Progress in Aerospace Sciences 84 (2016) 1–28

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

Review article

A review of design issues specific to hypersonic flight vehicles

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ARTICLE INFO

Article history:
Received in revised form
4 April 2016
Accepted 6 April 2016
Available online 13 April 2016

Keywords:
Hypersonic Transport
Space Launcher
Design review

ABSTRACT

This paper provides an overview of the current technical issues and challenges associated with the design of hypersonic vehicles. Two distinct classes of vehicles are reviewed; Hypersonic Transports and Space Launchers, their common features and differences are examined. After a brief historical overview, the paper takes a multi-disciplinary approach to these vehicles, discusses various design aspects, and technical challenges. Operational issues are explored, including mission profiles, current and predicted markets, in addition to environmental effects and human factors. Technological issues are also reviewed, focusing on the three major challenge areas associated with these vehicles: aerothermodynamics, propulsion, and structures. In addition, matters of reliability and maintainability are also presented. The paper also reviews the certification and flight testing of these vehicles from a global perspective. Finally the current stakeholders in the field of hypersonic flight are presented, summarizing the active programs and promising concepts.

Contents

Abbreviations: AETB, Alumina Enhanced Thermal Barrier; AFRSI, Advanced Flexible Reusable Surface Insulation; AOA, Angle of Attack; CFD, Computational Fluid Dynamics; CG, Centre of Gravity; EASA, European Aviation Safety Agency; EMU, Extravehicular Mobility Unit; ESA, European Space Agency; EMU, Extravehicular Mobility Unit; EVA, Extravehicular Activity; FAA, Federal Aviation Administration; FRCI, Silicon Fibrous Refractory Composite Insulation; FRSI, Felt Reusable Surface Insulation; GPS, Global Positioning System; GSO, Geostationary Orbit; GTO, Geostationary Transfer Orbit; HRSI/LRSI, High/Low Temperature Reusable Surface Insulation (tiles); ICAO, International Civil Aviation Organization; I_{sp}, Specific Impulse; ISS, International Space Station; L/D, Lift to drag ratio; LACE, Liquid Air Cycle Engine; LEO, Low Earth Orbit; M, Mach number; MHD, Magneto-hydrodynamic; MTSO, Multiple Stage to Orbit; NGSO, Non-Geostationary Orbit; ODS, Oxide Dispersion Strengthened (alloy); OMS, Orbital Manoeuvring System; RCC, Reinforce Carbon-carbon Composite; RCS, Reaction Control System; ROCCI, Refractory Oxidation Resistant Ceramic Carbon Insulation; SHARP, Slender Hypervelocity Aerothermodynamic Research Probe; SPFI, Surface Protected Flexible Insulation; SSO, SpaceShipOne; SSTO, Single Stage to Orbit; STS, Space Transportation System; TPS, Thermal Protection System; TSTO, Two Stage to Orbit; TUFI, Toughened Uni-Piece Fibrous Insulation; TUFROC, Toughened Uni-piece Fibrous Reinforced Oxidation-resistant Composite; USAF, United States Air Force

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http://dx.doi.org/10.1016/j.paerosci.2016.04.001
0376-0421/

1. Introduction

Currently most large airframe manufacturers are focusing on developing more efficient, cheaper, greener aircraft designs.

There are, however, other requirements which have to be considered in addition to economic and environmental aspects. The ability in itself, to drastically reduce travelling time, could justify the existence of a Hypersonic Transport for applications such as emergency response, time critical business trips, not to mention military applications. A typical Hypersonic Transport is estimated to travel from Tokyo to Los Angeles in only 110 min [1]. While not fundamentally different, another distinct form of application for hypersonic flight is the Space Launch System. Compared to contemporary space access technology, Space Launchers offer a significant advantage: they can reach, operate in and return from orbit without expending the vehicle. Expendable launch vehicles add significant overhead cost to any space access mission, as the cost of launching the payload includes the acquisition cost of the launcher. Also, time between launches is limited by the availability of new launch vehicles, which potentially prevents rapid response missions from being performed.

To develop a successful hypersonic vehicle, it is not enough to concentrate on the vehicle itself, but rather it has to be looked at from a systems point of view. This ensures that not only performance goals are met, but also safety, security, maintainability, operational flexibility, reliability and sustainability as well.

This paper aims to investigate the challenges associated with the design of hypersonic vehicles. Past designs and concepts, current solutions and developments and likely future trends are considered to present the state of the art and the possible vehicles of tomorrow. The design of this special class of vehicle is investigated from a multidisciplinary point of view.

A brief historical background of the hypersonic vehicles is presented, highlighting the successful concepts. Operational issues are then investigated, dealing with both economic and environmental questions, from both the users and global point of view. A summary of the technological issues to overcome is also presented, highlighting the aerothermodynamics and propulsion aspects, the two main challenges with hypersonic vehicles. In addition to these, the topics of reliability and maintainability are also considered. Further challenges, testing and prediction methods, along with the current state of certification issues are also covered. Finally, a list of stakeholders is presented along with current projects to show the state of the art in the field of hypersonic vehicles.

2. Historical background

Surprising though it may seem, the concept of hypersonic flight surfaced relatively early. In the late 1930s Eugene Sänger had conceived a rocket-powered boost-glide vehicle in Germany, named Silbervogel [2] (Silver bird) which could have been used to attack the United States, and land safely in Japan afterwards. Although the project was cancelled by the Reich Air Ministry in 1941, Sänger never gave up his dream, and continued working on the concept, paving the way for many aerospace vehicle designs to come (Fig. 1).

After the thirties, many concepts were investigated, but due to lack of funding, or technological immaturity, the vast majority of these remained on the drawing board. Up to now only 5 aerospace vehicles have made it into space and returned safely, these are: X-15, Space Shuttle, Buran, SpaceShipOne and X-37. It has to be noted, that the generally accepted definition of space means an altitude above the Kármán line, at least 100 km.

The pioneer in the field of hypersonic flight was the North American Aviation X-15 [4]. The program began in 1954, with the first flight occurring on the 8th of June, 1959. There were 3 test aircraft manufactured, taking part in a total number of 199 flights. They were dropped at high altitudes from a modified B-52 aircraft, after which their own engines would start, and the flight testing phase could begin. The maximum altitude reached was 107.96 km (Flight 91), while the highest speed attained was 7273 km/h (Flight 188). The X-15 provided large amounts of high speed flight data, including lift distribution and control systems effectiveness.

The Space Shuttle program (formerly known as the Space Transportation System) was initiated in 1969, when President Richard Nixon formed the Space Task Group. The official approval (and government funding) of the STS program began in 1972, with the first powered flight taking place on 12th April 1981. Although the program run until 2011, and a total of 135 missions were flown, the STS program did not satisfy all of the original requirements, especially in terms of cost and turnaround times. Also, the Shuttle system was only partially reusable, because of the expendable fuel tank, and the recoverable boosters required almost full reconstruction between each launch, resulting in high cost, and man-hour requirements. In addition to launching a maximum of 25 ton payload to LEO, the Shuttle had the additional benefit of performing maintenance tasks in orbit, and it could also return objects from space when required. The Space Shuttle re-entered the atmosphere at around the speed of M 25.

The Buran was the Soviet answer to the Space Shuttle. Shortly after completing one unmanned autonomous flight on 15th