehicle is designed to be launched on expendable rockets, return from space by gliding, and autonomously land on conventional runways. The potential further development of the spaceplane includes a human-rated version which would be capable of carrying up from two to seven people to and from LEO. Dream Chaser design is derived from NASA HL-20 lifting body which was itself like the Soviet BOR-4 [1, 14, 31].

The experience and data obtained by Europe so far on Hermes, FESTIP, and FLPP programs served as stepping stones toward a vehicle called Space Reusable Integrated Demonstrator for Europe Return (Space RIDER), underdeveloped by ESA [29]. The Italian Space Agency (ASI), with the project being led by the Italian Aerospace Research Centre (CIRA), presented its own Programme for Reusable In-orbit Demonstrator in Europe (PRIDE) to develop the prototype named Space RIDER [30]. It is an unmanned spacecraft aiming to provide the ESA with affordable and routine access to space.

5. Designing hypersonic vehicles and preset book aims

Such a limited number of operating HVs are due to the high operative cost and, especially, to the complexity in designing such vehicles, especially for human-rated missions. Indeed, HVs' design is an extremely challenging process involving several disciplines, e.g., aerodynamic, aerothermodynamic, control, avionics navigation systems, propulsion, and structure. As well known, these disciplines are strongly coupled with one another and generally influence each other because they involve antagonistic objectives. Therefore, it is expected that synergistic interactions, between vehicle subsystems and functions, can produce an optimized multidisciplinary vehicle design with significant performance and economic improvements [32–40].

This suggests using specific methodologies to assess trade-off analyses between the enabling disciplines as the only way to obtain a satisfactory (global optimal) vehicle design, referred to as multidisciplinary design optimization (MDO) [41–48].

The book aims at highlighting that the design of HVs must pass from a conventional design to a more complex and challenging highly integrated design framework, according to the MDO approach.

Several chapters in the present book focused attention on this fundamental topic, especially for what concerns the design of scramjet-propelled vehicle configurations. For instance, the design and optimization about the integration of airframe-propulsion design issue are discussed as well as the design of vehicle TPS with parametric integral soft object-based procedure. Anyway, investigations of more conventional topics are also provided in the book, as numerical simulations of base pressure and drag of typical reentry vehicles.

In this framework, the ambition of the present book is to support industries, research centers, and space agencies in their own design and development of next-generation HVs. Therefore, this book is recommended for both students and research engineers involved in all design phases, typical for hypersonic vehicles.

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